

Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery

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ABSTRACT

Generalized additive models (GAMs) were applied to examine the relative influence of various factors on fishery performance, defined as nominal catch-per-unit-effort (CPUE) of swordfish (*Xiphias gladius*) and blue shark (*Prionace glauca*) in the Hawaii-based swordfish fishery. Commercial fisheries data for the analysis consisted of a 5 year (1991–1995) time series of 27 901 longline sets. Mesoscale relationships were analysed for seven physical variables (latitude, longitude, SST, SST frontal energy, temporal changes in SST (Δ SST), SST frontal energy (Δ SST frontal energy) and bathymetry), all of which may affect the availability of swordfish and blue shark to the fishery, and three variables (number of lightsticks per hook, lunar index, and wind velocity) which may relate to the effectiveness of the fishing gear. Longline CPUE data were analysed in relation to SST data on three spatiotemporal scales (18 km weekly, 1°-weekly, 1°-monthly). Depending on the scale of SST data, GAM analysis accounted for 39–42% and 44–45% of the variance in nominal CPUE for swordfish and blue shark, respectively. Stepwise GAM building revealed the relative importance of the variables in explaining the variance in CPUE. For swordfish, by decreasing importance, the variables ranked: (1) latitude, (2)

time, (3) longitude, (4) lunar index, (5) lightsticks per hook, (6) SST, (7) Δ SST frontal energy, (8) wind velocity, (9) SST frontal energy, (10) bathymetry, and (11) Δ SST. For blue shark, the variables ranked: (1) latitude, (2) longitude, (3) time, (4) SST, (5) lightsticks per hook, (6) Δ SST, (7) Δ SST frontal energy, (8) SST frontal energy, (9) wind velocity, (10) lunar index, and (11) bathymetry. Swordfish CPUE increased with latitude to peak at 35–40°N and increased in the vicinity of temperature fronts and during the full moon. Shark CPUE also increased with latitude up to 40°N, and increased westward, but declined abruptly at SSTs colder than 16°C.

As a comparison with modelling fishery performance in relation to specific environmental and fishery operational effects, fishery performance was also modelled as a function of categorical time (month) and area (2° squares) variables using a generalized linear model (GLM) approach. The variance accounted for by the GLMs was \approx 1–3% lower than the variance explained by the GAMs. Time series of swordfish and blue shark CPUE standardized for the environmental and operational variables quantified in the GAM and for the time-area effects in the GLM are presented. For swordfish, both nominal and standardized time series indicate a decline in CPUE, whereas the opposite trend was seen for blue shark.

Key words: blue shark, fishery oceanography, generalized additive models, longline fishery, North Pacific, remote sensing, swordfish

INTRODUCTION

Environmental influences on the distribution of fishery resources are important factors that should be included in fisheries management models (Sharp *et al.*, 1983). Environmental conditions (e.g. temperature, salinity, colour and turbidity) affect fishing success for pelagic species (Sharp, 1978; Laurs *et al.*, 1984; Maul *et al.*, 1984; Mendelssohn and Roy, 1986; Podesta *et al.*, 1993; Hinton and Deriso, 1998). Environmental factors may influence pelagic fish availability and vulnerability on a variety of spatiotemporal scales, yet models of resource dynamics typically ignore

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environmental processes or treat them as stationary noise (Bartoo and Coan, 1989; Hoey *et al.*, 1995).

Nominal catch-per-unit-effort (CPUE) representing the 'success' of fishing (Ricker, 1975) from commercial fishery statistics is a fishery performance index often used to investigate trends in resource abundance. It is affected by many factors in addition to abundance, such as spatial dispersion of resources (Lange, 1991), and fishing strategy (He *et al.*, 1997). By this definition, fishery performance is equivalent to relative apparent abundance (Marr, 1951): a relative measure of the number of fish in a population (N) as affected by availability (r) where

$$CPUE = qrN \quad (1)$$

The fraction (q) of rN that is actually caught by a unit of fishing gear is termed vulnerability when $r < 1$, or catchability when $r = 1$ (Ricker, 1975). Availability (Marr, 1951) is the fraction of the population exposed to fishing owing to intrinsic behavioural responses of fish to the environment (e.g. seasonal aggregations) and owing to extrinsic behaviour of the fishery (e.g. choice of fishing grounds). This study is limited to the Hawaii-based longline fishery, although the range of the fish populations is probably more widespread. A narrow definition of availability (Ricker, 1975) would be the fraction of a population living within the region susceptible to Hawaii-based fishing. Instead, the term 'regional abundance' will be used to describe the number of fish within this region, to retain Marr's (1951) broader definition of availability as all variations in catch not associated with fishing intensity or abundance.

In our study, we first attempt to quantify how some environmental and operational variables contribute to variation in fishery performance (nominal CPUE). We also quantify how fishery performance is affected by simple time-area strata. Next, we standardize CPUE for these factors, and propose that the standardized CPUE time series represent improvements over nominal CPUE as indices of regional abundance. We assume that the environmental and operational factors, or the season-area strata, primarily affect qr (not N). For example, aggregation of fish in response to thermal fronts could increase the availability of fish on a local (subregional) scale without affecting regional abundance, and changes in swimming depth in response to moon phase could change fish vulnerability to a specific depth of longline gear.

The Hawaii-based swordfish fishery

Swordfish and blue shark are found in tropical, subtropical and temperate oceans and seas of the world

(Palko *et al.*, 1981; Compagno, 1984). In the North Pacific, swordfish are predominantly caught in US and Japanese swordfish longline fisheries or as incidental bycatch in international tuna longline fisheries. Swordfish longlining is characterized by night fishing at shallow (≈ 30 – 90 m) depths (Boggs and Ito, 1993). In contrast, tuna longlining is characterized by day fishing at moderate depths (≈ 100 – 250 m) to target albacore, *Thunnus alalunga*, and yellowfin tuna, *Thunnus albacares*, or at greater depths (≈ 250 – 400 m) to effectively target bigeye tuna, *Thunnus obesus* (Hanamoto, 1976; Suzuki *et al.*, 1977; Boggs, 1992). Domestic US longline vessels have been operating in the Hawaii Exclusive Economic Zone (EEZ) since the 1920s (Boggs and Ito, 1993). Traditionally, the longline fishery has targeted tuna species, but since 1990 the number of vessels targeting swordfish has dramatically increased. Hawaii-based longliners landed 6100 t (metric tons) of swordfish in 1993 (Ito *et al.*, 1998), which represented a large fraction (30%) of the total multinational swordfish catch in the north-west and eastern-central North Pacific (FAO areas 61 and 77, FAO, 1995). Blue shark bycatch occurs in all North Pacific pelagic longline fisheries. Since the expansion of the swordfish longline fishery, blue shark have become the most numerous species in the longline catch as more than 150 000 blue sharks were reported caught in 1993 (Ito, 1995). The geographical range of the swordfish and blue shark populations exploited by the fishery remains uncertain. A recent hypothesis envisions that Hawaii-based fisherman may exploit swordfish belonging to a stock ranging from Japan to the western coast of North and Central America (Hinton and Deriso, 1998). Blue sharks are ubiquitous in the North Pacific and a single stock is presumed (Nakano, 1994).

Pelagic longline swordfish gear in the US North Pacific fishery consists of a monofilament main line hung in a sagging curve between surface floats. Branch lines descend from the main line, each terminating with a single baited hook. For targeting swordfish, two general gear configurations adopted from the US Atlantic fishery are used. The 'east-coast' or 'Florida' style has two or three hooks attached between floats with a lightstick attached to each branch line above the bait. The 'Gulf of Mexico' style has three to five hooks between floats with one lightstick per three to five branch lines (Ito *et al.*, 1998). About 30–40 miles (48–64 km) of gear are set during the early evening, allowed to soak overnight for 6–10 h, and retrieved starting early in the morning. Retrieval may take most of the day. Swordfish fishermen commonly seek fishing areas with SST gradients and current shear to deploy

their surface gear. The fishing depth of the gear depends on the length and sag of the main line between floats, which tend to increase with the number of hooks deployed per float. Depth is also affected by wind and ocean currents that may spread out and lift, or compress and deepen the longline. Although some inference of fishing depth may be obtained from operational data on numbers of hooks and floats deployed, data on gear configuration (i.e. hooks/float) were not required to be reported on US logbooks until 1995. Preliminary observations made by deploying time–depth recorders on 10 commercial swordfish trips indicate that the mean depth of the deepest hook was 70.6 m (SD = 40.8, min = 6, max = 228, n = 116 sets, C. Boggs unpublished data, NMFS Honolulu Lab, 2570 Dole St, Honolulu, HI, USA).

Physical oceanographic regions in the North Pacific

Oceanographers have divided the central North Pacific into three regions: (1) subarctic domain extends northward of 41°N and is characterized by cool, low-salinity surface layer, about 120 m deep in winter and 30 m in summer; (2) subtropical domain extends northward from 20°N to about 31°N and is characterized by a warm, saline surface layer, about 125 m deep in winter and 60 m in summer; and (3) the North Pacific Transition Zone (NPTZ) occupies the region between the subarctic and subtropical domains where temperatures and salinities gradually increase southward (Roden, 1991). A shallow salinity maximum (SSM) occurs near the base of the mixed layer from the southern NPTZ to 50°N in the subarctic domain (Yuan and Talley, 1992). The depth of the SSM is less than 100 m in the NPTZ and subarctic domain, but is deeper and below the mixed layer to the south of 34°N.

Two principal frontal zones extend throughout the longitudinal range (≈ 180 – 145°W) of the US fishery in the central North Pacific. The subarctic frontal zone (SAFZ) occurs throughout the year between latitudes 40° and 43°N (at 155°W, Roden, 1975), and is characterized by a strong halocline between 120 and 180 m, and weak SST gradients of 5°C per 100 km in winter to 2°C per 100 km in summer (Roden, 1980; Yuan and Talley, 1992). The northern and southern boundaries of the SAFZ are defined by the subsurface 33.0‰ and 33.8‰ isohalines, respectively (Roden, 1991). The subtropical frontal zone (STFZ) occurs between 27° and 33°N (at 155°W, Roden, 1981). The STFZ occurs from late fall to early summer as an SST front and throughout the year as a surface salinity front. The STFZ is characterized by SST gradients on the order of 3°C per 100 km, although gradients of up

to 0.39°C km⁻¹ occur across highly contorted filaments evident in SST data measured from satellites (Roden, 1980; van Woert, 1982). In winter, the northern boundary of the STFZ is defined as a thermohaline front composed of the 34.8‰ isohaline and 18°C isotherm, whereas the southern limit is defined as the subsurface 35.2‰ isohaline. Although the general location and characteristics of the STFZ have been identified, the front is not a simple zonal feature. One or several fronts may occur within the STFZ, with the individual fronts being convoluted in shape and shedding eddies that retain frontal characteristics (Roden, 1991).

Fishery oceanographic relationships

Swordfish concentrate in areas where food is abundant, commonly along frontal zones where ocean currents or water masses intersect to create turbulence and sharp gradients of sea surface temperature (SST) and salinity (Sakagawa, 1989). The association of swordfish with frontal zones may not be linked to temperature gradients, but rather to increased convergence or divergence, which results in a higher prevalence of plankton and forage species (Olson and Backus, 1985). Studies relating environmental parameters to pelagic fish distribution on fine scales (based on behaviour studies) and broad scales (based on long-term averages) are numerous (Carey and Robison, 1981; Sund *et al.*, 1981; Carey, 1990; Carey and Scharold, 1990), but applications of environmental data to analysis of fishery performance trends or to resource dynamics are rare for swordfish and nonexistent for blue shark. A review by Palko *et al.* (1981) suggested that temperature was important to swordfish distribution in all oceans. Podesta *et al.* (1993) investigated the association between swordfish CPUE and the shelf-break front on the Atlantic seaboard. They found that being near a front appeared to be necessary for successful fishing, but no association was established between CPUE and frontal variables such as SST gradient and frontal density. Hinton and Deriso (1998) modified nominal CPUE to account for the overlap between the depth of the longline hooks and the temperature-based habitat depth of swordfish.

The choice of explanatory variables in developing fishery oceanographic relationships depends on the objectives of the analysis and the spatial and temporal scale of available environmental data, e.g. time-series measurements or long-term (climatological) averages. Our objective was to describe fishery performance using contemporaneous data, rather than long-term averages. This precludes the use of some climatological data (e.g. salinity, ocean colour (CZCS), ocean

currents) that could provide additional explanatory information. Salinity in particular may be an important variable as it relates to the structuring of fish habitat, but we chose not to mix climatological and contemporaneous data in the analysis because of the differing scales of temporal smoothing.

Difficulties impeding the inclusion of environmental factors in analyses of fishery performance and resource dynamics include environmental variability that may be functionally related to biological processes on a variety of scales (Bakun, 1983). Also, analytical tools frequently used assume a linear relationship between fishery performance and environmental variables. In this paper, we develop estimates of thermal habitat using a range of spatial and temporal scales for definition of mesoscale ocean features. We explore the relationships between environmental variables and catch rates using generalized additive models (GAMs, Hastie and Tibshirani, 1990), which do not assume functional relationships between the predictor and response variables. GAMs have been used in fisheries research to detect trends in abundance of groundfish in the Bering Sea and of walleye pollock in relation to depth and temperature (Swartzman *et al.*, 1992; Swartzman *et al.*, 1995) and to detect the upper thermal limits of salmonid distribution (Welch *et al.*, 1995).

For comparison with the GAM analyses, we also employ a more conventional method of accounting for variation in nominal CPUE using generalized linear models (GLMs). Allen and Punsly (1984) and Punsly (1987) used GLMs to remove effects of variation in vessel efficiency, mode of fishing, and environmental variables from nominal yellowfin tuna (*Thunnus albacares*) CPUE, stating that "Differences in catch rates among years, which are not attributable to other variables in the model, can serve as indices of relative annual abundance (Punsly, 1987). As in the present study, these authors were attempting to index abundance in a region (the eastern Pacific) which may not represent the entire range of the population. Season-area strata were found to be an effective means of standardizing yellowfin tuna CPUE for environmental effects (Punsly, 1987). In the present study, swordfish and blue shark CPUE are standardized for time-area effects using GLMs.

DATA AND METHODS

Data from Hawaii-based longline fishermen were obtained from the mandatory logbook programme of the National Marine Fisheries Service (NMFS) that was initiated in late 1990. Logbook data include vessel

identification, fishing locations, starting times of setting and retrieval, number of hooks deployed and number of fish caught by species. Although the NMFS logbook data are nominally categorized by trip type as tuna, swordfish, and mixed trips, this classification is subjective, based sometimes on the report of fishermen and sometimes on the evaluation of NMFS staff who receive the data. Further, fishermen frequently switch target species (tuna, swordfish, or mixed) to efficiently exploit the changing availability or marketability of different resources. Ideally, sets would be classified by fishing depth and other operational characteristics, but these data are often suspect or incomplete. To restrict our analysis to sets in which swordfish was the target species, we applied a hierarchical cluster analysis (He *et al.*, 1997) on 58 643 longline sets from 5 years (1991–1995) of commercial fishery data to classify them according to species composition in the catches. The cluster dendrograms were interpreted as in He *et al.* (1997). At the highest level, two clusters of sets were resolved: tuna and mixed species sets, and swordfish sets. The swordfish cluster included 27 901 sets, which were analysed in relation to environmental variables in the current study.

Uncertainty in fishery data

Uncertainty exists in the geographical location of the longline for most of the logbook data (1991–1994), as positions were reported once for each deployment and once for each retrieval of the longline. These positions may represent one end of the longline, opposite ends, or somewhere in between. Therefore it is uncertain whether the full length of the longline extended between or away from these two points, and if away, in which direction. We averaged the deployment and retrieval locations to get one geographical position per longline set, but a radius of uncertainty of 48–64 km, the typical range in length of longlines, exists for the location of catches. To a degree, this uncertainty dictates the appropriate scale for integration of environmental data. The logbooks were amended in 1995 to require reporting of starting and ending positions of the longline deployment and longline retrieval, but because the location of catch along the line is not reported, the geographical resolution of catch locations is still on the order of 60 km.

Swordfish catch statistics are relatively accurate, as indicated by comparison of logbook catches with estimates from market monitoring programmes (NMFS unpublished data, Honolulu Lab, 2570 Dole St, Honolulu, HI, USA). Blue sharks are usually discarded at sea to maintain ice-hold capacity for higher-valued species. A comparison of reported blue shark catch

rates with catch rates observed by NMFS longline observers on 78 trips from March 1994 to August 1995 indicated that under-reporting by fishermen was not a problem (He and Laurs, 1998). Uncertainty still exists regarding the accuracy of blue shark catches reported prior to the observer programme (pre-1994), but on recent (1994–95) swordfish longline trips without observers, the reported blue shark catch rates tended to be as high as, or higher than, catch rates reported on trips with observers (He and Laurs, 1998). We assumed that the catch statistics are reliable and that catch rate expressed as the number of fish per 1000 hooks is an acceptable measure of nominal CPUE.

Physical covariates

A mesoscale (≈ 18 –100 km) approach was taken in exploring relationships between environmental variables and nominal CPUE because of the spatial uncertainty in longline location. The environmental and operational variables selected for analysis were: (1) the SST at the fishing location, (2) an index of SST frontal energy at the fishing location, (3) temporal changes in SST, (4) temporal changes in frontal energy, (5) a lunar index based on the illuminated percentage of the moon's face, (6) wind velocity at the fishing location, (7) bathymetry at the fishing location, (8) the number of lightsticks per hook, (9) latitude, and (10) longitude.

We use satellite-derived estimates of SST and SST frontal energy to characterize fish habitat, because swordfish and blue shark have a near-surface distribution at night (Carey and Robison, 1981; Carey, 1990; Carey and Scharold, 1990). Longline CPUE data were analysed in relation to SST data on three spatiotemporal scales. SST fields for 1991–1994 were obtained from multichannel sea surface temperature (MCSST) data (McClain *et al.*, 1985) derived from AVHRR (advanced very high resolution radiometer) measurements. MCSST data were provided by the University of Miami Rosenstiel School of Marine and Atmospheric Sciences/Jet Propulsion Laboratory and consisted of day and night weekly composites of SST at 18 km resolution. SST fields for 1991–1995 were obtained from the National Centers of Environmental Protection and consisted of two products based on an optimal interpolation (OI) analysis (Reynolds and Smith, 1994) of blended *in situ* (ship and buoy) SST data and AVHRR satellite retrievals. The OI data were computed on a 1° grid at weekly and monthly time scales. Fine-scale (1 km pixel) AVHRR data were available for a portion of the fishing period (1993–1995), but were not used owing to the aforementioned inaccuracies in longline location.

An index of SST frontal energy was calculated by using a 3×3 pixel Sobel operator (Schowengerdt, 1983), a common spatial filtering technique used in image analysis for gradient estimation. The Sobel operator is computationally simple, but estimates of SST frontal energy are not interpretable in terms of the SST change per unit distance owing to the nonlinear nature of the calculation (Herron *et al.*, 1989). The operator was calculated for each pixel in both the weekly (18 km or 1° square) and the monthly (1° square) SST data fields, which produced zonal and meridional components of the SST gradient. An index of SST frontal energy or gradient magnitude was computed from the two vector components [SST frontal energy = $\sqrt{(\text{zonal component}^2 + \text{meridional component}^2)}$]. Values of SST frontal energy were extracted for the pixel corresponding to each fishing location and time. At each fishing location, the temporal change in SST (Δ SST) and frontal energy (Δ SST frontal energy) were calculated for each of the three SST data products. Values of Δ SST may indicate the rate of isotherm movement through the fishing area, while values of Δ SST frontal energy may indicate whether a front is evolving or decaying.

A lunar index of the illuminated percentage of the face of the moon was calculated for each day in the 5 year time series. The index, which ranges from 0 (new moon) to 1 (full moon), was calculated from an astronomical algorithm (Meeus, 1991). Wind velocity at each fishing location was obtained from atmospheric numerical weather-prediction models at the National Center for Environmental Modelling. The model output contains 6 h estimates of zonal and meridional velocity components on a 2.5° grid. Daily wind velocity estimates [wind velocity = $\sqrt{(\text{zonal component}^2 + \text{meridional component}^2)}$] corresponding to fishing location were obtained by averaging four 6 h estimates.

The bathymetry at each fishing location was estimated from the ETOPO5 database (NOAA, 1988). The resolution of the gridded bathymetric data is 5 minutes of latitude and longitude, and a vertical resolution of 1 metre; however, the actual accuracy is difficult to define because the disparate data sources vary from a resolution of 5 min to 1 degree. Given the geographical uncertainty in longline position, we calculated both the shallowest and mean depth which occurred in a 65 km (45 nautical mile; n.m.) radius around the longline location. Bathymetric data with finer resolution and higher accuracy (e.g. sidescan sonar) exist for portions of the fishing area, but ETOPO5 was the only database covering the geographical range of fishing effort.

Generalized additive models (GAMs)

The functional relationships between fishing performance and environmental conditions are very likely to be nonlinear. GAMs were used to identify variables influencing catch rates and to determine the nature of the relationships. GAMs are nonparametric generalizations of multiple linear regression and are less restrictive in assumptions about the underlying statistical distribution of the data (Hastie and Tibshirani, 1990). Scatterplot smoothers replace least-squares fits in regression. Our nonlinear components were fitted with a locally weighted polynomial scatterplot smoother (*loess* smoother, Cleveland and Devlin, 1988) using the S-PLUS software package (Stat Sci Inc., 1700 Westlake Ave. N., Suite 500, Seattle, WA 98109, USA). The span or neighbourhood size of the *loess* smoother determines the fraction of the data set used in smoothing at each point. Initially, smoothing with 10% (span = 0.1) of the total number of observations was used, but some of the responses were unrealistically bumpy and complex. In further analyses, we considered that *CPUE* may be bumpy in space and time because the environment is bumpy, but other variables needed additional smoothing to provide realistic results. Therefore, a span of 0.1 was used for the space (latitude and longitude) and time variables, and a greater span of 0.25 (i.e. 25% of surrounding data) was used for the environmental and operational effects. In GAMs, a link function describing the total explained variance is modelled as the sum of the *loess* functions of the covariates. Histograms of nominal *CPUE* data for both species were not normal or log-normal because there were zero data points (swordfish $n = 1601$; blue shark $n = 6980$). In our link function, we assumed that the underlying probability distribution of the nominal *CPUE* data was a Poisson distribution, and we added 0.1 fish per 1000 hooks to all *CPUE* values because zero data points pose a problem to the Poisson link function. The addition of a constant still isolated the zero values from the smallest data value, thus not affecting the nonzero part of the distribution. The GAMs were fitted in the following form:

$$\ln(\text{CPUE} + 0.1) = a + \text{lo}_1(x_1) + \dots + \text{lo}_{ij}(x_i, x_j) + \dots + e, \quad (2)$$

where a is a constant, $\text{lo}_1(x_1)$ is a *loess* smoother function of independent variable x_1 , $\text{lo}_{ij}(x_i, x_j)$ is an additive *loess* smoother function of two independent variables x_i, x_j (analogous to an interaction term in regression), and e is a random error term. Ten independent variables plus a time effect were included in the analysis in the form:

$$\begin{aligned} \ln(\text{CPUE} + 0.1) = & a + \text{lo}_1(\text{Latitude}) + \text{lo}_2(\text{Longitude}) \\ & + \text{lo}_3(\text{SST}) + \text{lo}_4(\text{SST frontal energy}) \\ & + \text{lo}_5(\Delta\text{SST}) + \text{lo}_6(\Delta\text{SST frontal energy}) \\ & + \text{lo}_7(\text{Light sticks}) + \text{lo}_8(\text{Lunar index}) \\ & + \text{lo}_9(\text{Wind velocity}) + \text{lo}_{10}(\text{Bathymetry}) \\ & + \text{lo}_{11}(\text{Time}) + e. \end{aligned} \quad (3)$$

Models were fitted in a forward and backward stepwise manner to decrease the problems associated with multicollinearity. Reduced models including only SST or SST frontal energy were also estimated. The model selection process for the best predictive model for our *CPUE* data was based on an Akaike information criterion (AIC, Akaike, 1974) in S-PLUS (Hastie and Tibshirani, 1990).

As a comparison with modelling fishery performance in relation to specific environmental and fishery operational effects, fishery performance was also modelled as a function of categorical time and area effects using a (GLM) approach:

$$\ln(\text{CPUE} + 0.1) = a + bM + gA + dMA + \ln(\text{Time}) + e, \quad (4)$$

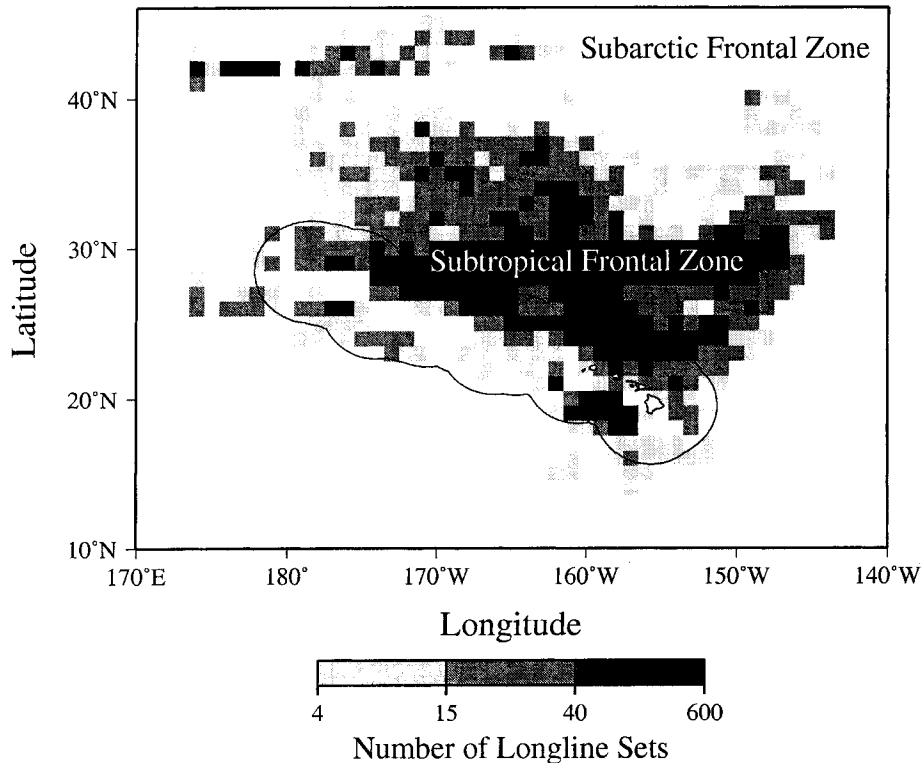
where a, b, g and d are constants, M is month, A is the fishing area (2° square) and MA is an interaction of month and area, $\ln(\text{Time})$ is a time effect and e is a random error term. The GLMs were estimated using the GAM procedure in S-PLUS, but with categorical variables there are no *loess* functions and the model is exactly equivalent to a GLM with each month, area, and month–area interaction having a singular effect on nominal *CPUE*.

RESULTS

Distribution of swordfish fishing effort and fishery performance

Swordfish longline sets from 1991 to 1995 were broadly distributed from the Hawaiian Archipelago to 45°N and from 175°E to 145°W (Fig. 1). Effort was concentrated to the north and north-west of the main Hawaiian Islands in association with the subtropical (STFZ) and subarctic (SAFZ) frontal zones. The trend in nominal *CPUE* was modelled as a *loess* function of *Time* with no other explanatory variables (Fig. 2). The annual seasonality in catch rates is evident from the *Time* effect as swordfish *CPUE* usually peaked during spring (also in fall 1992 and in 1993) and blue shark

Figure 1. Spatial distribution of fishing effort in the Hawaii-based swordfish longline fishery from 1991 to 1995. Spatial resolution of fishing effort is one degree. Fishing areas with <4 sets per nautical degree were deleted owing to confidentiality rules in NOAA fisheries. The 200 n.m. (nautical mile) exclusive economic zone (EEZ) boundary is shown around the Hawaiian Archipelago.



CPUE peaked during fall. Intra-annual variation in CPUE was greater for blue shark.

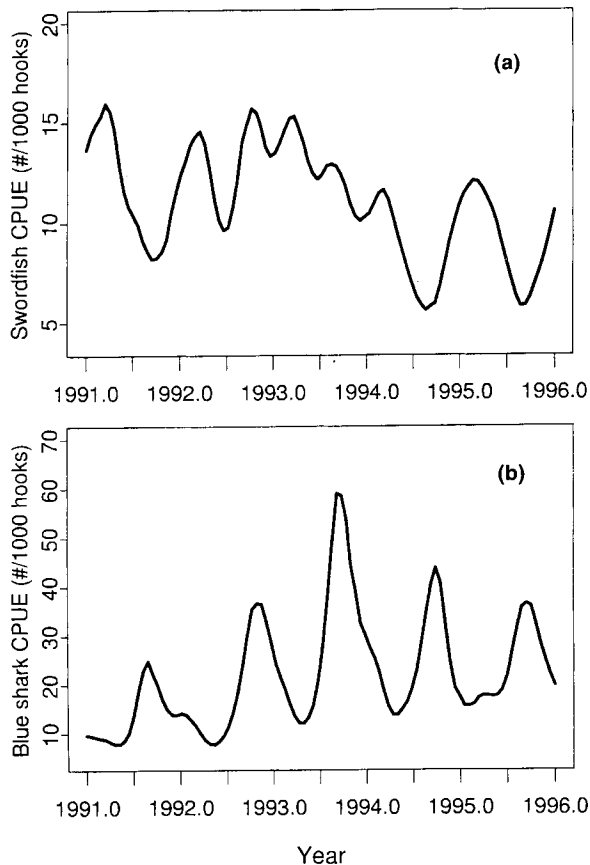
A three-dimensional view of how effort and fishery performance (nominal CPUE) vary with temperature and time was produced by assigning the 1°-weekly SST estimates to each fishing operation and summarizing total effort and mean CPUE by 0.5°C and 2 week cells from January 1991 to December 1995 (Fig. 3). The y-axis (temperature) is inverted so that the top of the figure is approximately north. Time series of SST along the 30°N and 41°N parallels, the two major frontal zones (STFZ = lower white line, SAFZ = upper white line, Fig. 3), are superimposed on the time-SST field to provide surrogate coordinates. The frontal zone SST lines are averages of the 1°-weekly SST data for 30°N and 41°N taken across the longitudinal range of the fishery (about 180° to 145°W). The frontal zone lines show periodic cold peaks (up = cold) in the spring and periodic warm dips (down = warm) in the fall, reflecting the annual SST cycle in the North Pacific. In relation to these temperature approximations of the main frontal zones, the subarctic domain is to the north or above the

SAFZ line, the North Pacific Transition Zone (NPTZ) is between the lines, and the subtropical domain is to the south or below the STFZ line (Fig. 3).

Effort directed toward swordfish is highest in the first and second quarters of each year (Fig. 3a). During the first quarter, effort is mostly concentrated in 17–20°C water in and around the STFZ. During the second quarter, effort is still concentrated near the STFZ, but the epipelagic habitat has warmed to 20–25°C. During the third and fourth quarters, effort decreases around the STFZ, with effort briefly concentrated around the SAFZ and in the subarctic domain during the third quarter. In the fourth quarter, some effort takes place from the SAFZ to the subtropical domain, but effort is most concentrated in the NPTZ.

Although there are additional variables influencing fishery performance, some general trends with respect to thermal habitat are apparent. Swordfish and blue shark CPUE are poor in subtropical water > 23°C throughout the time series. Catch rates tend to be highest when SST at the STFZ is near its seasonal minimum, or at the SAFZ, its seasonal maximum.

Figure 2. Generalized additive model (GAM) derived effect of Time on (a) swordfish and (b) blue shark nominal CPUE.



Swordfish CPUE near the STFZ was highest in spring when SST was coolest (16–19°C, Fig. 3b). Swordfish CPUE near the SAFZ and in the subarctic domain tended to be highest when SST was warmest (13–19°C). Blue shark CPUE remained low at the STFZ throughout the year, and tended to be highest in the SAFZ and the NPTZ during summer and fall (Fig. 3c). Around the SAFZ ($\approx 41^\circ\text{N}$), the highest blue shark CPUE is often adjacent to but separated in the time–SST field from the highest swordfish CPUE, suggesting that distribution or catchability reflect segregation in the habitat or in the capture process.

Generalized additive models (GAMs)

All 11 variables were highly significant ($P < 0.0001$, d.f. = 27 899, Table 1) in the stepwise GAM. No interaction terms were included in this model. The very large number of data points in the analysis makes it easy for explanatory variables to be statistically significant in the model, even though some have minor effects. Other models were fitted using many of the same variables with first-order interaction terms

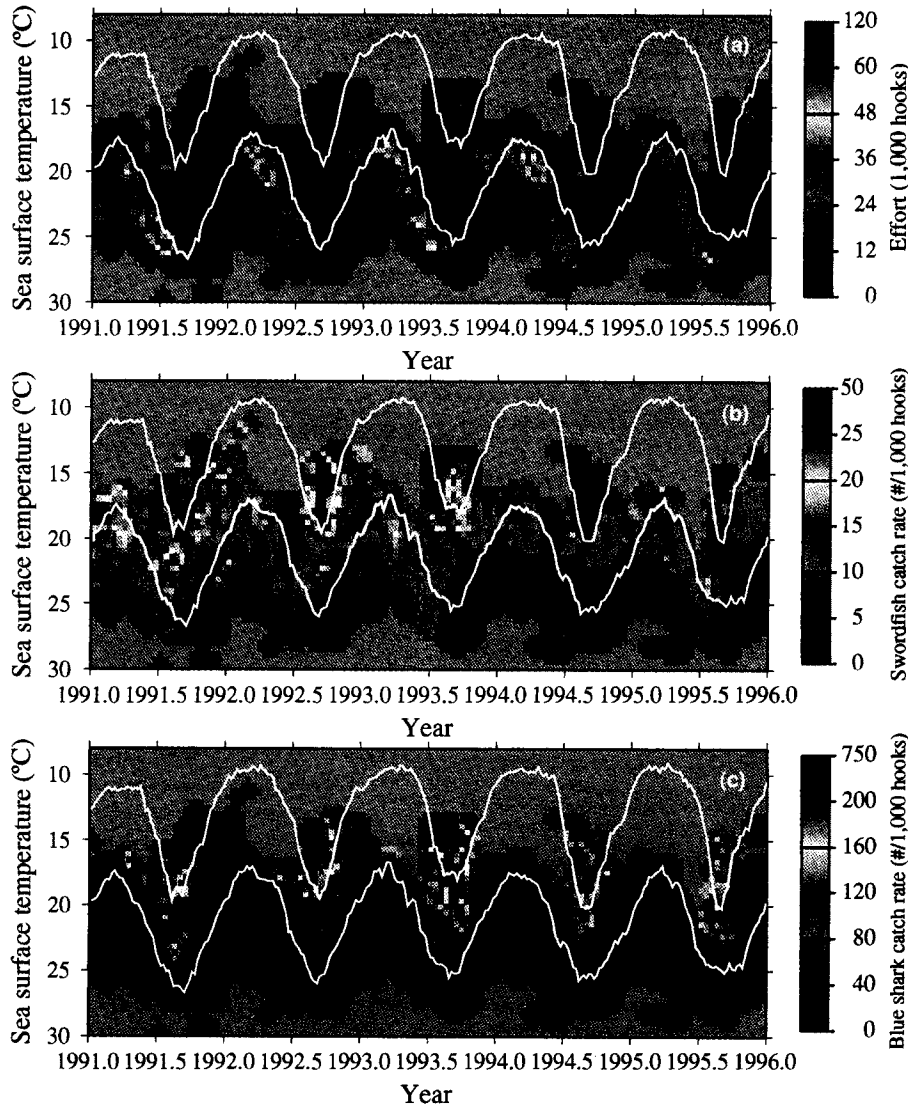
included, but the interaction effects did not appreciably alter the main effects, nor the goodness of fit.

Results from a total of six GAMs (two species \times three spatiotemporal SST scales) are presented (Table 2). The effects of the explanatory variables may be illustrated by plotting the fitted contribution of each variable to total deviance in fishery performance as a *loess* function of that variable. For both species, *Latitude* is the most significant explanatory variable in explaining CPUE (Table 1); thereafter, the order in which variables enter into the model differs slightly depending on species or SST scale. *Latitude* alone explains 24% and 31% of the deviance in swordfish and blue shark CPUE, respectively (Table 1). *Latitude* and *Longitude* effects on CPUE are illustrated in Fig. 4 as *loess* smoothing functions with 95% confidence bands. The relative density of points for different covariate values is shown by the 'rug' on the x-axis. An explanatory variable is typically insignificant if a horizontal line can be drawn through the 95% confidence bands. In general, confidence bands were wider for effects on blue shark CPUE. For swordfish and blue shark, CPUE increases with *Latitude* from 15°N and 23°N (Fig. 4a,c). The effect of *Latitude* to the south of 15°N is unclear because the reduced density of data points leads to larger standard error ranges. The effect of *Longitude* is greater on blue shark CPUE than swordfish CPUE. Swordfish CPUE is reduced at 160°W , which corresponds to the meridian of the island of Oahu in the Hawaiian Archipelago (Fig. 4b). Blue shark CPUE decreases almost monotonically from the dateline to 140°W (Fig. 4d).

The relative magnitudes of the effects of the explanatory variables are judged by the relative y-axis ranges of *loess* functions. The *loess* function for *Latitude* has a y-axis range of 2.0 (–1.8 to 0.2) for swordfish (Fig. 4a) and 3.0 (–0.8 to 2.2) for blue shark (Fig. 4c). These ranges amount to a difference of 12 swordfish per 1000 hooks $\{\exp[0.2 + \ln(11.6, \text{mean swordfish CPUE})] - \exp[-1.8 + \ln(11.6)]\}$ and 167 blue sharks per 1000 hooks $\{\exp[2.2 + \ln(19.6, \text{mean blue shark CPUE})] - \exp[-0.8 + \ln(19.6)]\}$, respectively. Additive effects on log-transformed CPUE are multiplicative when back-transformed into the original units (fish per 1000 hooks), and these multiplicative effects apply to very different minimum values for each species and variable. Therefore, it is best to compare the magnitude of effects using the untransformed *loess* functions.

The effects of SST and SST *frontal energy* on fishery performance are intermediate with a *loess* range of about 0.75–1.0 (Figs. 5 and 6) for the full 11-variable GAM of eqn 3. A reduced GAM with only a *loess* function of either SST or SST *frontal energy* and no other indepen-

Figure 3. Three-dimensional view of effort (a) and nominal CPUE (b, swordfish; c, blue shark) in relation to time, temperature (°C inverted so that north is up), and approximate oceanographic domain in the Hawaii-based swordfish longline fishery. Each cell represents the total effort or mean nominal CPUE by 0.5°C and 2 week intervals. Because the temperature at fronts is more variable seasonally than is their latitudinal position, the annual cycles of SST indicative of the subtropical ($\approx 30^\circ\text{N}$) and subarctic ($\approx 41^\circ\text{N}$) frontal zones bounding the subtropical (bottom) and subarctic (top) domains are indicated by the lower and upper white lines, respectively.



dent variables had a range of *loess* values considerably greater (≈ 2.0) than when all independent variables were included in the full GAM. Therefore, SST and SST *frontal energy* effects on nominal CPUE in the full GAM are substantially dampened by the inclusion of other explanatory variables. Although dampened, both the SST and SST *frontal energy* effects were qualitatively similar between the reduced and full GAMs for swordfish. Swordfish CPUE was highest in 15°C water, and decreased at higher temperatures (Fig. 5a). Although

confidence bands are not shown, the effect of SST was similar regardless of the spatiotemporal scale of SST model input (Fig. 5). SST *frontal energy* had a positive effect on swordfish CPUE (Fig. 6a), although the shape of the effect depended on the scale of model input. Effects were similar at high frontal energy regardless of scale, but significant differences were evident at low frontal energy as confidence bands (not shown) did not overlap. At low frontal energy, fishing performance was poorer (≈ 2 swordfish per 1000 hooks) when SST *frontal*

Table 1. Stepwise Generalized Additive Model building for factors affecting swordfish and blue shark CPUE (1991–1995)

Explanatory variable	1°- monthly SST data		
	Residual d.f.	Residual deviance	Cumulative variance explained in CPUE
<i>Swordfish</i>			
Mean	27899	203538	
Latitude	27879	155006	24%
Time	27861	134759	33%
Longitude	27842	130099	36%
Lunar index	27835	126623	38%
Lightsticks per hook	27826	123877	39%
SST	27819	122082	40%
Δ SST frontal energy	27811	120711	41%
Wind velocity	27803	119927	41%
SST frontal energy	27795	119220	41%
Bathymetry	27788	118766	42%
Δ SST	27780	118350	42%
<i>Blue shark</i>			
Mean	27899	1138868	
Latitude	27879	777916	31%
Longitude	27860	693180	39%
Time	27842	656668	42%
SST	27835	647613	43%
Lightsticks per hook	27827	639775	44%
Δ SST	27819	635367	44%
Δ SST frontal energy	27810	631798	45%
SST frontal energy	27803	628448	45%
Wind velocity	27795	626847	45%
Lunar index	27788	626265	45%
Bathymetry	27780	625805	45%

Table 2. Variance explained in Generalized Additive Models (GAMs) and Generalized Linear Models (GLMs) with an assumption of a Poisson distribution. GAMs used environmental factors to explain swordfish and blue shark CPUE. GLMs used time–area (2– monthly) strata to explain CPUE

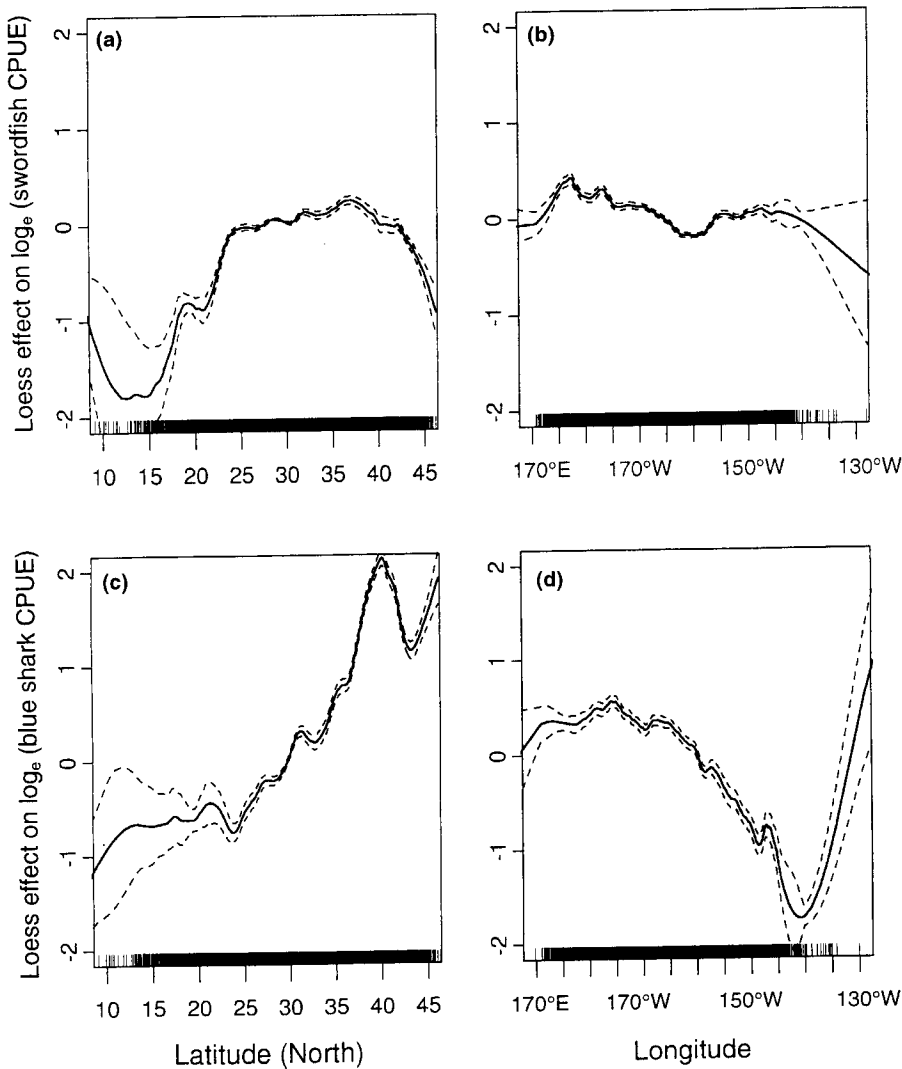
Strata	Swordfish CPUE		Blue shark CPUE	
	GAMs	GLMs	GAMs	GLMs
1°-monthly SST (1991–1995)	41.8%		45.1%	
1°-weekly SST (1991–1995)	41.5%		44.4%	
18 km weekly SST (1991–1994)	39.3%		44.3%	
2°-monthly (1991–1995)		38.7%		43.1%

energy was calculated on 1°-weekly or 1°-monthly scale rather than on an 18 km-weekly scale.

For blue shark, SST and SST frontal energy effects on CPUE differed substantially in shape and magnitude between a reduced and full GAM. In the reduced GAM, blue shark CPUE was high at 16°C and decreased continuously as SST increased. The full GAM also showed high CPUE at 16°C, but CPUE declined more gradually as SST increased from 16°C to 24°C, and CPUE increased gradually as SST increased above 24°C (Fig. 5b). In the reduced GAM, SST frontal energy had a positive effect on CPUE with a loess range of 2.5. but the effects were relatively flat or complex in the full GAM (Fig. 6b).

The Δ SST and Δ SST frontal energy effects provide information on how temporal dynamics of the thermal and frontal habitat affect fishery performance. The effect of Δ SST is slightly positive for each species. A warming trend has some tendency to produce higher CPUE for swordfish, although the overall effect is relatively minor (Fig. 7a). The effects were complex

Figure 4. Generalized additive model (GAM) derived effects of *Latitude* and *Longitude* on (a and b) swordfish and (c and d) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 3). Dashed lines indicate 95% confidence bands. The relative density of data points is shown by the 'rug' on the x-axis.



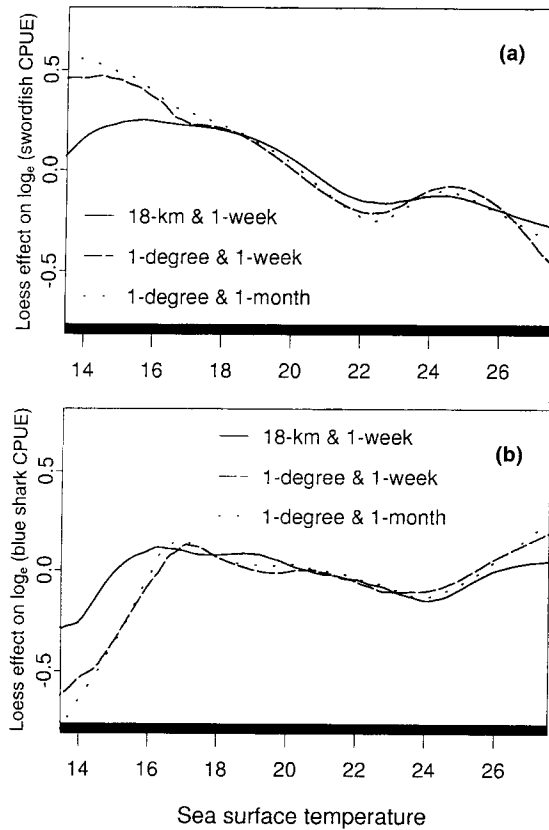
for blue shark (Fig. 7b). Higher swordfish CPUE occurred in decaying frontal environments when *frontal energy* was decreasing (Fig. 8a). Conversely, lower blue shark CPUE occurred when *frontal energy* was decreasing (Fig. 8b).

The number of *Lightsticks per hook*, *Lunar index* and *Wind velocity* probably affect the vulnerability of fish to the fishing operation. These effects were relatively small, with *loess* ranges of ≈ 0.4 . In both species, low CPUE occurred when few (<0.15 for swordfish, <0.25 for shark) *Lightsticks per hook* were deployed (Fig. 9a,c). An increase in the number of *Lightsticks per hook* from 0.15 to 0.4 caused a slight increase in swordfish CPUE with variable effects at higher levels. In contrast, an increase in *Lightsticks per hook* from 0.25 to 1.0 caused a

substantial increase in blue shark CPUE. *Lunar index* was the penultimate variable entered in the blue shark GAM (Table 1), and the effect appears almost insignificant (Fig. 9d). The effect of *Lunar index* was more pronounced on swordfish CPUE (Fig. 9b). GAM predictions suggest an increase of ≈ 3 swordfish per 1000 hooks when fishing during a full moon (*Lunar index* = 1.0) compared with a new moon (*Lunar index* = 0.0). The effect of *Wind velocity* was opposite for the two species, an increase having a negative effect on swordfish CPUE (Fig. 10a) and a positive effect on blue shark CPUE (Fig. 10c).

With regard to *Bathymetry*, separate models were fitted to the shallowest and mean depth estimates. Model results were not sensitive to the depths chosen,

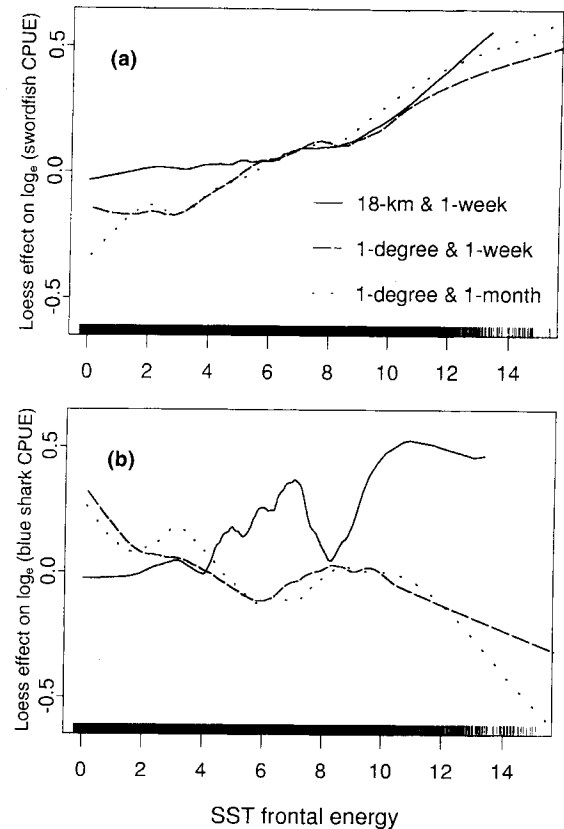
Figure 5. Generalized additive model (GAM) derived effects of Sea surface temperature (SST) on (a) swordfish and (b) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 3). Three line types correspond to averaging environmental data at different spatiotemporal scales. The relative density of data points is shown by the 'rug' on the x-axis.



therefore the shallowest depth is illustrated in relation to fishery performance. Swordfish CPUE increased in the vicinity of seamounts, banks, or islands (< 2000 m bottom depth), was lowest over a depth range of 2000–3000 m bottom depth, and then increased in deeper water (Fig. 10b). The *Bathymetry* effect on blue shark CPUE was less pronounced but showed some increase at bottom depths shallower than 3000 m (Fig. 10d).

The amount of deviance in the nominal CPUE time series that was explained by the GAMs was affected by the spatiotemporal scale of SST model input (Table 2). Coarser scales (i.e. 1°-monthly or 1°-weekly) of SST data typically explained slightly more deviance in nominal CPUE than did finer-scale data, but the results were generally similar. Most of the deviance in nominal CPUE was explained by including five terms in the GAM model, as the inclusion of the remaining variables only explained an additional

Figure 6. Generalized additive model (GAM) derived effects of Sea surface temperature (SST) frontal energy on (a) swordfish and (b) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 1). Three line types correspond to averaging environmental data at different spatiotemporal scales. The relative density of data points is shown by the 'rug' on the x-axis.



3% in deviance (Table 1). For swordfish and shark, GAMs explained significantly more deviance (1–3%; swordfish, $f=4.5$, blue shark, $f=3.4$, $P < 0.00001$) than did GLMs based on month, area, and month–area interaction effects (Table 2). Similar to the GAM results, the analysis of deviance table (Table 2) shows that each factor in the GLM was statistically significant. While interaction terms were not included in the GAM, the GLM model benefited significantly from the month–area interaction effects (Table 2).

Standardized CPUE

Standardized CPUE was calculated from the *Time* effect in eqns 3 and 4 by standardizing the dependent variable (nominal CPUE) for all effects other than time. The resulting GLM- and GAM-standardized CPUE estimates, as functions of time (Fig. 11), serve

Figure 7. Generalized additive model (GAM) derived effects of Δ SST (change in Sea surface temperature over one week) on (a) swordfish and (b) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 3). Dashed lines indicate 95% confidence bands. The relative density of data points is shown by the 'rug' on the x-axis.

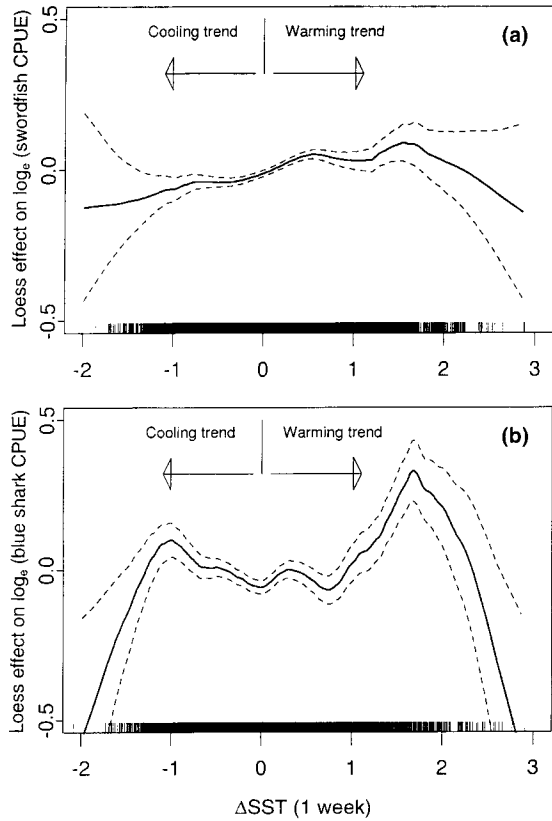
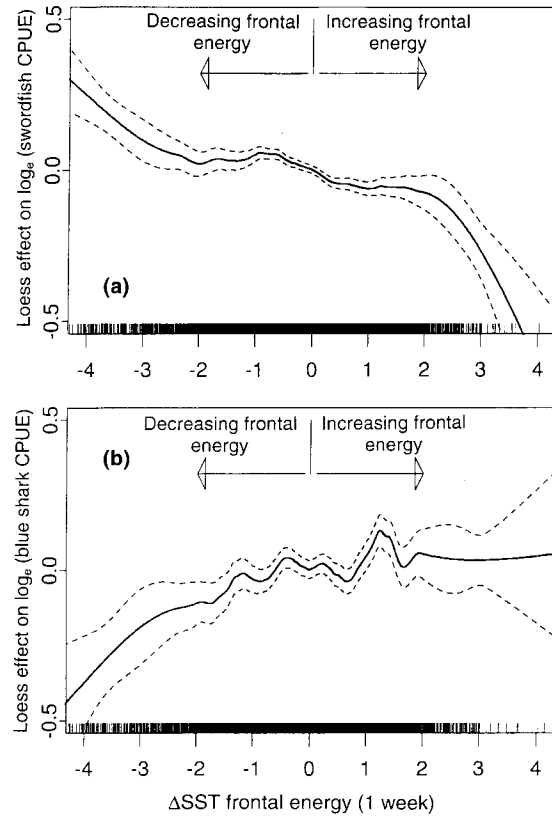


Figure 8. Generalized additive model (GAM) derived effects of Δ SST frontal energy (change in sea surface temperature frontal energy over one week) on (a) swordfish and (b) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 3). Dashed lines indicate 95% confidence bands. The relative density of data points is shown by the 'rug' on the x-axis.

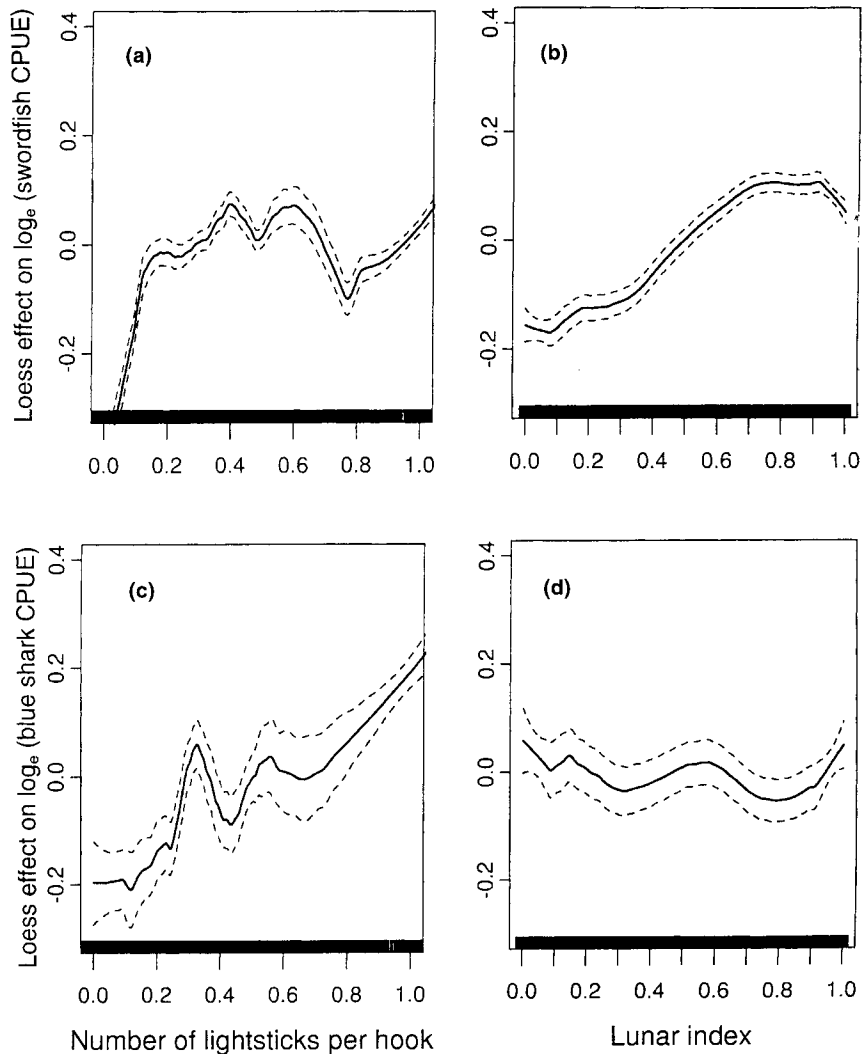


as improvements over nominal CPUE trends as indices of relative abundance (Punzly, 1987) within the overall region of the Hawaii-based fishery (Fig. 1). This procedure was not intended to provide standardized CPUE indices at any finer spatial scale, because spatial and seasonal variations in the local density of fish were among the effects attributed to environmental variables in the GAM or to month and area variables in the GLM. All remaining variation in the standardized CPUE estimates (Fig. 11) was attributed to time and error. Among the various GAM models, we chose the 1°-monthly GAM model to illustrate standardized CPUE.

The standardized CPUE time series differ moderately from the nominal CPUE time series. Confidence bands are not illustrated, but were narrow and seldom overlapped. GAM- and GLM-standardized swordfish

CPUEs were significantly higher than nominal CPUE during 1991 and lower from mid-1993 to mid-1994 (Fig. 11a). Standardizing CPUE using the GAM explained (removed) a peak in nominal CPUE in the second half of 1992 that was not explained by the GLM. Both standardized CPUE indices indicated more moderate CPUE declines in late 1994 and 1995 than were indicated by nominal CPUE. Standardized CPUE declines in mid-1993 to late 1994 and late 1995 were statistically significant. Strong seasonal cycles in nominal CPUE, particularly for blue shark (Fig. 11b), were not evident in the standardized CPUE series. GAM- and GLM-standardized, as well as nominal blue shark CPUE time series all reflected an overall increasing trend throughout the 5 year time series. Both standardized time series indicate that the record high nominal CPUE in 1993 did not reflect a major peak in regional abundance.

Figure 9. Generalized additive model (GAM) derived effects of *Lightsticks per hook* on (a) swordfish and (c) blue shark nominal CPUE deviances (log transformed) and GAM effects of *Lunar index* on (b) swordfish and (d) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 3). Dashed lines indicate 95% confidence bands. The relative density of data points is shown by the 'rug' on the x-axis.



DISCUSSION

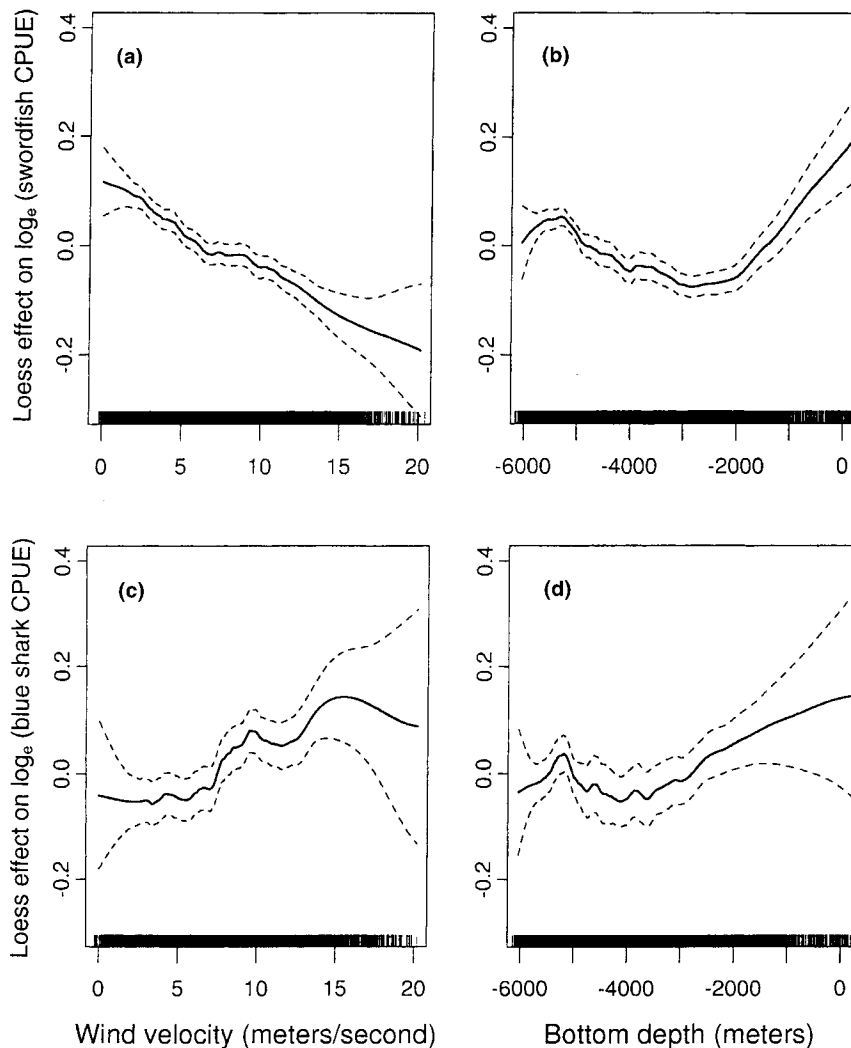
Identification of significant associations between fish species and environmental conditions is the initial step toward incorporating environmental information into stock assessment models and understanding by-catch problems. Pelagic fishing performance can depend on environmental conditions influencing the availability (Marr, 1951) and vulnerability (Ricker, 1975) of the resource (Sharp, 1978; Mendelsohn and Cury, 1986; Hanamoto, 1987). Relationships were developed for seven variables (*Latitude*, *Longitude*, *SST*, *SST frontal energy*, Δ *SST*, Δ *SST frontal energy*, and *Bathymetry*) which impinge on swordfish and blue

shark availability. All of these variables, and the remaining three – *Lightsticks per hook*, *Lunar index*, and *Wind velocity* – may also affect the vulnerability of fish to being caught by the fishing gear.

Environmental variables affecting fishing success

In the GAM analysis, mesoscale oceanographic data had moderate power for predicting fishery performance (nominal CPUE). Results presented are more pertinent to the subtropical domain and the NPTZ than in the SAFZ and subarctic domain, as little longline effort was expended north of 40°N. Geographical distribution in swordfish effort varies seasonally in response to SST

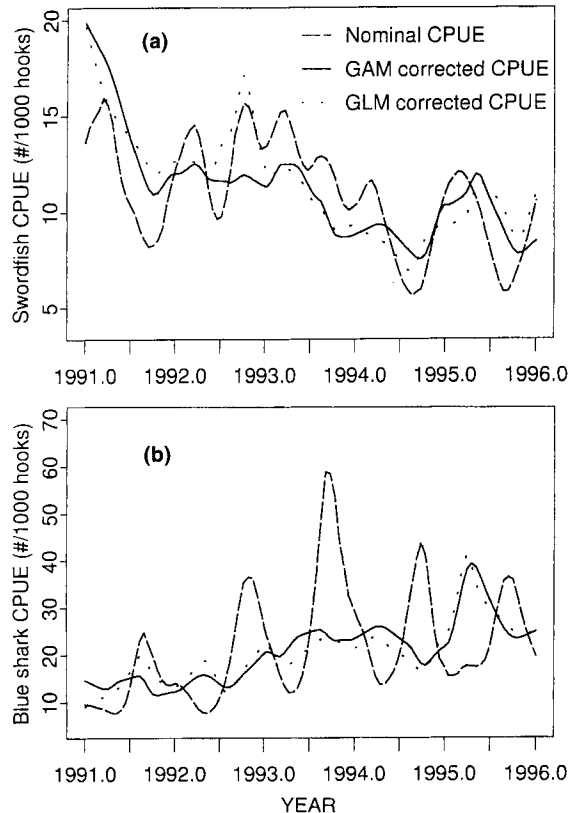
Figure 10. Generalized additive model (GAM) derived effects of *Wind velocity* on (a) swordfish and (c) blue shark nominal CPUE deviances (log transformed) and GAM effects of *Bathymetry* on (b) swordfish and (d) blue shark nominal CPUE deviances (log transformed). All independent variables are included in the GAM (eqn 3). Dashed lines indicate 95% confidence bands. The relative density of data points is shown by the 'rug' on the x-axis.



isotherm movements and variation in SST frontal energy. Historical catches in the Japanese tuna longline fishery in the central North Pacific indicate large-scale spatiotemporal variation in nominal CPUE similar to that observed in the Hawaii-based swordfish fishery. Japanese data aggregated by 5° and monthly periods from 1952 to 1985 indicate high CPUE throughout the year near the SAFZ where the Kuroshio Current Extension meets the Oyashio Current and from January to May at the STFZ and NPTZ (Sakagawa, 1989; Sosa-Nishizaki and Shimizu, 1991). In the Hawaii-based fishery, high CPUE occurred over an SST range of 15°–20°C and where there was strong SST frontal energy. The mechanisms associated with increased swordfish fishery

performance at greater SST frontal energy may not be linked to a preference for SST gradients, especially because swordfish are capable of diel vertical migration through a temperature change of as much as 19°C (Carey and Robison, 1981). Changes in water clarity often accompany temperature changes across fronts and may provide additional cues to locate fronts (Olson and Podesta, 1987). Biomass of forage organisms may be higher in fronts owing to increased lateral and vertical mixing, which often stimulates primary and secondary production (Olson and Backus, 1985). Swordfish and blue shark are opportunistic predators which typically feed on nektonic squids and fishes (e.g. Ommastrephidae, Onychoteuthidae, Gonatidae, Bramidae, Myc-

Figure 11. Generalized additive model (GAM) and generalized linear model (GLM) standardized CPUE index of relative regional abundance as a function of Time for (a) swordfish and (b) blue shark, compared with nominal CPUE (fishery performance) as a function of Time.



trophidae). In particular, prey species such as the neon flying squid (*Ommastrephes bartramii*) and Pacific pomfret (*Brama japonica*) have higher abundances during spring and summer near the SAFZ and during winter near the STFZ (Pearcy, 1991) and probably influence swordfish aggregation.

The effect of low SST frontal energy on fishery performance differed, depending on the time and space scale of model input. The difference results from the spatial area over which SST frontal energy was calculated. The 3×3 Sobel operator encompasses an area ≈ 38 times larger for the 1° data ($\approx 32\,400$ n.mi.²) than the 18 km data (≈ 861 n.mi.²). So a low SST frontal energy value calculated from the 1° data indicates an isothermal ocean over a much larger area than a low value calculated from the 18 km data. Given that fronts are important, a very large isothermal area would be more likely associated with poor fishery performance than a small isothermal area, because in the latter case a front might not be far away.

Given the uncertainty in longline location, the longline might indeed cross an area of high SST frontal energy in the 18 km data even though there was low energy at the recorded location of the set.

Blue sharks are believed to make seasonal migrations northward into subarctic waters during the summer and southward into the NPTZ and subtropical domain during winter (Strasburg, 1958; Nakano, 1994). Our oceanographic variables suggest low nominal CPUE in the subtropical domain and higher nominal CPUE in the NPTZ and subarctic domain, consistent with surface driftnet fisheries, in which blue shark CPUE was highest from 35 to 45°N over a range in SST from 14°C to 18°C (Nakano *et al.*, 1985). Our relationships were developed on individuals of unknown sex, and may be slightly biased because subadult blue sharks (100–150 cm precaudal length) geographically segregate by gender, with females inhabiting 40–50°N and males 30–40°N (Nakano, 1994). Adult blue sharks occur mainly from the Equator to 40°N and mate in summer within the subtropical domain. Blue shark CPUE in subtropical tuna longline fisheries was highest when SST ranged from 17°C to 24°C and from 14°C to 18°C at a depth of 100 m (Nakano, 1994). Adult blue shark habitat in the subtropics has been hypothesized to shift to deeper, cooler water compared with the NPTZ (Nakano, 1994). If the optimal thermal habitat is 14–18°C, our reduced blue shark CPUE in the subtropics may reflect inefficient exploitation of the habitat by near-surface swordfish gear. Whereas latitudinal gradients in blue shark abundance have been documented, our higher CPUE values in the western part of the fishery suggest that there is also a longitudinal gradient in abundance. Noteworthy features in the western basin affecting availability include the Emperor Seamount chain ($\approx 170^\circ\text{E}$) and strong boundary currents that penetrate the NPTZ and generate large mesoscale perturbations such as eddy shedding of the Kuroshio extension (Roden, 1991).

Individual fronts at the STFZ and SAFZ are in various stages of evolution and decay, but the exact formation and dissipation times are unknown (Roden, 1991). At time lags of one week or one month, results indicate that higher swordfish and blue shark CPUE occurred in decaying and evolving frontal environments, respectively. Higher catch rates in decaying frontal environments may indicate that biomass of forage organisms has accumulated through either increased upwelling in a divergent front or concentration in a convergent front.

One limitation in the GAM analysis was that ocean structure was inferred only from SST estimates.

Salinity estimates should also be included in the model, but a salinity time series was not available and we chose not to use climatological data as model inputs. Salinity data could improve the explanatory ability of the model by: (1) providing better estimates of frontal energy, especially as thermohaline structure differs between the STFZ and SAFZ; and (2) incorporating the depth of the shallow salinity minimum (SSM). Salinity estimates are more valuable than SST to describe frontal structure, especially in the SAFZ, which is characterized by strong salinity structure and weak SST gradients throughout the year. Though SST poorly describes the frontal magnitude at the SAFZ, there is little bias in our results, which are more indicative of the subtropical domain and NPTZ, as mentioned previously. The SSM is usually less than 100 m and forms in winter in the NPTZ and subarctic domain (Yuan and Talley, 1992). The depth of the SSM is related to upper ocean structure and could be included as an explanatory variable in the model framework.

Association with oceanic fronts has been demonstrated for several pelagic species (e.g. albacore tuna – Laurs and Lynn, 1977; Laurs *et al.*, 1984; bluefin tuna – Maul *et al.*, 1984; swordfish – Podesta *et al.*, 1993). Swordfish catch rates in the Atlantic longline fishery were rigorously investigated in relation to three parameters derived from fine-scale (6 km² pixels) satellite-derived SST: (1) the spatial (Sobel operator) SST gradient analogous to our SST *frontal energy* parameter; (2) the distance to objectively identified surface thermal fronts; and (3) an index of temporal frontal density (Podesta *et al.*, 1993). High CPUE occurred more frequently in the vicinity of fronts than would be expected by chance, but no association was evident between CPUE and SST gradient or frontal density, in contrast to our results. Lack of SST or frontal density relationships in the Atlantic study may have resulted from several shortcomings in the longline data, including spatial uncertainty in longline location, which was greater than the length scale of potential frontal effects, and the lack of independence in effort distribution because two-thirds of longline sets were deployed within 25 km of the shelf-break front. Also in contrast with our results, no relationship was apparent between yellowfin tuna abundance in the Gulf of Mexico and satellite-derived SST parameters (Power and May, 1991). Spatial uncertainty in longline location, targeting for other species and yellowfin migratory ability may have masked the tuna–temperature relationship. A more important factor may be that yellowfin tuna habitat in the daytime extends deeper than the mixed layer (Holland *et al.*, 1990), and therefore

satellite SST data may not be useful for explaining CPUE variation in a daytime tuna longline fishery.

Acoustic tracking results describe swordfish and blue shark as diel vertical migrators. Swordfish are near the surface (0–50 m) at night, but during the day they are deep (500–600 m) in offshore waters or near the bottom (100–200 m) near an inshore bank (e.g. Baja California, George's Bank, Carey and Robison, 1981; Carey, 1990). Similar to swordfish, blue sharks over the continental shelf and slope between George's Bank and Cape Hatteras are confined to the lower mixed layer and upper thermocline (0–100 m) at night and conduct regular, large excursions into the thermocline to 400 m during the day (Carey and Scharold, 1990).

Fishing over shallow bottom depths resulted in significantly higher swordfish CPUE and slightly higher blue shark CPUE in the Hawaii-based fishery. In coastal habitats in the Atlantic, swordfish commonly spend the day on a bank feeding on bottomfish (Scott and Tibbo, 1968), and commercial longline fishermen feel that submarine canyons along the edge of the continental shelf provide good swordfish catch rates (Carey and Robison, 1981). The Hawaii-based swordfish fishery primarily fishes in a pelagic habitat with bottom depths of > 4000 m. Although the Hawaiian Archipelago has relatively few banks or shelves to provide swordfish habitat, swordfish availability increases at the steep topography near the archipelago or near seamounts or guyots to the north of the archipelago.

Depending on species, lunar phase and wind velocity may affect vulnerability. Vision is important to swordfish and their depth distribution may be altered in response to moonlight (Carey and Robison, 1981). Swordfish CPUE was highest during full moon events, when fish are more vulnerable to longline gear because of enhanced visual acuity or a behavioural modification possibly favouring increased vertical movements. Wind velocity may affect the vulnerability of fish to capture by modifying fish behaviour and the depth distribution of the longline gear. From sparse tracking results (Carey and Robison, 1981), swordfish swam at deeper depths when wind velocity was high, which reduces their vulnerability to capture. Wind effect on gear depth may overwhelm effects of fish behaviour because longline gear may not reach the desired depth at high wind velocities. Gear retrieval may also be prolonged, thereby increasing blue shark vulnerability.

Standardized CPUE trends

Our purpose in modelling CPUE is first to understand how fishery performance (nominal CPUE) varies with

certain environmental and fishery operational variables, and secondly, to produce standardized CPUE estimates more indicative of trends in regional abundance. The GAM and GLM models may miss important factors, and our standardized CPUE may still reflect a mixture of factors related and unrelated to abundance. However, this weakness applies more or less to all nominal and standardized CPUE data in this imperfect science. Domestic commercial CPUE data is the only current source of information on regional abundance trends in the largest fishery managed by the Western Pacific Regional Fishery Management Council (WPRFMC).

We assume that the environmental factors in our analysis primarily affect availability and vulnerability within the region, not overall abundance. There are no factors in the GLMs that could be hypothesized to affect regional abundance, and the GLM-standardized CPUE series are very similar to the GAM-standardized series. This strongly suggests that we have not confounded any major environmentally driven changes of abundance in the GAM analysis.

Our analyses cover only a few years of a relatively new fishery. Given the number of variables and short time series, it may be premature to draw strong inferences regarding human impacts. Nevertheless, because swordfish predominate in the US longline catch and have been depleted in US Atlantic fisheries (Hoey *et al.*, 1995; Mace, 1995), and because blue shark are a very prominent and 'charismatic' bycatch, fishery managers are intensely interested in human impacts on these populations. The GAM-standardized CPUE model provides the best available estimates of recent trends in relative abundance within the region of greatest concern to the WPRFMC (Fig. 1). The only other recent standardized CPUE indices for swordfish (Hinton and Deriso, 1998) are for the eastern Pacific and extend only through 1987, before the advent of the Hawaii-based swordfish fishery. In 1994 and 1995, swordfish and blue shark catches by the US longline fishery declined substantially, in part owing to a decrease in sets targeting swordfish (over 6000 per year during 1991–1993, to 5119 in 1994 and 4247 in 1995 – He *et al.*, 1997). The nominal swordfish CPUE time series (Fig. 11) indicated a decline in 1994, and the standardized CPUE time series indicated a more moderate but statistically significant decline that actually began in 1993. The minimum standardized CPUE in the corrected index is only about 30% below the mean of ≈ 11.7 swordfish per 1000 hooks, and all the swordfish CPUE indices showed some recovery in 1995. The standardized blue shark CPUE gives no indication of a decline.

Our CPUE analysis is based on numbers of fish and does not consider changes in the size and age structure of the population. Preliminary analyses suggest little change in the average size of swordfish landed in Honolulu (NMFS unpublished data, Honolulu Lab, 2570 Dole St, Honolulu, HI, USA). Very few blue shark are landed, and research data on their size distribution are limited. Different ontogenetic stages may react differently to the environment and there would be great value in trying to incorporate size structure information in future analyses of fishery performance.

GLMs based on categorical time–area effects account for nearly as much variation in fishery performance as the GAMs based on environmental and operational variables, and standardization of CPUE based on GAMs or GLMs provided similar indices of relative regional abundance. This similarity resulted because most of the variables included in the GAMs were highly correlated with season and area (*Latitude*, *Longitude*, and *Bathymetry*). *SST*, *SST frontal energy*, and *Wind velocity* will be correlated with season and area in the absence of significant anomalies from average seasonal patterns. The GAMs explain more variation than the GLMs because some explanatory variables were somewhat independent of season and area, especially moon phase and lightsticks. The time series is short and the probability of significant environmental anomalies increases with time. Some evidence suggests that there were seasonal anomalies in the circulation of the North Pacific in 1994 (J. Polovina, NMFS Honolulu Lab, pers. comm.) that were not reflected by variables chosen for our analysis at the scales we defined. These anomalies may have negatively influenced swordfish CPUE in 1994.

Models based on environmental variables will only predict or detect the effects of environmental anomalies or changes in operations, and require such data. These models have the advantage of suggesting mechanisms for the effects on fishery performance that may be tested by altering operations or by the occurrence of environmental anomalies. In contrast, the more empirical time–area models have the advantage in ease of application to fisheries data as soon as those data become available. Specifically, the 2° area GLM analysis in this study may be applicable to the resolution of foreign longline fishery data for the North Pacific, which may become available.

Additional explanatory variables

This fisheries oceanography study is one of the few (Laurs *et al.*, 1984; Mendelssohn and Roy, 1986; Swartzman *et al.*, 1995; Hinton and Deriso, 1998) that span the mesoscale in scope. Our success in

demonstrating plausible relationships between swordfish and blue shark CPUE and environmental variables suggests that methods used here could be applied to model pelagic fishing performance on finer time and space scales, especially because gear location data are improved in current longline data. Approximately 42–45% of the deviance was explained in the swordfish and blue shark CPUE data, and additional explanatory variables of statistical significance potentially exist. Relevant data may include salinity gradients to describe frontal activity, fine-scale temperature gradients, current velocity estimates made by an acoustic Doppler current meter, estimates of primary productivity or abundance of forage species. Our analysis demonstrated that SST frontal energy affected fish availability, but further work is needed with higher-resolution AVHRR (e.g. Pathfinder) data on the appropriate time and space scales of pelagic fish aggregation. A spatial (two-dimensional) edge-detection algorithm (Cayula and Cornillion, 1990) used to identify SST fronts in the Atlantic swordfish study (Podesta *et al.*, 1993) has recently been improved to include a temporal component (Cayula and Cornillion, 1995). This three-dimensional approach to objectively and automatically determine what constitutes a front could prove more valuable in determining SST frontal energy than our image analysis approach. Given the potential importance of salinity as a model input, a time series could be accommodated in future fisheries oceanographic analyses by using output from ocean general circulation models (OGCMs).

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