# ANALYSES OF OBSERVED LONGLINE CATCHES OF BLUE MARLIN, MAKAIRA NIGRICANS, USING GENERALIZED ADDITIVE MODELS WITH OPERATIONAL AND ENVIRONMENTAL PREDICTORS 

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#### Abstract

Five generalized additive models (GAMs) were developed and evaluated to analyze blue marlin, Makaira nigricans Lacépède, 1802 catches reported by fishery observers in the Hawaii-based longline fishery from March 1994 through February 2004. The coefficients from three GAMs were applied to the corresponding predictor variables in logbooks from unobserved fishing trips to predict catches ( $\mathrm{n}=$ 97,557 longline sets). Results demonstrated that application of an overparameterized GAM (7 predictors, 40 degrees of freedom per predictor) yielded an inaccurate ( $26.6 \%$ greater than corrected logbook data) and imprecise (breadth of $95 \%$ prediction interval (PI): $105 \%$ of the point estimate) unobserved catch estimate. The same operational and environmental predictors allotted $66 \%-70 \%$ fewer degrees of freedom predicted unobserved catches accurately (apparent error: $-3.4 \%, 6.5 \%$ ) and with reasonable precision (breadth of 95\% prediction intervals: $21 \%, 24 \%$ of the estimated catch). Several extrinsic factors (e.g., hooks per float) not previously evaluated were significantly associated with blue marlin catches when used in another explanatory GAM. Results are discussed relative to the need to utilize fishery observer data effectively with billfishes, which are generally taken as by-catch or incidental catch in longline fisheries, because observer data are likely to be the most accurate available information.


Walsh et al. (2005) presents a corrected catch history for blue marlin, Makaira nigricans Lacépède, 1802, a species of considerable ecological, economic, and recreational importance taken as incidental catch, in the Hawaii-based longline fishery from March 1994 through June 2002. The analysis was characterized by an integrated use of fishery observer data, federally mandated longline logbooks, and sales records from the main public fish auction in Honolulu. It was initiated by fitting a generalized additive model (GAM) of blue marlin catches to fishery observer data (Walsh and Kleiber 2001), with several operational (e.g., position, number of hooks) and environmental (e.g., sea surface temperature) variables as the predictors. Because the chosen predictors were also required logbook entries, the fitted GAM coefficients were applicable to predict catches on unobserved longline sets, as had been done previously with blue shark, Prionace glauca (Linnaeus, 1758) (Walsh et al., 2002). The predicted and reported catches were then compared by regression techniques; logbook data considered suspect in terms of numbers or species identifications and with large residuals were checked against auction sales records. Results demonstrated that the nominal blue marlin catch by this fishery throughout the study period was inflated by approximately $29 \%$, caused primarily by misreporting striped marlin, Tetrapturus audax (Philippi, 1887), as blue marlin, although several other types of misidentifications and bias were also present in the logbook data. It was concluded
that the analysis, with its GAM methodology, had yielded corrected catch data that were substantially more accurate than the nominal and that represented a more realistic catch history.
Here we present additional and updated GAM analyses of observed blue marlin catches in this fishery from March 1994 through February 2004. The results include several newly fitted GAMs, parameterized so as to meet three analytical objectives distinct from catch history correction. The first was to seek parsimony in predicting blue marlin catches. This was considered important because the GAM employed in Walsh et al. (2005) was recognized as overparameterized. The second was to assess the explanatory power of GAMs with either operational or environmental predictors, but not both, relative to larger models. This analysis was conducted because the effects of certain operational and environmental factors (e.g., date and position of fishing, SST) are closely related and can therefore present difficulties in interpretation. Even within these categories, many variables are related and difficult to interpret. The final objective was to create a GAM that would best explain the stochastic process. Because this model was not intended for prediction of unobserved catches, we were not limited to variables present in the commercial longline logbooks.

Our results should prove informative to analysts using fishery observer data for catch history correction (Walsh et al., 2005), by-catch estimation (Walsh et al., 2002; National Marine Fisheries Service 2003), or stock assessment. In addition, identification of extrinsic factors that affect longline catches of blue marlin should aid in the interpretation of apparent long-term variation in relative abundance or distribution. Finally, improved understanding of such effects should also benefit stock assessment scientists and fisheries managers charged with making recommendations in the near-term.


#### Abstract

Methods Data Types and Sources.-Two types of data were employed in this study. The first consisted of catch and operational data gathered by fishery observers on 13,816 longline sets from March 1994 through February 2004, which represented $95.9 \%$ of the observer effort in this fishery during the first 10 yrs of the Hawaii Longline Observer Program (Pacific Islands Regional Office, 2003), after deleting fishing trips when observers misidentified marlins (Walsh et al., 2005). Sets deleted from the analyses had missing predictor values ( $0.1 \%$ of all observed longline sets) or extreme, highly influential predictor values (4.0\%). Walsh et al. (2005) provided a detailed summary of observer catch and effort data from March 1994 through June 2002. The second data category consisted of several remotely sensed or calculated environmental variables.

The daily observer records included species-specific catch tallies, the date of fishing, numbers of hooks and hooks per float, begin-set time, latitude, longitude, target species, and bait type. Vessel lengths were obtained from U.S. Coast Guard documentation. Hooks per float, target species, and bait types were not previously used as predictors (Walsh et al., 2005) because the logbook form did not always include the entry (hooks per float) or because the entry proved confusing to many captains (target species) (W. A. E. Machado, pers. comm.). At present, however, evaluation of hooks per float in an explanatory model is appropriate because this variable is used to distinguish between deep- and shallow-set longline gears, which are regulated differently in this fishery (Western Pacific Fishery Management Council, 2004). Similarly, target species and bait types were categorical variables assessed in the explanatory model in an effort to increase understanding of relationships, if any, between target and incidental catches. In reality, these operational factors are characterized by many internal


relationships in this fishery; e.g., tuna-directed fishing generally involves setting longline gear deep, which requires a large number of hooks per float, at or near dawn, whereas swordfish sets are shallow and deployed around sunset.

The environmental variables of interest were measurements of sea surface temperature (SST) and height (SSH), wind, and currents. Temperature was expected to predominate by exerting both controlling and directive effects on blue marlin (sensu Fry, 1971). Temperature may also affect catches by its influence on the behavior of fishermen, who are known to seek swordfish, Xiphias gladius Linnaeus, 1758 for example, along temperature fronts (Sakagawa, 1989). SSH was expected to represent changes in subsurface conditions (e.g., stratification intensity or mixed layer depth). Wind and currents were expected to influence blue marlin catches by affecting the location or configuration of longline gear; currents were also expected to influence movements of blue marlin.

SST values were obtained from an optimal interpolation analysis of Advanced Very High Resolution Radiometers (AVHRR) and in situ ship and buoy data (Reynolds and Smith, 1994), with $1^{\circ}$ square resolution at monthly intervals. Monthly SST anomaly (SSTA) values were obtained by subtracting the monthly climatological SST field from the monthly SST field. An SST-based frontal index (SSTF) was calculated for each longline set as the difference between the averages of the three nearest SST measurements to the north and south, respectively. SSH data were provided by the Ssalto program of the Centre National d'études Spatiales, France, and mapped at a global $0.3^{\circ} \times 0.3^{\circ}$ resolution at weekly intervals (SALP-MU-P-EA-21065CLS, Edition 1.2, 2004). The geostrophic current velocities were estimated according to the procedures described in Polovina et al. (1999). Wind stress curl (WSC) data were provided by IFREMER/CERSAT, France, at weekly intervals. These data incorporated measurements from Advanced Microwave Instruments (AMI) on ERS-1 (1991-96) and ERS-2 (1996-99) and the SeaWinds sensor on QuikSCAT (2000-2004). The spatial resolution was either $1^{\circ} \times 1^{\circ}$ (ERS) or $0.5^{\circ} \times 0.5^{\circ}$ (QuikSCAT).

General GAM Fitting Procedures.-General procedures employed in the fitting and evaluation of GAMs follow those previously used with blue shark (Walsh and Kleiber, 2001; Walsh et al., 2002) and blue marlin (Walsh et al., 2005). Each GAM was fitted as a robust Poisson model. Additional specific details are provided below. All statistical procedures were conducted in either S-Plus Version 6.1.2 (Insightful Corp. 2002) or S-Plus Version 7.0 for Windows (Insightful Corp. 2005).

A GAM can be expressed as:

$$
\begin{equation*}
\log (\mu)=\sum_{j=1}^{p} S_{j}\left(x_{j}, d_{j}\right) \tag{1}
\end{equation*}
$$

where $\mu$ represents the conditional mean catch for the set of predictors ( $x_{1}, x_{2}, \ldots, x_{p}$ ), $S_{j}$ an unspecified smooth function, and $d_{j}$ the degrees of freedom of the smoother. The smoother plots depict the effects of individual predictors on the logarithm of catch; the rug plots along the $x$-axis depict the distributions of the values of the predictors. Detailed discussions of GAM theory and methodology are presented by Hastie (1992), Venables and Ripley (1994), and Schimek and Turlach (2000).

Specific Procedures.-Two GAMs were fitted as adaptations from that in Walsh et al., (2005), which had been developed by allotting four degrees of freedom per year per predictor, to assess bias caused by overparameterization. The first (Full model) differed from its predecessor in having its degrees of freedom increased in proportion to the longer time series and two marginally significant variables [catches of bigeye tuna, Thunnus obesus (Lowe, 1839) and yellowfin tuna, Thunnus albacares (Bonnaterre, 1788)] deleted. The second (Reduced model) included the same variables as the full model, but with the model degrees of freedom reduced by $70 \%$. These models were then compared in terms of explanatory power and bias.

The second objective was met by fitting two additional GAMs, denoted as the Operational and Environmental models, respectively. The former was characterized by the same predic-
tors and degrees of freedom as the Reduced model, but without SST. The Environmental model was fitted to six candidate predictors (SST, SSTF, SSTA, SSHA, WSC, velocity). The anomalies were expected to describe interannual variability; hence, SSTA and SSHA were allotted 10 degrees of freedom. SSTF was expected to reflect both intra- and interannual variability, and was therefore allotted 20 degrees of freedom. WSC and current velocity were allotted five degrees of freedom, lacking a conceptual basis for more. The order of entry into these models was determined by reductions in the Akaike Information Criterion (AIC).

The final objective was met by developing a GAM (Explanatory model) from the entire suite of candidate predictors, including those not previously tested. Their order of entry was predicated upon reductions in the AIC and the Bayesian Information Criterion (BIC) (Schwarz 1978). Both criteria were used because AIC tends to overfit whereas BIC tends to underfit a model. F-tests were computed to determine whether predictors yielded significant ( $\mathrm{P}<0.05$ ) reductions in the residual deviance upon entry into the GAM.

The coefficients from the fitted predictive models were applied to 97,557 unobserved longline sets with the "predict.gam" function in S-Plus Version 6.1.2 (Insightful Corp. 2002). This sample size represented $88.0 \%$ of unobserved fleet-wide effort during the study period. Sets with predictor ranges greater than those in the observer data ( $6.5 \%$ ) or missing predictor values ( $5.5 \%$ ) were deleted from the analyses. The correspondence between reported and predicted catches was assessed by regression techniques (Walsh et al., 2002; Walsh et al. 2005). The $95 \%$ prediction intervals about the predicted catches were computed according to the bootstrapping algorithm described in McCracken (2004), Walsh et al. (2002), and Walsh et al. (2005).

## Results

Observed Catch and Effort.-The number of observed sets per year (Table 1) increased 7.1-fold between 1994 and 2003. Blue marlin were caught on $22.4 \%$ of the observed sets used to fit the GAMs, with multiple catches reported on $8.9 \%$. The observed catch varied in three phases. The highest catches and CPUE values were those from 1995-1997. A decline in 1998 was followed by a second period (1999-2001) with catches and CPUE approximately $40 \%$ and $50 \%$ lower, respectively, than previously. The final phase began in 2002 and continued thereafter, with catches and CPUE again stabilized below the prior levels.

GAM Development and Comparisons.-The variable with the strongest relationship with blue marlin catches and first entry into four GAMs (Table 2) was the date of fishing (Fig. 1; Table 2), representing the seasonal pattern of high blue marlin catches in summer followed by relative scarcity in winter (Fig. 1A). The trace of this variable against a logarithmic scale (Fig. 1B) represents this relationship in each of the four GAMs. The relatively smooth, cyclic trace suggested that its allotted degrees of freedom were reasonable.

Table 1. Summary of effort and catches on observed longline sets deployed by the Hawaii-based fleet from March 1994 through February 2004. Total catch refers to all fishes; other entries refer to blue marlin $(\mathrm{CPUE}=$ catch per 1,000 hooks).

| Year | Trips* | Gear sets | Total catch | Blue marlin | Catch/set | CPUE | centage |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Data used in analysis: |  |  |  |  |  |  |  |
| 1994-2004 | 1,177 | 13,816 | 651,271 | 5,127 | 0.37 | 0.25 | 0.79 |
| All data: |  |  |  |  |  |  |  |
| 1994-2004 | 1,195 | 14,414 | 687,002 | 6,102 | 0.42 | 0.24 | 0.89 |

[^0]Table 2. Analyses of deviance of observed blue marlin catches. The deviance reduction, F-test for curvature, and F-test for entry are presented for each predictor (Null deviance $=21,871.5$ ).

| Full model |  |  |  |  |  |  |  |
| :--- | ---: | ---: | :---: | :---: | :---: | :---: | :---: |
| Predictor | $\Delta$ residual <br> deviance | $\mathrm{F}_{\text {(npar) }}$ | $\mathrm{df}_{\text {(npar) }}$ | P | $\mathrm{F}_{\text {enter }}$ | df | P |
| Date of fishing | $5,233.480$ | 16.660 | 38.9 | 0.000 | 66.300 | 39.8 | 0.000 |
| Begin-set time | $1,017.890$ | 8.167 | 39.0 | 0.000 | 13.979 | 39.8 | 0.000 |
| SST $\left({ }^{\circ} \mathrm{C}\right)$ | $1,004.111$ | 4.048 | 38.7 | 0.000 | 14.399 | 39.9 | 0.000 |
| Longitude | 395.551 | 3.520 | 38.7 | 0.000 | 5.886 | 39.6 | 0.000 |
| Latitude | 198.092 | 5.018 | 38.7 | 0.000 | 2.922 | 40.0 | 0.000 |
| Hooks/set | 528.439 | 10.530 | 38.9 | 0.000 | 8.413 | 39.8 | 0.000 |
| Vessel length | 578.166 | 9.970 | 38.8 | 0.000 | 9.823 | 39.7 | 0.000 |

Residual deviance $=12,915.77 ;$ Residual mean deviance $=0.954 ;$ Pseudo- $\mathrm{R}^{2}=40.9 \%$.
Reduced model

| Predictor | $\Delta$ residual <br> deviance | $\mathrm{F}_{\text {(npar) }}$ | $\mathrm{df}_{\text {(npar) }}$ | P | $\mathrm{F}_{\text {enter }}$ | df |  |
| :--- | ---: | ---: | :---: | :---: | ---: | ---: | ---: |
| Date of fishing | $5,233.480$ | 14.397 | 38.8 | 0.000 | 66.300 | 39.8 | 0.000 |
| Begin-set time | 633.519 | 37.521 | 4.0 | 0.000 | 66.714 | 5.0 | 0.000 |
| SST $\left({ }^{\circ} \mathrm{C}\right.$ ) | 897.575 | 6.895 | 9.0 | 0.000 | 49.072 | 10.0 | 0.000 |
| Longitude | 281.560 | 4.579 | 8.9 | 0.000 | 15.757 | 9.9 | 0.000 |
| Latitude | 117.446 | 9.570 | 8.9 | 0.000 | 6.602 | 10.0 | 0.000 |
| Hooks/set | 161.833 | 31.021 | 4.0 | 0.000 | 18.953 | 4.9 | 0.000 |
| Vessel length | 248.048 | 12.615 | 4.0 | 0.000 | 30.383 | 4.9 | 0.000 |

Residual deviance $=14,298.04 ;$ Residual mean deviance $=1.041 ;$ Pseudo- $\mathrm{R}^{2}=34.6 \%$.
Operational model

| Predictor | $\Delta$ residual <br> deviance | $\mathrm{F}_{\text {(npar) }}$ | $\mathrm{df}_{\text {(npar) }}$ | P | $\mathrm{F}_{\text {enter }}$ | df |  |
| :--- | ---: | ---: | ---: | :---: | ---: | ---: | ---: |
| Date of fishing | $5,233.480$ | 21.587 | 38.7 | 0.000 | 66.300 | 39.8 | 0.000 |
| Longitude | 668.720 | 5.236 | 8.9 | 0.000 | 35.481 | 9.9 | 0.000 |
| Begin-set time | 636.176 | 37.542 | 4.0 | 0.000 | 69.636 | 5.0 | 0.000 |
| Latitude | 301.580 | 14.169 | 8.9 | 0.000 | 16.706 | 9.9 | 0.000 |
| Vessel length | 239.200 | 12.718 | 4.0 | 0.000 | 27.718 | 4.9 | 0.000 |
| Hooks/set | 178.966 | 28.960 | 4.0 | 0.000 | 21.582 | 4.9 | 0.000 |

Residual deviance $=14,613.38 ;$ Residual mean deviance $=1.064 ;$ Pseudo- $\mathrm{R}^{2}=33.2 \%$.
Environmental model

| Predictor | residual <br> deviance | $\mathrm{F}_{\text {(npar) }}$ | $\mathrm{df}_{\text {(npar) }}$ | P | $\mathrm{F}_{\text {enter }}$ | df |  |
| :--- | ---: | ---: | ---: | :---: | ---: | ---: | ---: |
| SST | $3,721.382$ | 8.084 | 9.0 |  | 0 | 158.073 | 10.0 |
| SST front | 373.133 | 1.962 | 18.9 | 0.008 | 8.169 | 19.9 | 0.000 |
| SST anomaly | 118.335 | 4.431 | 9.0 | 0.000 | 5.198 | 10.0 | 0.000 |
| SSH anomaly | 80.564 | 2.568 | 9.0 | 0.006 | 3.569 | 10.0 | 0.000 |
| Wind stress curl | 53.304 | 5.411 | 4.0 | 0.000 | 4.766 | 5.0 | 0.000 |
| Current velocity | 64.684 | 2.854 | 4.0 | 0.022 | 5.809 | 5.0 | 0.000 |

Residual deviance $=17,460.1 ;$ Residual mean deviance $=1.269 ;$ Pseudo $-\mathrm{R}^{2}=20.3 \%$.

The Full and Reduced models (Fig. 2; Table 2) differed by 6.3 percentage points in explanation of the null deviance (Full model: pseudo- $\mathrm{R}^{2}=40.9 \%$; Reduced model: pseudo- $\mathrm{R}^{2}=34.6 \%$ ) and $10.7 \%$ in their residual deviances (Full model $=12,915.77$; Reduced model $=14,298.04$ ). Begin-set time explained $4.6 \%$ of the null deviance when allotted 40 degrees of freedom in the Full model, but $2.9 \%$ with only five in the Reduced model. The final two entries into the Full model (hook numbers and vessel

Table 2. Continued.

| Explanatory model |  |  |  |  |  |  |  |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| Predictor | $\Delta$ residual <br> deviance | $\mathrm{F}_{\text {(npar) }}$ | $\mathrm{df}_{\text {(npar) }}$ | P | $\mathrm{F}_{\text {enter }}$ | df | P |
| Date of fishing | $5,233.480$ | 15.978 | 38.9 | 0.000 | 66.300 | 39.8 | 0.000 |
| SST | 931.246 | 6.146 | 8.9 | 0.000 | 48.954 | 10.0 | 0.000 |
| Hooks per float | 722.095 | 9.817 | 4.0 | 0.000 | 78.342 | 4.7 | 0.000 |
| Begin-set time | 289.334 | 19.503 | 4.0 | 0.000 | 32.312 | 5.0 | 0.000 |
| Longitude | 262.850 | 5.734 | 8.9 | 0.000 | 15.038 | 9.9 | 0.000 |
| Vessel length | 194.593 | 5.363 | 4.0 | 0.000 | 23.308 | 4.9 | 0.000 |
| Bait type | 145.182 |  |  |  | 14.719 | 6.0 | 0.000 |
| Latitude | 124.649 | 14.080 | 8.9 | 0.000 | 7.652 | 10.0 | 0.000 |
| Target species | 102.303 |  |  |  | 7.807 | 8.0 | 0.000 |
| Hooks | 121.527 | 11.005 | 4.0 | 0.000 | 15.615 | 4.9 | 0.000 |
| SST front | 106.532 | 2.102 | 18.9 | 0.003 | 3.396 | 19.9 | 0.000 |
| SSH anomaly | 45.753 | 2.205 | 9.0 | 0.019 | 2.928 | 10.0 | 0.001 |
| Wind stress curl | 33.591 | 3.579 | 4.0 | 0.007 | 4.333 | 5.0 | 0.001 |
| SST anomaly | 33.137 | 3.100 | 9.0 | 0.001 | 2.103 | 10.1 | 0.021 |
| Current velocity | 31.339 | 3.552 | 4.0 | 0.007 | 4.046 | 5.0 | 0.001 |

Residual deviance $=13,493.89 ;$ Residual mean deviance $=0.988 ;$ Pseudo- $\mathrm{R}^{2}=38.3 \%$.
length) accounted for an additional 5.1\% of the explanation of the deviance, but 1.9\% in the Reduced model. Thus, the additional 70 degrees of freedom allotted to hook numbers and vessel length in the Full model accounted for more than half of the difference in the explanation of the null deviance. The additional 90 degrees of freedom allotted in the Full model to SST, latitude, and longitude increased the explanation of the null deviance by 1.4 percentage points relative to the Reduced model.

The predictor plots (Fig. 3) from the Full and Reduced models revealed the effects of excess model degrees of freedom, with SST, begin-set time, and hook numbers presented as examples. The Full model SST trace (Fig. 3A) was rough and irregular, with sharply ascending limbs near both extremes. The corresponding trace for the Reduced model was smoother and lacked pronounced ascending limbs. The effects of the degrees of freedom were even more apparent with begin-set time (Fig. 3B) and hooks per set (Fig. 3C). The Full model traces for both were highly irregular, with rug plots revealing fits to individual or very small numbers of observations. The begin-set time and hook numbers traces for the Reduced model were smoother and more comprehensible; for example, $99.1 \%$ of the sets deployed before 0500 h targeted tunas or a mixed species assemblage, while $88.3 \%$ of the sets deployed between 1600 h and 2000 $h$ targeted swordfish or mixed species. Hence, the trace described relatively homogeneous groupings rather than variation among individuals or a few observations. The predictor traces for latitude, longitude, and vessel lengths (not shown) with 40 degrees of freedom exhibited extreme irregularities, whereas the corresponding traces with five or 10 degrees of freedom were smooth and their rug plots did not reveal fits to individual or very small numbers of observations.

Operational and Environmental Models.-The Operational model (Table 2), fitted to six predictors with the order of entry determined by reductions in the AIC, had a pseudocoefficient of determination 1.4 percentage points lower and residual deviance $2.2 \%$ greater than those of the Reduced model. Latitude and longitude


Figure 1. (A) Quarterly mean observed blue marlin catches per set, and (B) relationship between the date of fishing and observed blue marlin catches per set (logarithmic scale) from March 1994 through February 2004 in the Hawaii-based longline fishery.
explained $4.4 \%$ of the null deviance in this model, compared to $5.9 \%$ explained by the positions and SST in the Reduced model (SST: $4.1 \%$; longitude: $1.3 \%$; latitude: $0.5 \%$ ).
The Environmental model (Fig. 4; Table 2) included six significant predictors, with a pseudocoefficient of determination (pseudo- $\mathrm{R}^{2}=20.2 \%$ ) considerably lower and residual deviance $(17,460.1)$ considerably greater than all others. SST, the first entry, explained $17.0 \%$ of the null deviance of this model, equivalent to $71 \%$ of the explanation provided by the date of fishing ( $23.9 \%$ ) as the first entry into the others. Its trace (Fig. 4A) was smooth, with a descending limb near the minimum and a somewhat dome-shaped region ca. $26-28^{\circ} \mathrm{C}$. As was also true of the Reduced model, this trace described an upward trajectory toward a small number of observations near the SST maximum. The trace for SSHA (Fig. 4B) suggested that positive values for this vari-


Figure 2. Development of two generalized additive models (GAMs) of blue marlin catches per set. The pseudocoefficients of determination and reductions in the residual deviances are plotted in relation to the entry of predictor variables.
able would exert a neutral or slightly positive effect on blue marlin catches. WSC (Fig. 4C) exhibited two dome-shaped regions in the trace, which suggested that both upwelling (positive values) and downwelling (negative values) could affect catches depending upon whether the longline gear was set deep or shallow. The SSTF trace (not shown) exhibited some roughness and irregularities with 20 degrees of freedom, but reductions to five or 10 degrees of freedom did not yield appreciably smaller standard errors. The trace for the SSTA (not shown) suggested that negative values would be associated with positive effects on blue marlin catches, whereas values at or above ca. $0.75^{\circ}$ would exert negative effects. The trace for currents (not shown) suggested that catches would tend to vary directly with velocities of approximately $30 \mathrm{~cm} / \mathrm{s}$ and above.
Explanatory model.-The Explanatory model (pseudo-R ${ }^{2}=38.3 \%$; residual deviance $=13,493.89$ ) demonstrated that 15 predictors significantly affected blue marlin catches (Table 2). It explained 2.6 percentage points less of the null deviance and had a residual deviance $4.5 \%$ greater than the Full model, but with a $45 \%$ reduction in the model degrees of freedom. There were no conflicts between AIC and BIC concerning the order of entry. The operational factors were the predominant influences, as nine of the first 10 entries, with SST the sole exception. It was noteworthy that hooks per float was the third entry, explaining $3.3 \%$ of the null deviance, with highest catches at 10 hooks per float or less. The seven operational factors entered after hooks per float explained only an additional 5.7\% of the null deviance. Among these, use of squid bait and designation of albacore, Thunnus alalunga (Bonnaterre, 1788), as target species were associated with positive effects on blue marlin catches. Five environmental factors (SSTF, SSTA, SSHA, WSC, current velocity) were the late model entries, explaining $1.1 \%$ of the null deviance.
Applications of GAM Coefficients to Unobserved Longline Sets.-Application of the coefficients (Table 3) from the Reduced and Operational models to unobserved effort during the study period yielded point estimates close to and prediction intervals that bracketed the corrected logbook blue marlin catch total. The


Figure 3. Relationship between (A) sea surface temperature, (B) begin-set time, and (C) hook numbers and blue marlin catches per set (logarithmic scale) in the Full and Reduced models. Note that the response scale in $(\mathrm{B})$ and $(\mathrm{C})$ are reduced by half from (A).


Figure 4. Relationship between (A) sea surface temperature, (B) sea-surface height anomaly, and (C) wind stress curl and blue marlin catches per set (logarithmic scale) in the Environmental model. Note that the response scale of (B) and (C) is reduced by two-thirds from (A).
Table 3. Summary of applications of GAM coefficients to commercial logbook data from the Hawaii-based longline fishery from March 1994 through February
$2004(n=97,557$ sets; corrected logbook catch total $=40,795$ blue marlin; uncorrected logbook catch total $=49,629$ blue marlin).

| Model | Regression | $\mathrm{S}_{y, x}^{2}$ | $\mathrm{r}^{2}$ | Predicted catch | $95 \% \mathrm{PI}$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Full | $\log _{\mathrm{e}}(Y+1)=0.0683+0.4797 \log _{\mathrm{e}}(X+1)$ | 0.4099 | 0.130 | 51,627 | $32,994-87,056$ |
| Reduced | $\log _{\mathrm{e}}(Y+1)=0.0150+0.6712 \log _{\mathrm{e}}(X+1)$ | 0.4028 | 0.160 | 39,389 | $36,766-45,055$ |
| Operational | $\log _{\mathrm{e}}(Y+1)=0.6614 \log _{\mathrm{e}}(X+1)$ | 0.4027 | 0.322 | 43.6 |  |



Figure 5. Monthly mean corrected blue marlin catches per set (unobserved effort) in relation to predictions from the Reduced and Operational models.

Full model, however, yielded a point estimate for total catch that was significantly greater than the corrected logbook total. The discrepancy was largely attributable to the manner in which vessel length was modeled. Specifically, 47 sets deployed by the smallest vessel in the fleet had predicted mean blue marlin catches of 173 per set, corresponding to $75.1 \%$ of the difference between the corrected logbook and predicted totals. The regressions for the Reduced and Operational models, in contrast, had higher coefficients of determination, smaller variances about the regression, and in the latter case, a non-significant intercept term, which permitted regression through the origin. Both models (Fig. 5) generated predictions that were very highly correlated with the monthly mean catches from the unobserved effort (Reduced model: r $=0.861, \mathrm{df}=118, \mathrm{P}<0.0001$; Operational model $\mathrm{r}=0.879 ; \mathrm{df}=118 ; \mathrm{P}<0.0001$ ). The coefficients from the Environmental and Explanatory models were not applied to the unobserved effort because the former model was inadequate for such purposes, whereas the latter could not be fitted because there were large numbers of missing values for certain variables.

## Discussion

We achieved our three analytical objectives while clarifying important aspects of one use of fishery observer data. Because blue marlin and other billfishes are generally taken as incidental catch or by-catch in longline fisheries, and consequently logged less accurately than the target species (Walsh, 2000), it is imperative that analytical opportunities with observer data, likely the most accurate relevant information, be well understood. The timeliness and utility of these results can be inferred from the fact that development of statistical models from observer data has been favorably assessed by both the National Marine Fisheries Service (2003) and Oceana (Babcock et al., 2003), a nongovernmental conservation organization, as appropriate methodology. As such, this work represents a contribution to the ongoing development of
sound management practices for blue marlin, other billfishes, and large pelagic fishes in general.

Comparisons of the Full and Reduced models revealed that the latter was more parsimonious and yielded more accurate and precise estimates of blue marlin catches than the former model. This supported our judgment that identification and removal of bias caused by overparameterization of a GAM was important. In particular, these results demonstrated that predictors with distributions characterized by gaps between small numbers of isolated observations or individual outliers should not be allotted large numbers of degrees of freedom, as exemplified most dramatically by the effect of the minimum vessel length on the predicted catch estimate for the Full model. SST was also fitted unrealistically, with an ascending limb at low temperatures; this species is considered the most tropical istiophorid, largely confined to waters of $24^{\circ} \mathrm{C}$ or above (Nakamura, 2001). The discrepancy between the predicted catches from the Full model and the corrected logbook total (26.6\%) approached the $29.4 \%$ apparent logbook error previously estimated and subsequently verified by use of auction sales records (Walsh et al., 2005). If an overparameterized GAM such as the Full model had been used as a standard for logbook accuracy, the misidentifications problem in this fishery could have remained unresolved.

The Reduced and Operational models, in contrast, appeared promising on the grounds of accuracy, reasonable precision, and comprehensibility. The prediction limits were equivalent to $21 \%$ and $24 \%$ of the point estimates for the Reduced and Operational models, respectively. In addition, the Operational model demonstrated that useful results could be obtained without the inclusion of SST and the associated complexities of the interrelated effects of season and position. Because begin-set time represented the type of fishing (i.e., tuna-directed sets are deployed near dawn, whereas swordfish-directed sets are deployed near sunset), vessel length represented fishing power (i.e., larger vessels with greater fuel and hold capacity may range further and longer), and hook numbers represented effort, the Operational model can be regarded as a function of seasonality, position, fishing type, power, and effort.

The lower pseudocoefficient of determination and greater residual deviance of the Environmental model relative to the others were predictable. The predictors were either remotely sensed variables or calculated therefrom, averaged over time and space, so their values contained greater measurement error than the directly gathered set-specific operational variables. Nonetheless, this model demonstrated that SST exerted strong effects on blue marlin catches, even as SSTF and SSTA exerted lesser but still significant effects. These findings suggest that SST functioned as a controlling factor governing metabolism, while SSTF and SSTA functioned as directive factors influencing orientation and behavior, as expected from the classification of the environment provided by Fry (1971). As such, this model clarified aspects of the physiological ecology of blue marlin, despite its inadequacy as a predictive tool. Because the temperature effects were biologically comprehensible, it would seem that a useful predictive model could be developed if the spatial and temporal resolution of the environmental variables was improved. Two other aspects of this model also require consideration. The first is that SSTF and SSTA exert "directive" effects of another sort entirely; i.e., fishermen may utilize these variables (Sakagawa, 1989), but in such cases the cues of interest would be related to expectations of encounters with target species, not the incidental catch. The second is that WSC and current velocity significantly influenced catches, but probably did so through forces exerted
on the longline gear itself. Thus, although this model was fitted to a nominally homogeneous class of predictors (i.e., environmental), the actual mechanisms of action probably involved physiological and behavioral effects on fish, behavioral influences on fishermen, and physical perturbations of their means of interaction.
The Explanatory model was informative because it demonstrated that several previously untested variables significantly affected longline catches of blue marlin. The greatest such effect was that of hooks per float, supporting its use in distinguishing between types of longline effort. However, Walsh and Kleiber (2001) did not use this variable in their analyses of blue shark catches because it was highly correlated with hook numbers, which had always been recorded in the logbooks and did not cause missing values problems. At present, therefore, hook numbers remain preferable for use as a variable in a predictive model. The Explanatory model may be useful to fishery managers seeking to assess techniques for reduction of by-catch or incidental catch, to stock assessment scientists attempting to understand the effects of as many extrinsic factors as possible to aid in the interpretation of catch trends, or to observer program managers wishing to evaluate the importance of various logbook entries and ensure that the most important data are gathered with maximum efficiency.
We conclude on the basis of parsimony, accuracy, and precision that the Reduced and Operational models are useful for predicting blue marlin catches, with the likeliest applications consisting of by-catch estimation and correction of misidentifications if an appropriate means of verification (e.g., auction sales records) is available. The Reduced model appeared slightly preferable to the Operational model, although the presence of SST did create some complexities in interpretation. The Full model, in contrast, yielded predictions that were both inaccurate and imprecise. The Environmental model was comprehensible but not yet suitable for prediction. The Explanatory model revealed that several extrinsic factors not previously tested were significantly related to blue marlin catches, with hooks per float most strongly associated.

The results presented herein are being utilized in our current research and should serve as a fundamental component of future projects. Correction of the catch histories of the other istiophorids taken by this fishery [striped marlin; shortbill spearfish, Tetrapturus angustirostris Tanaka, 1915; black marlin, Makaira indica (Cuvier and Valenciennes, 1832); and sailfish, Istiophorus platypterus (Shaw in Shaw and Nodder, 1792)] is in progress. Planned research is expected to entail development, application, and interspecific comparisons of GAMs in order to improve understanding of the effects of operational and environmental factors on catches of these very important and closely related fishes. We (W.A.W., K.A.B.) are currently investigating the use of a GAM to standardize CPUE for use in stock assessments.

## Acknowledgments

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[^0]:    * The total number of trips exceeds the annual sums because some included sets in two calendar years.

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