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[Article]

Use of Catenary Geometry to Estimate Hook Depth during Near-Surface Pelagic Longline Fishing: Theory versus Practice

PATRICK H. RICE*
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33133, USA

C. PHILLIP GOODYEAR
1214 North Lakeshore Drive, Niceville, Florida 32578, USA

ERIC D. PRINCE, DERKE SNODGRASS, AND JOSEPH E. SERAFY
National Marine Fisheries Service, Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, Florida 33149, USA

Abstract.—Management and conservation of many highly migratory fish species are based on population assessments that rely heavily on catch and effort data from the pelagic longline fishing industry. In 2003, we monitored hook time at depth for shallow-set commercial longlines (i.e., four hooks between surface buoys) targeting swordfish *Xiphias gladius* in the Windward Passage between Haiti and Cuba. We deployed temperature–depth recorders (TDRs) on about every 13th hook and attached them to branchlines just above the hook. Most TDRs were placed on branchlines that were predicted by catenary geometry to be at the deepest hook position between floats. Additional TDRs were also placed at the shallowest predicted hook position. We monitored 10 pelagic longline sets with a length (mean ± SE) of 44.9 ± 2.0 km. Time at depth for each TDR was binned into 5-m depth intervals. The expected bimodal distributions of hook time at depth were not observed; modes were 40 m for both the shallowest and deepest predicted hook positions. The majority of the hook depth distributions for shallow and deep hook positions achieved only 43% and 31%, respectively, of the depths predicted by catenary equations (i.e., <92 and <127 m). Individual TDRs were poor estimators of hook time at depth for other TDRs in the same catenary hook position during the same set (significant mean depth differences = 76.2–100%) and were even worse predictors of the depths fished during other sets (significant mean depth differences = 100%). Hook depth predictions based on catenary geometry drastically overestimated actual fishing depth in this study. These results indicate that the use of catenary geometry for estimating hook depth and subsequent vertical fishing effort is inadequate and fails to capture both within- and among-set variability, potentially resulting in biased stock assessments.

Catch per unit 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:

$$N = C \times (q \times f_n)^{-1}, \quad (1)$$

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 (i.e., probability associated with the capture potential of a specific fish per unit of fishing effort), and f_n is the nominal fishing effort (i.e., nonstandardized effort) (Hinton and Nakano 1996). However, this model assumes that (1) the animal population is homogeneously distributed throughout the body of water fished and (2) there are no variations in fishing effort (i.e., all fishers use the same fishing strategies and have an equal probability of catching fish). These conditions are not realistic; therefore, catch and effort data require standardization for inferential statistics.

Several methods are typically employed to standardize catch and effort data, including general linear models (GLMs), general additive models, neural networks, habitat-based standardization (HBS), and statistical HBS (statHBS) (Hinton and Maunder 2004). Habitat-based standardization of pelagic longline (PLL) CPUE time series for billfishes (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

* Corresponding author: patrick.rice@noaa.gov

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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, or other factors. Regardless of the HBS methodology used, the model 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 that the gear orients in the vertical plane and that 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:

$$D_j = h_a + h_b + l\left\{(1 + \cot^2\phi)^{0.5} - [(1 - 2j/n)^2 + \cot^2\phi]^{0.5}\right\}, \quad (2)$$

where D_j is the depth of the jth hook in a longline segment between surface buoys (hereafter, baskets), h_a and h_b are the branchline and floatline lengths, respectively, l is one-half 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 jth branchline 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 floatline (Figure 1). Yoshihara (1954) correlated ϕ to the "sagging" rate (S) of the PLL gear. As the name implies, sagging of the mainline occurs due to gravity pulling downward 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 or wind, the amount of sag in the mainline decreases and shoaling of the gear occurs. Therefore, ϕ is not a constant but rather is 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; Nakano et al. 1997; Brill and Lutcavage 2001). However, Takeuchi (2001) suggested that gear configuration information, including historical information on the number of hooks between floats, is inadequate for CPUE standardization. Goodyear

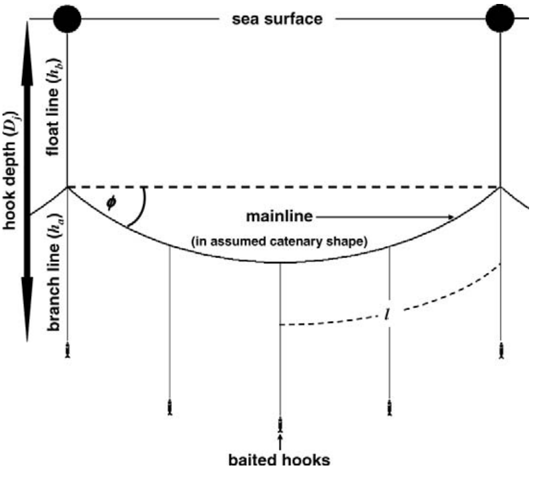

FIGURE 1.—Schematic representation of a single basket of typical near-surface pelagic longline fishing gear, showing the geometric components necessary to calculate hook depth using the catenary equation developed by Yoshihara (1951, 1954) and refined by Suzuki et al. (1977).

(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 organized by the Methods Working Group of the International Commission for the Conservation of Atlantic Tunas (Anonymous 2003), which recommended additional research into species and hook distributions.

Many factors have been identified that affect hook depth during PLL fishing; these include: (1) vertical current shear between surface and subsurface currents (Boggs 1992; Berkeley and Edwards 1998; Mizuno et al. 1999; Bigelow et al. 2006), (2) wind (Yano and Abe 1998; Ward and Myers 2005), (3) the 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 and Snodgrass 2003). 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 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 (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 gear deployments for swordfish *Xiphias gladius* and 266 commercial deployments for tunas *Thunnus* spp. 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 is limited in these prior studies because they (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. In the second year of their study, Yano and Abe (1998) 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 our study were to (1) 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) analyze both within-set and among-set variability in hook depth distribution; (3) compare these observed depth distributions with (a) predicted depths based on catenary depth calculated from PLL configuration information and (b) the most conservative adjustments to depth predicted by catenary algorithms; (4) develop a suitable methodology, based on information currently obtained and reported by the commercial PLL industry, for determining *S*-values, indicating horizontal changes in gear shape (i.e., stretching and compression) that translate into vertical changes is fishing depth; and (5) increase the amount of data available on the variability associated with hook depth during PLL fishing under a variety of environmental conditions.

Methods

Ten longline sets were deployed in the Windward Passage between Haiti and Cuba (Figure 2) during June 2003 from the U.S. commercial PLL fishing vessel, F/V *Carol Ann*. The F/V *Carol Ann* is a 16.76-m fiberglass vessel that typically targets swordfish and multiple tuna species (e.g., bigeye tuna *T. obesus* and yellowfin tuna *T. albacares*) depending on the time of year, location, and fishing season. In this study, longline sets targeting swordfish were deployed at dusk and allowed to soak overnight. Fishing locations (latitude and longitude) were recorded during longline gear deployment and retrieval. The gear configuration consisted of four branchlines between 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; 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 branchlines with terminal gear (i.e., hooks), buoys, and radio beacons were attached as the boat moved forward. The length of the set was calculated by multiplying the vessel's velocity with the deployment duration. Vessel velocity was determined using Global Positioning 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 3). Longline gear drift was employed as a proxy for current direction and velocity (Nishi 1990; PFRP 1998). We calculated *S* as the ratio of the final horizontal distance between floats and the estimated

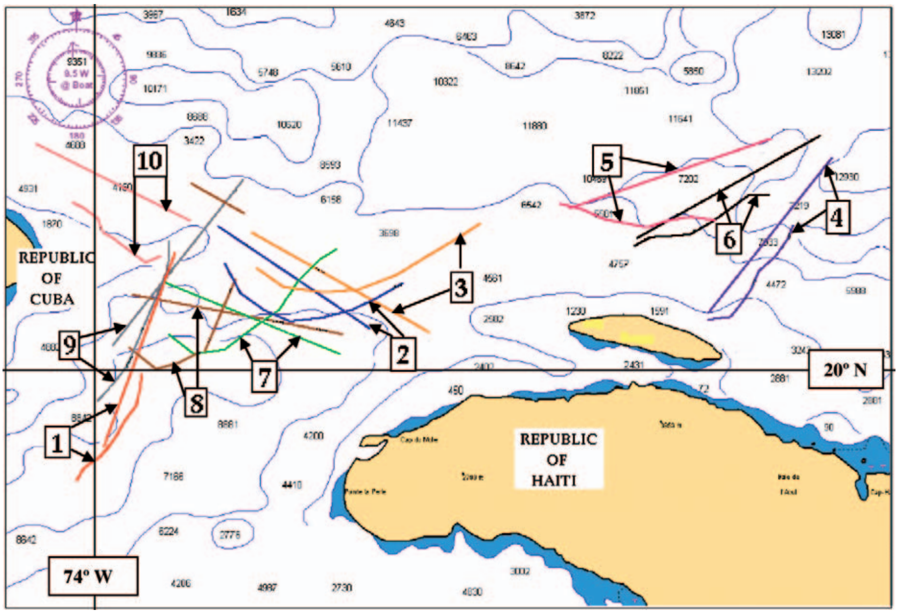

FIGURE 2.—Plot of 10 sets of pelagic longline gear (targeting swordfish) deployed in the area of the Windward Passage between Haiti and Cuba by the F/V *Carol Ann* during June 2003. Straight lines represent gear deployment positions. Nonlinear tracks represent gear retrieval positions. Numbered squares with arrows indicate consecutive longline gear deployment and retrieval locations. Examples of gear compression (set 10) and gear stretching (set 7) during the soak are illustrated.

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) consisting of 20 baskets (Figure 4). Each basket contained four hooks between floats, and about 560 hooks/set were deployed during all 10 sets.

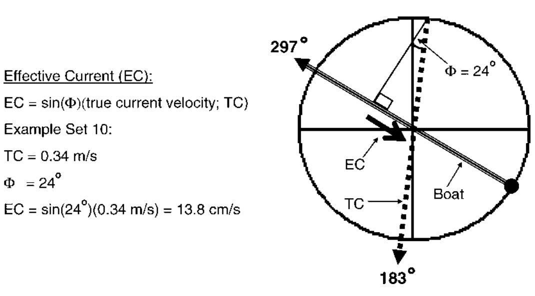

FIGURE 3.—Method for calculating the effective current (EC) experienced by a pelagic longline fishing vessel during gear deployment. The right triangle created by the angle between the direction of the vessel and the direction of the current is used to calculate the current vector either opposing or assisting the vessel.

The hooks were stainless-steel 18/0 circle hooks (Lindgren-Pittman, Inc.) with an offset of 0° (i.e., nonoffset) or 10°. Bait consisted of squid *Ilex* spp. (~300 g each). Each floatline was 18.3 m in length. Each branchline (160-kg test; 2.1-mm diameter) was 20.1 m in length with a 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.) that was subsequently fastened to the mainline (Figure 4) and used to corroborate the time of fish strikes, 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 and other factors. 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; in specific baskets throughout the set, a second TDR was placed on the assumed shallowest

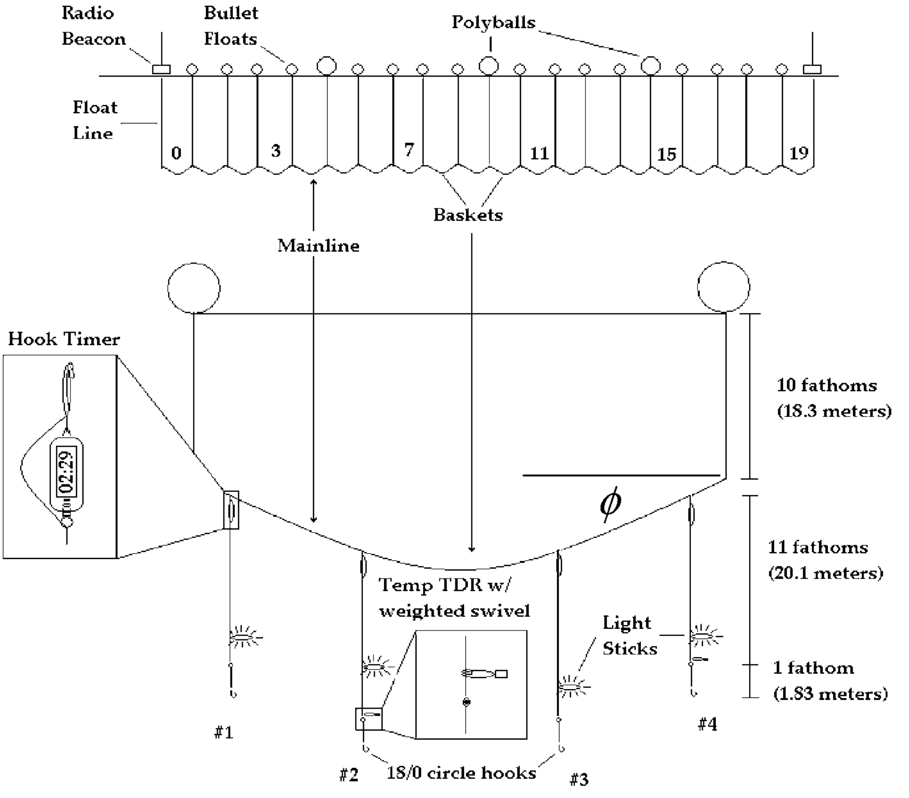

FIGURE 4.—Schematic representation of an entire section of pelagic longline gear (top) with numbered baskets containing temperature–depth recorders (TDRs), and enlarged diagram of a basket (bottom) equipped with hook strike timers, TDRs, light sticks, and hooks, and showing floatline, branchline, and leader lengths. 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.

hook (i.e., hook 1 or 4) as illustrated in Figure 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 s, and time at depth was calculated in a manner similar to that used by Yokawa and Takeuchi (2003). To distinguish malfunctioning TDRs (e.g., unreasonable temperature or pressure measurements) and to determine variability in temperature and pressure measurements between TDRs before gear deployment, the TDRs were tested against one another by deploying them into the water column simultaneously 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 (Lotek Wireless).

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 before deployment. Pressure was converted to depth (6.8948 kPa [1 lb/in^2] = 0.6838533 m), allowing a nearly continuous record of the fishing depth for each monitored branchline. Temperature–depth recorders on branchlines where hook strike timers indicated fish interactions (e.g., capture or fish strike and subsequent escape) were excluded from this 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 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

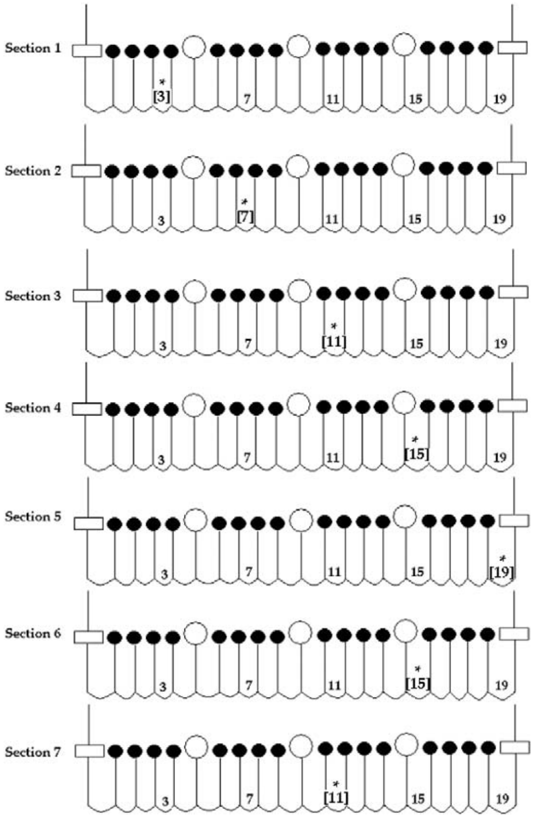

FIGURE 5.—Schematic representation of a pelagic longline by sections (1–7). Asterisks above bracketed numbers indicate baskets with two temperature–depth recorders (TDRs; one each on the shallowest and deepest hooks). Numbers without brackets or asterisks indicate baskets with only one TDR on the deepest hook.

P-values less than 0.05. Statistical analysis was performed using the SAS system, version 9.0 (SAS Institute 2003).

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 10 sets made in the Windward Passage (Figure 2). The mean (±SE) set distance was 44.9 ± 2.0 km; initial and final average distances between floats were 0.32 and 0.29 km, respectively, and the average S for all 10 sets was 0.91 (Table 1). In several cases, S was reported as greater than 1.0, indicating that the PLL gear was stretched beyond the initial deployment length.

Statistical analysis revealed that high variability in hook depth is the norm rather than the exception and that the cumulative time at depth for each TDR was highly variable both within and across sets. The within-set variability for mean hook depth (percent significant depth differences) in the presumed shallow and deep hook positions ranged from 72.2% to 100% and from 92.4% to 96.0%, respectively (Table 2). Pairwise comparisons of mean hook depth between sets for shallow and deep hook positions revealed 100% significant differences in all cases (Table 2).

For the presumed shallowest catenary hook positions (hooks 1 and 4), variance in the distribution patterns between each of the 10 sets illustrates the high variability in hook time at depth (Figure 6). For the deepest presumed catenary hook positions (hooks 2 and 3), variance in the distribution patterns between each of the 10 sets illustrates the same high variability (Figure 7).

The majority of the time (32%) fished by hooks in the shallowest catenary hook position for all 10 sets was spent in the 40-m depth bin; the maximum fishing depth was about 95 m (Figure 8). Similarly, the majority of the time (25.5%) fished by hooks in the deepest catenary hook position for all 10 sets was spent in the 40-m depth bin; however, in this hook position, the maximum reported fishing depth was about 160 m (Figure 9). The mean (±SE) estimated initial distance between hooks was 64 ± 3 m; therefore, the predicted depth using our gear configuration and catenary geometry (Yoshihara 1951; Suzuki et al. 1977) was 92 m for the shallowest hook position (Figure 8) and 127 m for the deepest hook position (Figure 9). Therefore, most of the observed hook depth distribution, regardless of hook position, was considerably shallower than that predicted by the catenary equation. For the majority of the time, the shallow and deep hook positions occupied only 43% and 31%, respectively, of estimated hook depth.

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 fail to (1) provide accurate estimates of fishing depth, (2) provide the proportion of time spent at a particular fishing depth, and (3) capture the variability in fishing depth associated with PLL fishing.

Catch and effort statistics require standardization of the nominal fishing effort (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

TABLE 1.—Details of commercial swordfish gear deployment in the Windward Passage for each set or 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 (GPS distance, including curvature of the Earth's surface). Total PLL gear deployed equals the EC multiplied by the set duration and added to or subtracted from the recorded great circle distance depending on the direction of the current (i.e., [EC × set duration] × [±1 + great circle distance]). An EC of zero suggests that the current was oriented perpendicular to the vessel during gear deployment. Sag ratio (*S*) is the ratio of the final distance between floats (DBF) to the initial DBF. An *S*-value greater than 1.0 indicates that the PLL gear was stretched. Color codes correspond to those in Figure 2.

Set or haul number	Color code	EC (km/h)	Set duration (h)	PLL adjustment (km)	Great circle distance (km)	EC (+/−)	Initial gear length deployed (km)	Initial DBF (km)	Final gear length (km)	Final DBF (km)	*S*
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
Average		1.36	3.61	4.66	45.6		44.9	0.32	40.01	0.29	0.91

fishing strategies change over time. For example, before the mid-1970s, PLL gear configuration was dominated by near-surface (i.e., shallow) deployments realized by few hooks per basket (i.e., ≤7) (Hinton and Nakano 1996). Initially, the primary target was yellowfin tuna, but there was a shift towards albacore tuna *T. alalunga* around 1962 (Saito 1973; Nakano 1996; Uozumi 1996). In the early 1970s, the development of super cold freezers (−50°C) 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 that live deeper in the water column: bigeye tuna, southern bluefin tuna *T. maccoyii*, and northern bluefin tuna *T. thynnus* (Nakano 1996; Uozumi 1996). To target these deeper-dwelling tunas, 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 before the mid-1970s with present CPUE data prove problematic without proper standardization (Serafy et al. 2005).

TABLE 2.—Within-set and among-set comparisons of mean hook depth in longline gear targeting swordfish in the Windward passage, revealing the percentage of significant differences for hooks in the same catenary-predicted shallow and deep hook positions.

Set or haul number	Within sets (%)		Among sets (%)	
	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

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 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 2°-latitude × 5°-longitude segments (i.e., about 222 × 555 km at the equator) and considered fishing effort to be uniform within these strata. However, PLL fishers target specific fishing areas where concentrations of fish are high, such as oceanic fronts (Olson 2002). They 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 tunas, billfish (Istiophoridae), and swordfish (Xiphiidae) have been reduced by as much as 90% from historical levels based on commercial Japanese PLL catch data and assuming homogeneous fishing effort apportioned into 5° × 5° segments. However, our results indicate high

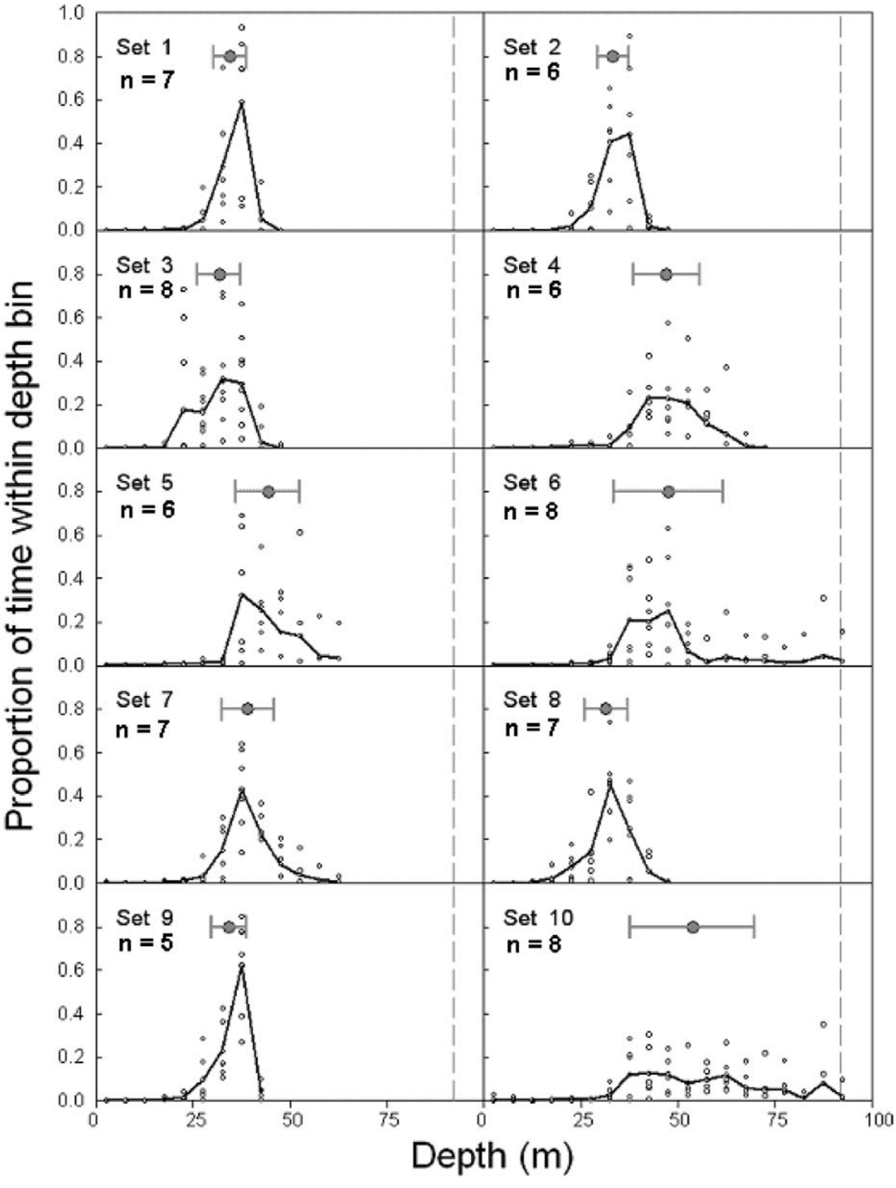

FIGURE 6.—Observed proportion of time at depth (5-m bins) for individual temperature–depth recorders (TDRs) attached to the shallowest hook positions monitored during 10 pelagic longline sets targeting swordfish in the Windward Passage, June 2003. The solid line through the data distribution depicts the mean TDR observation for shallow hooks within the given set. The vertical dashed line indicates the fishing depth predicted by catenary algorithms (Suzuki et al. 1977). The single solid circle with horizontal error bars above the distribution indicates the overall mean depth and 95% confidence interval. Note the amount of variance within each set and between consecutive sets (n = number of hooks monitored by TDR during the specific set).

variability even within a spatial scale of less than 0.5° (i.e., the length of our longlines, or about 55 km).

During HBS, nominal fishing effort is standardized by determining the effective effort (i.e., 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 stratum based on gear configuration information and catenary geometry, often adjusted by a scalar that is intended to correct for the mean deviation of hook depth from the catenary prediction. High proportions of the total catch of some species may be associated with the tails of the

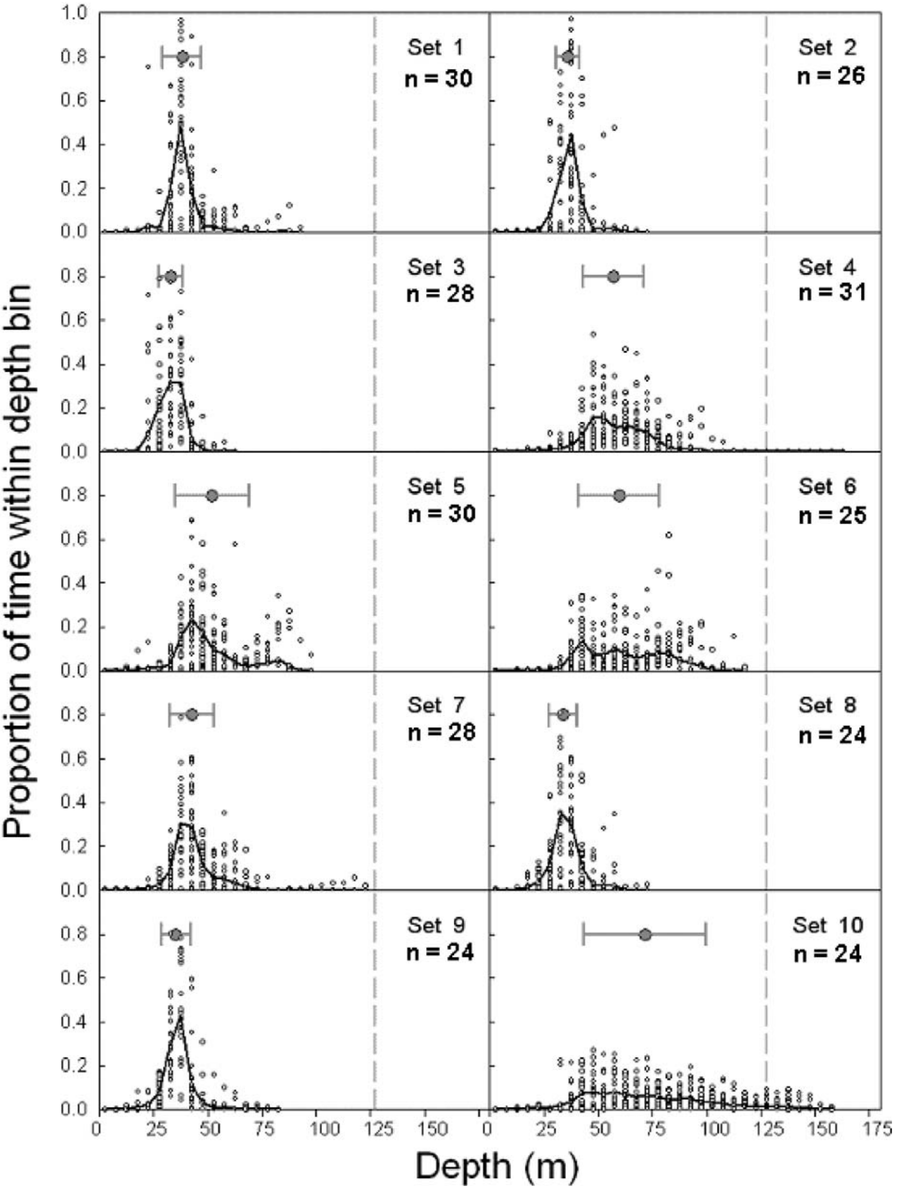

FIGURE 7.—Observed proportion of time at depth (5-m bins) for individual temperature–depth recorders (TDRs) attached to the deepest hook positions monitored during 10 pelagic longline sets targeting swordfish in the Windward Passage, June 2003. The solid line through the data distribution depicts the mean TDR observation for deep hooks within the given set. The vertical dashed line indicates the fishing depth predicted by catenary algorithms (Suzuki et al. 1977). The single solid circle with horizontal error bars above the distribution indicates the overall mean depth and 95% confidence interval. Note the amount of variance within each set and between consecutive sets (n = number of hooks monitored by TDR during the specific set).

distribution of fishing time across depths (Goodyear 2003b). If depth-specific effort 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 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 marlins and sailfish *Istiophorus platypterus* 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

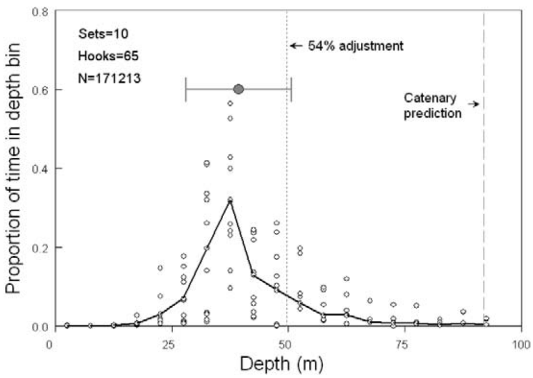

FIGURE 8.—Mean proportion of time at depth (5-m bins) for pooled temperature–depth recorders (TDRs) attached to the shallowest hook positions monitored during 10 pelagic longline sets targeting swordfish in the Windward Passage, June 2003. The solid line through the data distribution depicts the mean TDR observation for shallow hooks across all sets. The vertical dashed line indicates the depth predicted by 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 (*N* = total number of observations for shallow TDRs in all sets).

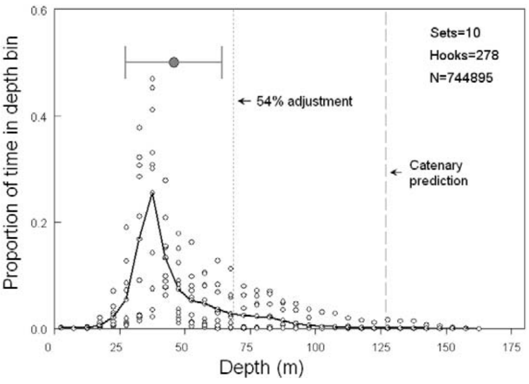

FIGURE 9.—Mean proportion of time at depth (5-m bins) for pooled temperature–depth recorders (TDRs) attached to the deepest hook positions monitored during 10 pelagic longline sets targeting swordfish in the Windward Passage, June 2003. The solid line through the distribution depicts the mean TDR observation for deep hooks across all sets. The vertical dashed line indicates the depth predicted by 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 (*N* = total number of observations for deep TDRs in all sets).

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 billfish catches occur in the upper 50 m and if recent gears fish just 2% instead of the assumed 1% of total effort in these depths, then the HBS CPUE estimates for 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 can cause the depth distribution of effort to depart from the catenary predictions. For example, Hinton and Nakano (1996) assumed that 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); for example, actual depths corresponding to 70–81% (Nishi 1990), 54–68% (Boggs 1992), and 50–70% (Bigelow et al. 2006) of predicted depth have been reported. 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.

Regardless of predicted hook position, hooks fished at 40 m for most of the time, thus occupying 43% (shallow) or 31% (deep) of the catenary predicted depth. 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 for the deep hook position were above the predicted depth of 127 m based on our gear configuration (Figures 8, 9). Hooks almost always fished at depths shallower than the catenary predicted depth, even when the most conservative scalar adjustments from previous studies were used (Figure 10). Several possible explanations for our shallower hook depth observations relative to those of previous studies include but are not limited to (1) stronger or more variable oceanic currents in the Windward Passage relative to other study areas, (2) variations in baits used in previous studies (e.g., mackerels *Scomber* spp. instead of squid), (3) various weights deployed on the mainline or branchlines (e.g., weighted swivel of 100 g instead of 60 g).

Variation in hook depth distribution is driven by many factors including but not limited to (1) hook position within a specific basket and along the mainline, (2) fish captured on or near neighboring hooks, (3) duration of deployment, and (4) speed and strategy used during gear deployment and retrieval. Understanding how these factors influence fishing depth is important, but the near-surface gear configu-

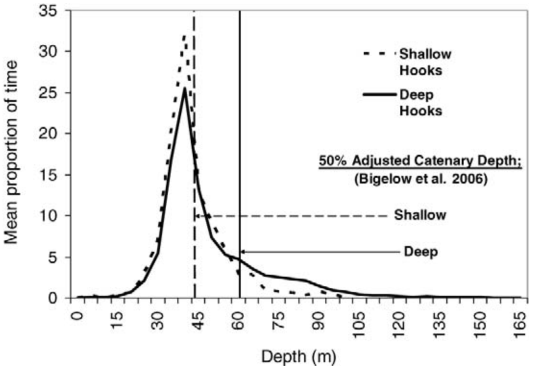

FIGURE 10.—Mean proportion of time at depth (5-m bins) for shallow (solid line) and deep (dashed line) hooks monitored by temperature–depth recorders during 10 pelagic longline sets targeting swordfish in the Windward Passage, June 2003. Note the similar distribution for shallow and deep catenary hook positions.

ration prevented us from examining such variables. Further research employing deeper gear configurations and greater TDR coverage is needed to explain how these factors, independently or together, influence fishing depth.

Many authors have described the behavior of PLL fishing gear using depth meters (Saito 1973), micro-bathythermographs (Mizuno et al. 1999), and TDRs (Boggs 1992; Berkeley and Edwards 1998; Yano and 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 or thousands of hooks. Several previous studies have deployed depth measuring device(s) on the PLL gear in a single basket and have assumed that the interbasket variance 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 poorly estimated time at depth of TDRs at the same catenary position in other baskets during the same set or different sets (Figures 6, 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, occupying many different depths for varying periods (Figures 6, 7). Therefore, it seemed reasonable to expect bimodal depth distributions for hooks placed in the shallow and deep 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 10). Thus, in addition to indicating other shortcomings of catenary geometry in determining fishing depth, our study also revealed that the two fishing depths and the expected bimodal hook depth distributions were not realized.

Sagging rate (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 tunas typically employs a "line thrower" that deploys the mainline at a speed defined by the fishers. When line throwers are used, S is the ratio of line thrower speed to fishing vessel speed 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 S.

Previous studies have only reported S-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 or swordfish), when the 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 when 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 that targets 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; 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, calculations of S based on equation (3), where the denominator is the assumed stretched mainline length in a unit basket, will always result in S-values less than 1.0. We used average gear drift as a proxy for directional current velocity (Nishi 1990; PFRP 1998), which was incorporated into mainline deployment length calculations (Figure 3) and subsequent calculations of distance between buoys (Table 1). Based on our results, S was occasionally reported as greater than 1.0, indicating stretching of the gear, while S-values less than 1.0 indicate gear compression. These changes in horizontal shape of the gear may potentially translate into changes in the degree of sagging or shoaling and vertical fishing depth.

Our results suggest that the estimation of fishing depth (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 depth 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/basket). Further study and analysis of vertical habitat use by target and bycatch species is also warranted (Luo et al. 2006).

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