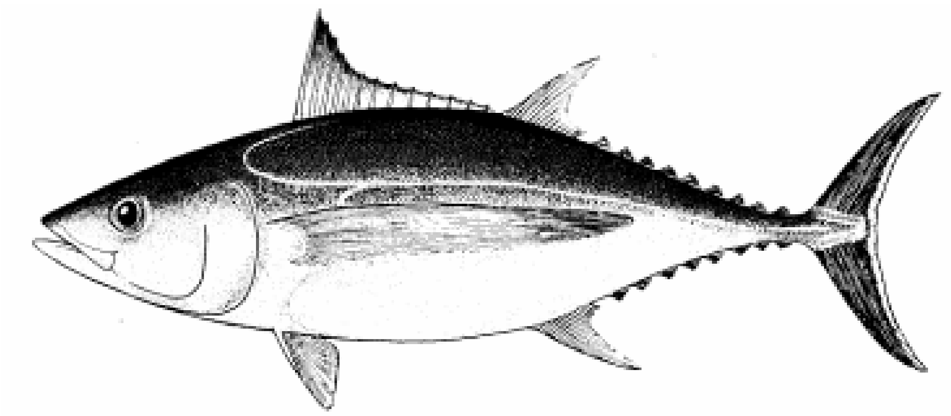
Western and Central Pacific Fisheries Commission

1st Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission
WCPFC–SC1
Noumea, New Caledonia
8–19 August 2005

WCPFC–SC1 **SA WP–5**

Standardized CPUE for the New Zealand albacore troll and longline fisheries



M. Unwin, K. Richardson, M. Uddstrom, L. Griggs, N. Davies & F. Wei

National Institute of Water and Atmospheric Research, New Zealand.

August 2005

Standardised CPUE indices for longline- and troll-caught albacore tuna in the New Zealand EEZ, 1993-2004

Martin Unwin
Ken Richardson
Michael Uddstrom
Lynda Griggs
Nick Davies
Fred Wei

National Institute of Water and Atmospheric Research, Christchurch, New Zealand

July 2005

Prepared for the First Regular Session of the WCPFC-Scientific Committee, 8-19 August 2005, Noumea, New Caledonia

Standardised CPUE indices for longline- and troll-caught albacore tuna in the New Zealand EEZ, 1993-2004

Martin Unwin
Ken Richardson
Michael Uddstrom
Lynda Griggs
Nick Davies
Fred Wei

NIWA, Christchurch, New Zealand

July 2005

Abstract

Data on albacore tuna catches within the New Zealand EEZ from 1993 to 2004, derived from Tuna Longline Catch Effort Returns and Catch Effort landing Returns, were used to model catch per unit effort (CPUE) for the longline and troll fisheries, respectively, and hence to generate standardised CPUE indices by year and quarter. In addition to operational data provided by the fishing returns (e.g., date, location, set and haul times), remote-sensed data on sea surface temperature (SST) and related measures such as SST anomaly were used to characterise local environmental conditions in the vicinity of each fishing operation. Grooming checks and data collocation procedures for each fishery are described.

Exploratory data analyses were used to identify and characterise potential candidate predictors of CPUE. In addition to year and quarter, these included latitude and longitude, depth, depth standard deviation, moon phase, day length, mean SST, SST anomaly, and two measures of SST variability, together with additional measures (specific to each fishery) such as vessel experience, effort, and target species.

Generalised additive models and/or generalised linear models were used to model CPUE for each fishery. These models have yet to be cross-validated and are therefore not necessarily optimal, but have been subjected to stepwise procedures to minimise the potential for over-fitting and appear to be robust. The final models explained 45.6% of deviance for the longline fishery, and 24.3% of deviance for the troll fishery.

Standardised CPUE indices for each fishery are presented and discussed. For the longline fishery, standardised CPUE was relatively high from 1993 to 1998, intermediate in 1999, and relatively low from 2000 to 2004. For the troll fishery, standardised CPUE showed little evidence of any long term trend, but provided some evidence for strong cohorts entering the fishery in 1999-2000 and 2002-03.

Introduction

Albacore tuna (*Thunnus alalunga*) are distributed throughout the South Pacific Ocean from the equator to at least 49 °S and from Australia to 100 °W, and are considered to form a single discrete stock (Murray 1994). Adult albacore are common throughout the New Zealand EEZ north of about 44 °S, particularly off the east coast of the North Island. Juvenile albacore (45-85 cm) occur off the west coast of both islands north of about 44 °S, in surface waters to about 120 m, moving northwards into deeper subtropical waters during autumn. Further details of their biology are given by Murray (1994).

Within the EEZ, albacore sustain significant longline and troll fisheries. The primary target species for longliners are bigeye tuna (*T. obesus*) and southern bluefin tuna (*T. maccoyii*), but albacore are a common and abundant bycatch and are targeted directly in about 10% of sets. Foreign vessels have fished in New Zealand waters since the late 1970s and were virtually the only longliners operating during the 1980s, but the domestic longline fishery has developed rapidly since 1990 and now accounts for about 90% of targeted longline effort (Griggs, L.H. & Richardson 2005). Annual effort averages 200-250 million hooks per year (Murray 1994), but has increased markedly in recent years with the entry of many new vessels into the fishery since 1998. Annual albacore catch averaged 4 583 t from 1991 to 2000 (Griggs, L.H. & Richardson 2005), with landings of 4 455 t in 2003-04 (Labelle & Hampton 2003). Other species caught (and in some cases occasionally targeted) include several species of sharks, butterfly tuna, broadbill swordfish, yellowfin tuna, and striped marlin.

The high seas troll fishery includes vessels from USA, Canada, NZ, French Polynesia and Fiji. Since the late 1960s the NZ surface troll fishery has operated approximately 40-80 miles off the west coasts of the North and South islands, during the summer season (Griggs, L.H. & Richardson 2005, Murray 1994). Currently the fishery comprises up to 200 vessels, can land 2000-4000 t annually. This fishery operates from 39° to 41° S on the high seas. Troll fisheries are restricted to the summer season (December – April) and sea surface temperatures (SSTs) of 16-21°C, and target almost exclusively albacore (Griggs, L.H. & Richardson 2005). Effort in the troll fishery has increased markedly to nearly 8000 troll-vessel days in 2001 (Griggs, L.H. & Richardson 2005).

South Pacific albacore were most recently assessed by the Standing Committee on Tuna and Billfish (SCTB) in 2003 using an assessment model developed by the Oceanic Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC). The assessment model (MULTIFAN-CL) is an extension from MULTIFAN that estimates proportions at age as free and independent parameters (Labelle & Hampton 2003). MULTIFAN-CL uses estimated growth, recruitment, catchability, selectivity, natural mortality, and other parameters, to estimate catch-at-age within length frequency samples (Fournier et al. 1998). It uses complex spatial and temporal stratification comprising three regions (0-10°S, 10-30°S, 30-50°S) and seven separate fisheries defined by method and region (distant water longline, domestic longline, New Zealand troll, STCZ troll, and drift net; see Murray 1994). The model uses quarterly seasons for the longline fisheries and monthly time steps for the surface fisheries, with juveniles recruiting to surface fisheries in the southern region (including New Zealand) and then to the STCZ areas in the central Pacific two years later.

In the absence of data on absolute abundance of albacore, a time series of relative abundance indices based on standardised catch per unit effort (CPUE) is an important input to the model.

Standardisation is necessary to take account of factors which may vary from year to year and can influence CPUE, but are not necessarily correlated with absolute abundance. Such factors typically include vessel and gear type, fishing location, and season, as well as stochastically varying environmental parameters such as sea surface temperature (SST). Accounting for such factors may be particularly important for bycatch species such as albacore, given that fishing practices when targeting other species are not necessarily optimal for catching albacore.

In this report we use data sets and methods, developed as part of ongoing research into the use of remotely sensed SST and chlorophyll data to characterise CPUE variation in the New Zealand longline fishery (Uddstrom et al. in revision, Uddstrom et al. 2003), to derive standardised albacore CPUE indices for the longline and troll fisheries from 1993 to 2004. These data sets include factors such as year, moon phase, latitude, longitude, and depth, traditionally used to model CPUE variation (e.g., Griggs, L.H. & Richardson 2005), together with SST and related measures (e.g., SST anomaly and variability) derived from remote sensing. We describe our data sets and methods, briefly summarise exploratory data analyses used to identify potential candidate factors for inclusion in the standardised CPUE models for each fishery, and present our main findings.

Data Sources and Methods

Catch and effort data sources

Catch and effort data for the longline and troll fisheries were derived from Tuna Longline Catch Effort Return (TLCER) and Catch Effort Landing Return (CELR) data provided by each fisher to the Ministry of Fisheries on standard statistical forms. TLCER data are stored in a centralised database *tuna* administered by NIWA, and include set-specific data such as date, position, number of hooks, set and haul times, and the number of fish and total weight of each species caught (Wei 2004). Data provided on CELR forms include date, effort (hooks and operation duration), statistical area, and daily catch by number or weight. Some under-reporting occurs, in that bycatch and discards are not necessarily reported.

Several data grooming checks were used to eliminate gross errors from the TLCER and CELR data sets, based on established guidelines and range checks for database *tuna* (Wei 2004). The most common errors for the longline data were incorrect or inconsistent dates and times for each set and haul, or invalid line lengths or hook counts (Table 1). A total of 51 004 sets passed these checks, representing 87.3% of the available records. Of 107 763 records available from the CELR database, 98 735 (91.6%) were retained after data grooming (Table 2).

Environmental data sources

Environmental factors that may impact on CPUE in tuna longline fisheries in the EEZ have been studied as part of a Foundation of Research Science and Technology (FRST) programme on remote sensing of fisheries (Uddstrom et al. 2003). This provides SSTs for the EEZ at 1 km spatial resolution and in overlapping 5-day temporal composites, derived from twelve years of locally received Advanced Very High Resolution Radiometer data from NOAA satellites 11, 12, 14 and 15 which provide up to eight observations per day. Instantaneous SST retrievals in this dataset have a standard deviation error of ~ 0.6°C, and a bias error less than ±0.1°C (Uddstrom & Oien 1999). We used a Bayesian algorithm (Uddstrom et al. 1999) to reduce the effects of missing data due to cloud cover, which ranged from 50% off the eastern North Island to 70% off the west of the South Island (Uddstrom et al. in revision).

The FRST study focussed on bigeye and southern bluefin tuna, and hence on the areas where these two species are targeted (Fig. 1). These include most longline locations where albacore were caught from 1993 to 2004, with the exception of the west coast of the North Island between 36 and 40 ^{o}S. Operations in this area comprised 3050 (6%) of those available for analysis after data grooming, reducing our final working TLCER data set to 47 954 records (82.1% of the original data).

To characterise SST and SST variation at a spatio-temporal scale appropriate to each longline operation, we computed SST mean, and two measures of SST variance, within a square with a side equal to half the longline length, and centred on the latitude and longitude at set start. We obtained one measure of SST variation (the temporal standard deviation) by calculating the standard deviation at the pixel corresponding to start of set, using all available data over the 5-day compositing window, and a second measure (the spatial standard deviation) using data for all pixels within the square associated with each longline oepration. These two measures potentially identify the location and strength of line-scale ocean fronts, with stationary fronts having high spatial variability but low temporal variability, and moving fronts scoring highly on both measures. We used a similar approach to characterise the bathymetry at each set location, in terms of mean, spatial standard deviation, and coefficient of variation, using a 1 km resolution bathymetry (CANZ 1997).

Most (~ 85%) CELR data are reported by statistical area rather than by latitude/longitude, representing a relatively large spatial scale (typically 1 deg^2). To characterise SST variability for the troll fishery, we calculated the same measures as for the longline fishery over a square centred on the centroid of the appropriate statistical area, with an edge equal to half the statistical area diagonal. For operations supplying a true latitude/longitude, we used a 20 × 20 km box centred on that location. The areas for which remote sensing data (as defined by the FRST programme) were available excluded part of the west coast of the North Island, between 36 and 40^{o}S. Troll operations in this area comprised 49% of the CELR records available after grooming. Excluding these operations reduced the total number of troll records to 49 622.

Results and Discussion

Trends in albacore CPUE

Longline fishery

Most longlining effort was recorded in Areas EAST and NORTH, which collectively accounted for 87.4% of fishing operations, 75.4% of hooks, and 99.0% of albacore landings. Virtually all of the remaining effort was recorded in Area SWEST, with less than 0.01% of landings from Area SEAST. For the purposes of this report we focused on Areas NORTH and EAST, which were merged into a single Area (NEAST). Over the 12 years of record this fishery was characterised by relatively stable levels of effort from 1993 to 1998, followed by a steady increase in effort from 1999 (Table 3). Total landings also increased over this period, although nominal CPUE from 1999 to 2004 was generally about half that recorded from 1993 to 1998 (Table 3).

Troll fishery
Most trolling effort is recorded on the west coast of New Zealand in FMA 7, 8, and 9 (Fig. 1). Remote sensing and fisheries (RSF) areas NORTH and SWEST account for 51.3% of trolling operations and have been combined for modelling troll CPUE below.

Trolling effort reached a maximum of more than 4300 operations in the combined area during 1994, declined to less than 2500 in 1999, and increased again to 4500-5000 operations in 2002 and 2003.

Exploratory data analysis

Longline fishery
As a precursor to developing standardised CPUE indices, we conducted a range of exploratory data analyses to identify potential predictors of CPUE. Variables showing no evidence of any correlation with CPUE, and/or with a high incidence of missing values, were excluded from further consideration. Variables dropped at this stage included cloud cover and wind speed (~50% and 80% missing values, respectively), number of light sticks, and bait type (available only for 2003 and 2004).

We examined a number of variables relating to environmental and operational conditions at the time of each longline set. We used date and time for start/end of each set and haul, as recorded on the TLCER form, to derive four additional variables related to each operation: moon phase, expressed as a fraction from 0 to 1; soak time in hours, defined as the time interval from start of set to start of haul; daylight interval from sunrise to sunset; and the fraction of the total soak time which occurred during the hours of darkness. To quantify variation in local fishing effort, we calculated the number of longline sets occurring within a 50 km radius of each set (based on the start of set location) during the previous 10 days. Finally, motivated by the need to allow for the possible confounding effect of large numbers of new and inexperienced vessels entering the fishery after 1998, we classified each vessel as either "experienced' or "inexperienced", based on their level of effort in each of the two six-year periods from 1993-1998, and 1999-2004. Vessels which fished for at least three years during the first period, and at least five years during the second period, were classified as experienced; all others were classified as inexperienced. Of 255 vessels fishing at least once between 1993 and 2004, only 24 (9.4%) were classified as experienced, but collectively these vessels accounted for 30.0% of all longline sets (12 601 out of 41 929).

Inspection of scatterplots, and plots of mean CPUE for environmental variables grouped into appropriate bins, suggested that CPUE was strongly influenced by fishing location, day length, night fraction, soak time, and mean SST, in some cases non-linearly, but was only weakly related to bathymetric depth and moon phase (Fig. 2). A comparison of set and haul times (Fig. 3) indicated that skippers typically began setting their lines between about 20:00 and 02:00 hours, taking about 3 h to do so; allowed the lines to soak for 11-15 h; and began hauling the line from about 11:00 to 16:00 hours, taking 6-8 hours to do so. For most sets, therefore, the night fraction is an index of the proportion of the soak time which occurs before dawn. We considered using the interval between end of set and start of haul as an alternative index of soak time, but the two measures were highly correlated (r = 0.88) and had essentially the same distribution; we therefore retained our original definition of soak time for all subsequent analyses. When developing CPUE models for this fishery, as described below, we compared base models using the two alternative measures of soak time, with virtually identical results in terms of explained deviance and smoothed fits.

Troll fishery
Information from CELR forms about trolling operations is more limited than for the longline fishery. For example, cloud cover and wind speed are not recorded, spatial information is often available only at the statistical area scale, and also appears to be of somewhat poorer quality. A set of environmental variables similar to that calculated for the longline fishery was computed, but is likely to be affected by the greater inaccuracies of the CELR data.

Histograms of catch and effort are shown in Fig. 4. Recorded operation duration appears to be quite variable – 10-15 hours seems typical. However, a significant number (>3000) of operations with durations > 24 hours were removed from the full dataset during the grooming process (Table 2). Similarly the number of hooks recorded was quite large (up to 45 in the combined NORTH and SWEST areas), but was generally between 10 and 20. These effort data have been used to compute a nominal CPUE index, defined as catch/(hooks × duration/24) with units catch/hook-day. This choice of CPUE unit was beneficial for the developing a standardised model. A significant number records having zero catches occurred in the troll data.

Fig. 5 shows histograms of nominal CPUE, calculated as described above, together with some SST-related environmental variables. Albacore are generally caught in this fishery between 16 °C and 22 °C, and within a SST anomaly of ±2 °C.

Scatterplots of troll CPUE against effort and environmental variables are shown in Figs. 6-7. As in the longline fishery, there appears to be evidence that troll CPUE depends on effort and spatial information. There may also be some indication of dependence on some SST related variables, but it is difficult to judge for others (e.g., chlorophyll anomalies). There was a clear change of CPUE for vessels with 6 years or more experience in the troll fishery, so a two-level experience factor was constructed for later modelling.

CPUE models and standardised CPUE indices

Longline fishery
We standardised CPUE for the longline fishery using Generalised Additive Models (GAMs) (Chambers & Hastie 1993, see also Griggs, L.H. & Richardson 2005 for further details on their application to the New Zealand tuna fishery). We used a Poisson distribution model with a logarithmic link function, thereby allowing zero catches to be included without transformation of the catch-rate data (c.f. Campbell & Hobday 2003, Griggs, L.H. & Richardson 2005). For the longline fishery, our base model included five factors and thirteen predictors, as follows:

Factors:
- Year (calendar year; 12 levels))
- Quarter (Jan-Mar = 1 etc.; 4 levels)
- Vessel nationality (Nation; NZL or OTH; 2 levels)
- Vessel experience (Exp35; E = experienced, N = not experienced; 2 levels)
- Target species (Targ; albacore (ALB), bigeye (BIG), southern bluefin (STN), other (OTH); 4 levels)

Covariates:
- Latitude (Lat)
- Longitude (Lon)
- Depth (Depth, metres)
- Depth standard deviation (DepthSD, metres)
- Number of sets within 50 km during previous 10 days (N10D50K)
- Soak time measured from start of set to start of haul (SSoakTime, hours)
- Moon phase (Phase)
- Day length (DayLen, hours)
- Night fraction (NightFract)
- Mean SST (SST, °C)
- SST anomaly (SST.Anom, °C)
- SST temporal standard deviation (SST.TSD, °C)
- SST spatial standard deviation (SST.SSD, °C)

Initial models were estimated using the gam( ) routine in S-Plus, with loess smoothers (denoted lo( )) fitted to all numerical predictors. We then used a modified version of the S-Plus step.gam( ) routine to refine the model, incorporating a variable penalty term for predictor degrees of freedom. The effect of this penalty term is to make the model more resistant to fitting a loess smoother when a linear fit will do almost as well under an approximate AIC criterion. At the time of writing cross-validation procedures designed to minimise the potential for over-fitting (c.f. Griggs, L.H. & Richardson 2005) have yet to be implemented, so the model presented here is not necessarily optimal. However, preliminary models fitted separately to Areas NORTH and EAST gave essentially identical fits for most predictors, suggesting that the fit is robust and that a fully optimised model is unlikely to differ significantly from the present one.

The final model was:

```
cpue.alb = Year + Quarter + Nation + Exper + Targ + lo(Lat) +
      lo(Lon) + lo(Depth) + lo(N10D50k) + SoakTime + lo(Phase) +
      lo(DayLen) + lo(NightFract) + lo(SST) + lo(SST.Anom) + SST.TSD
```

Of the predictors offered to the initial model, two (DepthSD and SST.SSD) were dropped, both at the first step, and two more (SoakTime and SST.TSD) were refitted as linear rather than smoothed terms. All other terms remained unchanged.

The model explained 45.6% of deviance relative to the null model, and required 52.3 degrees of freedom (Table 4). All factors appeared to have a significant influence on CPUE (Fig. 8). Strong yearly and quarterly effects were apparent, with CPUE being relatively high from 1993 to 1998, intermediate in 1999, low from 2000 to 2004, and – within each year – tending to be highest in the second quarter and third quarters. CPUE was lower for foreign vessels than for those of New Zealand origin, although foreign vessels accounted for less than 2% of the sets analysed and their inclusion as a factor is unlikely to have had much influence on the fit. CPUE increased significantly with increasing vessel experience and was also strongly influenced by the choice of target species, being highest for vessels targeting albacore, intermediate for those targeting bigeye, and least for those targeting southern bluefin.

Fitted terms for the eleven numerical predictors in the model (Fig. 9) were generally consistent with our exploratory analyses (Fig. 4). Mean SST had by far the strongest influence on CPUE, which showed a well-defined tendency to peak at 18-19 °C. Weaker SST signals were also apparent in relation to SST anomaly and temporal variability, although most fishing occurred within a very limited range of each parameter, and the confidence intervals away from the data centroids tended to be relatively broad. Day length was the second most important non-linear predictor, with CPUE being lowest for day lengths of 12-13 hours, and increasing for both shorter (9-11 h) or longer (13-15 h) day lengths. Given that day lengths of 12-13 hours correspond to March (before the autumn equinox) and late September to October (after the spring equinox), this result is consistent with the tendency for CPUE to be lowest during the first and last quarter, but also suggests the presence of additional seasonal effects not accounted for by quarter.

Albacore longline CPUE was strongly influenced by location, with clearly defined and approximately linear trends in terms of latitude (CPUE increasing from north to south), and longitude (CPUE decreasing from west to east). The pattern for longitude conflicts with that shown in Fig. 4, but is explained by a strong tendency for CPUE to be highest off East Cape, south of about latitude 37 ^{o}S and west of 178 ^{o}E. Once this effect is accounted for (in terms of latitude), the effect of longitude is consistent with Fig. 9. An alternative GAM analysis using a two dimensional loess smoother to fit latitude and longitude (not shown) confirmed this result, with CPUE tending to be highest at locations corresponding to shelf and inner slope waters out to about the 2500 m isobath. CPUE showed a slight tendency to increase with increasing depth, but this effect was relatively weak and appears to represent only a small secondary correction to the underlying spatial pattern defined by set location. Local fishing effort (N10D50K) also appeared to influence CPUE, although the predominant effect (a moderate increase in CPUE as this parameter increased from 0 to about 50) may simply reflect a tendency for fishing effort to increase in response to local increases in abundance. There was some evidence of a decline in CPUE as effort increased beyond this point, but the data are increasingly sparse for N10D50K > 100 and the confidence intervals are correspondingly broad.

Year and quarter effects were used to generate separate year and quarter indices (Figs. 10, 11), which were then multiplied to generate year-quarter indices (Fig. 12, Table 5), with relative standard errors added in quadrature (Cotter 1998). The standardised and nominal annual indices show very similar long term trends, with standardised CPUE being uniformly high from 1993 to 1998, intermediate in 1999, and uniformly low from 2000 to 2004. Differences between nominal and standardised CPUE are more apparent for the quarterly indices, with peak CPUE in quarter 3 for the standardised index compared to quarter 2 for the nominal index (Figure 11).

Troll fishery

CPUE (catch/hook-day) standardisation using quasi Poisson GAMs proceeded as described above for the longline fishery, with only minor changes. For comparison, negative binomial generalised linear models (GLMs; Richardson et al. 2001, Venables & Ripley 1999), incorporating (parametric) natural splines functions (ns() in S-plus) instead of non-parametric regression smoothers to fit predictor terms, were also used. While a little less flexible than GAMs, these models have the advantage of using a full likelihood model for calculating deviance, AIC etc. statistics. To make the GAM and negative binomial models more comparable, spline degrees of freedom were chosen to be the same as estimated by an equivalent quasi Poisson GAM. Stepping for the negative binomial models used the Splus/MASS function stepAIC(), with the same penalty on model degrees of freedom (4).

Initial fitting using catch as the response variable produced models that either failed to converge (negative binomial GLM) or had large estimated dispersion parameters and a relatively small number of predictor variables (quasi Poisson GAM). This suggests that standardising catch helps to reduce over-dispersion in the model and is therefore more likely to produce reliable selection and estimation of terms. For the negative binomial models, we also investigated the hypothesis that normalising the responses by their median would ensure even distribution of these data around unity, and hence optimise selection of the model variance function (Tait & Zheng 2003). These are distinguished below as either scaled or unscaled negative binomial models. For quasi Poisson GAMs scaling has no effect on the fitted terms, since the variance function does not change

The following predictors were investigated for the troll fishery CPUE model (all models):

Factors:

Year (yr: calendar year; 12 levels)
Quarter (qtr: Q1=Jan-March etc; Q3 excluded because of data scarcity; 3 levels)
Vessel experience (vessel.6yr.exp: less than 6 years in fishery, 6 years or more in fishery; 2 levels)

Covariates:

Operation duration (opn.duration)
Number of hooks (no.hooks)
Latitude (true.lat)
Longitude (true.lon)
Depth (z: decametres)
Depth standard deviation (z.sd: decametres)
Depth CV (z.cv)
Moon phase (moon.illum)
Day length (day.length: hrs)
Mean SST (env.data011: °C)
SST anomaly (sst.anom1: °C)
SST temporal standard deviation (env.data021: °C)

The final model for the (scaled) quasi Poisson GAM was:

```
ALBCE.scld ~ yr + qtr + lo(no.hooks) + lo(opn.duration) +
      lo(true.lat) + lo(true.lon) + lo(z) + z.std + lo(z.cv) +
      lo(day.length) + lo(moon.illum) + lo(env.data011) +
      lo(env.data021) + vessel.6yr.exp + lo(sst.anom1)
```

The only change to the predictors offered to the model was that depth standard deviation (z.std) was reduced to a linear term. The model explained 35% of the null deviance using 57 degrees of freedom (Table 6) with an estimated dispersion parameter of 1.4.

The final unscaled negative binomial GLM was:

```
ALBCE ~ yr + qtr + ns(no.hooks, 4) + ns(opn.duration, 3) +
      ns(true.lat, 3) + ns(true.lon, 3) + ns(z, 4) + ns(z.std, 4) +
      ns(z.cv, 4) + ns(env.data011, 5) + vessel.6yr.exp +
      ns(sst.anom1, 4)
```

Note that the second argument in the S-plus function ns() is degrees of freedom, which in this case is one more than the number of interior knots for a cubic natural spline. Sea surface temperature temporal standard deviation (env.data021), day length (day.length), and moon phase (moon.illum) have been dropped. None of these terms had very convincing partial residual plots in the GAM above (not shown). The model explained 15.5% of the null deviance using 48 degrees of freedom. The estimated variance shape parameter is 0.96, suggesting a moderate amount of over-dispersion.

Scaling noticeably improved the model fit (see Fig. 13 for scaled negative binomial residual plots). Consequently, the scaled negative binomial GLM was chosen as the basis for standardisation, and is reported in more detail. The model selected by the stepping process was:

```
ALBCE.scld ~ yr + qtr + ns(no.hooks, 4) + ns(opn.duration, 3) +
      ns(true.lon, 3) + ns(z, 4) + ns(z.std, 4) + ns(env.data011, 5)
      + vessel.6yr.exp + ns(sst.anom1, 4)
```

which added depth CV (z.cv) and latitude (true.lat) to the predictors dropped from the unscaled GLM. Neither of these predictors had convincing partial residual plots (not shown) in the unscaled GLM.

The scaled model explained 24.3% of the null deviance using 41 degrees of freedom (Table 7). Over-dispersion was significantly reduced with respect to the unscaled negative binomial model, with the estimated shape increasing to 4.3.

Partial residual plots for all individual fitted terms are shown in Fig. 14. Effort terms (hooks and operation duration) contribute significantly to the model (note the enlarged scale for these plots) suggesting a strong non-linear dependence. Catch rates peak around 170-172°E, which seems unsurprising given the dominance of the SWEST area relative to area NORTH. The SST (env.data011) plot, which peaks at around 18°C, is similar to, but somewhat more muted, than that found in the albacore longline fishery. Given the coarse nature of spatial and temporal information in the troll fishery, this result seems remarkable. Similar remarks seem appropriate for SST anomaly (sst.anom1). The depth terms suggest a moderate relationship between local bathymetry and albacore CPUE, but are difficult to interpret given the disjoint data coverage for this analysis (area NORTH and SWEST only), and the crude spatial resolution noted earlier. As in the longline fishery, troll catch rates increased with vessel experience. The year effect was strongest in 1995 and 2000, and weakest in 1997 and 2002, and the first quarter effect was larger than quarters two and four. No overall trend is apparent in the year effects, though there is considerable inter-annual variability.

Year and quarter effects were combined as for the longline model to generate year-quarter indices for the troll fishery (Fig. 15, Table 8). For comparison, the time series calculated from the scaled GAM is also shown. Both time series are normalised to unity in 1993 quarter 1.

The features evident in the nominal CPUE time series are apparent in both sets of fitted indices, although the amplitude of variation is somewhat smaller, particularly for the negative binomial model. Focussing on the latter, there appear to be broad peaks in the index in 1995 and 1999/2000, with minima in 1993-1995, 1997, and 2001-2004, but no long term trend. There seems to be correspondence between the pattern of the standardised troll indices with respect to strong and weak length modes in the troll length compositions (Griggs, L. 2005).

An apparently strong year class entered the fishery in 1999-2000 and subsequently formed the basis of catches in 2000-01. This cohort was first visible in 1998-99 in the length intervals 46-55 cm, and is likely to have contributed to the peak in CPUE in 1999 and 2000. A similar pattern is visible in 2002-03 and 2003-04, when a strong cohort enters in the first year then supports the fishery in the second year, and may account for a high CPUE in 2003 and 2004. Although qualitative, this pattern points to the potential utility of the troll CPUE for the albacore stock assessment in estimating relative year class strength estimates.

Acknowledgements

We would like to thank Michael Uddstrom, NIWA for providing the remote sensing data, and members of the Pelagic Fisheries Working Group, Ministry of Fisheries for helpful discussions.

References

Campbell, R.; Hobday, A. (2003). Swordfish – seamount – environment – fishery interactions off eastern Australia. *SCTB16 Working Paper BBRG–3.* 23 p.

CANZ (1997). New Zealand region bathymetry 1:4,000,000. *NIWA Chart Miscellaneous Series 73.* p.

Chambers, J.M.; Hastie, T.J. (eds). (1993). Statistical models in S. Chapman and Hall, New York. 608 p.

Cotter, A.J.R. (1998). Method for estimating variability due to sampling of catches on a trawl survey. *Canadian Journal of Fisheries and Aquatic Sciences 55*: 1607-1617.

Fournier, D.A.; Hampton, J.; Sibert, J.R. (1998). MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Canadian Journal of Fisheries and Aquatic Sciences 55*: 2105-2116.

Griggs, L. (2005). Catch monitoring of the New Zealand albacore troll fishery during the 2004-05 fishing year. *WCPFC-SC1 Stock Assessment Working Group working paper* 17 p.

Griggs, L.H.; Richardson, K. (2005). New Zealand tuna fisheries, 2001 and 2002. *New Zealand Fisheries Assessment Report 2005/4.* 58 p.

Labelle, M.; Hampton, J. (2003). Stock assessment of albacore tuna in the South Pacific Ocean. *SCTB16 Working Paper ALB-1.* 30 p.

Murray, T. (1994). A review of the biology and fisheries for albacore, *Thunnus alalunga*, in the South Pacific Ocean. *In*: Shomura, R.S.; Majkowski, J.; Langi, S. (eds). Interactions of Pacific tuna fisheries. Volume 2: Papers on biology and fisheries, *FAO Fisheries Technical Paper 336/2*. Food and Agriculture Organization of the United Nations, Rome, pp. 188-206.

Richardson, K.M.; Murray, T.; Dean, H. (2001). Models for southern bluefin tuna in the New Zealand EEZ, 1998-99. *New Zealand Fisheries Assessment Report* 21 p.

Tait, A.; Zheng, X. (2003). Mapping frost occurrence using satellite data. *Journal of Applied Meteorology 42*: 193-203.

Uddstrom, M.J.; Gray, W.R.; Murphy, R.; Oien, N.A.; Murray, T. (1999). A Bayesian cloud mask for sea surface temperature retrieval. *Journal of Atmospheric and Oceanic Technology 16*: 117-132.

Uddstrom, M.J.; Oien, N.A. (1999). On the use of high-resolution satellite data to describe the spatial and temporal variability of sea surface temperatures in the New Zealand region. *Journal of Geophysical Research-Oceans 104*: 20729-20751.

Uddstrom, M.J.; Unwin, M.J.; Zheng, X.; Murphy, R. (in revision). A fine-scale analysis of the relationships between remote-sensed sea surface temperature and catch rates in the New Zealand longline tuna fishery. *Fisheries Oceanography*.

Uddstrom, M.J.; Zheng, X.; Unwin, M.J. (2003). Fishery resource predictions using remote sensing data: fulfilling the promise. Presented at the 30th International Symposium on Remote Sensing of the Environment, Honolulu, Hawaii, 10-14 November 2003.

Venables, W.N.; Ripley, B.D. (1999). Modern applied statistics with S. 4th edition. Springer-Verlag, New York.

Wei, F. (2004). Database documentation: tuna. *NIWA Internal Report* 25 p.

Table 1. Numbers of catch-effort records remaining following stages in grooming with respect to fields in the TLCER (longline) database.

Number of sets in database *tuna* (1993 – 2004)	58 420
Gross error tests	
Start of set location (lat, long) unavailable	117
Set is over land	27
Inconsistent set or haul times (e.g. haul before set)	1 805
Invalid long-line length (allowable range 4 – 150 km)	1 352
Invalid set, soak, haul, or total elapsed time	3 096
More than 35% of hooks taken	64
Invalid distance between hooks (allowable range 15 – 100 m)	756
Other (e.g., invalid set distance, duplicate records)	199
Number of sets available for environmental analysis	51 004
Sets outside study area	3 050
Sets available for albacore CPUE analysis	47 954

Table 2. Numbers of catch-effort records remaining following stages in grooming with respect to fields in the CELR (troll) database.

Number of operations in CELR dataset (1993 – 2004)	107 763
Gross error tests	
Location (lat, long) or statistical area unavailable	0
Missing hook counts	4 963
Hook count out of range (> 300)	326
Location over land	141
Missing operation duration	3 352
Invalid operation duration	182
Other (e.g., duplicate records)	64
Number of sets available for environmental analysis	98 735

Table 3. Number of sets, number of hooks, total albacore catch, and mean nominal CPUE (albacore per 1000 hooks), by year, for longliners operating in Area NEAST from 1993 to 2004[1], based on TLCER returns.

Year	Number of sets	Number of hooks (× 1000)	Number of albacore landed	Mean CPUE
1993	1 259	1 651.6	33 284	28.81
1994	1 446	1 237.4	49 247	45.51
1995	1 725	1 481.1	49 126	37.18
1996	1 458	1 229.3	47 251	39.50
1997	1 504	1 335.7	52 283	40.39
1998	2 503	2 478.0	112 811	47.85
1999	4 214	4 418.7	126 606	28.97
2000	5 259	5 799.3	97 958	17.26
2001	6 221	7 188.3	165 086	23.39
2002	6 673	7 875.8	171 552	21.68
2003	5 937	7 156.7	190 180	26.53
2004	3 730	4 355.3	86 914	19.56
Total	**41 929**	**46 207.3**	**1 182 298**	**27.14**

[1] January to September

Table 4. Analysis of deviance for final albacore GAM for longliners in Area NEAST, 1993-2004. Note that for terms fitted by a loess smoother, the non-parametric F value measures the significance of the tendency towards non-linearity rather than the significance of the effect itself. Terms with a high F value are strongly non-linear and highly significant; terms with a low F-value are only weakly non-linear, but may still be significant predictors of CPUE. See Figs. 8-9 for a visual representation of the significance of each term.

```
Null Deviance: 1209987 on 34939 degrees of freedom
Residual Deviance: 658831.4 on 34884.13 degrees of freedom

              Df Npar Df   Npar F      Pr(F)
   (Intercept)  1
          Year 11
       Quarter  3
        Nation  1
         Exper  1
          Targ  3
       lo(Lat)  1     2.1   16.065 0.00000006
       lo(Lon)  1     2.1   36.869 0.00000000
     lo(Depth)  1     2.8    9.318 0.00000804
      lo(N5Day)  1     2.9   82.377 0.00000000
      SoakTime  1
     lo(Phase)  1     2.4    9.006 0.00003519
    lo(DayLen)  1     2.2  617.640 0.00000000
lo(NightFract)  1     3.6   62.089 0.00000000
       lo(SST)  1     2.0 2452.975 0.00000000
  lo(SST.Anom)  1     2.2   47.540 0.00000000
   lo(SST.TSD)  1     2.6    3.498 0.01940347
```

Table 5. Nominal and standardised albacore CPUE indices for the longline fishery, by year and quarter, January 1993 to September 2004. Indices denoted "mean = 1" have been normalised to have a geometric mean of one.

Year	Quarter	Nominal CPUE (raw)	Nominal CPUE (mean = 1)	Standardised CPUE (mean = 1)	Standard error (× 2)
1993	1	17.00	0.694	0.952	0.000
1993	2	41.55	1.696	1.552	0.129
1993	3	14.63	0.597	1.839	0.062
1993	4	17.55	0.716	0.964	0.049
1994	1	25.38	1.036	1.117	0.096
1994	2	69.78	2.848	1.822	0.161
1994	3	9.88	0.403	2.158	0.114
1994	4	29.50	1.204	1.132	0.108
1995	1	20.88	0.852	0.974	0.089
1995	2	68.48	2.795	1.589	0.157
1995	3	25.52	1.042	1.882	0.109
1995	4	39.95	1.631	0.987	0.102
1996	1	18.12	0.739	0.947	0.086
1996	2	62.79	2.563	1.544	0.155
1996	3	39.92	1.629	1.829	0.106
1996	4	33.44	1.365	0.959	0.099
1997	1	21.95	0.896	1.021	0.090
1997	2	54.33	2.217	1.665	0.158
1997	3	28.52	1.164	1.972	0.109
1997	4	49.69	2.028	1.034	0.102
1998	1	30.10	1.229	1.149	0.102
1998	2	63.05	2.573	1.874	0.165
1998	3	64.39	2.628	2.220	0.119
1998	4	29.68	1.211	1.164	0.113
1999	1	10.69	0.436	0.752	0.065
1999	2	61.30	2.502	1.227	0.145
1999	3	22.69	0.926	1.453	0.090
1999	4	21.35	0.871	0.762	0.081
2000	1	8.31	0.339	0.442	0.038
2000	2	32.41	1.323	0.721	0.135
2000	3	14.85	0.606	0.854	0.073
2000	4	9.27	0.378	0.448	0.062
2001	1	13.19	0.538	0.584	0.049
2001	2	38.33	1.564	0.952	0.138
2001	3	21.44	0.875	1.128	0.079
2001	4	15.64	0.638	0.592	0.069
2002	1	11.51	0.470	0.524	0.044
2002	2	41.35	1.687	0.855	0.137
2002	3	11.68	0.477	1.013	0.076
2002	4	7.75	0.316	0.531	0.066
2003	1	21.17	0.864	0.486	0.042
2003	2	30.73	1.254	0.793	0.136
2003	3	27.38	1.118	0.939	0.075
2003	4	17.49	0.714	0.493	0.065
2004	1	15.13	0.618	0.442	0.038
2004	2	23.71	0.968	0.721	0.135
2004	3	16.05	0.655	0.854	0.073

Table 6. ANOVA table for the scaled quasi Poisson GAM of the albacore troll fishery.

Dispersion Parameter for Quasi-likelihood family taken to be 1.396855
Null Deviance: 75286.64 on 38618 degrees of freedom
Residual Deviance: 48935.86 on 38560.96 degrees of freedom

	Df	Npar Df	Npar F	Pr(F)
(Intercept)	1			
yr	11			
qtr	2			
lo(no.hooks)	1	2.7	446.735	0
lo(opn.duration)	1	2.3	2554.102	0
lo(true.lat)	1	2.5	2.842	0.045728
lo(true.lon)	1	2.5	35.12	0
lo(z)	1	3.7	13.839	0
z.std	1			
lo(z.cv)	1	3.4	17.921	0
lo(day.length)	1	2.1	9.99	3.14E-05
lo(moon.illum)	1	2.4	12.823	3.6E-07
lo(env.data011)	1	3.5	11.658	2E-08
lo(env.data021)	1	3.5	12.195	1E-08
vessel.6yr.exp	1			
lo(sst.anom1)	1	2.5	11.817	7.8E-07

Table 7. Anova table for scaled negative binomial GLM of the albacore troll fishery. Note that the shape parameter is fixed for computation of this table.

	Df	Deviance	Resid. Df	Resid. Dev	F Value	Pr(F)
NULL			38618	53601.48		
yr94	11	2416.559	38607	51184.92	217.162	0
qtrq2	2	379.763	38605	50805.16	187.699	0
ns(no.hooks, 4)	4	2794.214	38601	48010.94	690.525	0
ns(opn.duration, 3)	3	6516.084	38598	41494.86	2147.065	0
ns(true.lon, 3)	3	302.932	38595	41191.93	99.817	0
ns(z, 4)	4	104.046	38591	41087.88	25.712	0
ns(z.std, 4)	4	153.156	38587	40934.73	37.849	0
ns(env.data011, 5)	5	79.294	38582	40855.43	15.677	0
vessel.6yr.exp	1	279.157	38581	40576.27	275.949	0
ns(sst.anom1, 4)	4	22.362	38577	40553.91	5.526	0.0002

Table 8. Nominal and standardised albacore CPUE indices for the troll fishery (normalised to have a geometric mean of unity), by year and quarter, January 1993 to September 2004. Lack of data precludes inclusion of quarter 3.

Year	Quarter	Nominal CPUE (mean = 1)	Standardised CPUE (mean = 1)	Standard error (× 2)
1993	1	1.009	0.975	0.000
1993	2	0.737	0.788	0.045
1993	4	0.651	0.909	0.082
1994	1	1.267	1.065	0.059
1994	2	0.926	0.861	0.072
1994	4	0.817	0.993	0.101
1995	1	1.759	1.397	0.066
1995	2	1.286	1.129	0.080
1995	4	1.135	1.302	0.117
1996	1	1.220	1.038	0.070
1996	2	0.892	0.839	0.080
1996	4	0.787	0.967	0.107
1997	1	1.042	0.936	0.057
1997	2	0.761	0.757	0.068
1997	4	0.672	0.873	0.098
1998	1	1.322	1.111	0.070
1998	2	0.967	0.897	0.080
1998	4	0.853	1.035	0.109
1999	1	1.672	1.291	0.078
1999	2	1.223	1.043	0.088
1999	4	1.078	1.203	0.121
2000	1	2.067	1.357	0.064
2000	2	1.511	1.096	0.078
2000	4	1.333	1.264	0.113
2001	1	1.120	0.980	0.053
2001	2	0.819	0.792	0.066
2001	4	0.723	0.913	0.096
2002	1	1.066	0.905	0.057
2002	2	0.780	0.732	0.066
2002	4	0.688	0.844	0.096
2003	1	1.128	1.076	0.057
2003	2	0.825	0.869	0.070
2003	4	0.728	1.003	0.101
2004	1	1.148	1.186	0.066
2004	2	0.839	0.959	0.078
2004	4	0.741	1.105	0.109

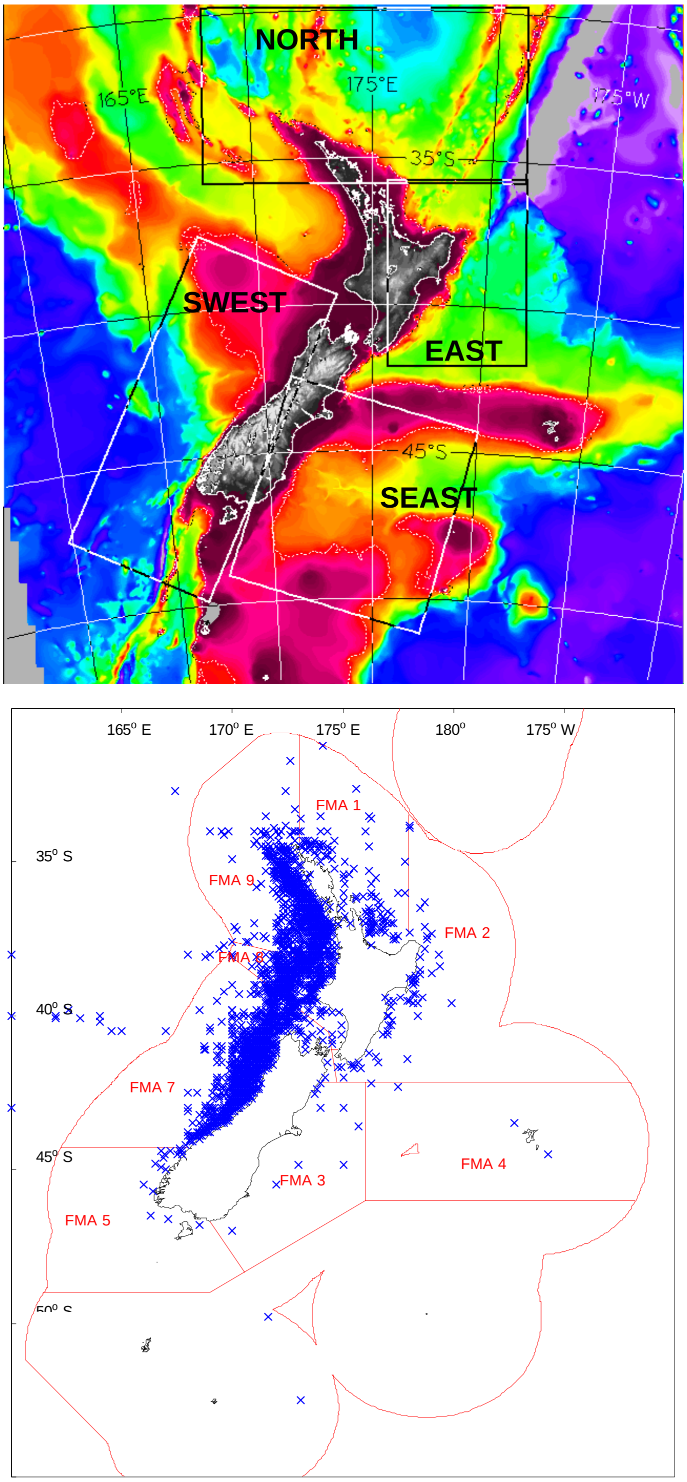


Figure 1. New Zealand and surrounding waters, showing areas used for the albacore longline analyses (upper), and Fisheries Management Areas (FMAs) used for the albacore troll analyses, overlaid with locations of trolling operations from 1993 to 2004 (lower), . Bathymetric contours (upper) range from 0 to 7000 m; the 1000 m isobath is shown by a dashed white line.

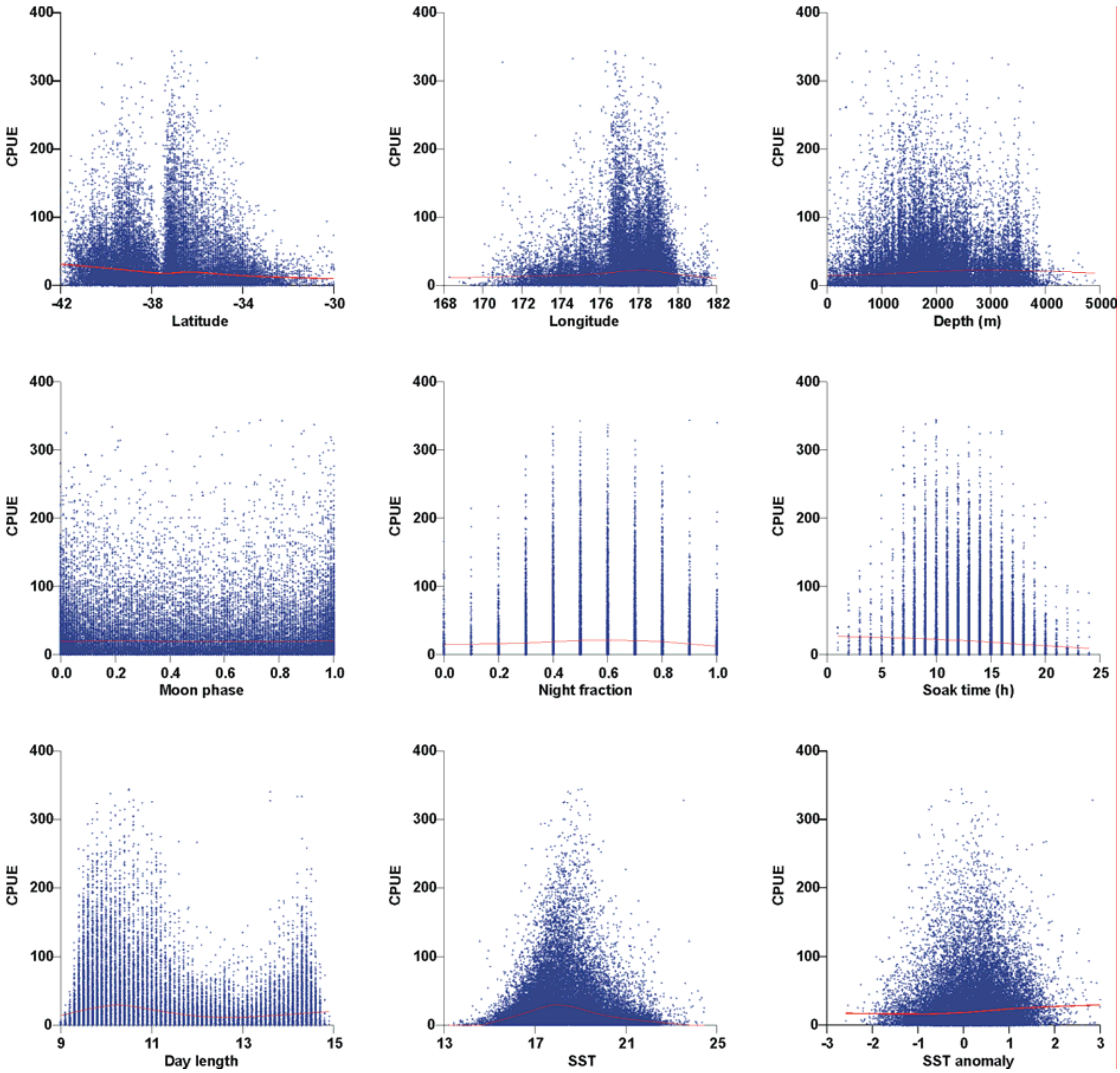


Figure 2. Scatterplots of albacore CPUE (fish per 1000 hooks) versus selected environmental and operation related variables for the longline fishery, 1993-2004. Loess smoothers for each plot are shown in red.

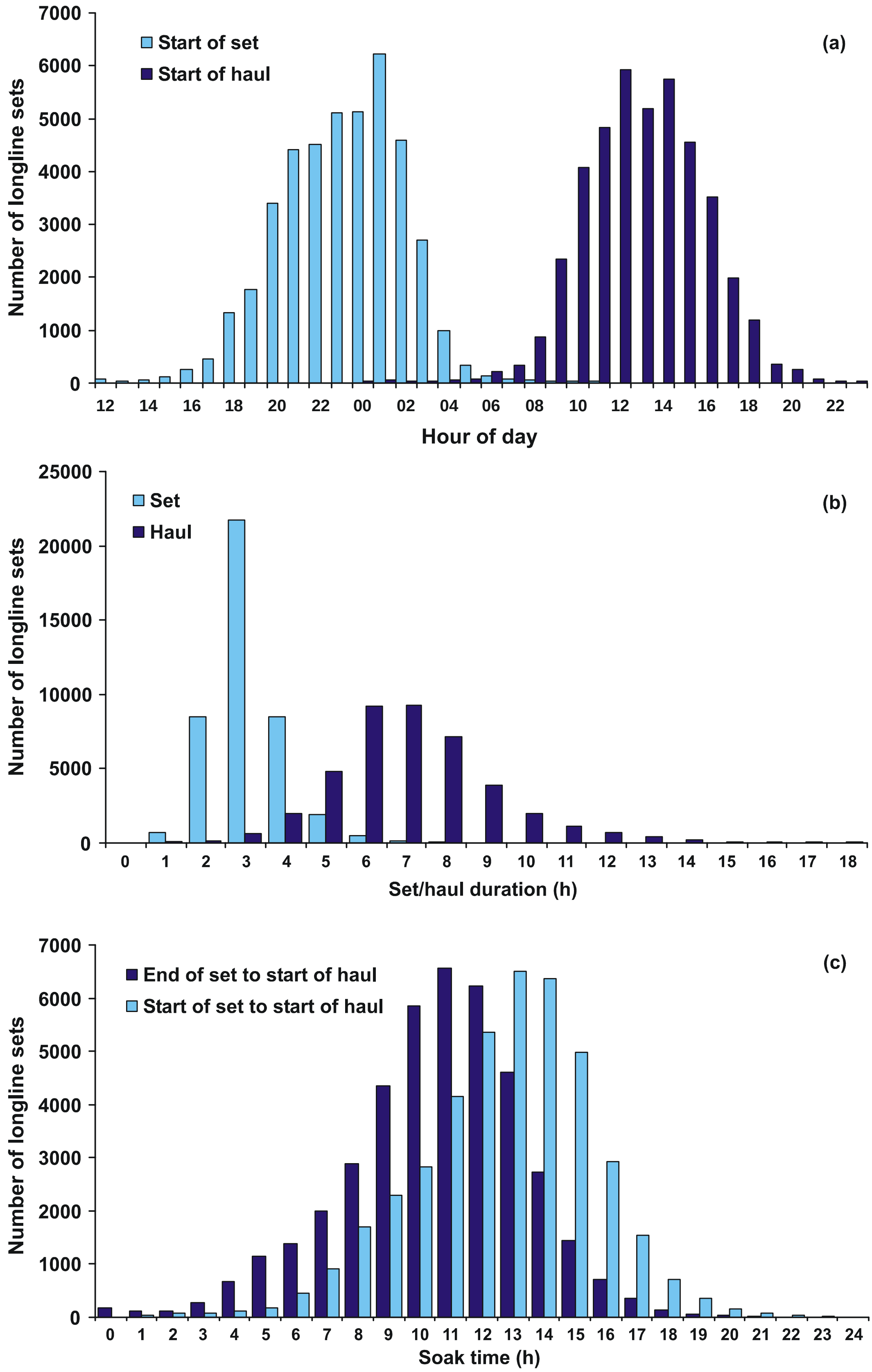


Figure 3. Set/haul times and related parameters, for longliners in Area NEAST, 1993-2004. Successive plots show (a) time of day at start of set and start of haul; (b) set and haul duration (end of set/haul – start of set/haul); and (c) two alternative indices of soak time.

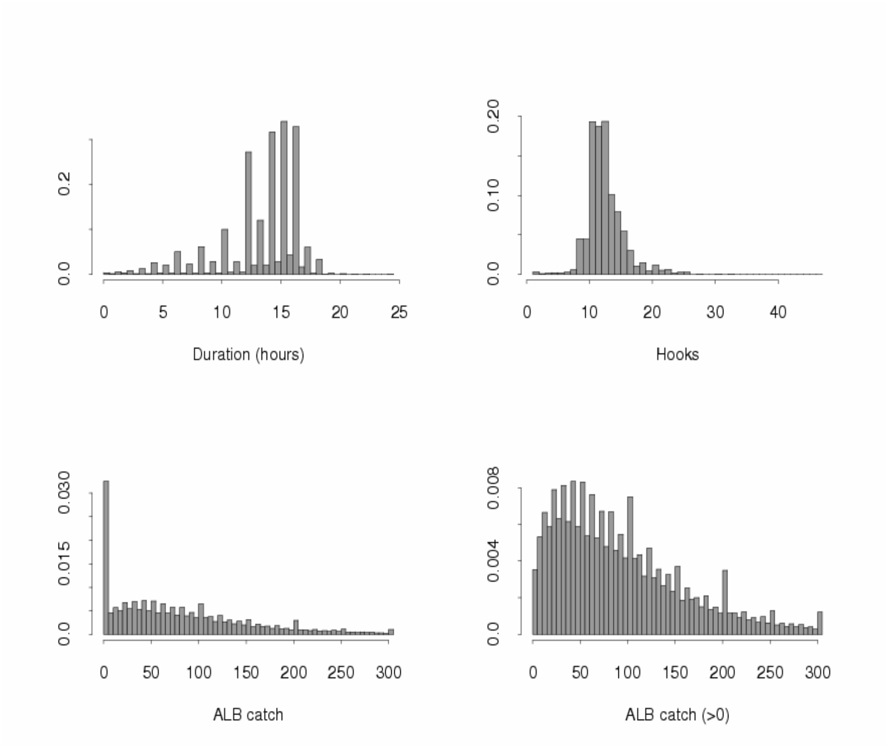


Figure 4. Histograms of catch and effort for the albacore troll fishery in the combined areas NORTH and SWEST. Note the significant number of zero catches

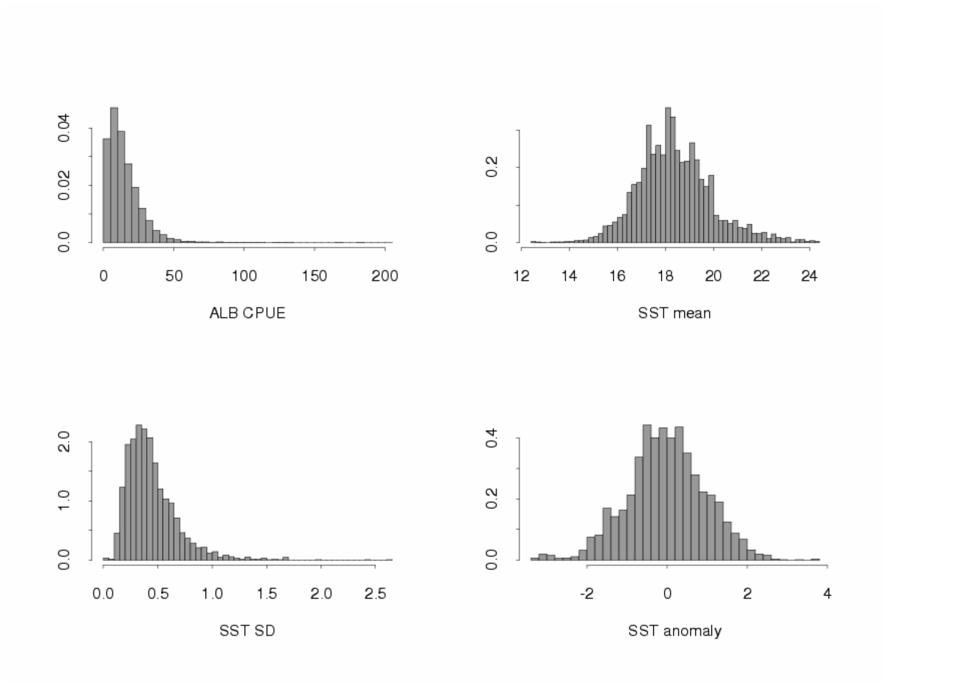


Figure 5. Histograms of CPUE and selected environmental variables for the albacore troll fishery.

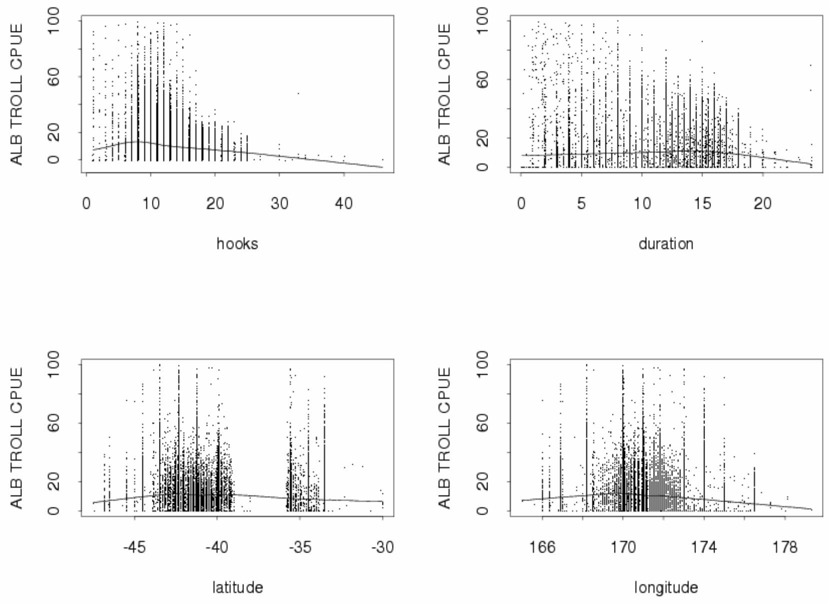


Figure 6. Variation in albacore troll CPUE for combined areas NORTH and SWEST, 1993-2004, for selected environmental and operation-related variables. Each panel shows operation CPUE as a scatterplot, with smooth curve fitted via the Splus loess function to summarise trend. The latitude and longitude plots show evidence of the discontinuous locations of stat areas, and of the two areas used in this study.

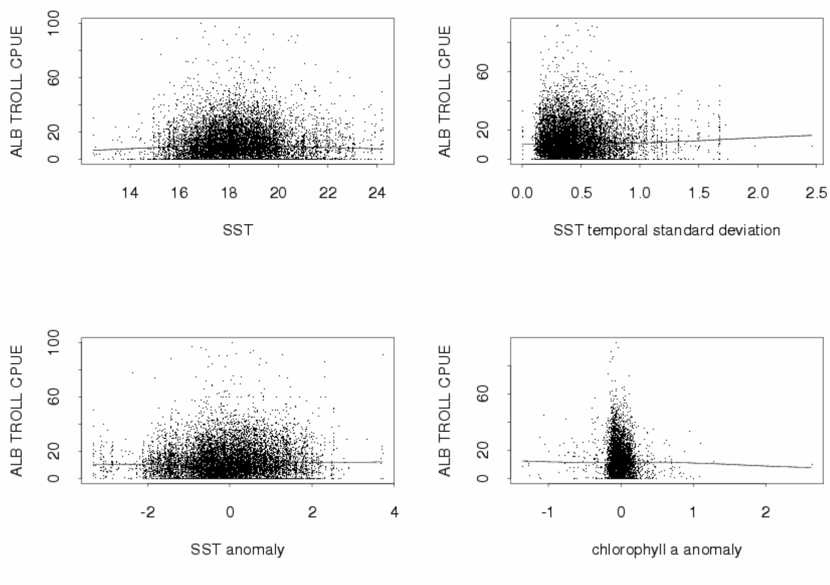


Figure 7. Variation in albacore troll CPUE for combined areas NORTH and SWEST, 1993-2004, for selected environmental related variables. Each plot shows operation CPUE as a scatterplot, with a smooth curve fitted via the Splus loess function to summarise trend.

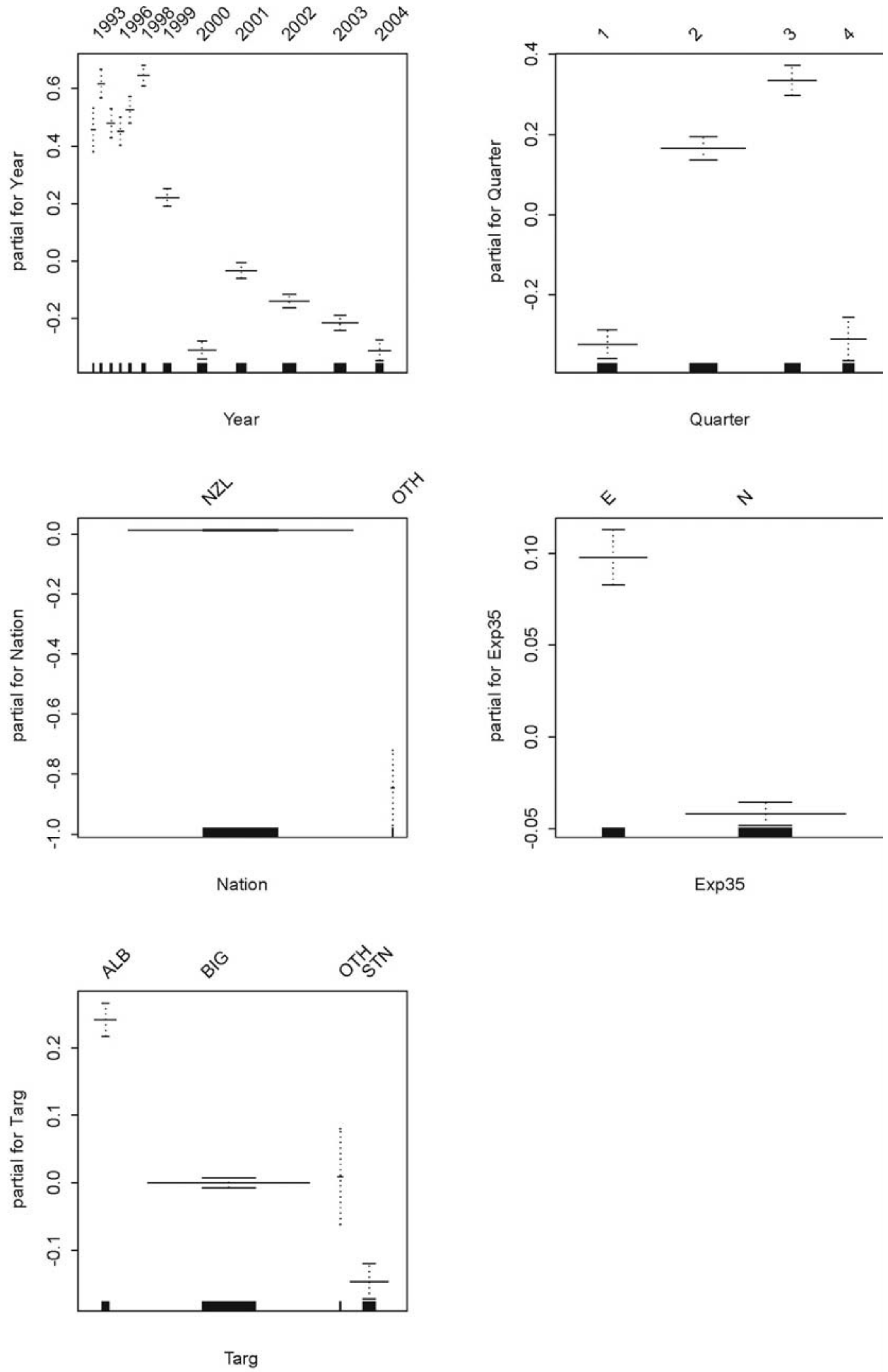


Figure 8. Partial residual plots for all fixed factors in the final longline GAM. Confidence intervals (shown as ± 1 standard error) and differences between the vertical scales for each plot help to indicate the relative strength and significance of each effect.

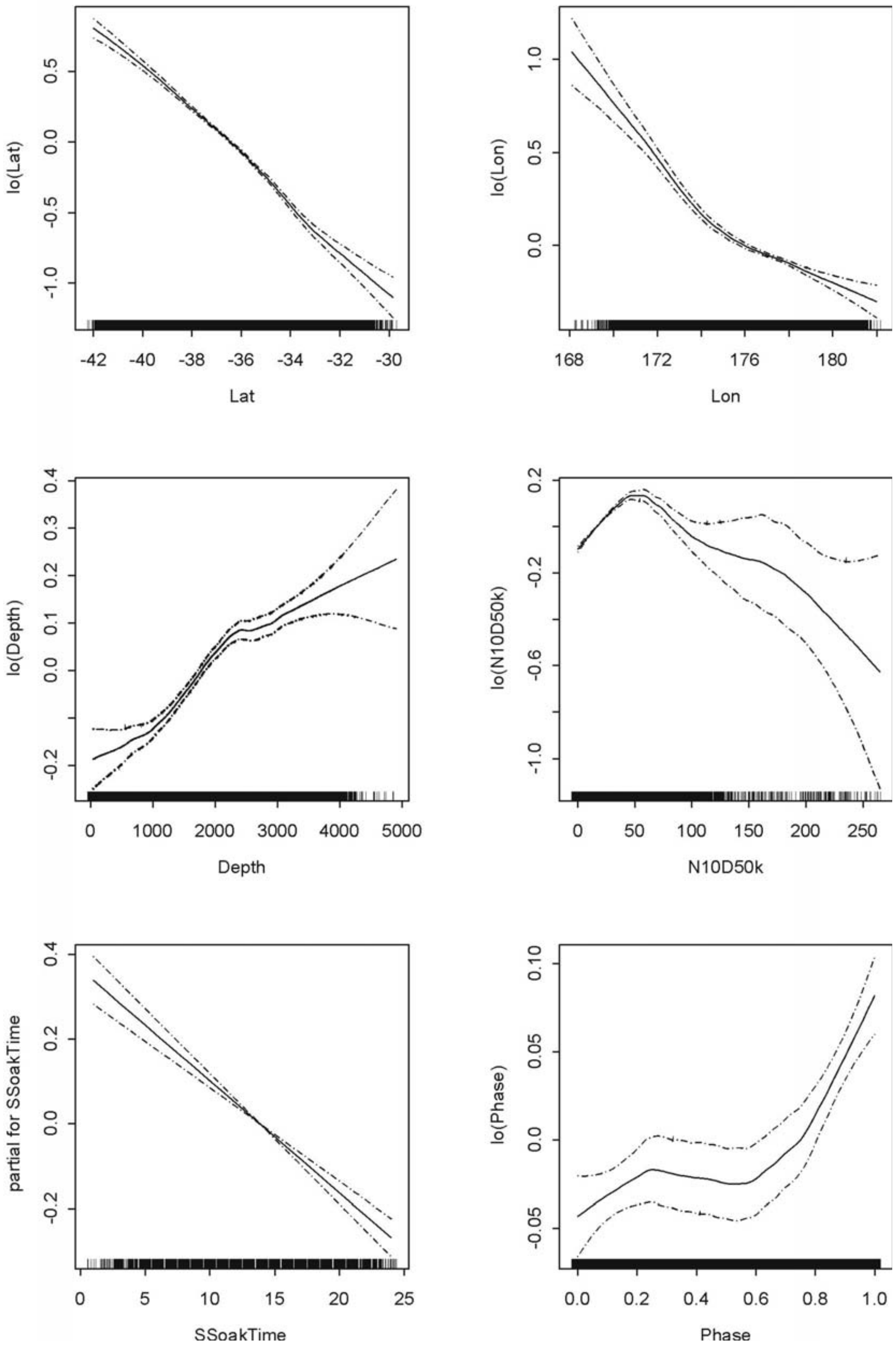


Figure 9. Partial residual plots for all covariates in the final longline GAM. Confidence intervals (shown as ± 1 standard error) and differences between the vertical scales for each plot help to indicate the relative strength and significance of each effect.

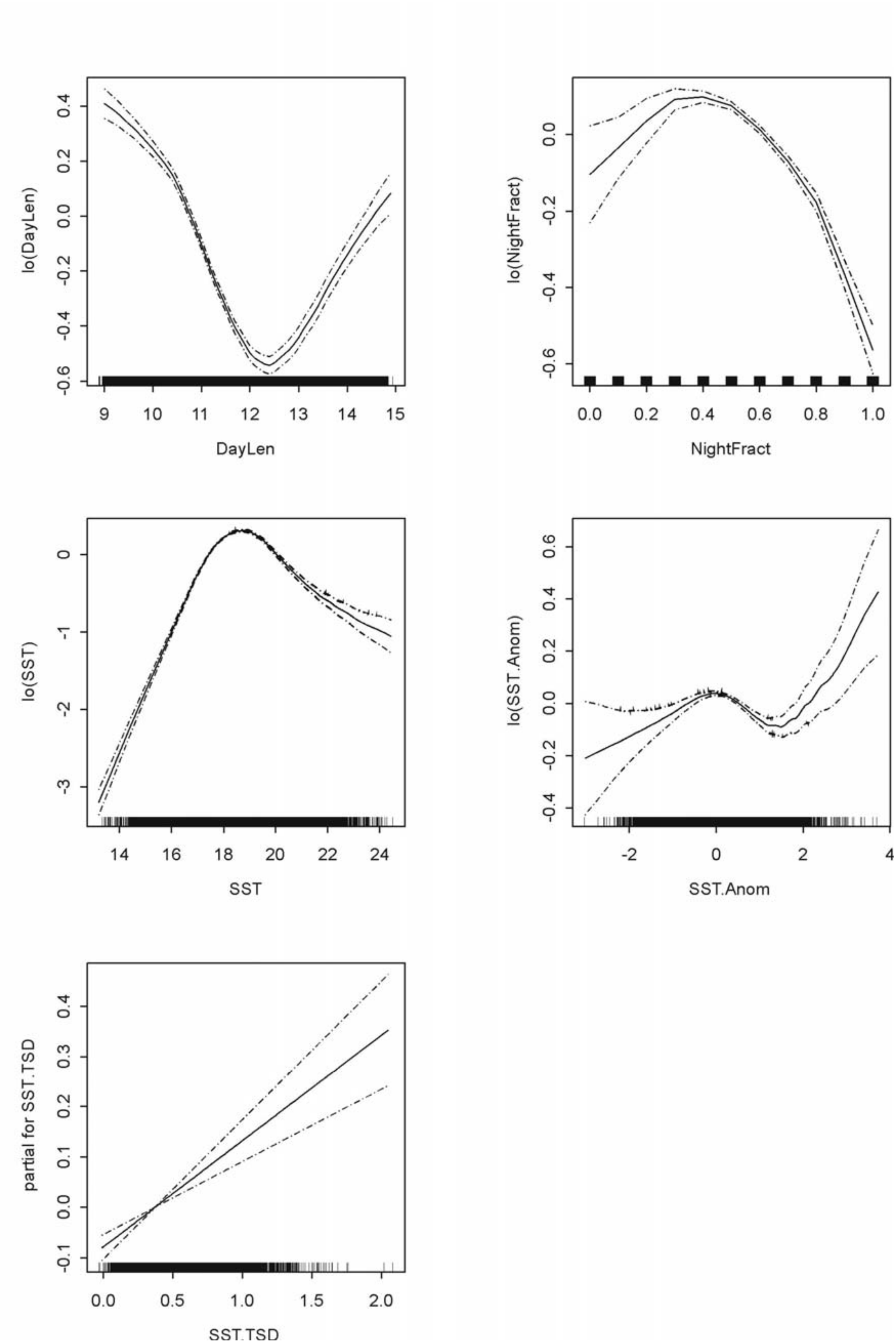


Figure 9 (continued). Partial residual plots for all covariates in the final longline GAM.

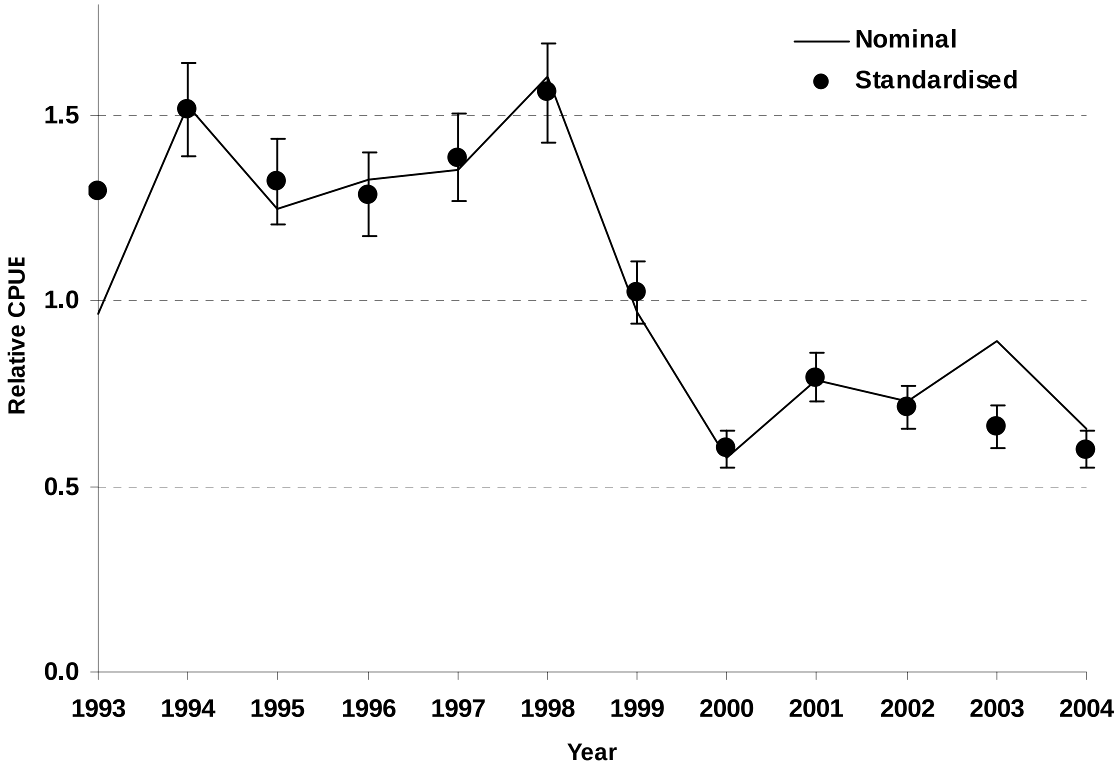


Figure 10. Nominal and standardised annual CPUE indices (normalised about the geometric mean for each time series) for the longline fishery, 1993-2004. Vertical bars indicate two standard errors.

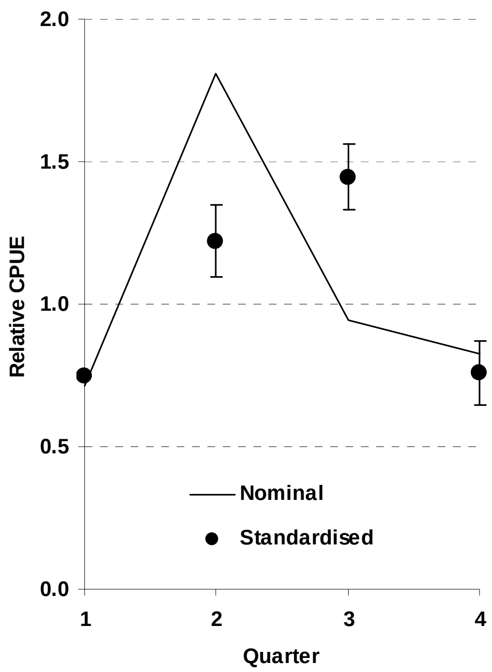


Figure 11. Nominal and standardised quarterly CPUE indices (normalised about the geometric mean for each time series) for the longline fishery, 1993-2004. Vertical bars indicate two standard errors.

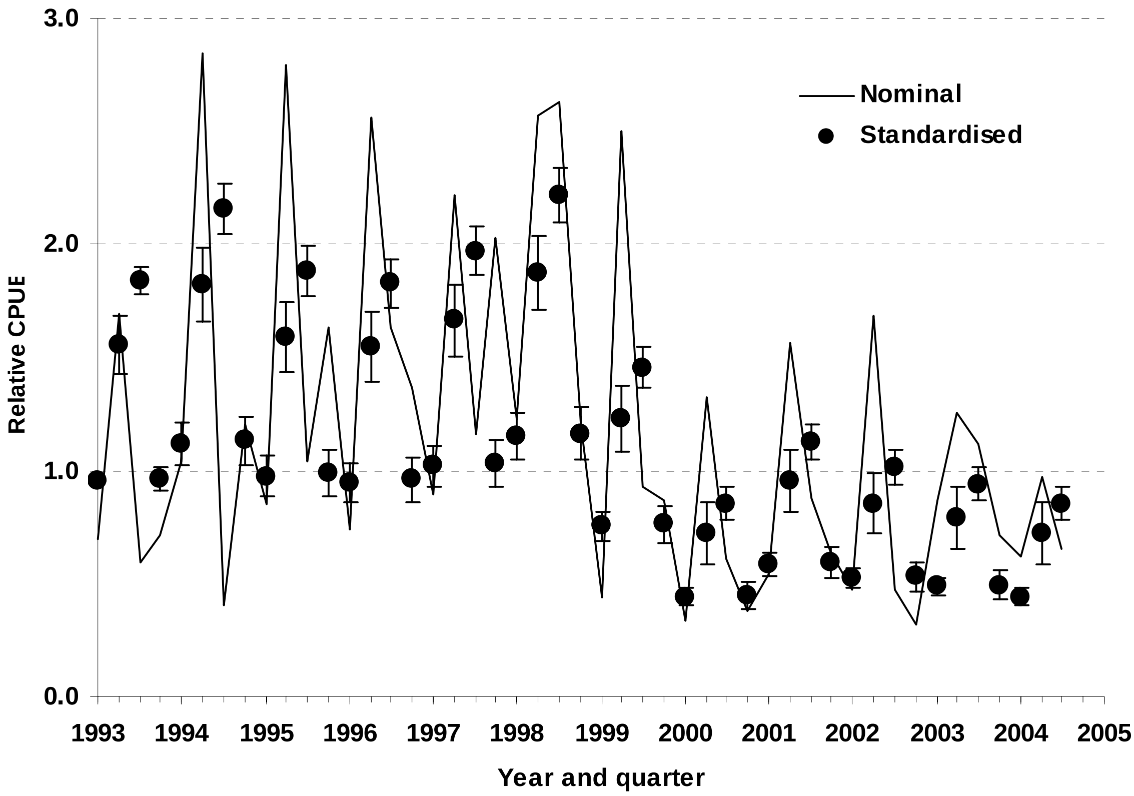


Figure 12. Nominal and standardised year × quarter CPUE indices (normalised about the geometric mean for each time series) for the longline fishery, 1993-2004. Vertical bars indicate two standard errors.

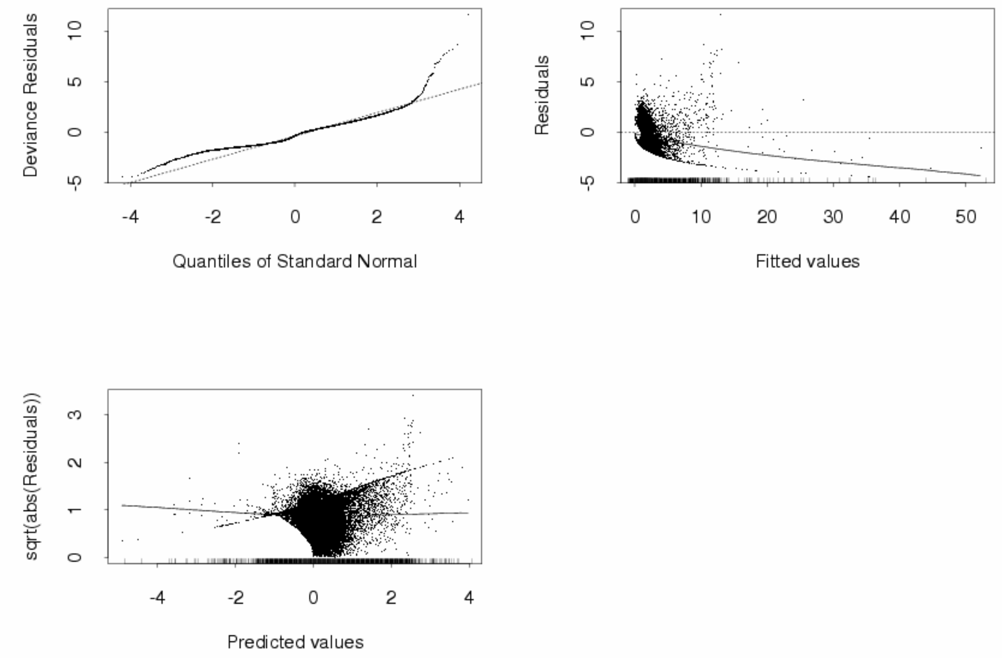


Figure 13. Residual plots for the final scaled negative binomial albacore CPUE. Smooth curves through the plots are drawn using a local regression algorithm to summarise trend.

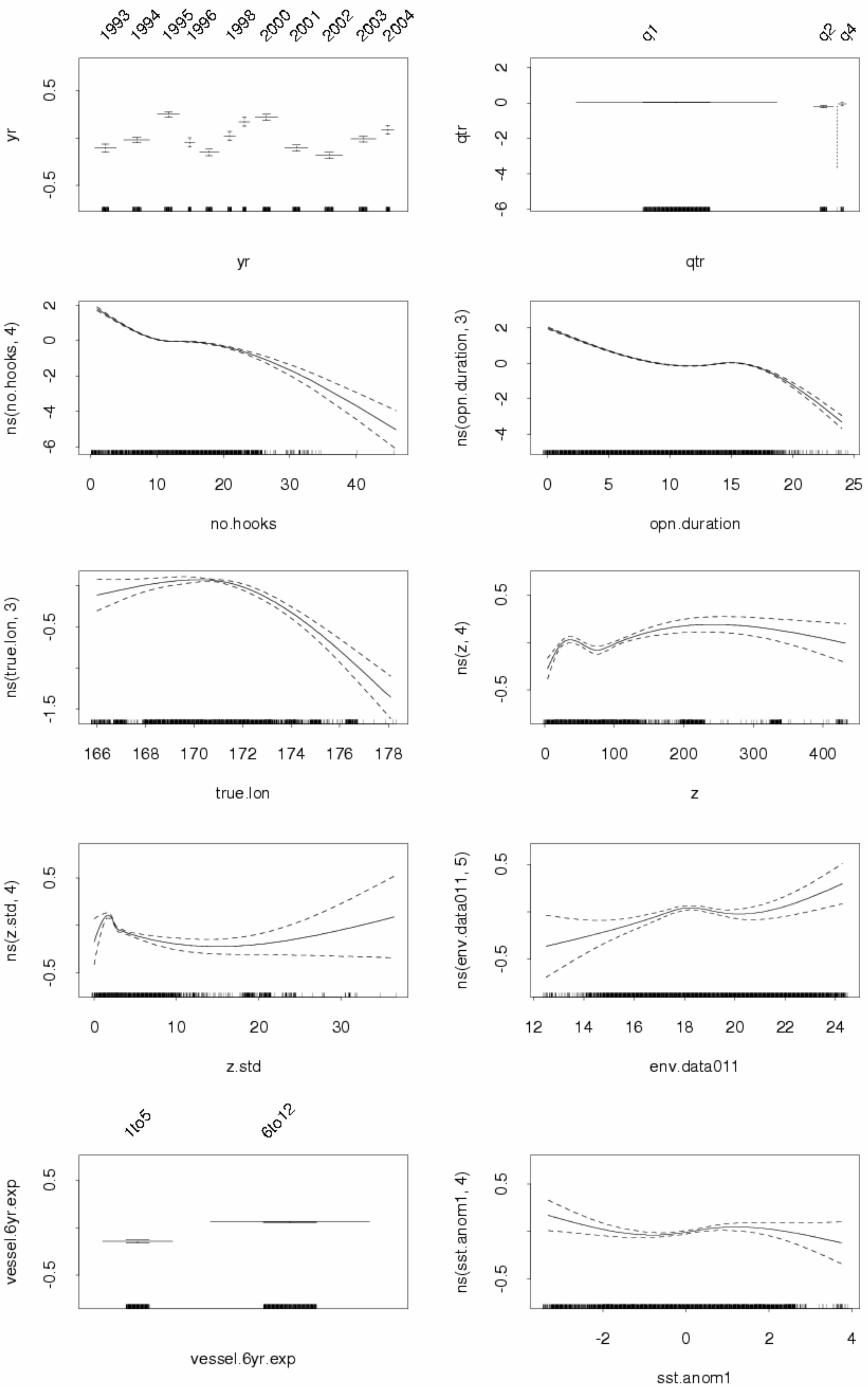


Figure 14. Partial residual plots all factors and covariates in the scaled negative binomial model for the albacore troll fishery. Dotted lines are pointwise standard errors.

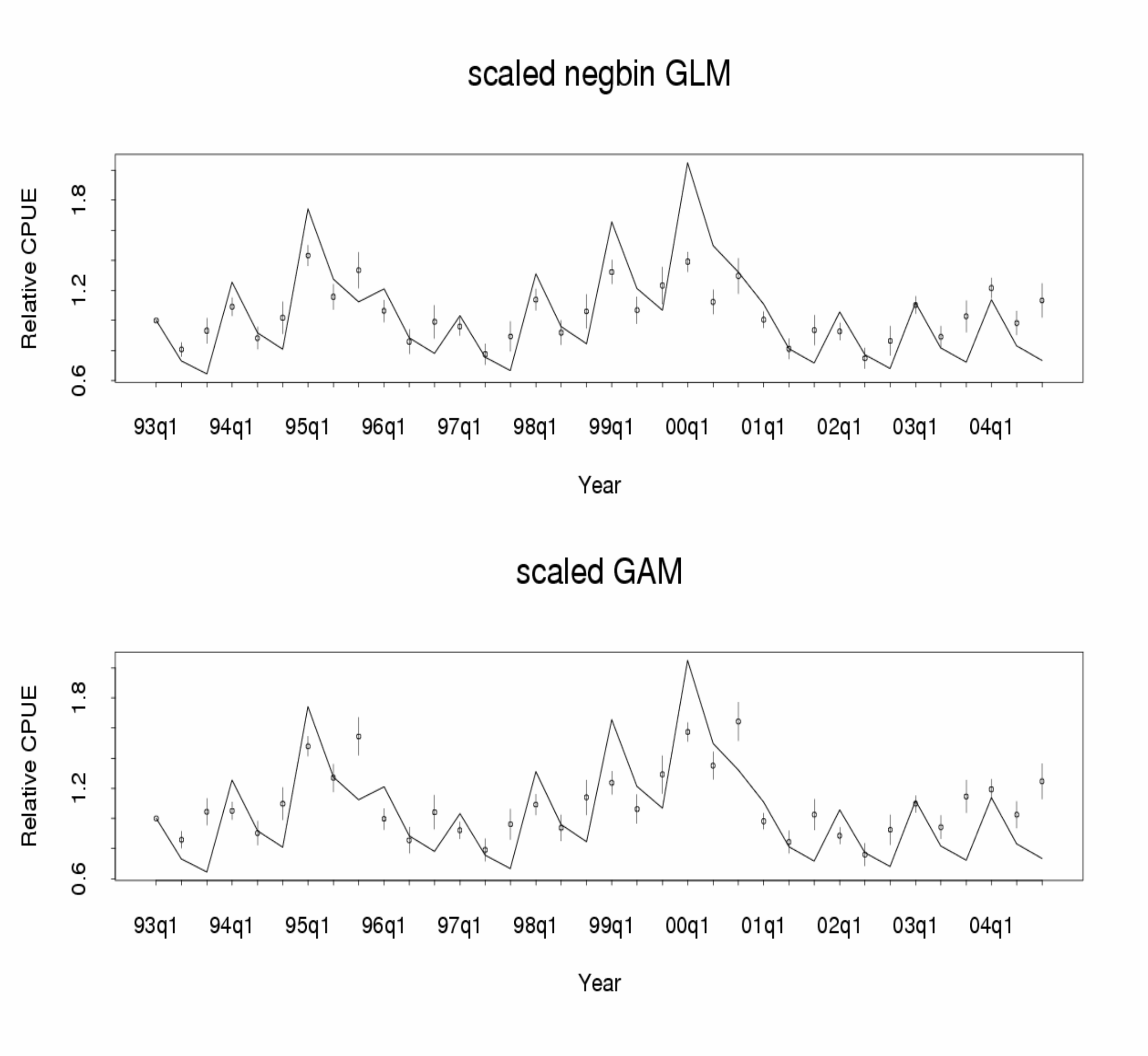


Figure 15. Quarterly time series constructed from the year and quarter terms estimated in the final scaled negative binomial GLM and quasi Poisson GAM, normalised to unity in 1993 quarter 1.