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INCORPORATION OF OTHER OCEANOGRAPHIC FACTORS INTO CPUE STANDARDIZATIONS

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INCORPORATION OF OTHER OCEANOGRAPHIC FACTORS INTO CPUE STANDARDIZATIONS[1]

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1. Introduction

Assessments of Highly Migratory Species (HMS) in the Pacific Ocean typically date from the early 1950s or 1970s, depending on the species and data quality. In this context, it is important to recognize that catchability of and vulnerability to pelagic longlines have changed during these time periods in response to changes in target species, spatial expansion and contraction of fisheries, gear and fishing methods. The majority of fisheries stock assessments, particularly for tunas for which surveys are not possible, use catch rates (CPUE) as a critical source of information. Standardizing catch rates for factors other than abundance, such as historical changes in catchability, is one of the most commonly applied techniques in fisheries science (see Maunder and Punt 2004 for a review).

The predominant factor governing the efficiency and species composition of a longline fishing operation is the overlap in the vertical and spatial distribution between hooks and a species catchability. Techniques to assess catchability in pelagic longline fisheries currently include three CPUE standardization approaches: 1) statistical methods such as generalized linear (GLMs), generalized additive models (GAMs) and neural networks, 2) habitat-based and 3) depth-based methods.

The first and more traditional method employs a statistical approach of GLMs/GAMs to account for the variation in CPUE of a particular species based on nominal effort as:

CPUE ~ f(time + area (latitude, longitude) + operational variables + CPUE of other species + interaction terms + *e*),

where the categorical or continuous explanatory variables are time, area, longline operational attributes, CPUE of other species for an indication of targeting and a random error term (*e*). The advantage of GLMs/GAMs is that they are general in scope. This methodology is the most established approach as GLMs have been applied during the last 20 years to tunas and billfishes in the Pacific, Atlantic and Indian Oceans. They usually do not, however, include variations in vertical distribution of environmental conditions and the fishes' responses to them. These effects can be difficult to quantify in a GLM/GAM framework and critical values that are of interest to population modelers are not usually included.

The second method, habitat-based standardization (HBS) was developed by Hinton and Nakano (1996), entails standardization of CPUE by estimating effective longline effort from the vertical distribution of hooks, species-specific habitat preferences and the vertical, horizontal, and

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temporal distribution of environmental conditions. Initial implementations of a deterministic approach (detHBS) used habitat preference data collected from acoustic tracking and electronic (PSAT) tags (Bigelow et al. 2002, 2003). For some species, however, analyses have shown that the application of habitat preference data may not approximate the probability that a fish will be vulnerable to longline gear (Bigelow et al. 2003). The reason is that the time-at-habitat data from PSAT tags do not match the vulnerability to longline gear with regard to habitat. The development of statistical tests for the deterministic approach (Maunder et al. 2002) led to the development of a statistical approach (statHBS, Maunder et al., In Press) where habitat preferences are estimated. Habitat preferences can either be used as a prior in a Bayesian context and updated in the analysis or estimated within the analysis. This method has been applied to tunas (Bigelow et al. 2003), billfishes and blue shark in the Pacific Ocean.

The third approach estimates vertical distribution in catchability that is assumed to be depth-related. The depth distribution of catchability was estimated for 37 fish species caught on pelagic longlines in the central Pacific Ocean (Ward and Myers 2005). Adjustments to relative abundance are then applied external of the catchability estimation process with additional assumptions on gear depth. Catchability estimates from the central Pacific Ocean have been applied to bigeye tuna in the south Atlantic (Ward and Myers 2005) and oceanic sharks in the Gulf of Mexico (Baum and Myers 2004).

The purpose of this working paper is to evaluate factors that may be important in CPUE standardization. The study concentrates on two aspects that largely affect longline catchability – the vertical distribution of hooks and the vertical distribution of a species catchability based on depth and habitat (oceanography).

2. Methods

2.1 Catchability estimation from known catch and hook depth

Depth and habitat derived catchability were estimated from monitored longline sets in the central North Pacific Ocean (Figure 1). Fishery observers of the National Marine Fisheries Service (NMFS) attached single time-depth recorders (TDRs) to obtain actual longline fishing depths for swordfish (n=333 sets) and tuna (n=266 sets) gear in the Hawaii-based fishery from February 1996 to April 1999 (Bigelow et al. 2006, presented at WCPFC SC2 FT−IP1). This study concentrated on monitored tuna sets. The geographical area of the monitored tuna sets was large (4º−32ºN, 170º−154ºW) and represents fishing in several current systems and water masses of the North Pacific (Sverdrup 1942).

Two data sets were produced to reflect oceanographic properties and allow catchability comparisons with previous studies. One data set (n=44 sets) was stratified from 4º to 14ºN an area dominated by the north equatorial current and countercurrent and characterized by the N. Pacific equatorial water mass. The second data set (n=244 sets) was stratified from 4º to 25º N which incorporates the N. Pacific central water in the subtropics. No data were used from latitudes to the north of 25ºN as these 22 sets occurred within the subtropical frontal zone, an area with differing thermohaline circulation.

Hook depth in each tuna longline set was estimated by two methods: 1) catenary depth formula and 2) interpolation of shallower hooks from the observed depth of the deepest settled hook from TDR monitoring. Hook depth from the catenary formula followed Ward and Myers (2005) and Bigelow et al. (2006). Briefly, the requirements for catenary estimation were longline dimensions reported by the observer or vessel operator such as: length of branchline, length of floatline, length of mainline deployed between two floats, hook number, catenary hook midway between floats and the angle (ϕ) between the horizontal and tangential line of the mainline where the floatline was attached. The angle (ϕ) is based a sag ratio or the length of the mainline deployed between two successive floats and the horizontal distance between the two floats. We followed the criterion of Ward and Myers (2005) by assuming a value of 72º for ϕ when the sag rate could not be estimated or did not fall within reasonable bounds (sag rate ranging from 0.20 to 0.73; ϕ=62º−90º; respectively).

Depth estimation in the TDR monitoring followed Boggs (1992). Hook depth was interpolated between either a) the TDR observed depth of the deepest hook and the calculated depth of the middle hook or b) between the depth of the middle hook and the shallowest depth of the mainline depending on the hook position. The ratio between the middle hook and deepest hook TDR positions was assumed as 0.737 (Boggs 1992) and the shallowest depth of the mainline was assumed to be equal to the length of the floatline.

Observers identified each individual that was caught to a species or species assemblage level and recorded the sequential hook number of capture on the longline segment deployed between two floats. The depth of catch and effort (hooks) was estimated for each longline deployed and binned into 40-m depth categories ranging from 0 to 800 m. The vertical distribution in catchability was analyzed for bigeye tuna and blue shark. These species were selected because they are caught primarily when the gear is settled, thus the recorded hook number is unlikely to be substantially biased due to capture upon longline deployment and retrieval (Boggs 1992).

2.2 Environmental covariates

Environmental covariates of ambient temperature, thermocline gradient and climatological oxygen were obtained to model catchability. TDR monitoring provided temperature and depth measurements every 5 minutes; however, mixed layer depth and gradients describing the upper thermocline may be poorly determined as the TDR only recorded upper ocean thermal structure while sinking or rising rapidly upon longline deployment and retrieval. As an alternative, temperature at discrete depths was obtained from the Global Ocean Data Assimilation System (GODAS) developed at the National Centers for Environmental Prediction (http://cfs.ncep.noaa.gov/cfs/godas/). The model has 10 and 31 vertical layers in the upper 100 and 1000 m; respectively, and a spatio-temporal resolution of 1/3º latitude and 1° longitude by one month (1980−2005). The estimated temperature profile from the TDR monitoring agreed well with the GODAS model values (mean profile difference = 0.09ºC with a root mean squared or RMS difference = 1.19). We implemented a cubic smoothing spline (smooth.spline) in R (version 2.2.0 for Linux) for each temperature profile to predict temperature and gradient (1st derivative) for each meter of the profile (Figure 2). Mean temperature and gradient were then estimated for each 40-m depth category. Figure 3 illustrates model output of the depth of the 15ºC isotherm and thermocline gradient from 200 to 240 m during one month of the time-series. Climatological dissolved oxygen profile data were obtained from Levitus and Boyer (1994) and mean estimates were interpolated for each 40-m.

2.3 Modeling longline catchability from known catch and hook depth

Generalized linear models (GLMs, Splus version 6.2.1 for Linux) were developed to explain the vertical distribution in catchability by depth and habitat. A Poisson error distribution was assumed. For modeling catchability by depth, the model predicts mean catch ($\mu_{i,D}$) in longline operation *i* at depth *D* using a log link:

$$(1) \qquad \log(\mu_{i,D}) = N_i + \beta_1 D_{i,D} + \beta_2 D_{i,D}^{\ 2} + \beta_3 D_{i,D}^{\ 3} + \log(H_{i,D})$$

where N_i is the mean local abundance and β are estimated parameters. The regression coefficients in eq. 1 describe how catchability changes with depth as a third order (cubic) effect similar to analyses of Ward and Myers (2005). Models were also calculated with no depth information (null model) and depth as a linear and quadratic parameterization.
For modeling catchability by habitat, the model predicts mean catch ($\mu_{i,D}$) in longline operation *i* at depth *D* using a log link:
(2)

$$\log(\mu_{i,D}) = N_i + \beta_1 T_{i,D} + \beta_2 T_{i,D}^{\ 2} + \beta_3 T_{i,D}^{\ 3} + \beta_4 \Delta T_{i,D} + \beta_5 \Delta T_{i,D}^{\ 2} + \beta_6 \Delta T_{i,D}^{\ 3} + \beta_7 Oxy_{i,D} + \log(H_{i,D})$$

where *T* is the ambient temperature, ΔT is the temperature gradient and *Oxy* is the oxygen concentration. Mean catch was modeled as a function of temperature and gradient effects with up to a third order (cubic) effect. Oxygen was modeled as a two piece linear effect as high values would not be expected to result in lower catches, The two linear stanzas were separated at a particular threshold (concentration), with a linear decay in catch below the threshold and no effect (slope=0) at oxygen values above the threshold. Three oxygen thresholds were considered for each specie: bigeye tuna had linear stanzas separated at 1, 2 and 3 ml l^{-1} while blue shark are less oxygen tolerant and had stanzas separated at 2, 3, and 4 ml l^{-1}. GLMs were fit in forward and backward selection and the order of entry into the GLM was determined by reductions in the Akaike Information Criterion (AIC).

3. Results

3.1 Precision of depth and catchability estimates

The vertical distribution of hooks and fish capture were known for 44 longline sets from 4 to 14ºN and 244 sets from 4º to 25ºN (Table 1). Hook depths based on catenary formula were substantially deeper (mean=310 m) than observed hook depths (mean=183 m, Figure 4). Similar biases occur when estimating the vertical distribution in catch and corresponding CPUE. Depth distribution in catchability for bigeye tuna based on observed hook depths indicated an increase in CPUE from the surface, peaking at 180 m and a slight decline in catchability to a depth of 420 m (Figure 4). No inferences can be made from TDR monitoring at depths deeper than 420 m as confidence intervals widen due to a lack of fishing effort. In contrast, CPUE appears to linearly increase from the surface to a depth of 600 m based on catenary assumptions.

3.2 Modeling catchability from known longline catch and hook depth

Results on modeling catchability by depth and habitat are presented for bigeye and blue shark for the geographical area from 4º to 25ºN (Tables 2−3). A latitudinal depiction from this area indicates that the vertical structure of temperature and oxygen is dynamic (Figure 5). From 4º to 14ºN, the thermocline is shallow (80−280 m) with large gradients (~0.25ºC m^{-1}) and a shallow oxycline. Proceeding northward (14º−20ºN), the thermocline occurs at moderate depth (100−320 m) with smaller gradients (~0.1ºC m^{-1}) and a deepening oxycline. From 20º to 25ºN, the thermocline is diffuse (<0.1ºC m^{-1}) and the oxycline is deep with a concentration of 4 ml l^{-1} at ~350 m.

A cubic depth model was preferred over null, linear and quadratic depth effects; however, AIC and residual deviance indicated that all GLMs fit to catch with habitat as explanatory variables were preferred over models using depth (Tables 2−3). For each species, temperature variables (ambient and gradient) were the initial entrants in the GLM, but the entry of each variable was area dependent. The thermocline gradient was large in the tropics (4º−14ºN) and was the initial entry in the bigeye tuna model (not shown); however, ambient temperature was the initial entry for the larger area (4º−25ºN). The relationship between ambient temperature and catch for the larger area suggested a maximum catch at ~10ºC with a decline at increasing temperature, while the trace in temperature gradient indicated low catch at strong gradients (Figure 6). For blue shark, the temperature effect was similar to bigeye tuna, though the temperature gradient effect indicated high catches at moderate gradients (Figure 6). The effects of both temperature variables imply that bigeye tuna catches are highest at the bottom of the thermocline, while high blue shark catches occur within the thermocline.

Predictions of catchability at depth were generated for the GLM models based on habitat (Figure 7). The vertical distribution in catchability changes markedly between the tropical area (4º−14ºN) and the subtropics (14º−25ºN). Bigeye and blue shark CPUE peak at 180 and 60 meters; respectively, in the tropics, but CPUE peaks occur 80 m deeper in the subtropics.

Dissolved oxygen was always the third entry in GLM. AIC results indicate a linear stanza separation at 1 ml l^{-1} for bigeye tuna and 4 ml l^{-1} for blue shark, but AIC values were similar at other thresholds considered. Separations at these thresholds may not have been driven by oxygen, but may result from a species position in the thermocline which has more explanatory power.

4. Discussion

4.1 Precision of depth and catchability estimates

Longline catchability models require an understanding of gear behavior and hook depth distribution. The vertical distribution of longline hooks is central to estimating habitat and depth specific catchability. Monitored longlines indicated that catenary estimates of hook depth and corresponding catchability estimates were not robust and highly sensitive to the assumption of 72º for the sag angle. The Hawaii-based fishery had an estimated mean catenary angle of ~60º, but actual gear depth in the fishery was still 30% shallower than empirical catenary estimates due to shoaling (Bigelow et al. 2006).

4.2 Catchability comparisons with previous studies

Several longline monitoring studies have investigated depth and habitat relationships for bigeye tuna in the Pacific Ocean. Hanamoto (1987) hypothesized that the optimum bigeye habitat occurred between 10º and 15ºC, but habitat limited vertical distribution at temperatures below 10ºC and dissolved oxygen concentration below 1 ml l^{-1}. Boggs (1992) conducted longline monitoring in a similar area (14º−20ºN) to the present study and demonstrated the bigeye CPUE was low (<2 fish per 1000 hooks) in shallow depth strata (40−120 and 120−200m), but much higher (8−10 fish per 1000 hooks) in deeper depth strata (200−280 and 280−400m). High bigeye CPUE occurred at DO concentrations of 1.4−2.1 ml l^{-1}, but no fishing occurred at DO concentrations of <1 ml l^{-1} to test the hypothesized limitations.

There are few studies on depth and habitat relationships for blue shark in the tropical and subtropical Pacific for comparison. There was no evidence of a depth effect on CPUE neither

between the equator and 30º N (Strasburg 1985) nor in equatorial waters and the central Pacific (Nakano et al. 1997), albeit each longline study developed relationships based on catenary formula.
Habitat and depth derived catchability estimates differ by species and fish size due to physiological requirements (Brill 1994). Habitat gradients have been hypothesized to be more important in determining catchability than ambient values (Cayré and Marsac 1993, Bach et al. 2003). Cayré and Marsac (1993) postulated that gradients (e.g. temperature and oxygen) had a greater effect on the vertical distribution of yellowfin tuna than ambient values, though gradients had to occur within the range of ambient values based on physiological limitations. Bach et al. 2006 characterized bigeye tuna catch rates in the Society archipelago (French Polynesia) in relation to ambient values and gradients of temperature, DO and micronekton biomass. Bigeye captures occurred near high temperature gradients and 50 to 100 meters above the maximum micronekton biomass. No inferences could be made with respect to oxygen because fishing occurred in well oxygenated (>3 ml l^{-1}) water. Our results indicate that catchability for bigeye tuna in the Hawaii-based fishery is highest at the bottom of the thermocline, in contrast to results of Bach et al. (2003). Differences between geographical areas may relate to the position and strength of the thermocline which is shallower (100−320 m) and stronger (1−4ºC per 20 m) in our study (4−24ºN) compared to the thermocline (100−400, 1ºC per 20 m) in the Society archipelago (14º−20ºN). Alternatively, perhaps other factors, such as the deep scattering layer are more paramount in explaining bigeye tuna catchability as several studies have demonstrated an overlap between the vertical distribution of bigeye tuna and micronekton biomass during the day and night (Josse et al. 1998, Dagorn et al. 2000).

5. Future Research

The Pelagic Fisheries Research Program of the University of Hawaii has recently funded a project to assess the performance of longline catchability models in assessments of Pacific Highly Migratory Species. The 2-year project will concentrate on two aspects that largely affect longline catchability – the vertical distribution of hooks and the vertical distribution of a species catchability based on depth and habitat. Emphasis will be given to applying statistical models to the Japanese longline fishery given the long history (>50 yrs) of catch and effort data and the Hawaii-based longline fishery that can be analyzed at a variety of spatio-temporal scales and have additional information on gear configuration from logbook and scientific observer programs. The species of interest include tunas (bigeye, yellowfin and albacore), billfishes (blue and striped marlin, swordfish) and sharks (primarily blue shark).

The major objectives are:

1. Quantifying longline gear depth and variability
2. Reconsideration of environmental parameters that affect longline catchability
3. Improvements to the statHBS model and public domain release
4. Depth and habitat catchability comparisons and model validations
5. Simulation studies to compare performance of standardization methods

6. References

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Table 1. Number of fish and effort (sets, hooks) from monitored (time-depth recorders) longline sets in the Hawaii-based fishery.

		Number modeled	
Stratum	Effort − Sets (hooks)	Bigeye tuna	Blue shark
4−14ºN	44 (86,888)	639	148
4−25ºN	244 (412,834)	2,509	1,308

Table 2. Analysis of deviance for bigeye tuna catch in relation to depth and habitat for the Hawaii-based longline fishery. The vertical distribution of hooks and fish catch in relation to environmental conditions and depth is known by longline monitoring with time-depth recorders (TDRs).

Bigeye tuna (4º−25ºN), Null deviance= 3652.4			
Model name	Residual d.f.	Δ Residual Deviance	AIC
No depth or habitat information	1416		5070.4
Depth information			
Depth (linear)	1415	273.0	4798.4
Depth (quadratic)	1414	405.5	4666.9
Depth (cubic)	1413	408.3	4665.1
Habitat information			
Ambient temperature (quadratic)	1414	442.6	4629.8
Ambient temperature and gradient (cubic)	1411	464.9	4610.5
Temperature gradient, ambient temperature and oxygen	1410	471.7	4604.6

Table 3. Analysis of deviance for blue shark in relation to depth and habitat for the Hawaii-based longline fishery. The vertical distribution of hooks and fish catch in relation to environmental conditions and depth is known by longline monitoring with time-depth recorders (TDRs).

Blue shark (4º−25ºN), Null deviance=2081.5			
Model name	Residual d.f.	Δ Residual Deviance	AIC
No depth or habitat information	1416		3499.5
Depth information			
Depth (linear)	1415	0.003	3500.5
Depth (quadratic)	1414	9.8	3491.6
Depth (cubic)	1413	12.9	3489.5
Habitat information			
Temperature gradient (quadratic)	1414	65.9	3435.6
Temperature gradient and ambient temperature (cubic)	1411	75.4	3429.1
Temperature gradient, ambient temperature and oxygen	1410	78.6	3426.8

Figure 1. Geographical areas of longline catchability analyses for the Hawaii-based tuna fishery (shaded) in comparison to the six-region spatial stratification used in Multifan-CL assessments of western and central Pacific yellowfin and bigeye tuna. Hawaii-based fishery was monitored with time-depth recorders (TDRs) and has known vertical distribution of hooks and fish catch in relation to environmental conditions and depth.

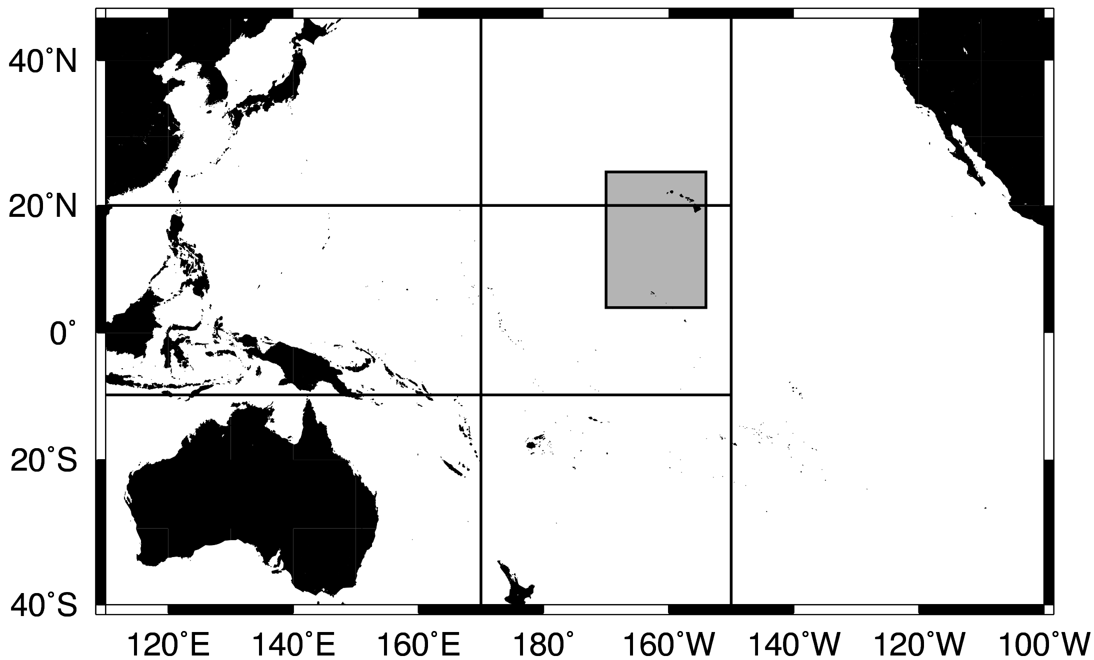

Figure 2. Processing of Global Ocean Data Assimilation System (GODAS) data to estimate 40−m bins of ambient temperature and thermocline gradient.

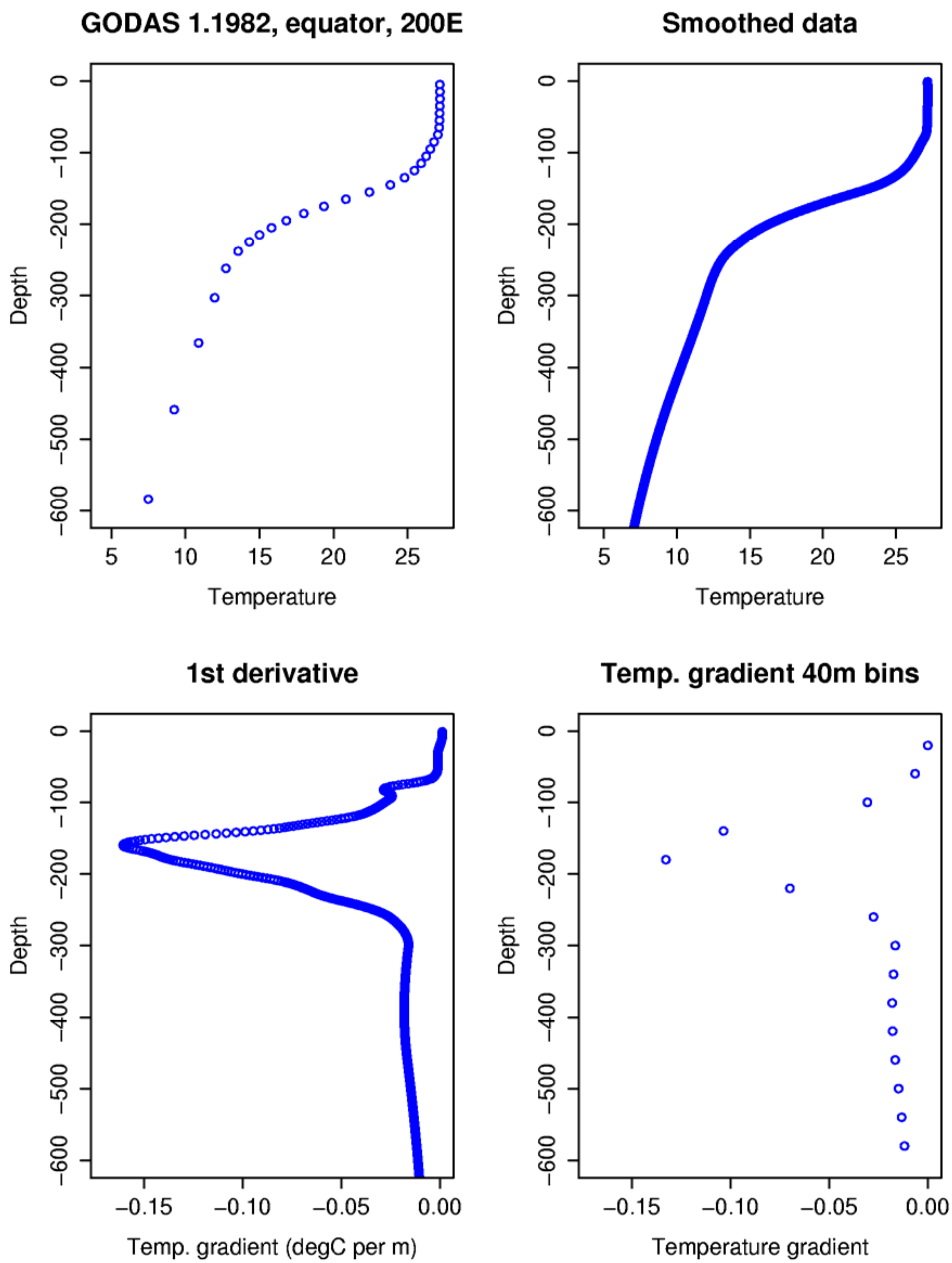

Figure 3. Illustration of oceanographic data derived from the Global Ocean Data Assimilation System (GODAS) for January 1982. Depth (meters) of the 15ºC isotherm (top) and thermocline gradient (ºC m^{-1}) corresponding to 200 to 240 m (bottom).

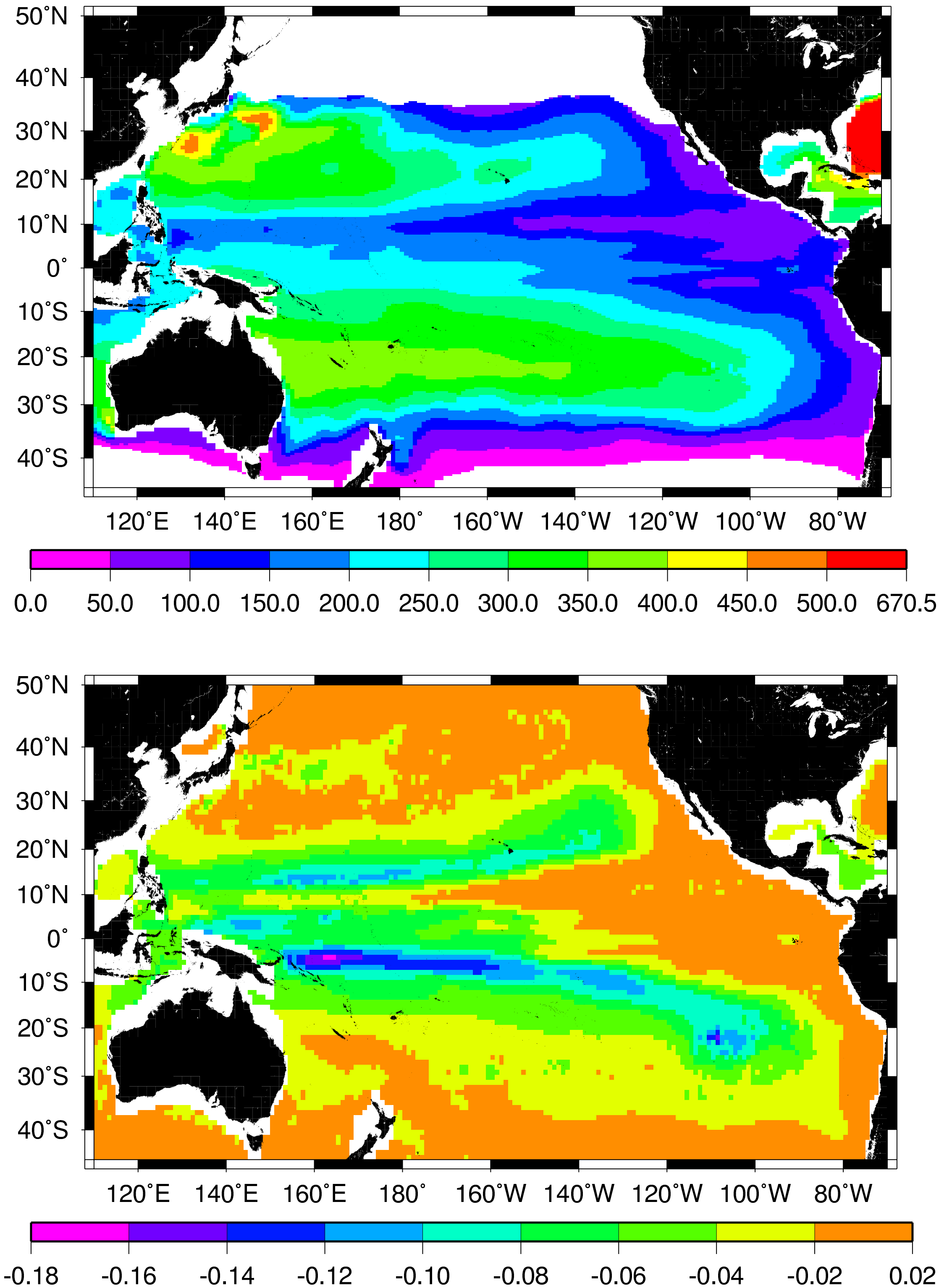

Figure 4. Comparison of bigeye catch (top), longline effort (middle) and catch rate (bottom) based on catenary depth estimates (left) and observed depth (right) for the Hawaii-based longline fishery (n=44 sets, 4º−14ºN, 170º−154ºW).

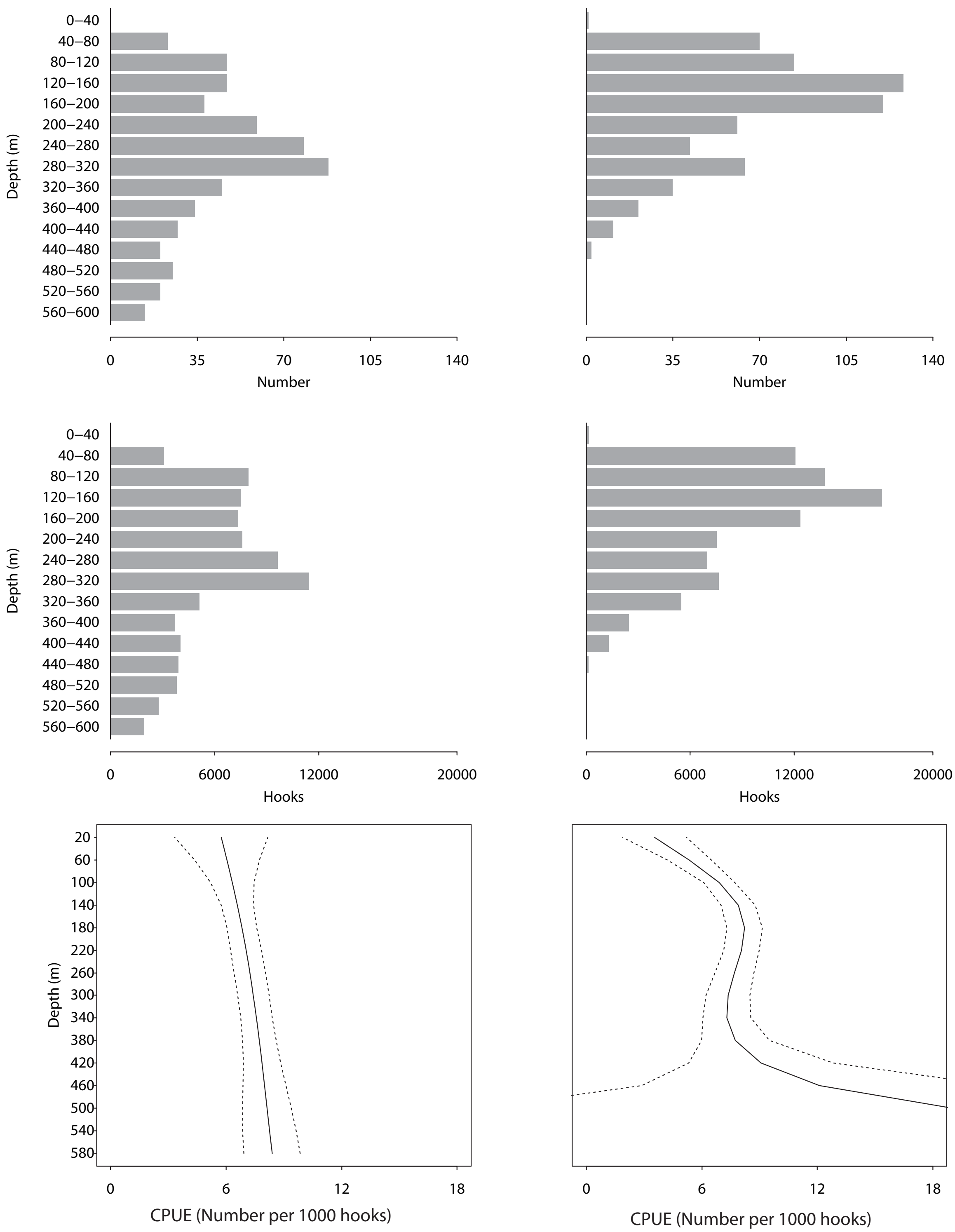

Figure 5. Latitudinal comparison of the vertical distribution of temperature (top), thermocline gradient (middle) and dissolved oxygen (bottom) corresponding to 244 sets in the Hawaii-based longline fishery (February 1996 − April 1999).

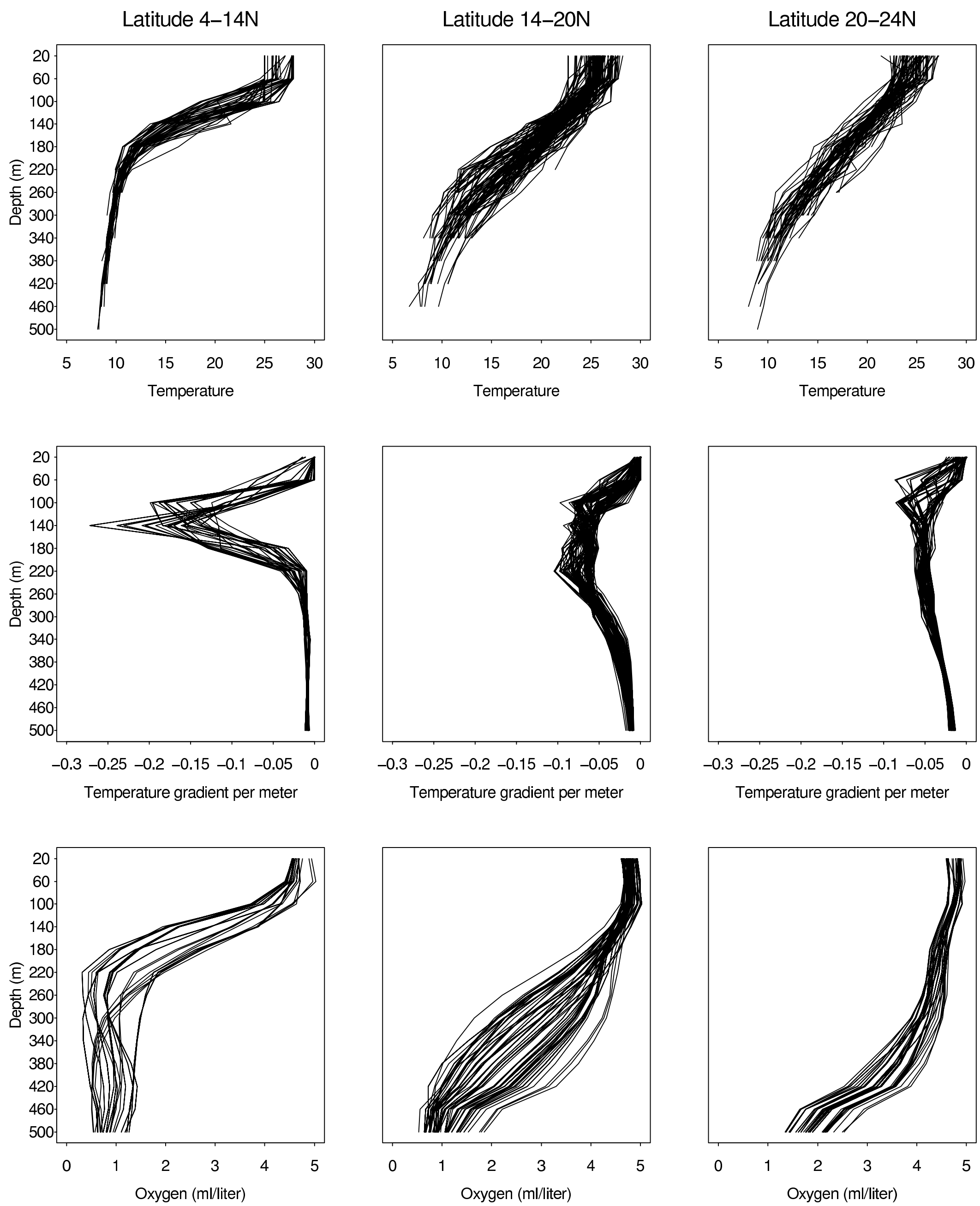

Figure 6. Generalized linear model (GLM) derived effects of temperature (left), thermocline gradient (middle) and dissolved oxygen (right) on catch rate of bigeye tuna (top) and blue shark (bottom) in the Hawaii-based longline fishery (n=244 sets, 4º−25ºN, 170º−154ºW).

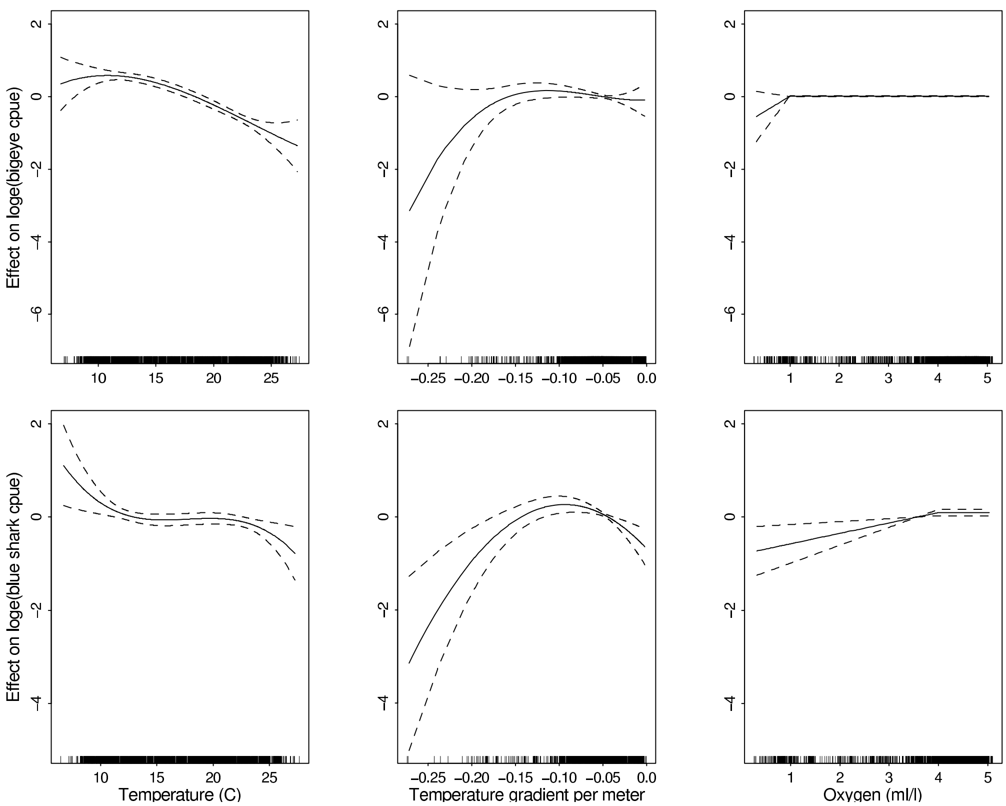

Figure 7. Predictions of catchability at depth from generalized linear models (GLMs) based on habitat for bigeye tuna (left) and blue shark (right). Solid line is the tropical area (n=44 sets, 4º−14ºN) and dashed lines are the subtropical area (n=128 sets, 14º−20ºN (short dashes), n=72, 20−24ºN (long dashes)).