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Factors influencing the size of albacore tuna sampled from the South Pacific albacore longline fisheries

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Executive Summary

The 2008 South Pacific albacore tuna stock assessment (Hoyle et al. 2008a) concluded that the stock was most likely in a healthy state ($F_{current}<F_{MSY}$ and $B_{current}>B_{MSY}$). However, significant uncertainty surrounded this conclusion, largely due to a conflict between historic trends in standardized catch rate and catch-derived size (length) composition data. The CPUE and length frequency data sets were identified as providing conflicting information to the model. Temporal trends in sampled albacore lengths may not reflect changes in the size structure of the population. A need to undertake research to identify factors driving these size trends was identified.

We have considered five hypotheses potentially driving the observed temporal trends in albacore size samples: length frequency data collection sampling bias, selectivity changes, growth changes, recruitment variability, and fishing pressure. In considering these hypotheses, a range of exploratory analyses of both port sampling and observer programme derived length frequency data were undertaken, including Generalised linear model (GLM) and Generalised additive model (GAM) based analyses. The key results and conclusions were as follows.

The Chinese Taipei and Korean fisheries appear to have progressively shifted into areas in which larger fish are caught, during the period in which mean sizes of fish sampled from these fisheries were increasing. However, including spatial terms in the GLM and GAM for albacore length did not remove the length trend. Data from small core areas throughout region 1 and 2 also indicated increasing size trends in many of those areas through that period. This supports the conclusions of Langley and Hoyle (2008) that other factors were contributing to the observed size trends.

Mean sizes were significantly correlated with recent average catches of albacore in region 2 (and to a lesser degree region 1). Catches may therefore be contributing to size changes, with periods of lower catch resulting in increasing sizes and periods of higher catch, decreasing sizes. There was also some evidence that changes in setting practices (e.g. hooks per basket) or times can affect the size of albacore tuna caught. To investigate these issues further, we require better information regarding changes in fishing practices by the Chinese Taipei and Korean fleets over time. The observed size changes may have resulted from a number of coincident events (e.g. fleet movement, catch reductions, and change in fishing practices), rather than a single factor.

The exploratory analyses presented in this paper provide significant insight into which hypotheses might be worth focusing on in future. Given the complexity of the issues and the importance of these results for the assessment, further analysis of these size data should be regarded as a high priority. In addition, these results suggest several possible changes to the assessment that should be further investigated. The multi-region movement approach used before the 2005 assessment should be reconsidered. Modelling separate sub-populations with movement among regions would improve the model’s ability to account for regional differences in fishing pressure, and the differences in fish size that might result. The spatial definitions of fisheries may also be adjusted to account for spatial size variation, such as the larger fish found in the east at 15-25° S. Such improvements to the way size is modelled are likely to reduce conflict with the CPUE data, and to increase the accuracy and precision of the assessment.

1. Introduction

1.1 Background

A revised and updated stock assessment for South Pacific albacore tuna (Hoyle et al. 2008a) was presented to the 4th Scientific Committee meeting of the WCPFC. While the assessment concluded that the stock was most likely in a healthy state ($F_{current}$<F_{MSY} and $B_{current}$>B_{MSY}), significant uncertainty surrounded this conclusion, stemming from a number of sources. One important problem pertained to conflict between historic trends in standardized catch rate and catch-derived size (length) composition data, which are two of the key "observed" data sets to which the model is fitted. The CPUE and length frequency data sets were identified as providing conflicting information to the model regarding stock size and condition. Doubts were raised over whether some of the temporal trends in albacore lengths truly reflected changes in the size structure of the albacore population. There was a clear need to undertake research which might identify factors driving these size trends.

1.2 Apparent size trends (temporal and spatial)

In this paper, we use the term "size" specifically in reference to ***lengths*** of albacore tuna. The trends in mean lengths of albacore by model region (see Figure 1), fleet, quarter, and year, as derived from raw length frequency data, indicate a number of distinct long-term temporal trends (Figures 2 and 3). These trends are also apparent from GLM based analyses of size trends (Langley and Hoyle 2008). For the Chinese Taipei and Korean fleets in particular, and to a lesser degree Japan, three key trends are apparent from Figures 2 and 3:

1. Relatively stable mean size (lengths) during the 1960s;
2. Increasing mean sizes during the 1970s and 1980s;
3. Declining mean size during the 1990s.

1.2.1 1960s – stable sizes

Mean size of albacore, while varying between seasons, is relatively stable in most regions during the 1960s. However, there is evidence that sampling processes at Pago Pago changed in 1971, the processes before 1971 are undocumented, and size (length) distributions in the data appeared to change in 1971 (Hoyle et al 2008a). The pre-1971 data have a significant effect upon stock assessment model outputs (e.g. biomass estimates over time). The most recent assessment (Hoyle et al., 2008a) excluded these data on the basis of the potential bias in sampling methods pre-1971.

1.2.2 1970-1990 – Increasing size trend

There is a general increasing trend in mean size between the early 1970s and the late 1980s (Figures 2 and 3). The length-based stock assessment model (MULTIFAN-CL) used for the albacore tuna assessment assumes that any individual fishery has constant (unchanging) selectivity over time. Consequently, any observed changes in the fish size within a fishery over time are interpreted by the model to represent changes in the actual size of the fish available for capture in the population. In order to fit as closely as possible to both the influential size frequency and CPUE data, the model adjusts biomass by changing recruitment. With biomass maintained at a relatively high level for much of the time series, catches have not been (until recently) large enough to drive biomass changes (Hoyle and Davies 2009).

Given the declines observed in standardized catch rate indices, the selectivity of the longline fishery for adult albacore, and the relatively high level of fishing effort throughout the period 1970-1990, it would be expected that the size of albacore caught might decrease over time, or at most, remain relatively stable. The observation of significant increases in the sizes of albacore over that time period has raised doubts as to whether these data sets accurately reflect changes in size composition and relative abundance of the south pacific albacore tuna population over time, and whether those trends might in fact be driven by changing selectivity or sampling biases occurring in the fisheries over time. Hoyle et al. (2008) noted the conflict between this trend and catch rate trends and the very significant effect this has on the stock assessment outputs. There was significant uncertainty regarding the likely condition of the stock as a result of this, with the SC recommending no further increase in fishing mortality on the south Pacific albacore tuna stock until such uncertainties were addressed (SC4 Executive Summary, 2008). As such, it is important to identify the mechanisms driving temporal trends in albacore sizes evident in the catch derived size sampling data.

1.2.3 1990s – Declining sizes

There is a general declining trend in mean size of albacore tuna in the 1990s. A declining trend in mean size might be expected in a relatively heavily exploited stock. However, given uncertainty over size trends in the first half of the time series, it will be equally important to investigate the factors driving the more recent trends in mean sizes in the fishery, and determine whether these are influenced by changes in the area or method of fishery operation, oceanographic changes, or changes in the size structure of the population that might result from, for example, fishing.

1.2.4 Other temporal and spatial size trends to note:

The trend of increasing mean length (size) of albacore tuna during the 1970s and 80s, apparent in the Korean and Chinese Taipei length frequency data, is less apparent in the data collected from the Japanese fishery (Figures 2 and 3). This is particularly the case in region 2 where those trends are strong for Chinese Taipei and Korea. However, interpretation of the Japanese length frequency data is complicated by the fact that that fishery underwent significant changes in gear and fishing method during the progressive switch from targeting yellowfin (and albacore) to bigeye tuna during the period 1975-1995. This will be discussed again later in the paper.

Aside from the long term temporal trends in the mean length data, a number of other temporal and spatial trends are worth noting:

1. Mean size of albacore shows seasonal cycles, with mean size typically lowest in the 2nd and 3rd quarters (when fishing effort is highest in the southern regions 3 and 4) and highest in the 1st

and 4th quarters (when fishing effort is more concentrated in northern regions 1 and 2) (Figure 2).

2. Inter-annual variability in mean size is considerably larger in the southern model regions (regions 3 and 4), probably as a result of the influence of recruitment variability, given that juvenile albacore are thought to recruit to regions 3 and 4 before migrating northward when they are older (Figure 3).

3. Mean sizes are generally significantly smaller in the two southern model regions (regions 3 and 4), consistent with the known southerly distribution of juvenile albacore tuna.

4. Size distribution (indicated by distance between the mean and 25th and 75th percentiles) is significantly broader in the southern regions, reflecting a mix of juvenile and adult size/age classes in that area of the fishery (Table 2).

It should be noted that length frequency data collected from a number of recently developed PICT longline fisheries targeting albacore tuna have also shown strong temporal trends in the mean lengths of albacore tuna (Molony 2008). The mechanisms driving those trends also require further investigation in future (Hoyle et al., 2008a,b), but are not dealt with specifically in this paper which concentrates on data from Japan, Chinese Taipei, and Korea.

1.3 Objectives and Research strategy

The objective of this paper is to present results from a number of exploratory analyses which were conducted in an effort to better understand the types of factors which can influence changes in size composition of sampled albacore catches over time, and where possible to provide information towards the assessment of some of the different hypotheses that might explain these trends.

In the lead up to undertaking the exploratory analyses, a general research strategy was developed to determine what key factors (e.g. sampling bias, selectivity changes, growth changes, recruitment trends etc) might be driving the observed trends in albacore catch size composition data. The strategy included the following steps:

1. Seek input from researchers from DW fishing nations (

2. Catalog hypotheses

3. Test those hypotheses for which data are available

4. Include remaining uncertainty in stock assessment via structural sensitivity analyses

5. Develop a research program to address the most important sources of uncertainty

Some progress has been made towards the first 4 elements.

2. Inputs from scientists from distant water fishing nations

OFP-SPC sought the advice of scientists from Chinese Taipei and Korea through informal communications after the 2008 Scientific Committee meeting, as well as more directly during the Pre-Assessment Technical Workshop (Harley et al., 2009) held in Noumea in April, 2009. The following points were noted during these discussions:

1. Small offshore Chinese Taipei longliners are known to catch larger albacore than larger distant water vessels. If this is simply due to where those vessels operate (small vessels in lower latitudes where large fish occur and larger vessels at higher latitudes where fish are smaller) then spatial factors included in models should pick up these effects. However, if it is due to actual differences in the fishing operations between vessel classes, then a change in the proportion of small to large vessels over time could introduce bias into the mean size estimates. Vessel size class is typically recorded in the logsheet data.

2. Caution is required in ensuring that size data can be assigned correctly to the region from which fish were caught (given vessels were fishing both in the northern and southern Pacific).

3. It might be useful to consider available Australian data

4. The regression tree methodology might be a useful approach to examine the data in addition to traditional GLM approaches;

5. Some of the more successful Chinese Taipei longline vessels targeting albacore tuna continue to achieve high catch rates on older gear types, and so have not updated their gear to take advantage of the newer monofilament lines. Differences in size selectivity between different gear types, if any, are unknown.

6. That the driftnet fishery occurred prior to the more recent decreasing trend in mean size which is not consistent with the driftnet fishery significantly impacting on recruitment (as this would typically result in increases in mean size); and

7. Access agreements may have led to fleet movements that could produce trends in size, e.g. EEZ's dominate the waters from 25S to 10S with the high seas dominating further south. Finer scale analyses of movements in albacore targeted effort, relative to areas dominated by different size classes, may be of use.

Taking consideration of these comments and past analyses, OFP-SPC developed a catalogue of hypotheses regarding potential mechanisms driving temporal changes in the size composition of the albacore catch from the South Pacific fishery.

3. Hypotheses

Mechanisms potentially driving the observed size changes can be classified into five groups:

1. ***Length frequency data collection sampling bias***

    a. Changes in length frequency port sampling practices in Pago Pago

    b. Changes in on-vessel catch sorting

    c. High grading / discarding practices

2. ***Selectivity changes***

    a. Changes in the spatial distribution (within MFCL model regions) of fishing effort through time, towards areas where larger fish are available. While this is not a true change in selectivity, it is modelled as such in the current MULTIFAN_CL model setup.

    b. Changes in fishing gear or fishing practices through time

        i. Physical selection (e.g., hook size, line strength, use of wire traces, etc)

        ii. Changing set depth – This can occur through varying factors such as the number of hooks set per basket (between floats), setting speed and line tension, bait type (specific gravity), hook size and weight.

        iii. Changing bait types and sizes

        iv. Changing set time

        v. Switch to monofilament (q.v. visibility and fish behavior)

    c. Changes in oceanography affecting availability and selectivity

3. ***Growth changes***

    a. Changes in oceanography affecting productivity, or growth parameters such as K or L_∞

    b. Density-dependent growth increases (e.g. with depletion of albacore and competitors due to overall fishing pressure).

    c. Decrease in natural mortality delaying maturation, with fish putting more resources into growth to maximize reproductive output

4. ***Recruitment variability***

    a. Changes in recruitment can affect the size distribution of fish in the population, as strong and weak year classes promulgate through the length distributions through time..

5. ***Fishing impacts***

    a. Increasing fishing mortality upon adult components of the stock can lead to declining mean size of fish in the catch over time.

    b. Conversely, where fishing pressure has been high and sizes declined, a subsequent cessation of fishing (or large reduction in fishing mortality) can lead to an increase in mean sizes of fish as more fish are able to grow through to older age classes

The separation of these hypotheses is not to imply that only one mechanism can be acting at any point in time. The hypotheses are not mutually exclusive and more than one might simultaneously influence size trends, in either complementary or opposing directions.

4. Methods

4.1 Data sources

Size data (or more specifically, length data) for albacore tuna caught in the South Pacific by the distant water longline fleets of Chinese Taipei, Korea and Japan, have been collected by a number of sampling programmes since the albacore longline fishery started (Table 1) and provided to SPC. Most samples collected until 1990 came from the Pago Pago cannery in American Samoa (data collected by the US National Marine Fisheries Service – NMFS) and the Japanese longline size sampling programme (Hoyle et al 2008a). Since the late 1980s a number of other size sampling programmes have collected data from Chinese Taipei, Korean and Japanese vessels (Table 1), including OFP port sampling during unloading at Levuka in Fiji, and national observer programs. Samples have been collected from each region defined within the albacore tuna stock assessment, the spatial boundaries of which are shown in Figure 1.

Catch data used in the following analyses comprise both aggregate data from distant water fishing fleets and logsheet level data collected by the US National Marine Fisheries Service (NMFS) from distant water longline vessels offloading catches to the Pago Pago cannery in American Samoa, and kindly provided to SPC.

4.2 Analyses

The exploratory analyses conducted were:

1. An examination of upper/lower percentile trends in albacore lengths sampled from catches taken by the distant water longline fleets of Chinese Taipei, Korea and Japan.

2. A characterization of fleet movement over time, relative to areas in which albacore of different sizes occur.

3. Generalised linear model (GLM) and Generalised additive model (GAM) analyses of length frequency data collected from Chinese Taipei, Japanese and Korean longline vessels operating in the South Pacific.

4. Generalised additive model (GAM) analyses of size data collected by observers operating across different EEZs within the South Pacific region.

4.2.1 Analysis of length frequency percentiles

Changes in mean length can arise from changes in the number of large or small fish caught, or both. The 25^{th} and 75^{th} percentiles of length were estimated to examine temporal and spatial trends in the lengths of small and large fish relative to mean length. Trends in the percentile lengths can provide additional information for evaluating the alternative hypotheses about changes in mean lengths over time.

4.2.2 Effort characterization

Under the assumption that logsheet data are representative of the movement of the distant water fleet components that specifically target albacore tuna in the South Pacific, an index of fleet movement (gravity center of effort distribution) was used to explore spatial shifts in fishing effort concentration and distribution over time. This index is calculated as a "mean" latitude or longitude of fishing effort which is weighted towards those latitudes or longitudes with the highest fishing effort levels. Temporal trends in this index can then be used to more easily visualize spatial shifts in fishing effort over time.

4.2.3 Generalised linear model (GLM) analyses of distant water fishery length frequency data

The initial GLM analyses update previous analyses (Langley and Hoyle 2008) as follows:

a. Include the most recent size data;

b. Remove data from pre-1970, which may not be representative of the catch or the size structure of the fish population (Hoyle et al. 2008a);

c. Remove strata that contain very low sample sizes (threshold set at 100 fish), which may also not be representative of the size composition of the catch in those strata.

The stratified length frequency data were then modelled with length as the dependent variable, weighted by frequency. Residuals were assumed to be normally distributed, and for each flag and region, a separate model was run, taking the form:

$$Length \sim f(month) + f(latitude) + f(longitude) + f(year)$$

The data included in the analyses are predominantly port sampling data from Pago Pago and Levuka, along with data from the Japanese longline size sampling programme, and some observer data where that has been collected from distant water vessels operating in zone. The analyses test the effect of these changes (a,b,c above) on the predicted year effect in those models.

4.2.4 Generalised additive model (GAM) analyses of distant water fishery length frequency data

GAM based analyses were undertaken to look at the effects of some additional parameters upon temporal trends in mean length of fish caught in the distant water fisheries. GAMs are useful preliminary analysis tools for identifying non-linear relationships between response and explanatory variables. In addition to spatial and temporal effects, these models explored the relationship between the lengths of albacore tuna sampled from the catches and the:

a. Sampling programme – to investigate if the variability in fish lengths reported might be related to differing sampling programme protocols.

b. Regional catch levels – are increases or decreases in regional catches related to trends in sizes of albacore tuna. In the input data table, each size strata was aligned with a mean average catch from the same model region, for the 2 or 3 years prior to the size sample being collected.

The stratified length frequency data were then modelled with length as the dependent variable, weighted by frequency. Residuals were assumed to be normally distributed, and for each flag and region, a separate model was run, taking the form:

Length ~ f(month) + f(latitude) + f(longitude) + s(prev.catch) + f(sampling program)

Any variants upon this are detailed in the results section for each region and flag specific model.

4.2.5 GAM analyses of regional observer data

Regional observers collect detailed information on species composition, the lengths of fish caught, and fishing effort, as well as a suite of information relating to the fishing methods being used. GAM-based analyses of regional observer data, partitioned by fleet and EEZ (fishery units), were undertaken to explore the nature of relationships between sizes of fish caught and:

a. Factors relating to fishing methods and gears. Factors examined were firstly, hooks per basket (or hooks between floats), which is used as a proxy for the depth of setting, and secondly, the time of day (or night) of setting.

b. Oceanographic/Environmental factors – Factors included in the final models were sea surface temperature, moon phase, and an index of climate state (the southern oscillation index), based on the latter being a general indicator of the types of oceanographic change known to occur under different climate conditions which are known to affect the movement and availability of fish to fishing gears.

c. Spatial and temporal factors – Specifically latitude, longitude, and year.

The form of these models followed the general form:

Length ~ SST + latitude + longitude + f(time of set) + moonphase + f(year) + f(climate state) + f(hooks per basket)

The last term is sometimes replaced by an interaction term between hooks per basket and thermocline depth.

5. Results

5.1 Analyses of percentiles

The key results to note from the analyses of percentiles are:

- The temporal trends of the 25th and 75th percentiles of length were generally similar to those for mean length for all regions and flags (Figure 3A). That is, the temporal trends in the percentile lengths generally ran parallel to the temporal trends in mean length. This suggests that the entire length distribution has shifted in the same general pattern through time as the mean length. The pooling of length data across seasons revealed a slight increasing trend in mean length and 25th and 75th percentiles of length for Japanese vessels in region 2 that was not evident when data were plotted by season.
- There is greater variability in the 25th percentile lengths in regions 3 and 4. This highlights the sensitivity of the 25th percentile to variations in recruitment
- The range of sizes in the catch is wider in the southern regions 3 and 4 than in the north.
- There is greater variability in the 25th percentile lengths in regions 3 and 4. This highlights the sensitivity of the 25th percentile to variations in recruitment.
- A dip in sizes across all regions in 1980 may represent a very strong recruitment entering the fishery at that time.
- Inter-annual variability is high, and often inconsistent between regions. This observation may be caused by one or both of a) sampling (or fishing) that does not represent the sizes in the population well, and b) slow mixing of fish and variable recruitment among the regions.
- Temporal trends in size show some similarities and some differences when compared between regions and between fleets. Trends in regions 1 and 2 are more consistent between fleets and regions then those in regions 3 and 4. Trends in the Japanese data differ from those in the Chinese Taipei and Korean data.
- The annual difference between the mean length and the percentile lengths followed a general mirrored pattern (Figure 3B). That is, in years when the difference between the 75th percentile length and mean length were large (small), the difference between the 25th percentile length and mean length was also large (small) suggesting a broader (narrower) length distribution was sampled in those years. This pattern reflects changes in the kurtosis (rather than skewness) of the length distributions, which may reflect differences in the sample size of lengths measured, with larger sample sizes yielding broader length distributions, or biases in the size of fish selected to be measured.
- There were a few notable exceptions to this pattern. For example, the Japanese length data in region 3 show a much smaller difference between the 75th percentile and mean length relative to the larger difference between the 25th percentile and mean length in 1996. For the same region and fleet, the length data show a much larger difference between the 75th percentile and mean length relative to the small difference between the 25th percentile and mean length in

2001. Such a pattern may be due to a strong recruitment pulse that entered the fishery in the mid 1990's.

5.2 Analyses of length frequency data from Chinese Taipei, Korean and Japanese vessels

Spatial-temporal trends in fishing effort distribution

Both spatial trends in albacore sizes and the movement of fishing effort are initially examined.

Figure 5a highlights the spatial variation in sizes of albacore tuna caught by longline in different areas within the South Pacific, patterns which have been broadly recognized for some time. The largest fish are typically caught in between latitudes 20-25S, with most of those further east past 180E, but with pockets of larger fish west of that evident in some decades. Smaller fish appear to dominate catches in the latitudes 30S-40S but are also evident in most decades in areas close to the equator, (0-10S) particularly in the north western part of the fishery. These observations are supported by a simple generalised additive model run for the entire model area which included terms for latitude and longitude (Figure 5b). These patterns will be influenced by the potentially differing selectivity of the longline fisheries operating in the different areas but appear to indicate some consistant patterns across the decades.

High variability in spatial distribution of albacore targeted distant water fleet fishing effort over time is evident from examination of annual aggregate logsheet derived effort data (for example, Figure 6) and from shifts in the longitudinal and latitudinal centres of effort distribution over time ("gravity center of effort" – see Methods) . The following trends in albacore targeted fishing effort distribution were noted:

1. Fishing effort for all three distant water fleets targeting albacore tuna (Chinese Taipei – 1962-present; Japan 1962-1970; Korea 1962-1990) has shown significant spatial variability, both seasonal (Figure 8-9) and interannual (Figures 7) with temporal patterns in fishing effort distribution also differing between flags.

2. *Seasonal variation*: Significant latitudinal shifts in albacore targeted fishing effort occured on a seasonal basis (Figures 9), with effort typically higher in northern latitudes during 1st and 4th quarters and increasing in southern latitudes in 2nd and 3rd quarters. It is also apparent that the areas of highest fishing effort have shifted longitudinally on an intra-annual basis also, over significant parts of the time period (Figure 8).

3. *Interannual variation*: Long-term (annual) shifts in the areas of highest fishing effort have also occurred (including shifts of up to 20° longitude and almost 10° latitude between consecutive years), with long-term shifts most significant for the Chinese Taipei and Korean fleets (Figure 7), as follows…

4. Since the mid-1970s there has been a general trend for the albacore targeted component of the **Korean** fleet (offloading at Pago Pago) to fish progressively further eastwards, but noting significant shifts back west in 1989/1990 and the mid 1990s (Figures 7-8). The areas of highest fishing effort concentration also shifted significantly southwards over the period 1975-1990

period, before a rapid migration northwards post 1990 (as the fleet switched to targeting tropical tunas) (Figures 7 and 9). Based on a comparison with Figure 6, the eastward and southward shifts in Korean fishing effort appear to have moved effort into areas where albacore tuna sampled in the catch have had, over many decades, a higher mean length.

5. Between the mid-1970s and 1990, the areas of highest **Chinese Taipei** longline fishing effort concentration could shift significantly east or westwards between consecutive years. Effort is concentrated *on average* further west after 1980 (due to increased fishing effort in the Vanuatu/Fiji region), than it was prior to that time point. Similar variability is apparent since 1990. During the period 1975-1990, fishing effort also shifted to be concentrated further south (Figure 6 and 9), where it appears to have remained concentrated until recent years. This shift is particularly apparent in Regions 1 and 2 data, where effort was concentrated between 5S-12S in the 1970s but by the late 1980s had shifted to concentrate between 15S-25S. These trends are generally consistent between logsheet and aggregate data sets. The southward shift of the Chinese Taipei fleet effort during the 1970s and 1980s appears to have moved fishing effort into areas where albacore tuna sampled in the catch have had, over many decades, a higher mean length.

6. Analyses of spatial shifts in the **Japanese** fishery have yet to be undertaken. Due to albacore targeting ceasing around 1970, there is little logsheet data collected from the canneries upon which to base the analyses. Aggregate data could be examined in future to look at shifts in non-targeted fishing effort.

5.3 Generalised linear models for spatial and seasonal effects

Figure 10 presents the year effect as derived from the GLMs, for each fleet and region, for both the previous analyses (Langley and Hoyle, 2008) and the current analyses. The majority of the temporal trends in size were consistent between the two analyses, despite the removal of pre 1970 data, addition of recent data and screening out of very low sample sizes. The following differences in trends between the original and current model outputs were apparent:

a. The Japanese fishery size trend in region 2 is now similar to those of Korea and Chinese Taipei in region 2, with an apparent increase in lengths through to 1990 and declining trend thereafter. This was not apparent in the previous analyses, nor is it evident from the raw length data trends presented in Figure 2. The shift in trend is due to the removal of some very low sample size strata previously included.

b. The temporal trend in sizes sampled from the Japanese fishery in region 3 is now less evident, and the recent downward trend in region 4 is no longer apparent due to the removal of very low sample size strata which drove that trend in the previous model.

c. The downward trend in lengths prior to 1970 (apparent in many fleet-regions previously) is no longer apparent due to the removal of that data. The actual trends during that period are uncertain, if the assumed biases in sampling data are true.

Despite these changes and the inclusion of spatial factors in the model, the key temporal trends of increasing fish length through to the late 1980s and declining lengths thereafter are still apparent in most models.

An analysis of size data from Chinese Taipei longline fishing operations in small 5x5 degree “core” fishing areas (small areas where fishing effort has more consistently occurred over many years in the time series) indicate that within many (but not all) of these small areas, and in the same seasons across years, there were trends of increasing size of albacore tuna caught during the period 1970-1990 (Figure 11). This is particularly apparent in core areas both in the north and south of regions 1 and 2.

5.4 GAM analyses of DWFN data, including the effects of regional catches

Total longline catch of albacore tuna in the South Pacific increased rapidly between 1952 and 1968 to almost 40 000 mt (Figure 12A). The vast majority of that catch was taken in Region 2 (Figures 12C and 13). Total catch then declined on average until the late 1980s (~ 20 000 mt), after which it increased rapidly to peak at almost 67 000mt in the early 2000s (Figure 12A). The overall trends in total SPO catch are driven in large part by trends in region 2 and in more recent years region 1 also. Over the period 1962 - present, mean size (length) of albacore for the whole fishery combined and for albacore sampled from the Chinese Taipei fishery present opposing temporal trends to those apparent in the catch data, with mean length declining as catches increase initially, mean length increasing as catches decline through to the late 1980s, and declining to some extent as catches increase again during the 1990s.

The results of the generalized additive models, which included a term for recent average catch (i.e., an average across the 3 years preceding each size sample) in each region, are summarized in Figures 14-26. For region 2, in which the temporal length trends are most apparent, alternate models were also explored which restricted the fishery data series to when the fishery targeted albacore tuna (Korea 1962-1990; Chinese Taipei 1962-2000).

From these analyses the following key results should be noted:

1. For the flag and region based models, year terms appeared to be highly confounded with the term describing previous regional catches, and hence for the purposes of exploring the relationship between catches and size trends, the year term was not included in following models.

2. In general, the models were only able to explain a moderate amount of the deviance in albacore tuna lengths sampled from the fishery (range: 10.8% to 22.6% for the majority of models, 39.7% for Japan Region 4 model).

3. In all models, for each fleet and region, the recent catch term (3 year average sub-regional catch prior to size sample) was significant. However the nature of the relationship with sampled fish lengths differed considerably between models, as follows:

4. There was a strong negative relationship between recent average catch and size(length) of albacore tuna taken by the Chinese Taipei and Korean longline fleets in Region 2. The strength of

that relationship was stronger when the data was restricted to the period in which each fleet targeted albacore tuna, with the deviance explained in the Chinese Taipei model almost doubling (11.9% to 20.6%) as a result of this.

5. Weaker but generally negative relationships were evident between recent catch and size in Region 1 for the Chinese Taipei and Korean fisheries, while the relationship between size and recent catch was significant but highly variable at different catch levels in regions 3 and 4, for each of the fleets.

6. The relationship between month and sampled albacore lengths varies between regions and fisheries. There is little relationship evident in region 1 fisheries, except for Japan which exhibits smaller fish caught in the middle of the year, a trend much more strongly evident across all fleets in region 2. In regions 3 and 4 the trends are variable between fleets.

7. Latitude tends to be the most significant model term in most of the models explored, with models of fisheries in regions 1 and 2 indicating sampled fish lengths to increase as latitude moves south away from the equator). In contrast, sampled fish lengths in Regions 3 and 4 increased as with decreasing latitude from 45°S to25°S. Overall, fish sizes appear to be largest across the SPO at around 20—25°S, supporting the results from the "whole region and fishery" model presented in Figure 5b.

8. Longitude was one of the least significant terms in the models but still typically explains part of the variation observed in sampled fish lengths. Trends vary between fleets, particularly in regions 1 and 3, and were most apparent and consistent in region 4, where sampled fish lengths increases from west to east. This trend was also apparent in two of the models for region 2 (to the north of region 4).

9. The term included in the models to identify different sampling programmes was typically a significant term in the models. In general, SPLL and SRUS sampled lengths were typically similar to one another but lower than lengths sampled via the Japanese, Chinese Taipei and Korean longline sampling programmes. However there was little temporal overlap between some sampling programmes and there was also a possibility of confounding between this term and spatial terms (latitude and longitude), which are discussed later.

5.5 Analyses of length frequency data from regional observer programmes

These analyses used observer data provided from observer programmes across the South Pacific, with the number of trips monitored by each program varying over time (Table 3) and the spatial distribution and concentration of observed catches of albacore tuna highlighted in Figure 25. Within the South Pacific region, sample sizes were highest from the Australian, New Zealand, Fiji and French Polynesian observer programmes. The relationship between sampled lengths and method, oceanographic and spatial factors was explored in 9 separate flag and EEZ specific models as follows:

Fishery ID	Flag	EEZ	Data period
JPAU	Japan	Australia	1991 - 1997
JPNZ	Japan	New Zealand	1987 - 2006
TWSB	Chinese Taipei	Solomon Islands	1997 - 2003
SBSB	Solomon Islands	Solomon Islands	1997 - 2004
FJFJ	Fiji	Fiji	2002 - 2008
NCNC	New Caledonia	New Caledonia	2002 - 2007
FPFP	French Polynesia	French Polynesia	2002 - 2008
TOTO	Tonga	Tonga	1997 - 2003
NZNZ	New Zealand	New Zealand	1995 - 2006

The key results to note from these analyses (provided in Figures 28-36) are:

1. The percentage of model deviance explained by these models varied between 14 – 44%. The fisheries for which the percentage deviance explained was highest were JPAUs, TWSB, SBSB, FPFP, NZNZ, and JPNZ. Most of the factors finally selected for inclusion in the models explained a statistically significant fraction of the overall model deviance.

2. Despite the EEZ and flag based partitioning of models, and differences in methods and target species across the fisheries examined, there were numerous commonalities in the relationship between albacore size (lengths) and fishing method factors, oceanographic and spatial factors, between the different fisheries.

3. **Sea surface temperature (SST):** There was a general and repeated relationship across the fisheries between sampled sizes of albacore and SST. Size generally increased with SST up until at least 24C (JPAU, TOTO, FPFP, NZNZ, FJFJ), after which there was no further increase, and in some fisheries (SBSB and FPFP) there was evidence of declining mean length where SST was greater than ~28C.

4. **Latitude: Latitude:** Size of albacore observed in longline catches was consistently highest between 20-22°S (JPAU,FPFP, NCNC, FJFJ). South of 22°S, size tended to increase with decreasing latitude (NZNZ) and sizes then decreased at latitudes close to the equator (FPFP, JPAU, FJFJ). In the most southern fishery (JPNZ), sampled albacore lengths were also higher at the extreme lower latitudes (around 44 – 48°S).

5. **Longitude:** trends in sizes with longitude are highly variable between fisheries, with little consistent (linear) trend in many fisheries.

6. **Moon phase:** There was significant variability in the apparent relationships between moon phase and albacore tuna sizes sampled in the different fisheries. In some fisheries there was evidence for an increase in the size of albacore caught as moon-phase approached the full moon (TOTO, JPAU, FPFP, FJFJ) however others suggest an opposing pattern (TWSB) or no consistent relationship.

7. **Climate state:** In six of the nine fisheries examined, the size of albacore tuna caught in the fisheries was higher during neutral and La Niña periods than during El Niño periods. This was most apparent for fisheries in the western and southern subregions (JPAU, TWSB, SBSB, NZNZ, JPNZ) while in Tonga the trend was opposite with lower sizes predicted during La Niña and Neutral periods.

8. **Time of setting:** Models for JPAU, TWSB and FPFP indicated that albacore caught in those fisheries are larger on night sets than on day sets. Some of these relationships, while statistically significant, appeared based on very small sample sizes for the night sets. Four fisheries did not have any data for night sets.

9. **Hooks per basket**: In eight of the models examined, hooks between floats explained a significant component of the model deviance, with evidence in each of these fisheries for larger albacore being caught on deeper hooks. However, in some fisheries the relationship did not appear strictly consistent (i.e. some instances of an apparent drop in size for some higher HPB categories) and in some the sample sizes at low HPB categories appeared very low. Hence HPB was only weakly significant in a number of these fisheries (e.g., NCNC, F=8.59, p=0.003). Only in two fisheries (TOTO and JPNZ) was there absolutely no evidence for size of fish caught on deeper hook categories being higher than on the shallowest hook categories.

6. Discussion

We have considered five hypotheses potentially driving the observed temporal trends in albacore sizes: length frequency data collection sampling bias, selectivity changes, growth changes, recruitment variability, and fishing pressure. The exploratory analyses presented in this paper provide significant insight into which hypotheses might be worth focusing on in future. Given the complexity of the issues and the importance of these results for the assessment, further analysis of these size data should be regarded as a high priority.

The Chinese Taipei and Korean fisheries appear to have progressively shifted into areas in which larger fish are caught, during the period in which mean sizes of fish sampled from these fisheries were increasing. However, including spatial terms in the GLM and GAM for albacore length did not remove the length trend, and analyses of small core areas throughout region 1 and 2 also indicated increasing size trends during that period. This supports the conclusions of Langley and Hoyle (2008) that other factors were contributing to the observed size trends.

Mean sizes were significantly correlated with recent average catches of albacore in region 2 (and to a lesser degree region 1). Catches may therefore be contributing to size changes, with periods of lower catch resulting in increasing sizes and periods of higher catch, decreasing sizes. This analysis also raises questions about the movement, mixing or residency of albacore tuna in or between different regions, since sizes and catches are correlated in region 2, but trends and correlations are also apparent in regions 4 and 1.

Changes in setting practices (e.g. hooks per basket) or times can also affect the size of albacore tuna caught, with these findings supported in part by other recent research (e.g. Campbell, 2009). To investigate these issues further, we require better information regarding changes in fishing practices for the Chinese Taipei and Korean fleets over time.

It appears that the observed size changes may have resulted from a number of coincident events, rather than a single factor. Fleets moved into areas with larger fish during a period in which catches were substantially reduced, and this may have been accompanied by changes in fishing practices to increase the probability of catching larger albacore tuna (e.g. increasing depth of setting or night setting). It is important to note that while the increase in sizes amounts at most, in the most affected regions, to a 7-10cm (~10-12%) increase in mean length of sampled albacore, this translates to an increase in fish weight of about 40-45% (Farley and Clear, 2008). Gains in weight per fish may have outweighed the biomass lost due to reduced numbers caught.

In addition, these results suggest several possible changes to the assessment that should be further investigated. The multi-region movement approach used before the 2005 assessment should be reconsidered. Modelling separate sub-populations with movement among regions would improve the model's ability to account for regional differences in fishing pressure, and the differences in fish size that might result. The spatial definitions of fisheries may also be adjusted to account for spatial size variation, such as the larger fish found in the east at 15-25° S. Such improvements to the way size is modelled are likely to reduce conflict with the CPUE data, and to increase the accuracy and precision of the assessment.

In the following section we discuss the 5 main hypotheses in more detail, in light of past and current research.

6.1 Length frequency data collection sampling bias

Three mechanisms were proposed as having potential to create bias in the sampling process that might result in the increasing size (length) trends through the 1970s and 1980s, being:

a. Changes in length frequency port sampling practices in Pago Pago

b. Changes in on-vessel catch sorting

c. High grading / discarding practices

None of the exploratory analyses described in this paper can directly provide information towards assessing the likelihood of either of the first two mechanisms proposed above. With respect to potential changes in port sampling practices (at Pago or any sampling program), a term identifying the sampling program from which size sample was derived was included in the models and ultimately were determined to have significant effects upon mean size. Interpreting these effects however was difficult. They may indicate some genuine differences in sampling protocols or biases in sampling between programmes. However, it is equally probable that this term is confounded with the spatial factors (latitude and longitude) and may in fact partially act as a spatial interaction term in the models, given that these sampling programs often operate within a defined sub-region within the model domain. Further exploration of these effects will be required before they can be more confidently interpreted.

Potential changes in port sampling practices at Pago Pago specifically could be followed up via direct communication with long term staff at the Pago cannery, samplers and long term fisheries staff in American Samoa. Evidence for or against on-vessel catch sorting can probably only be resolved through consultation (perhaps by Chinese Taipei and Korean scientists) with Chinese Taipei and Korean longline industry and fishers. However, it is worth noting that:

a. After low sample sizes were removed, the initial GLM analyses outlined in Section 6.3 indicated that the same increasing temporal size trend evident in the Korean and Chinese Taipei size data from Region 2 was also apparent in the Japanese data. The Japanese data was collected by a separate program (Japanese longline size sampling programme) to the Korean and Chinese Taipei data during the period 1970 – 1990. With albacore being a bycatch only in the Japanese fishery during that period, it seems less likely that the same bias in sampling that is proposed to have potentially occurred in Pago, would also occur in the sampling from Japanese longliners by a completely separate sampling programme, and thus result in the same temporal trend in sizes from each fleet. None the less, follow up with relevant industry members is required to further investigate these questions.

b. A change in port sampling practices is likely to manifest as a rapid change in the mean size of albacore over time, rather than the long term gradual change that was apparent in the 1970-1990 data period.

The potential for high-grading (via discarding of smaller fish) was also explored through analyses of temporal trends in mean lengths against trends in the 25th and 75th percentiles for the length data. High grading would likely result in a reduction in the proportion of smaller fish, which may be observed as an increase in the 25th percentile length, and a relatively stable 75th percentile length, relative to the mean length. The similarity in the annual difference between percentile and mean lengths does not support the hypotheses of high grading. Future analyses of percentiles might concentrate on those further towards the extremes of the size distribution (e.g. the 5th and 10th percentiles). High grading of albacore has been noted to occur in some longline fisheries (Robert Campbell, pers.comm.) but we do not have evidence for its occurrence in the fisheries examined here.

6.2 Selectivity changes

Numerous factors have the potential to impact upon the size selectivity of fisheries over time. The most likely factors identified prior to the current analyses as affecting selectivity of longline fisheries for albacore tuna were:

a. Changes in the spatial distribution of fishing effort through time

b. Changes in fishing gear or fishing practices through time

c. Changes in oceanography affecting availability and selectivity

Changes in fishing effort distribution: Effort in the Taiwanese and Korean fisheries shifted southwards (and for Korea, also eastwards) to be more concentrated than previously in areas in which larger fish occur (Figures 5 to 7), with that shift occurring over the period in which mean lengths are observed to have increased. The southward shift in effort is mainly occurred in regions 1 and 2, with effort shifting from around 5-10°S to around 20-25°S.Llatitudinal shifts in effort distribution in regions 3 and 4 are less apparent. Interpretation of spatial trends in fishing effort relies on the assumption that the logsheet data from which those trends are derived is representative of the shifts in the entire albacore targeting fishery. The Pago Pago data represent one significant component of the total Chinese Taipei logsheet data (See appendix 1.). Attempts to determine the precise coverage levels against aggregate DWFN data held by SPC indicated was complicated by the fact that that aggregate data will contain fleet components targeting other species. In addition, it is not currently possible for SPC to link the Pago Pago size data with the logsheet data collected at the cannery, hence whether the distribution of size sampling is representative of the distribution of effort is currently unknown.

Despite the apparent shift in effort to areas where larger fish occur, model-based analyses indicate that spatial shifts in the fishery do not fully explain the observed temporal trend of increasing sizes through the 1970s and 1980s. Core area analyses showed increasing mean lengths in numerous 5 degree areas throughout the Chinese Taipei fishery over time (Figure 11), confirming conclusions from the previous (Langley and Hoyle, 2008) and current model based analyses that factors other than shifting fishing effort are influencing temporal trends in mean lengths of albacore tuna. That said, Figure 5a indicates that there is significant spatial variability in size distribution of albacore tuna and that that variability might be better explained by interaction terms between latitudinal and longitudinal (and potentially time) explanatory variables in future models.

Changes in fishing gear/practices through time: There is relatively little regional observer data collected from distant water longline fisheries of Korea (in particular), Chinese Taipei and Japan. However, given that the Pago Pago logsheet data have limited gear related information(aside from HPB in recent years) and that those data cannot currently be linked to the size data, regional observer data currently represents the only data source by which potential effects of different gear settings and fishing practices upon the size of albacore caught can be investigated. Two fishing method related factors were investigated for their potential relationship to the size of albacore tuna caught by longline, these being the number of hooks per basket (which is used as a proxy for the depth of setting of the hooks) and the time of set.

Evidence was found in a number of the fisheries examined for larger albacore being caught when the gear is set deeper (or when HPB is higher), however this was not found in all fisheries. Campbell (2009) also found some evidence for a similar relationship, but only in one of three specific areas of the fishery examined. Care needs to be taken in examining HPB relationships as there often appears to be significant confounding with latitudinal effects. Preliminary observer data based models for the Hawaii and Australian longline fisheries (not presented here) initially suggested strong relationships between HPB and albacore size, but a large part of that variation was ultimately found to be a result of differences in depth of setting between sections of the fisheries operating at different latitudes (and at which albacore of different sizes occur anyway).

The relationship between HPB and albacore size has the potential to influence the mean size of albacore caught over time if there is a temporal trend in the number of HPB used in a given fishery. Hence an increasing trend in fish size in the catches over time might result from increasing depth of setting (increasing HPB) over the same time period in the fishery. Currently, Japan is the only fleet for which there is evidence for such a trend, whose longline fleets switched to more HPB (deeper setting) to target bigeye tuna. It is unknown if a similar trend has occurred in the Korean and Chinese Taipei fisheries targeting albacore tuna during the period 1970-1990. Again, consultation with Chinese Taipei and Korean fishing industry might assist in determining this. The shift in the Chinese Taipei and Korean fisheries to areas where larger albacore occur (discussed above) might be due to numerous factors (e.g. EEZ exclusion), but if it was specifically to target larger albacore (due to market value etc) then a change in depth of setting to catch deeper swimming larger albacore (which observer data analyses suggest is possible) might have occurred at the same time. Data and consultation with industry is needed to determine the likelihood of this.

The second fishing practice related factor explored was set time. There was a significant relationship between set time and the size of albacore tuna sampled from the catch in only a few of the fisheries assessed. In these, larger albacore appeared to be caught in night time sets. Domokos et al. (2007) demonstrated that albacore display diel vertical migratory behavior, occupying shallower water (<150m) during the night and deeper water (150-300m) during the day. Therefore, the average size of albacore landed may vary with set time if the size of albacore is stratified by depth. Such interactions require further investigation via electronic tagging of albacore tuna. The implication for these findings is that a temporal trend towards night setting could potentially result in an increasing size trend in the fishery catch. Examination of the Pago Pago data for time of set data should quickly confirm if this is a possibility, and if those data are not recorded, consultation with Chinese Taipei and Korean scientists and industry is required.

Many other fishing method related data have been collected by observers including bait type and size, the use of wire traces, lengths of float lines and branch lines, the line type (monofilament, rope etc) and other factors, which may inform future analyses and exploration of this hypothesis. Given statements regarding the mix of mainline materials used by different vessels in the Taiwanese fleet (Section 2) and the fact that these have different buoyancies (effecting the depth at which the gear fishes) and differing detectability (visibility) by fish, these may be important factors to investigate further.

Changes in oceanography affecting availability and selectivity: The current analyses of observer data indicated that the mean size of albacore tuna caught by longline fisheries operating in the South Pacific region was related in part to sea surface temperature (SST) in the area in which the fish were sampled. SST is known to be related to changes in catch rates for albacore tuna (Langley 2004). Our results indicate that large albacore tended to dominate the catch where SST was within the range 24°C – 28°C. Mean sizewas lower either side of this range. The potential for oceanographic "regime shifts" to effect the distribution and availability of different sized albacore tuna is clearly present. However, whether such oceanographic shifts *have* occurred was not investigated as part of this paper, due to a lack of time, but could easily be investigated in future. Some preliminary investigations into the relationship between mean size and thermocline depth were also undertaken and will be presented in future papers.

6.3 Growth changes

These hypotheses were not investigated in the current paper and few if any of the results appear relevant to assessment of this hypothesis.

6.4 Recruitment variability

The increase in mean size of fish in the fishery catch observed between 1970 and 1990 may have resulted from a period of above average recruitment. This has not been investigated as part of the current paper but could potentially be investigated via analyses of troll CPUE and size composition data, under the assumption that the relative strength of annual cohorts is indicative of recruitment strength. Predicted recruitment time series derived from the south Pacific albacore stock assessment model can not be used in such analyses, given the potential effect of size data upon recruitment estimates, as discussed by Hoyle et al (2008).

6.5 Fishing impacts

Increasing fishing mortality upon adult components of the stock can lead to declining mean size of fish in the catch over time. Conversely, the cessation of fishing (or a large reduction in fishing mortality) in a previously heavily exploited fish population can lead to an increase in mean sizes of fish as more fish are able to grow through to older age classes. The increasing size trend observed in the longline size frequency data between 1970 and 1990 is somewhat unusual in an exploited fish population, leading to the suggestion that this in fact represents either a change in selectivity or sampling bias (Hoyle et al 2008). However, the possibility that this could, at least in part, be due to a change (reduction) in fishing pressure should not be ignored.

The total longline catch of albacore tuna in the South Pacific declined by almost 25% during the period in which the mean size of albacore tuna increased regionally. It is apparent that much of the regional decline in catch was due to a 73% drop in catch in region 2 specifically (which comprised up to 65% of the SPO catch annually pre-1971) between 1967 and 1990, with the majority of reduction occurring by the mid 1970s. Furthermore, mean sizes appear to decrease during two separate periods of high or increasing fishing catch (1960s, and 1990s). The fact that the region in which the increasing size trend is most apparent is region 2, and that this occurred after a very large reduction in catches taken from that region, prompted a GAM based investigation of the relationship between regional catches and subsequent sizes of albacore tuna sampled from those regions.

In all models, for each fleet and region, the recent catch term (3 year average subregional catch prior to size sample) is significant. However the nature of the relationship with sampled fish lengths differed considerably between models. There is a strong negative relationship between recent average catch and size(length) of albacore tuna taken by the Chinese Taipei and Korean longline fleets in Region 2. The strength of that relationship is stronger when the data is restricted to the period in which each fleet targeted albacore tuna, with the deviance explained in the Chinese Taipei model almost doubling (11.9% to 20.6%) as a result of this. Weaker but generally negative relationships are evident between recent catch and size in Region 1 for the Chinese Taipei and Korean fisheries, while the relationship between size and recent catch is significant but highly variable at different catch levels in regions 3 and 4, for each of the fleets.

The findings from these analyses suggest that there is some possibility of a real increase in fish sizes in the population, and that the increasing trend in mean size apparent during the period 1970-1990 should not automatically be assumed to be due to other factors.

7. Conclusions – relevance of findings for stock assessment of albacore tuna

These results suggest several possible changes to the assessment that should be further investigated. The multi-region approach used before the 2005 assessment should be reconsidered. This would improve the model's ability to account for regional differences in fishing pressure, and differences in fish size that might result. The spatial definitions of fisheries may be adjusted to account for spatial size variation, such as the larger fish found in the east at 15-25° S. Such improvements to the way size is modelled are likely to reduce conflict with the CPUE data, and to increase the accuracy and precision of the assessment. In addition, to ensure size data feeding into the model is more representative of catches taken in each model strata, remove size samples from the stock assessment model that are not representative of catch, and reweight, using the process already applied to yellowfin and bigeye length frequency data.

Analyses of factors influencing the size composition of albacore catches, and the further exploration of the different hypotheses, can be progressed in future, via:

1. Inclusion of terms in the GLMs to describe the potential influence of recruitment variability. These might be derived from troll CPUE and size composition data.

2. Further exploration of the impact of sample sizes upon GLM derived results and interpretations. This could involve sequential removal of progressively larger samples and examination of the effects upon model outputs

3. Further exploration, potentially using simple population models, of the likelihood of catch driven changes in fish size occurring, given the assumed biological characteristics of albacore tuna.

4. Further consideration given to the modelling and interpretation of potentially confounding factors, such as latitude and SST, set time and moon phase, etc.

5. Explore the potential use of MULTIFAN_CL and the length frequency data inputs to investigate hypotheses relating to growth changes, by examining differences in growth estimates using different time blocks in the model.

6. A review of the linkages between size data and location (of sampling) and how that data is subsequently modelled.

7. Inclusion of spatial interaction terms in the GLMs to (hopefully) better capture and explain complexity in the spatial patterns of size distribution of albacore catches taken through the South Pacific.

8. Estimation of coverage rates to understand more easily how representative the Pago Pago logsheet data is of the total albacore targeted fishing effort (by fleet), and to understand how representative the size samples are (spatially and temporally) of the catches taken.

9. Analyses which link the logsheet level data to the size data to allow consideration of vessel specific effects and vessel class (size) effects upon the size of albacore tuna captured

10. In collaboration with Chinese Taipei and Korean scientists, gather information (data or anecdotal evidence) from the respective longline fishing industries regarding potential changes in fishing practices over time which might have impacted upon the size of albacore tuna being caught. Currently, while potential fishing method related factors have been identified as having the potential to influence size trends, evidence for such changes in fishing methods over time in the distant water fleets is lacking

11. In collaboration with Chinese Taipei and Korean scientists, obtain list of vessels offloading at Pago Pago, which were using older and newer (monofilament) mainline materials, and run analyses to determine if this has a significant effect on size composition of catch, given anecdotal evidence that the Chinese Taipei fleet is using a mix of gears.

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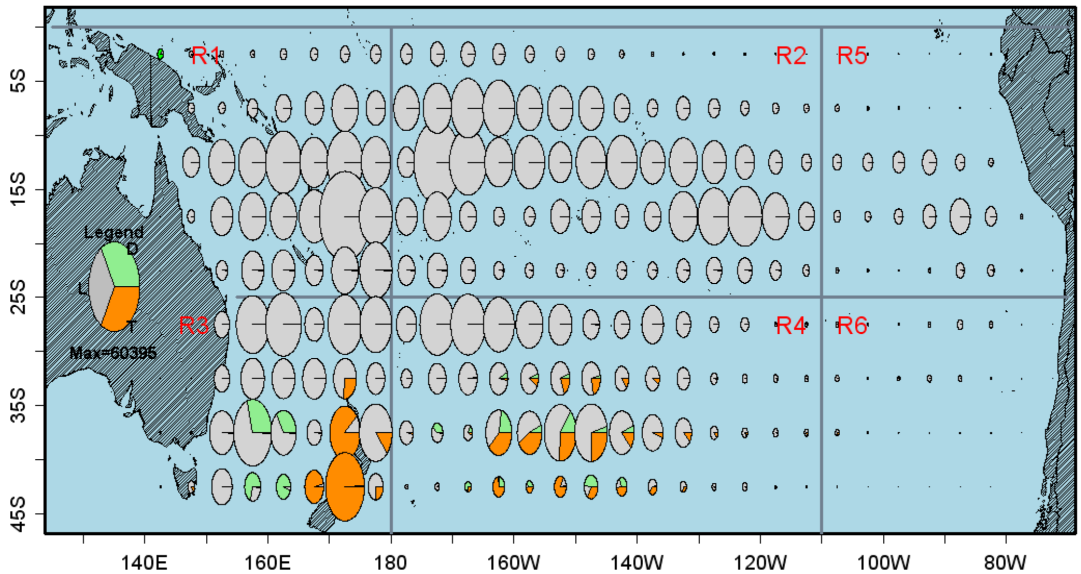
Table 1 – Number of albacore length frequency measurements, by year and sampling programe, sampled from Japanese, Chinese Taipei or Korean longliners in the South Pacific. Length frequency data is held by SPC and includes data collected by NMFS from the Pago Pago cannery (SRUS), by the longline size sampling programmes of Japan (JPLL), Korea (KRLL) and Chinese Taipei (TWLL), as well as by observers from Australia (AUOB), New Zealand (NZOB), Papua New Guinea (PGOB), Kiribati (KIOB), Solomon Islands (SBOB).

Year	AUOB	JPLL	KIOB	KRLL	NZOB	PGOB	SBOB	SPLL	SPOB	SRAU	SRUS	TWLL
1962	0	0	0	0	0	0	0	0	0	0	3895	0
1963	0	0	0	0	0	0	0	0	0	0	18143	0
1964	0	0	0	0	0	0	0	0	0	0	16577	0
1965	0	20400	0	0	0	0	0	0	0	0	21811	0
1966	0	28718	0	0	0	0	0	0	0	0	32736	0
1967	0	23070	0	0	0	0	0	0	0	0	37220	0
1968	0	9478	0	0	0	0	0	0	0	0	27615	0
1969	0	8730	0	0	0	0	0	0	0	0	25635	0
1970	0	12822	0	0	0	0	0	0	0	0	24200	0
1971	0	5194	0	0	0	0	0	0	0	0	23654	0
1972	0	4399	0	0	0	0	0	0	0	0	21281	0
1973	0	5191	0	0	0	0	0	0	0	0	27164	0
1974	0	2297	0	0	0	0	0	0	0	0	18217	0
1975	0	1837	0	0	0	0	0	0	0	0	9465	0
1976	0	3239	0	0	0	0	0	0	0	0	9051	0
1977	0	10411	0	0	0	0	0	0	0	0	9814	0
1978	0	11002	0	0	0	0	0	0	0	0	3929	0
1979	91	4080	0	0	0	0	0	0	0	0	2996	0
1980	0	1097	0	0	0	0	0	0	0	0	1435	0
1981	0	150	0	0	0	0	0	0	0	0	372	0
1982	1	480	0	0	0	0	0	0	0	1	986	0
1983	0	404	0	0	0	0	0	0	0	0	1583	0
1984	0	346	0	0	0	0	0	0	0	0	5228	0
1985	0	1780	0	0	0	0	0	0	0	0	5664	0
1986	0	858	0	0	0	0	0	0	0	0	9235	0
1987	90	1880	0	0	273	0	0	0	0	52	8901	0
1988	334	1274	0	0	572	0	0	0	0	254	5594	0
1989	599	1315	0	0	488	0	0	0	0	304	3762	0
1990	1749	2791	0	0	2052	0	0	0	52	1051	3037	0
1991	6411	12452	0	0	3269	0	0	0	0	3219	2450	0
1992	8192	3297	0	0	1948	0	0	1559	0	3820	2078	0
1993	12629	8808	0	0	3162	0	0	6539	0	4660	1300	0
1994	5649	5723	0	0	770	0	0	4335	0	2240	750	0
1995	5713	3473	0	0	264	0	0	5405	737	2156	300	0
1996	7519	4711	0	0	0	0	0	7177	4836	0	399	0
1997	11330	1828	0	0	1057	0	0	5775	1567	0	150	0
1998	131	4419	0	0	5932	0	4862	6664	122	0	0	0
1999	0	2869	0	0	1217	0	1264	2855	67	0	0	0
2000	0	563	0	0	742	0	2204	8836	0	0	0	0
2001	0	1469	0	0	1247	11	123	16172	0	0	0	0
2002	0	765	797	0	377	48	930	28735	0	0	0	0
2003	0	3943	0	0	1197	0	454	28612	0	0	0	0
2004	0	1078	0	0	0	507	369	18168	0	0	0	0
2005	0	123	228	0	0	44	0	12028	0	0	0	155160
2006	0	413	371	123	0	66	0	5742	0	0	0	111444
2007	0	0	36	340	0	0	0	2075	0	0	0	22313

A.



B.

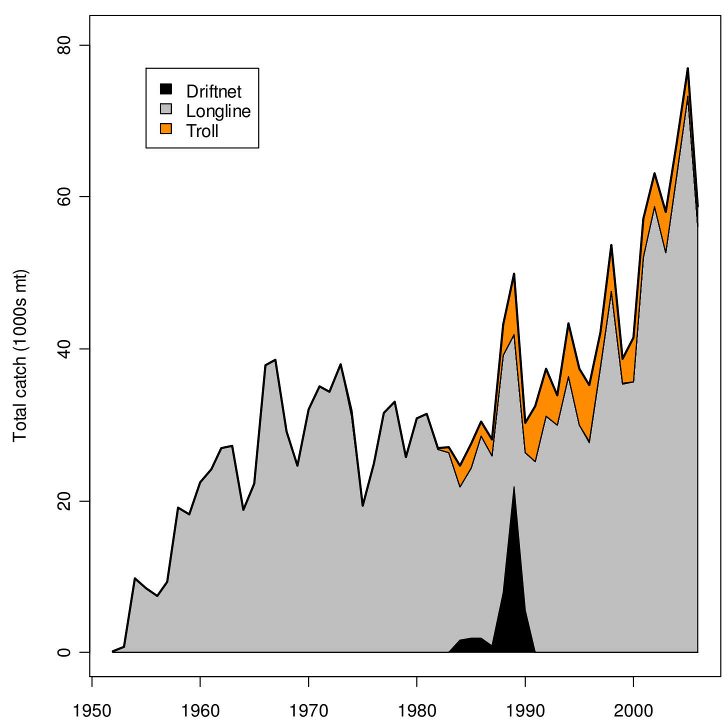


Figure 1: A) Total catch of albacore tuna from 1960 to 2006 by 5 degree squares of latitude and longitude by fishing gear; Longline (L), driftnet (G), troll (T). The area of the pie chart is proportional to the total catch. The boundary of the stock assessment area is delineated by the black line and regional boundaries are delineated by the grey lines. **B)** Total annual catch (mt) of south Pacific albacore by fishing method for 1952 to 2006. (Source: Hoyle et al 2008).

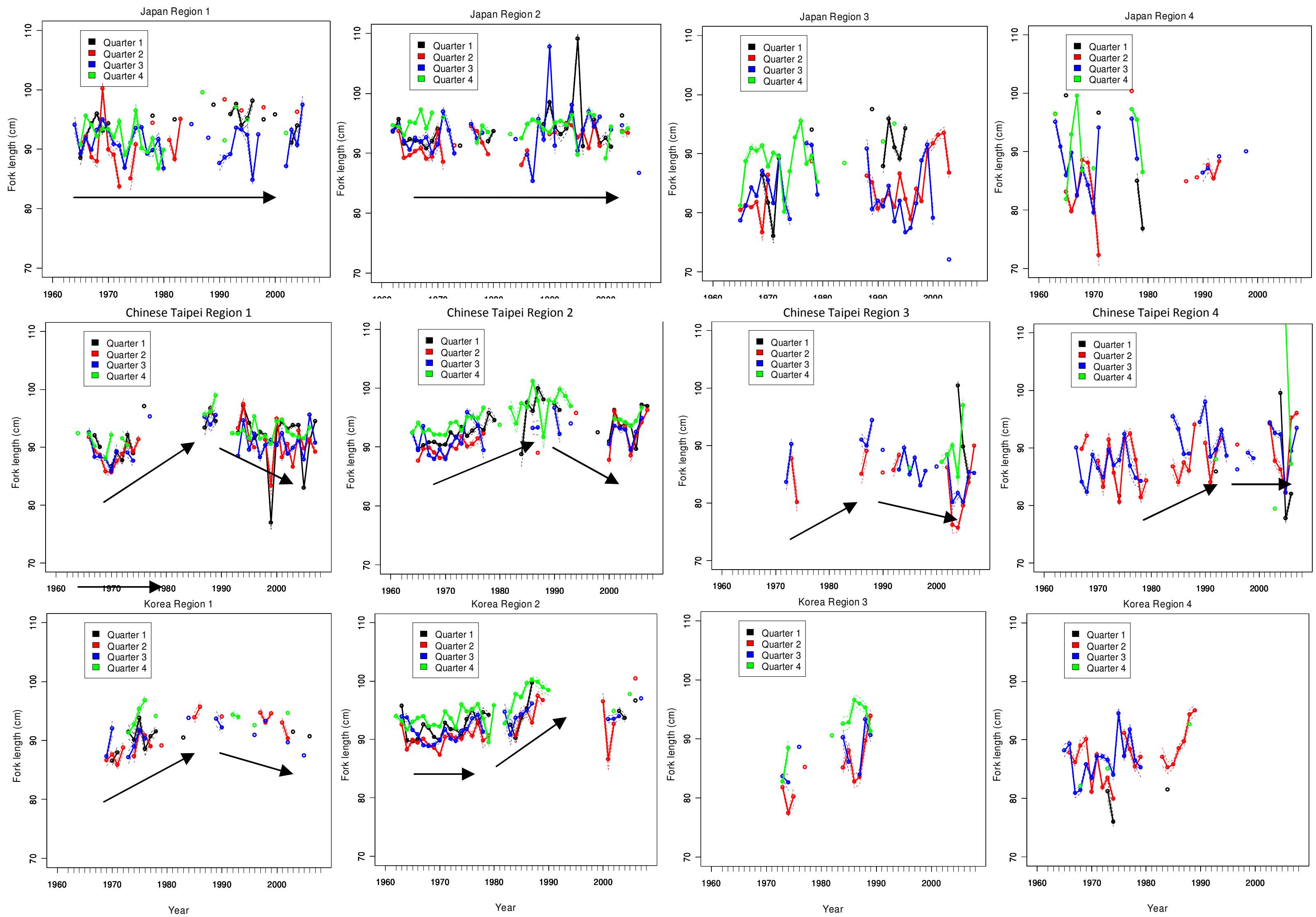


Figure 2: Trends in quarterly mean size (length) of albacore tuna taken in the Japanese (top panels), Chinese Taipei (middle panels) and Korean (bottom panels) longline fisheries operating in the south Pacific between 1962 and 2008. Sample sizes of less than 100 fish are excluded.

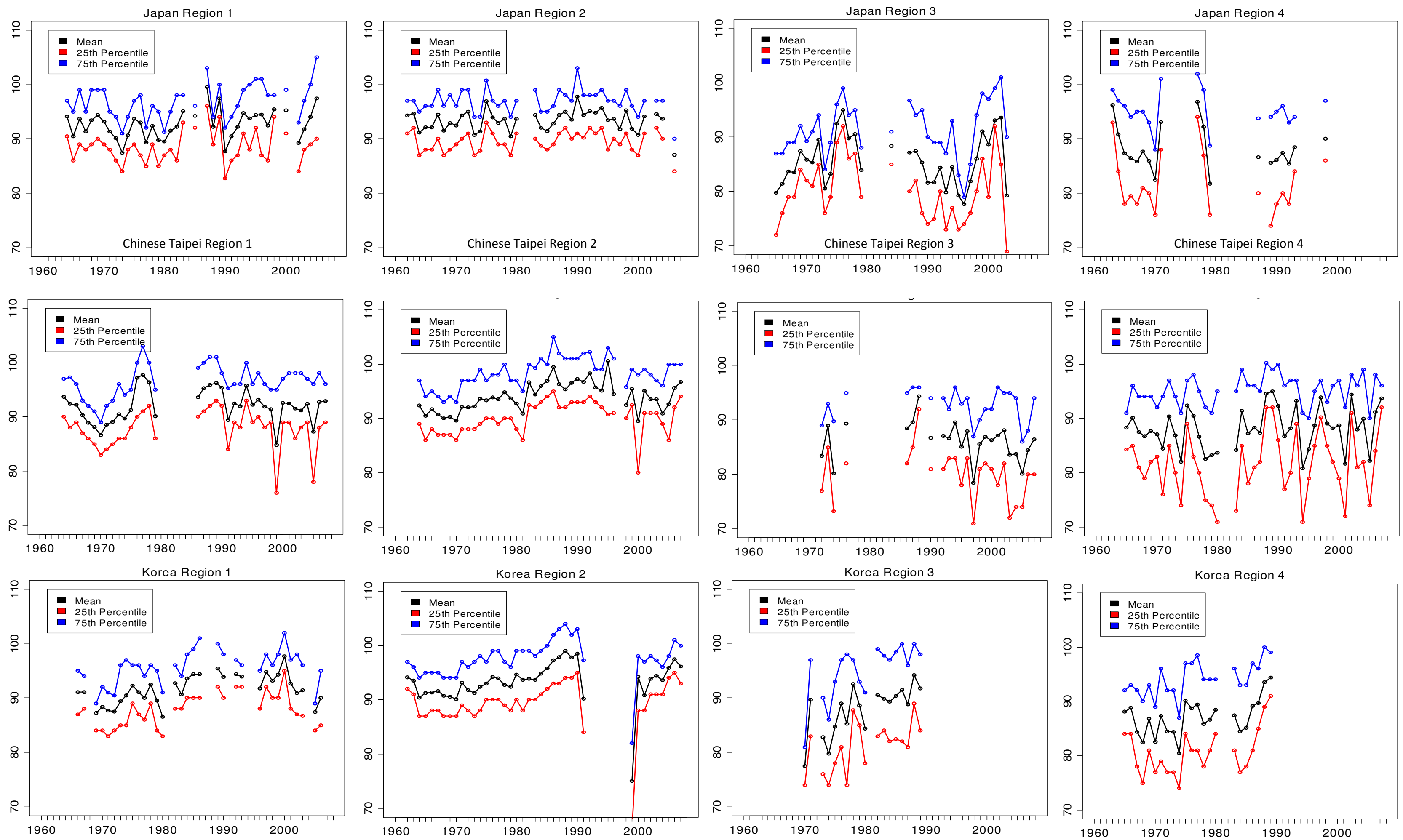


Figure 3A: Annual trends in mean length, 25th and 75th percentile lengths of albacore tuna taken in the Japanese (top panels), Chinese Taipei (middle panels) and Korean (bottom panels) longline fisheries operating across model regions 1 to 4 in the south Pacific between 1962 and 2008. Note, sample sizes of less than 100 fish are excluded (Data source: SPC length frequency database, 2009).

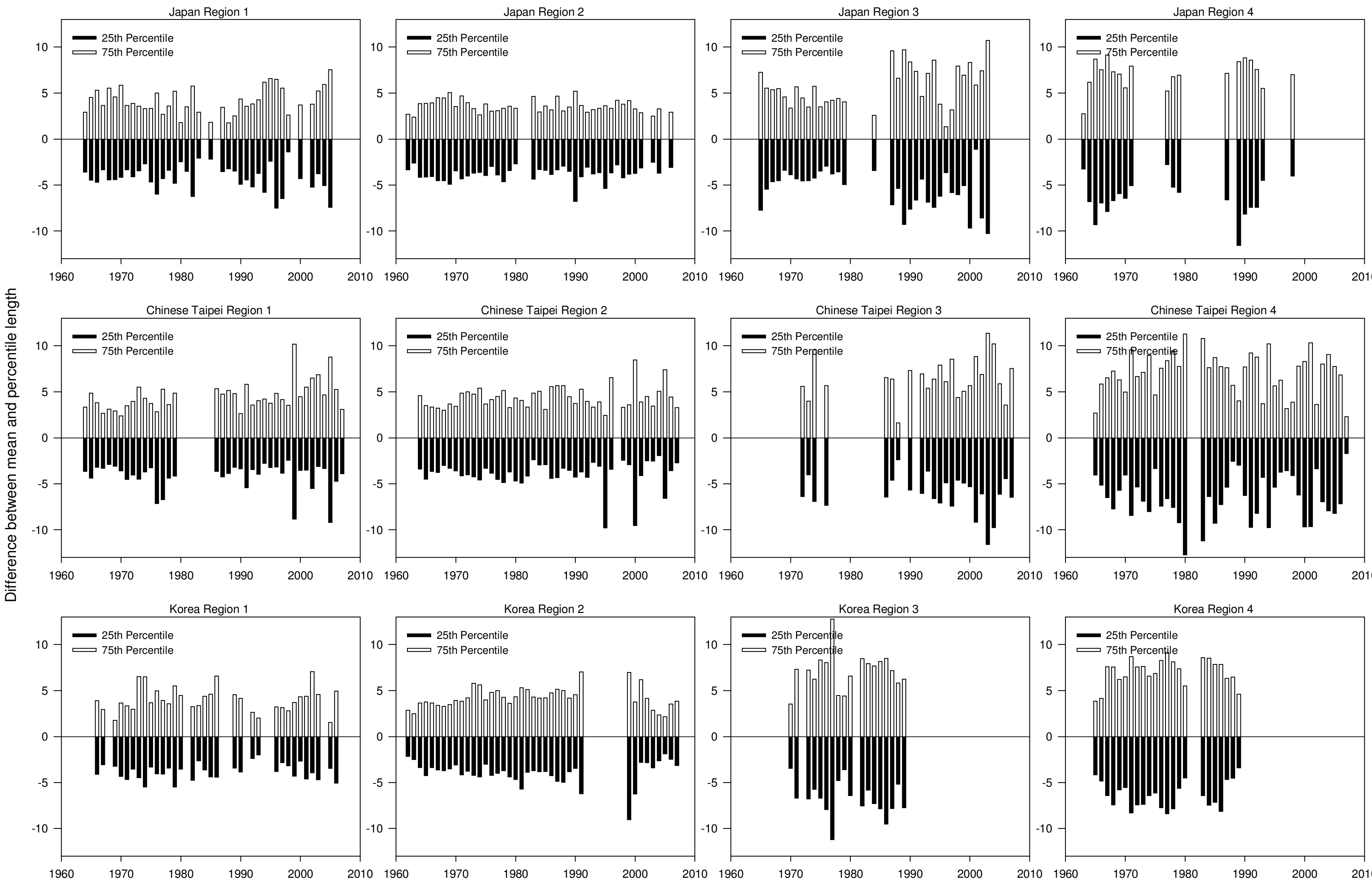


Figure 3B: Annual difference between mean length and percentile (25th and 75th) length of albacore tuna taken in the Japanese (top panels), Chinese Taipei (middle panels) and Korean (bottom panels) longline fisheries operating in the south Pacific between 1962 and 2008. Note, sample sizes of less than 100 fish are excluded (Source: SPC length frequency database, 2009).

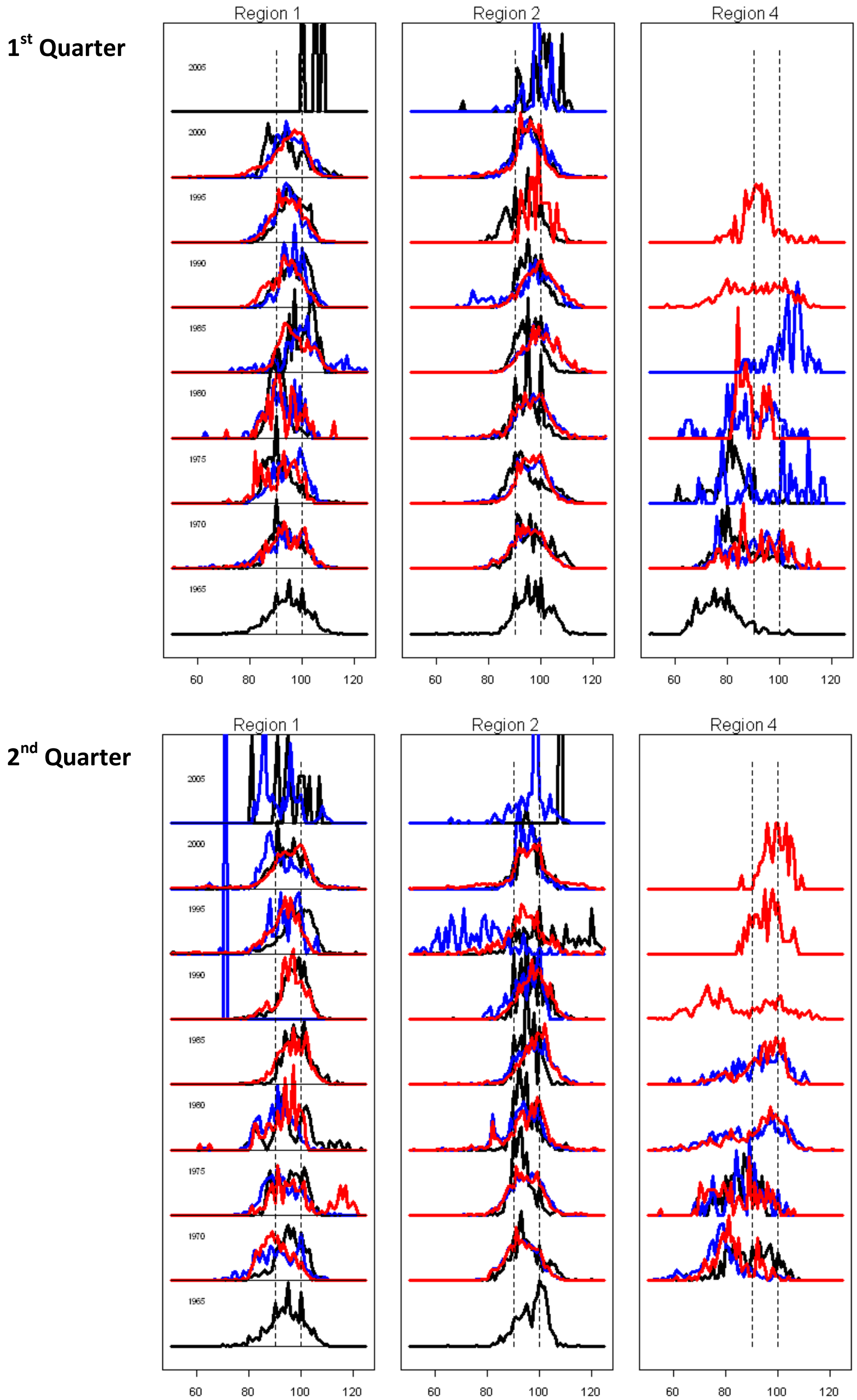


Figure 4: Five yearly aggregated length frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline in regions 1, 2, and 4, considered separately for the first quarter (top panels) and second quarter (bottom panels). Insufficient data were available from region 3. The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm. (Hoyle and Davies, 2009).

3rd Quarter

4th Quarter

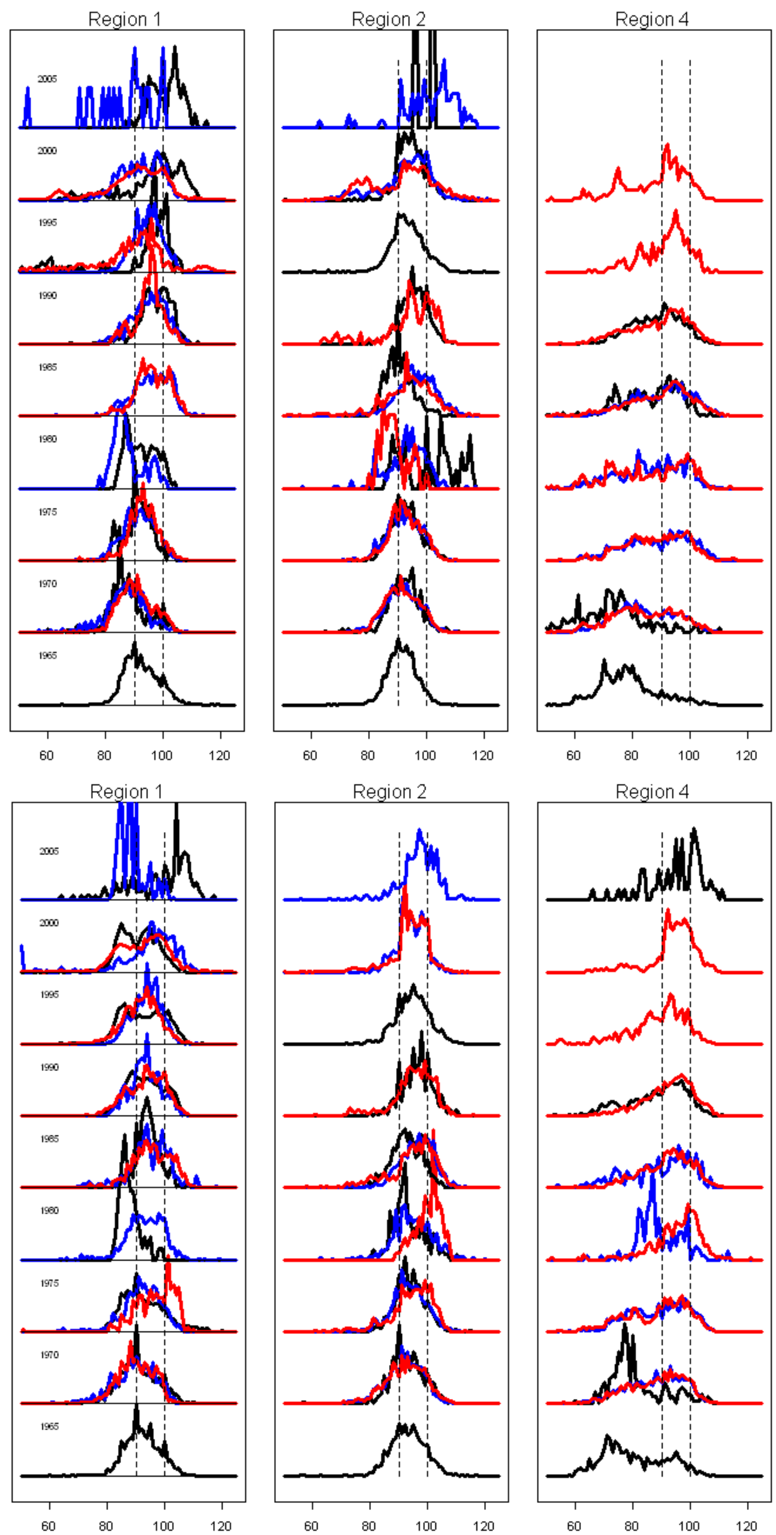
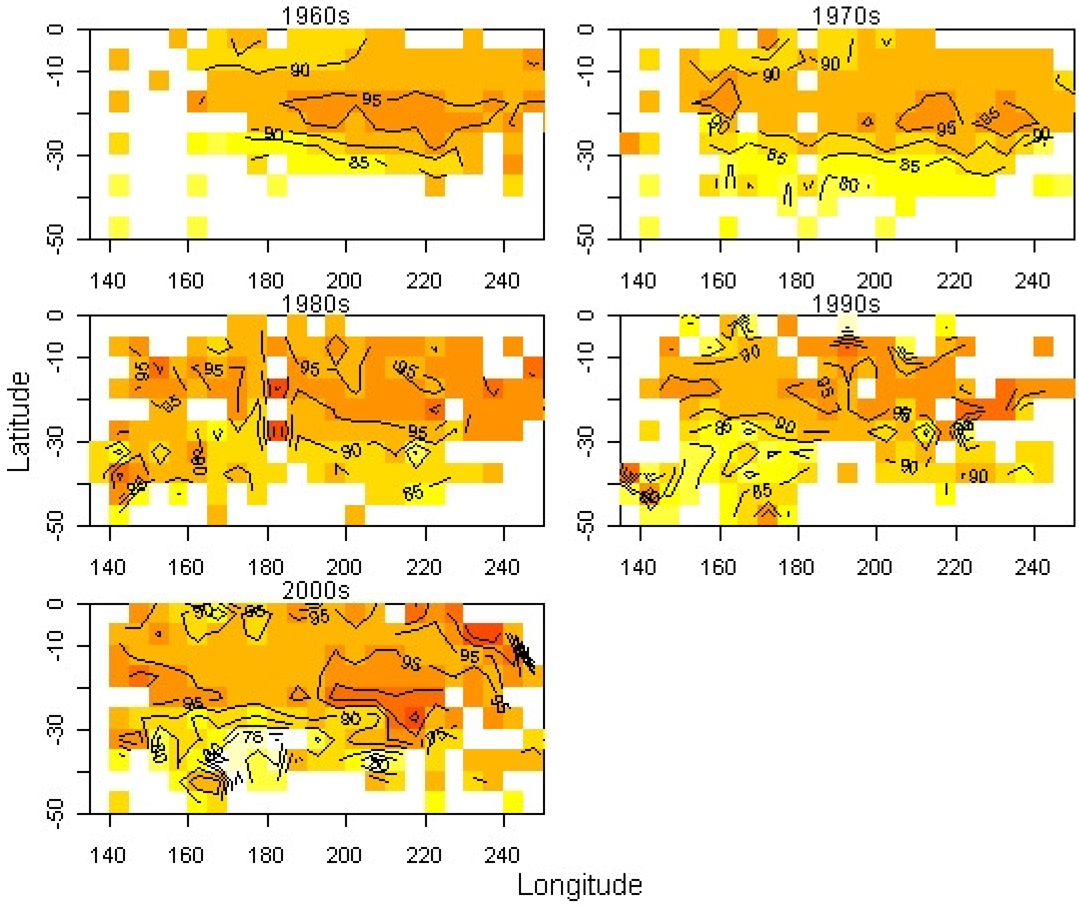


Figure 4 (continued): Five yearly aggregated length frequency distributions (fork length) of albacore from the Japanese (black), Korean (blue) and Chinese Taipei (red) longline in regions 1, 2, and 4, considered separately for the third quarter (top panels) and fourth quarter (bottom panels). Insufficient data were available from region 3. The year denotes the first year of the five-year period. The two dashed vertical lines are at 90 and 100 cm. (Hoyle and Davies, 2009)..

A.



B.

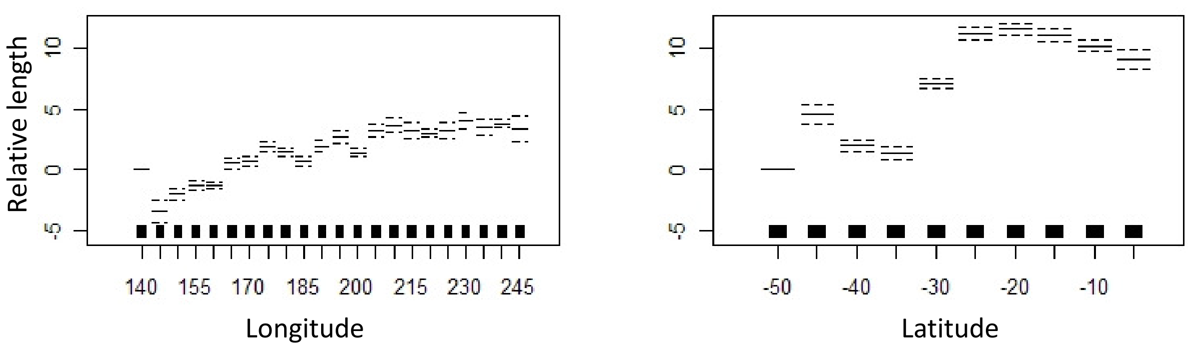


Figure 5 – A) Mean fork length of albacore tuna sampled by longline, by five degree squares of latitude and longitude, and by decade. **B)** Relationship between relative length of albacore sampled from longline catches and the longitude and latitude at which those catches were taken, as derived from a generalized additive model based on length frequency data from the Japanese, Chinese Taipei and Korean longline vessels operating in the South Pacific since 1962. Data Source: Length frequency database, SPC, 2009.

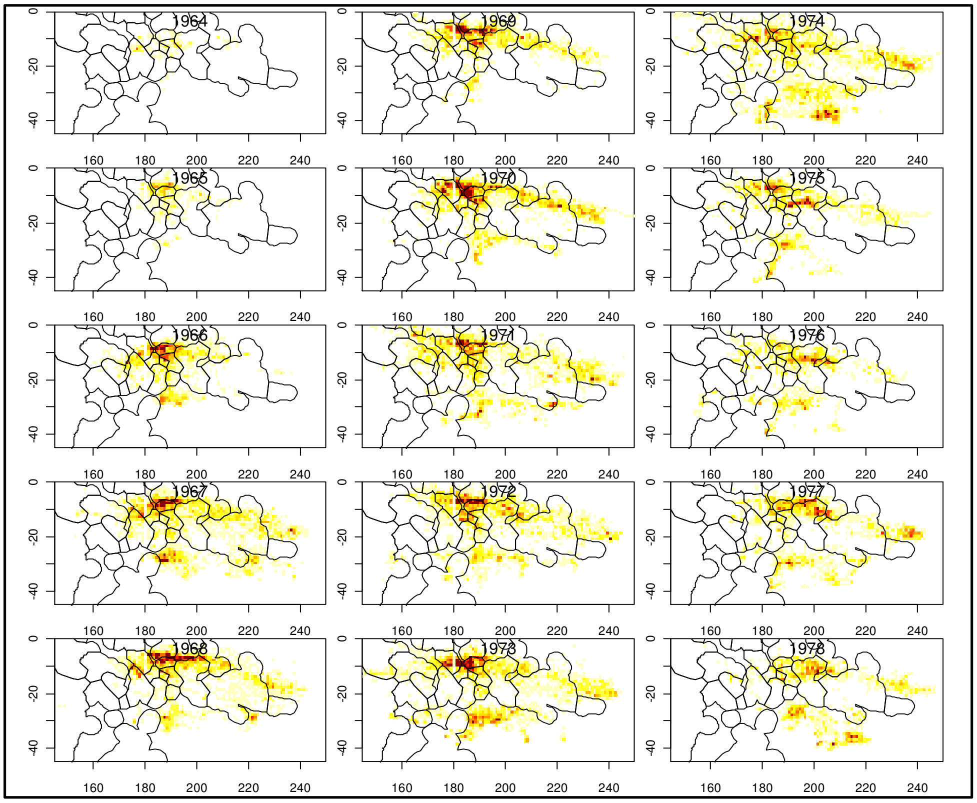


Figure 6 – An example of how spatial distribution of fishing effort can vary on an interannual basis. These maps present Chinese Taipei longline fishing effort for the period 1964-1978 (prior to EEZ formation but with subsequent EEZs superimposed), based on logsheet data collected by the US National Marine Fisheries Service from longliners unloading at the Pago Pago cannery, and provided to SPC (2009). Darker colours (orange/brown) denote higher effort levels.

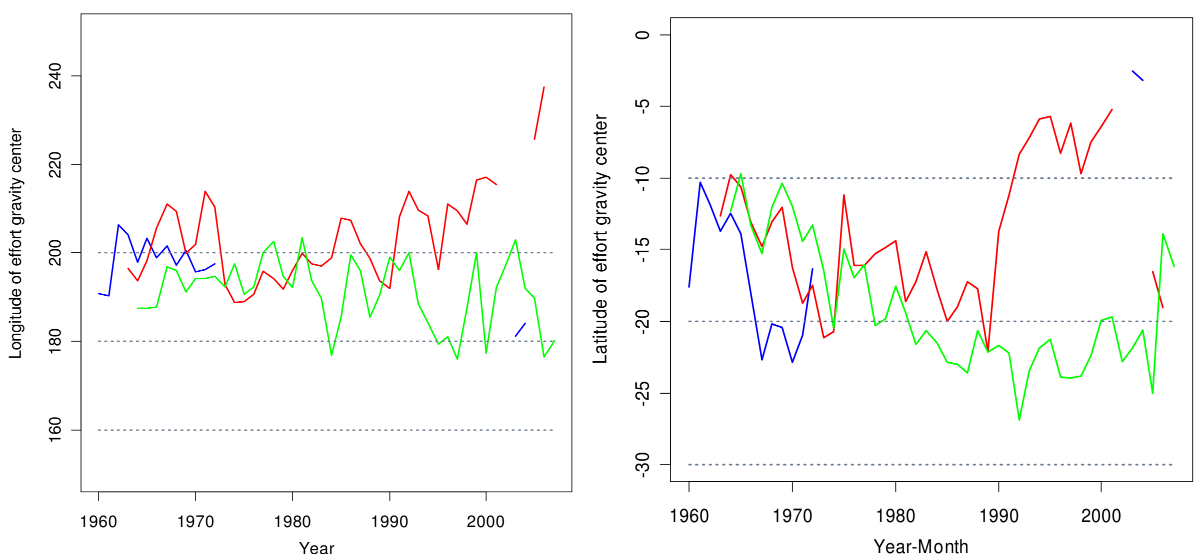


Figure 7: Annual shifts in the areas of highest longline fishing effort, by flag (green=Chinese Taipei, red=Korea, blue=Japan), as denoted by changes in the latitudinal and longitudinal gravity centres of effort distribution, based on logsheet data collected by the US National Marine Fisheries Service from vessels offloading in Pago Pago and including logsheet data collected from vessels offloading in Levuka, Fiji. The "gravity center" index provides information regarding latitudinal or longitudinal changes in the areas where fishing effort is most concentrated at any point in time (Data source: NMFS, 2009).

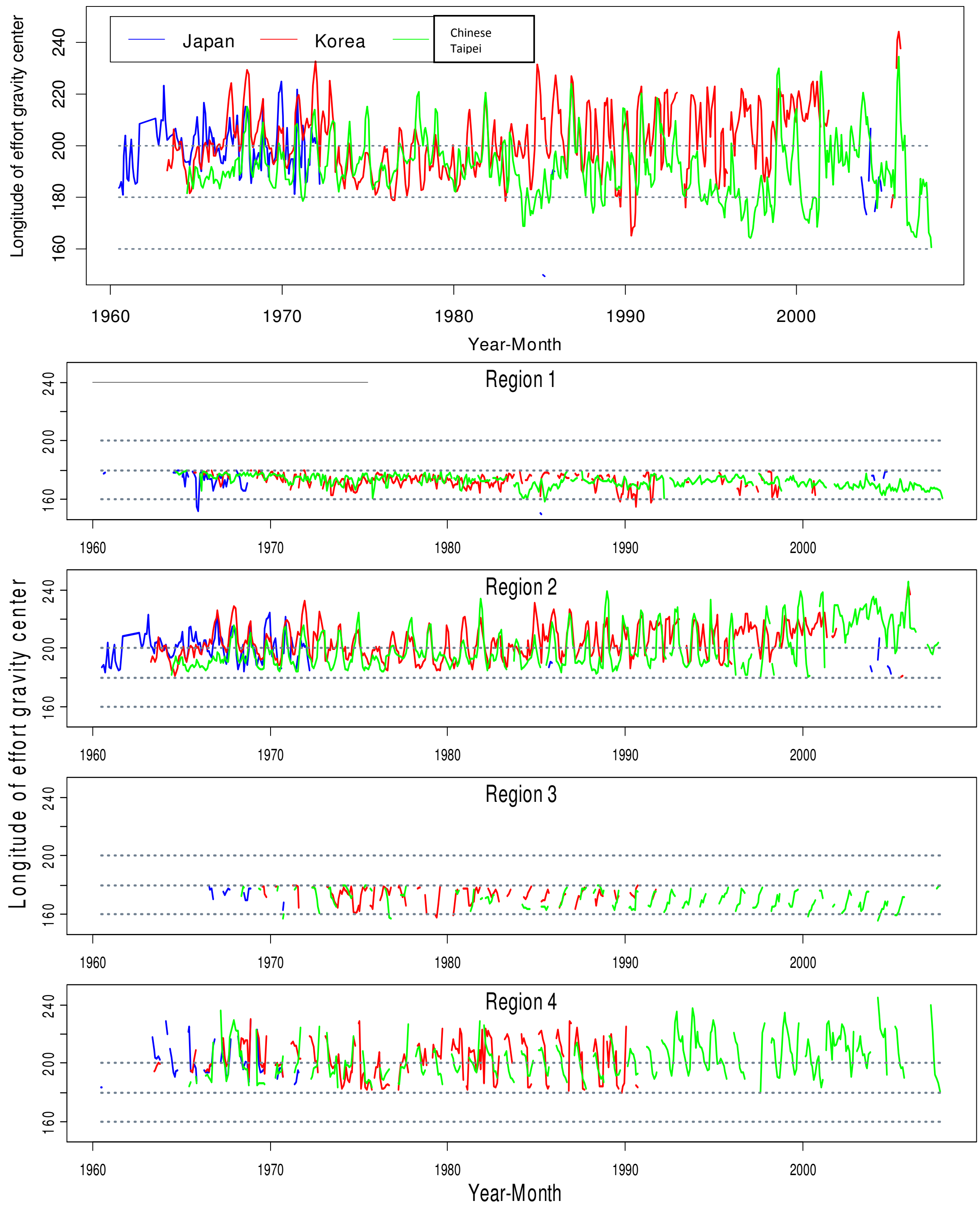


Figure 8: Quarterly and annual longitudinal shifts in longline fishing effort, for the entire model area (top panel) and by region (subsequent panels), by flag, as denoted by changes in the longitudinal gravity center of effort distribution. This index is derived from logsheet data collected by the US National Marine Fisheries Service from vessels offloading in Pago Pago and including logsheet data collected from vessels offloading in Levuka, Fiji. The "gravity center" index provides information regarding longitudinal shifts in fishing effort, indexing the center of the distribution of effort at each time point (Data source: NMFS, 2009; SPC, 2009).

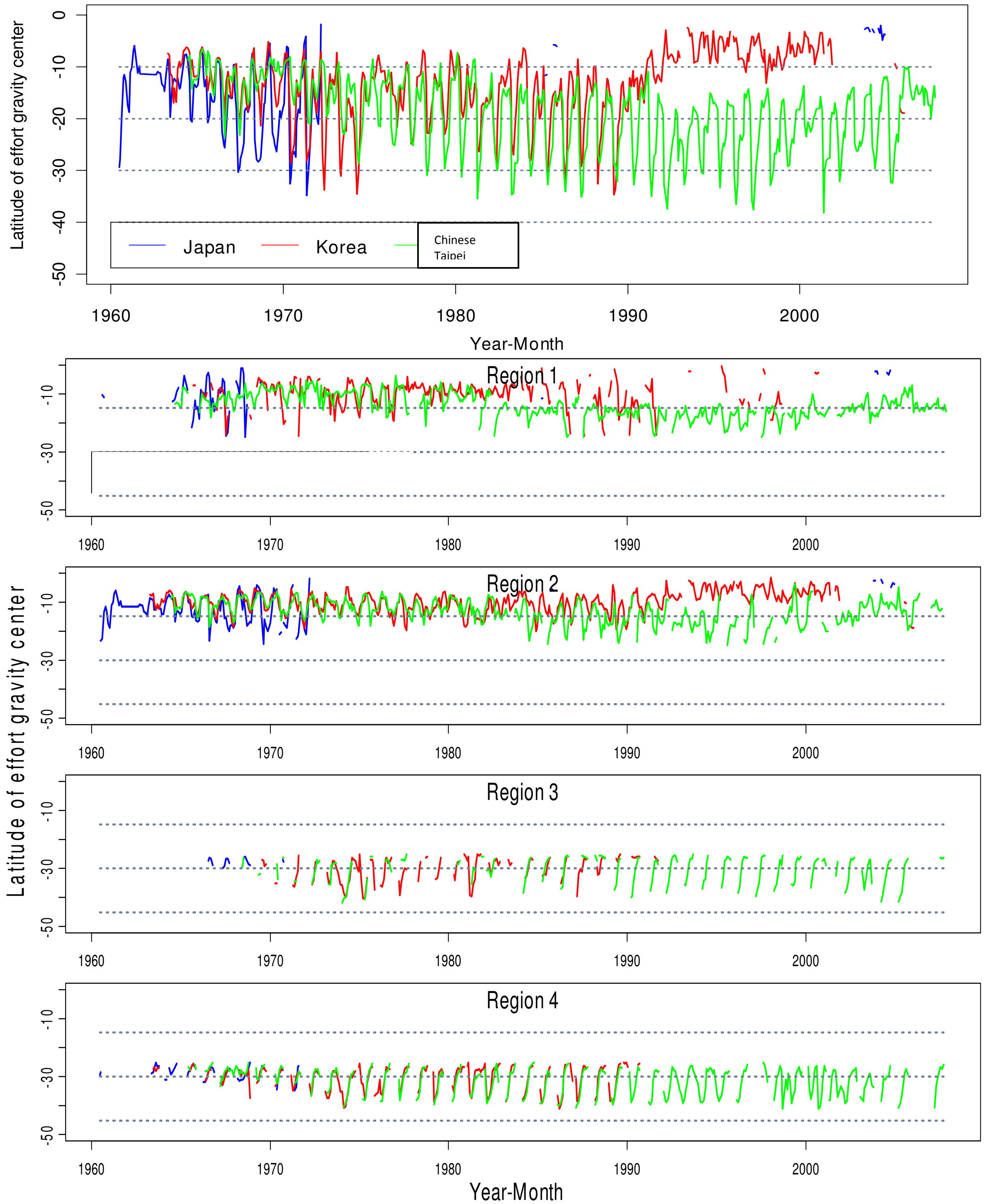


Figure 9: Quarterly and annual latitudinal shifts in longline fishing effort, for the entire model area (top panel) and by region (subsequent panels), by flag, as denoted by changes in the latitudinal gravity center of effort distribution. This index is derived from logsheet data collected by the US National Marine Fisheries Service from vessels offloading in Pago Pago and including logsheet data collected from vessels offloading in Levuka, Fiji. The "gravity center" index provides information regarding latitudinal shifts in fishing effort, indexing the center of the distribution of effort at each time point (Data source: NMFS, 2009; SPC, 2009).

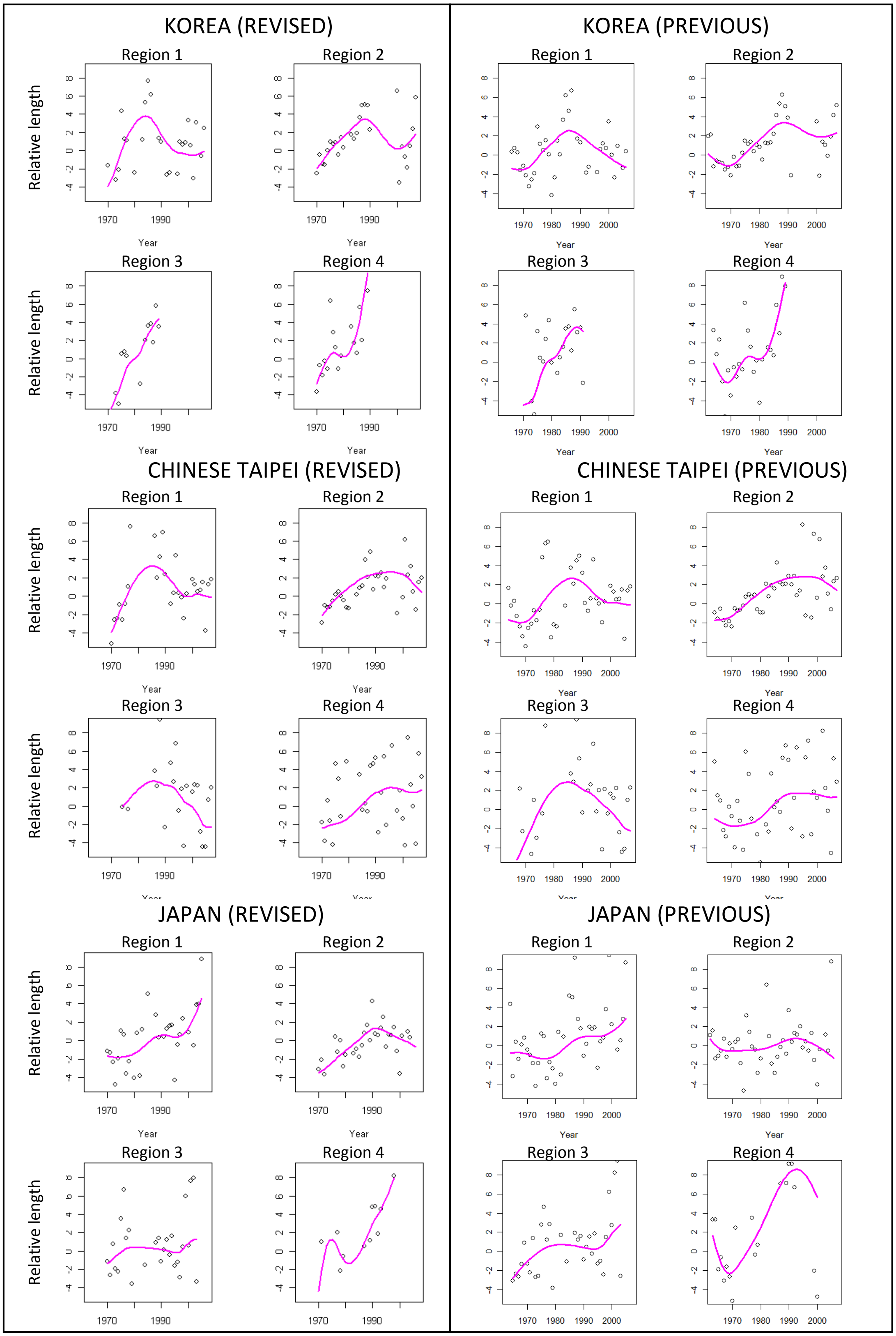


Figure 10 – Comparison of predicted annual trends in the relative length of longline caught albacore tuna by year, flag and region, derived from two Generalised Linear Models, being the original models of Langley and Hoyle (2008), and the same models revised to exclude small sample sizes, exclude data pre-1970, and include more recent data. The GLMs have length as the response variable and year, quarter, latitude and longitude as the explanatory variables.

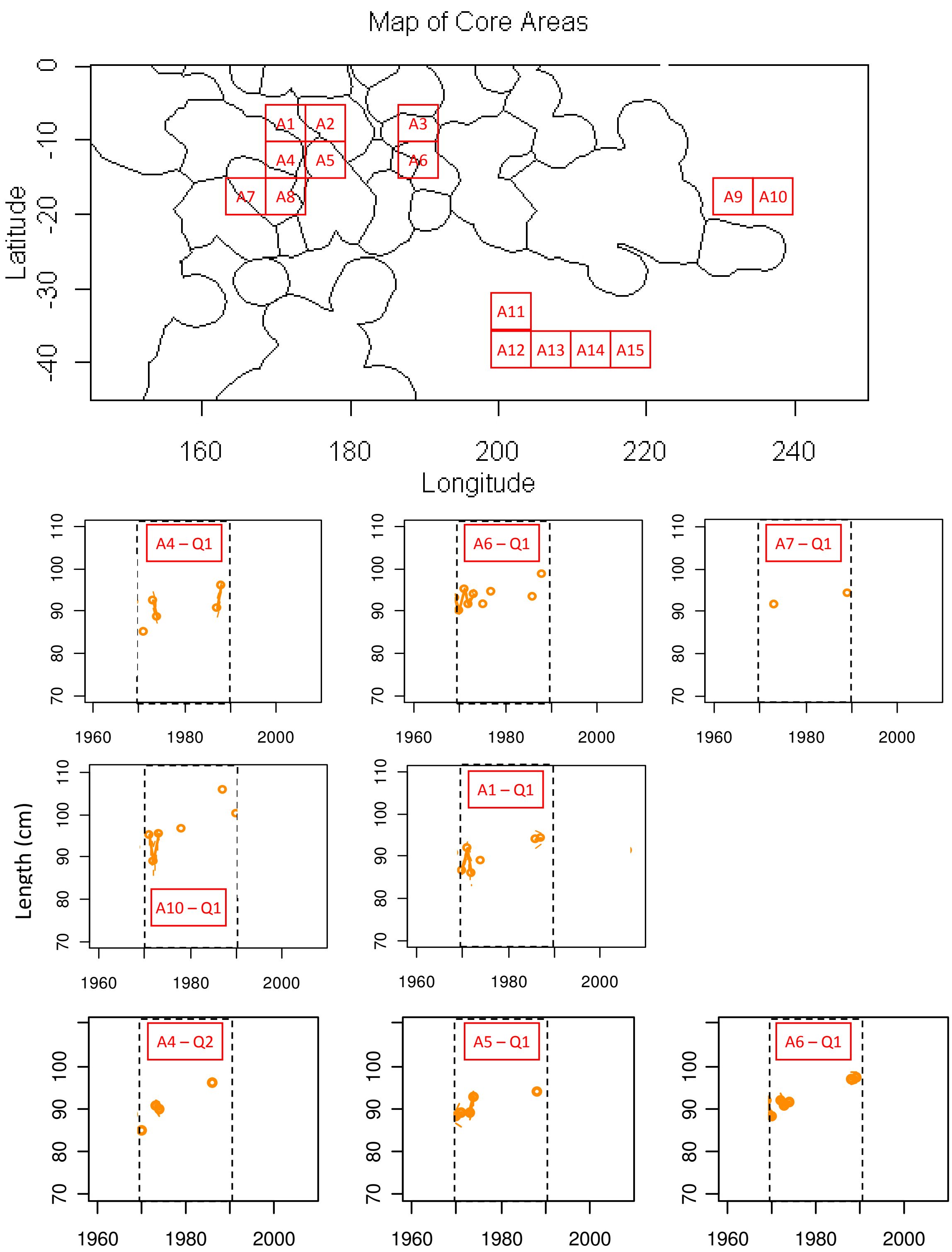


Figure 11 – A) Map of core areas chosen for analysis of temporal trends in mean length of Chinese Taipei longline caught albacore tuna by quarter over the period 1970-1990. B) Mean length of albacore tuna sampled from Chinese Taipei longline fisheries, by core area (15 x 5 degree latitude by longitude cells, labeled A1-A15), where "core" refers to areas fished in many years through the period being considered (1970-1990), and Q1 – Q4 indicate the quarter of the year sampled Dashed lines represent the period 1970-1990 (Data: SPC length frequency database, 2009).

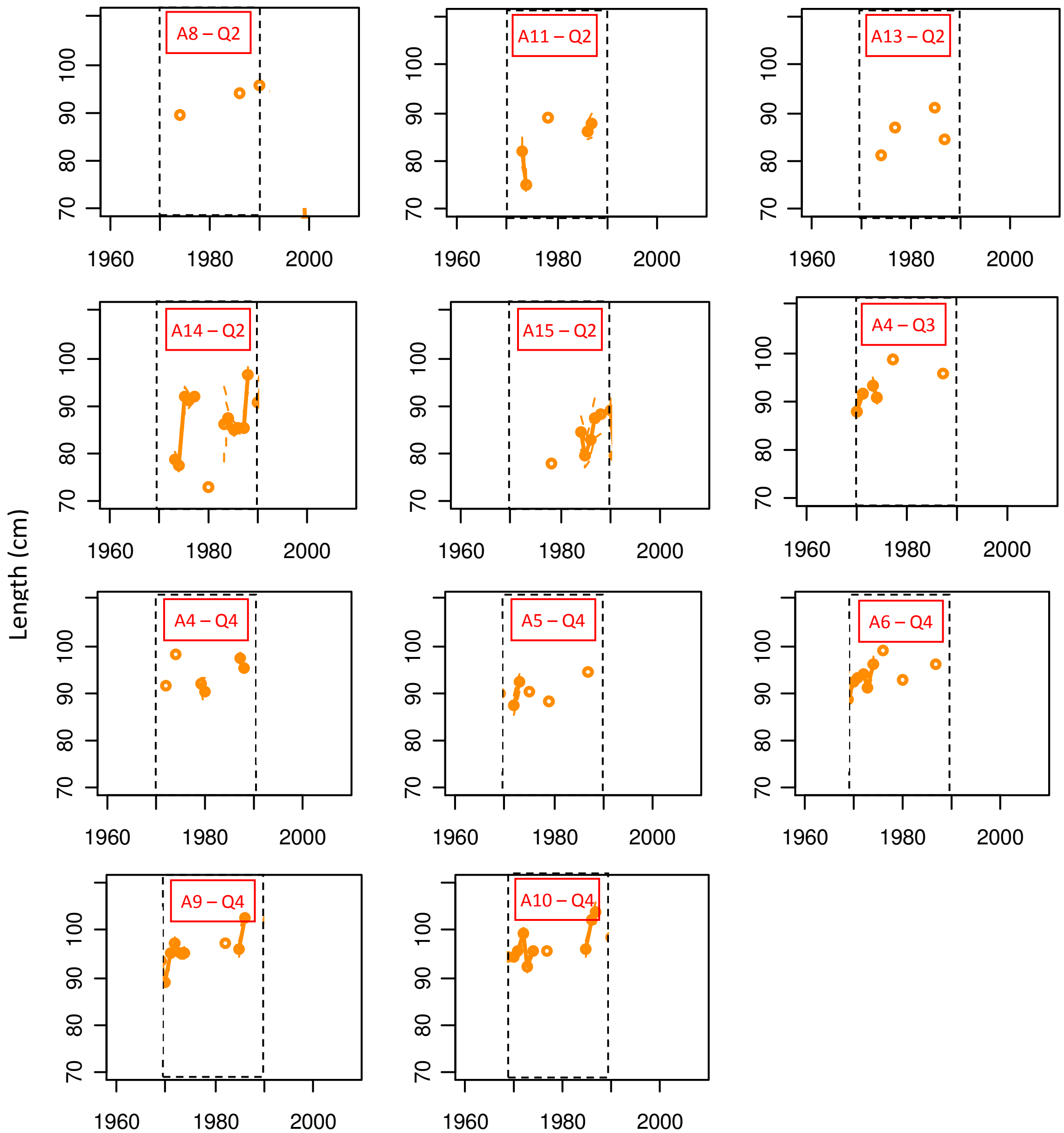


Figure 11 (continued)– Mean length of albacore tuna sampled from Chinese Taipei longline fisheries, by core area (15 x 5 degree latitude by longitude cells, labeled A1-A15), where "core" refers to areas fished in many years through the period being considered (1970-1990), and Q1 – Q4 indicate the quarter of the year sampled. Dashed lines represent the period 1970-1990 (Data: SPC length frequency database, 2009).

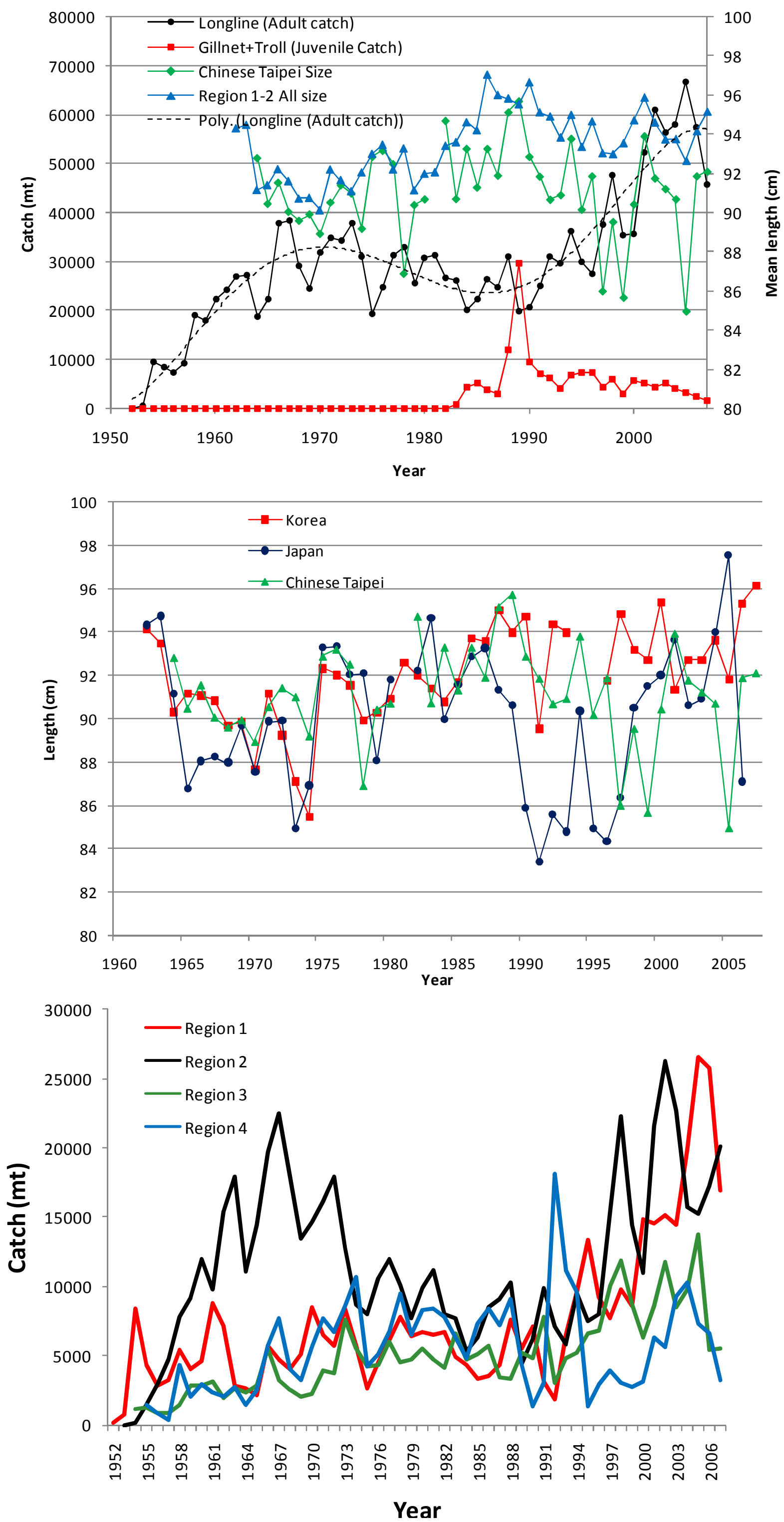


Figure 12 – A) Comparison of total South Pacific albacore catch with size trends derived for all fleets (including PICT) or from Chinese Taipei only. B) Mean length of albacore tuna based on size sampling of Japan, Korea and Chinese Taipei fleets (various sampling programmes). C) Total catch of albacore tuna by longline in regions 1-4. (Source: Aggregate catch/effort and length frequency data held by SPC, 2009)

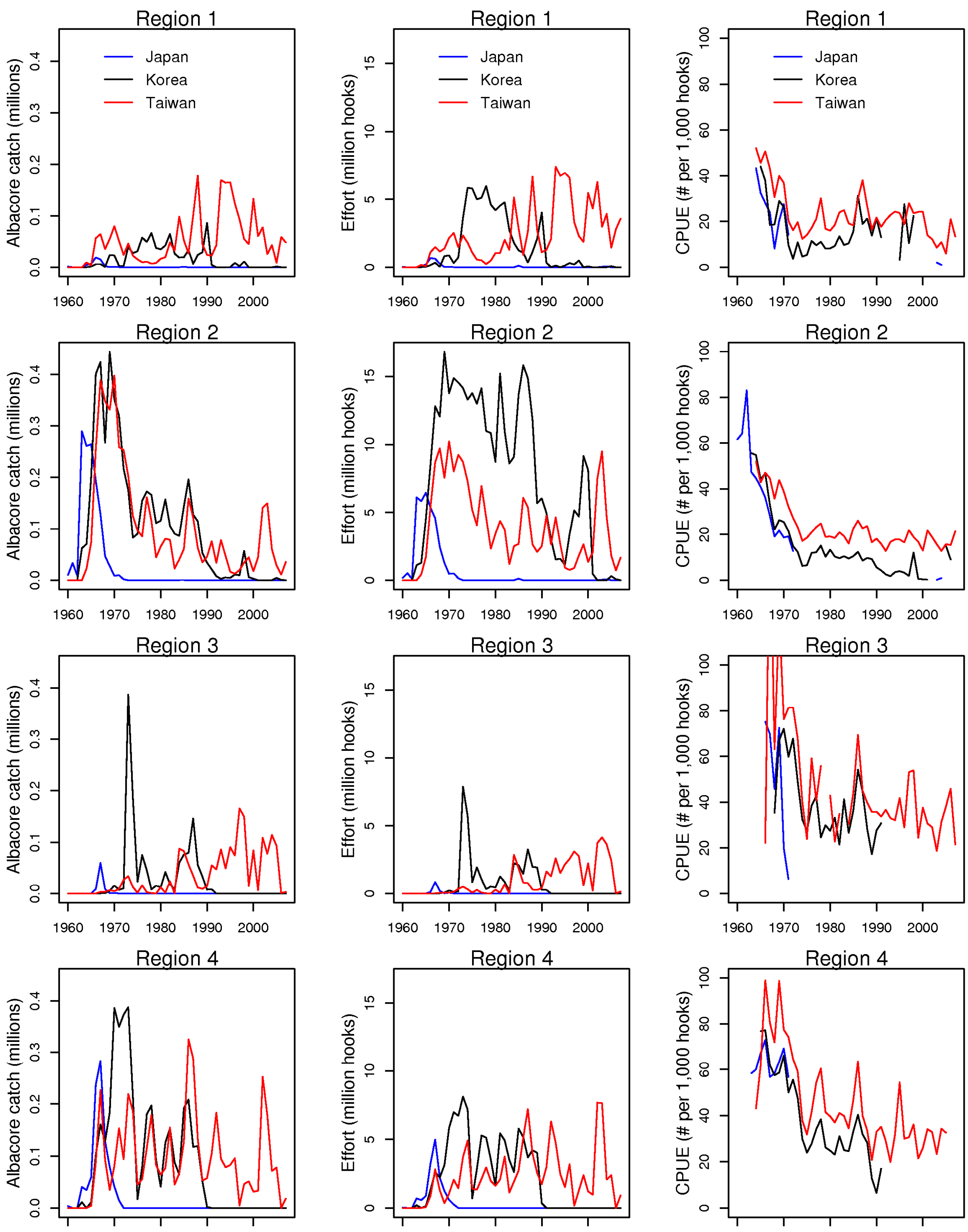


Figure 13 – Albacore catch (numbers), longline effort (million hooks) and albacore tuna CPUE by year, flag and model region, based on logsheet data from Chinese Taipei, Japan and Korean longline vessels operating in the South Pacific. Data collected by the National Marine Fisheries Service and Fiji/SPC (Figure from Bigelow and Hoyle, 2009).

REGION 1 - CHINESE TAIPEI

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(prev 3 yr av.region catch)+ f(sampling programme)

Parametric Terms:

	df	**F**	**p-value**
f(month)	11	8.176	2.21e-14
f(latitude)	4	26.803	< 2e-16
f(longitude)	6	5.526	1.01e-05
f(sampling programme)	3	0.372	0.773

Approximate significance of smooth terms:

	edf	**Ref.df**	**F**	**p-value**
s(prev 3 yr av.region catch)	8.502	9.002	46.63	<2e-16

Deviance explained = 11.4%
Sample size = 6457

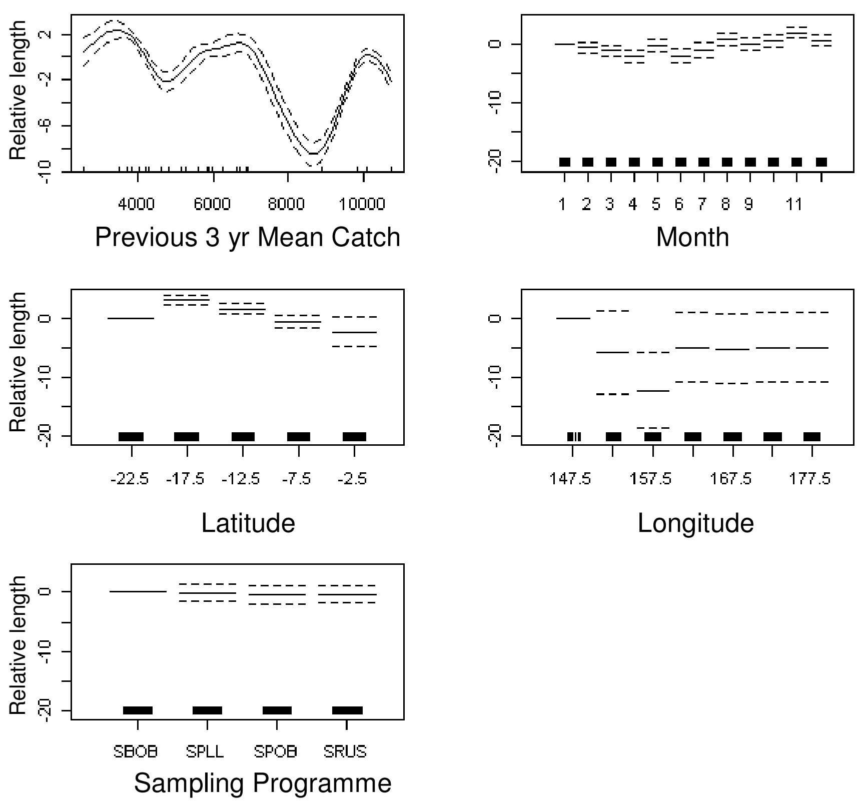


Figure 14 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Chinese Taipei** longline fishery that operated in **Region 1**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 1 - KOREA

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(prev 3 yr av.region catch)

Parametric Terms:

	df	**F**	**p-value**
f(month)	11	2.427	0.00523
f(latitude)	4	6.437	3.72e-05
f(longitude)	6	14.494	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(prev 3 yr av.region catch)	8.764	9.264	5.782	3.48e-08

Deviance explained = 10.8%
Sample size = 3217

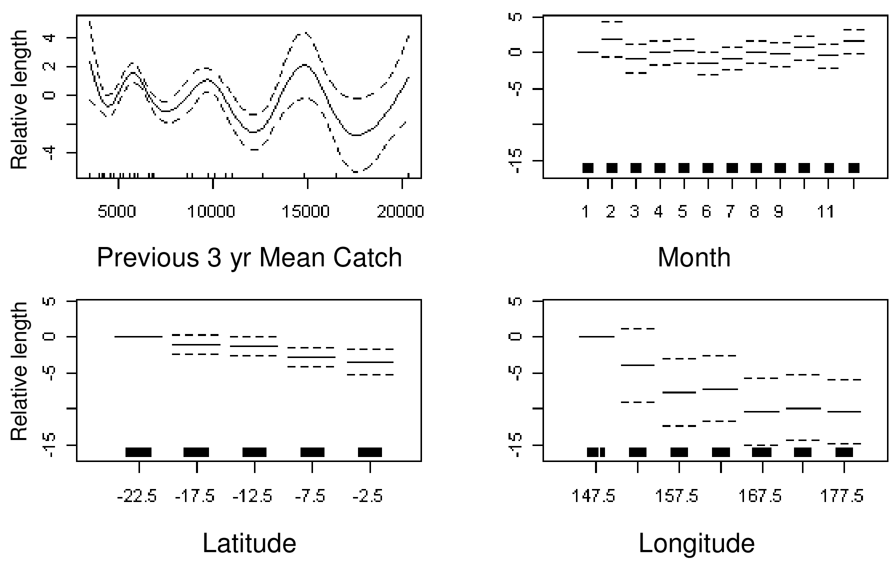


Figure 15 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Korean** longline fishery that operated in **Region 1**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 1 - JAPAN

Deviance explained = 11.7%
Samples size = 5501

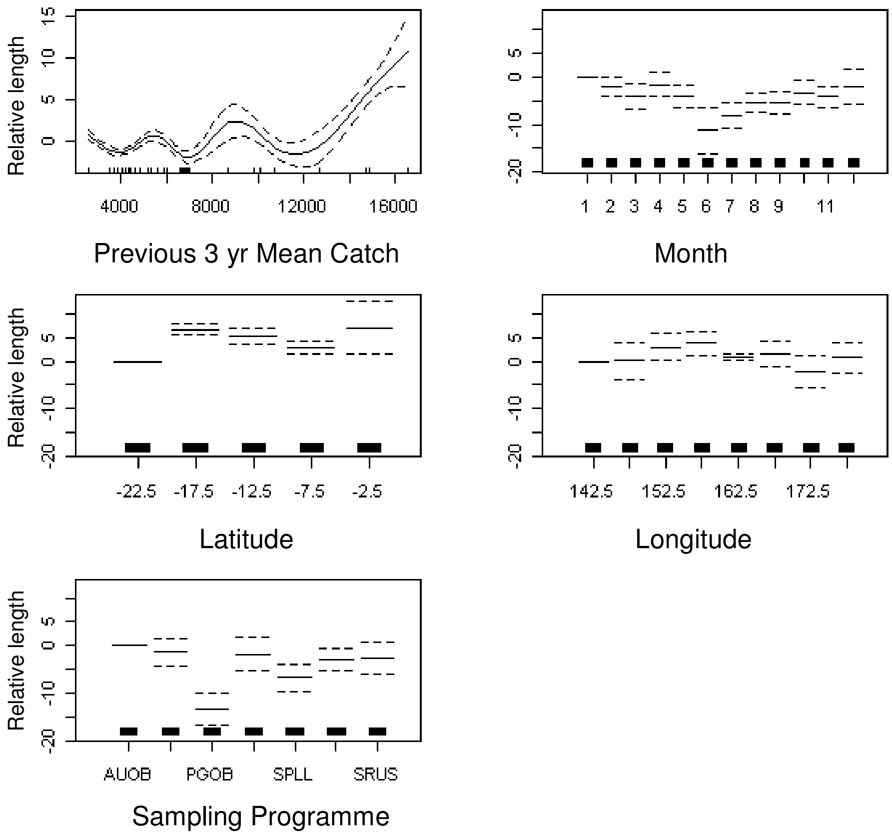


Figure16 – Predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 2- CHINESE TAIPEI (ALL PERIODS)

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch)+ f(sampling programme)

Parametric Terms:

	df	F	p-value
f(month)	11	23.95	<2e-16
f(latitude)	4	101.17	<2e-16
f(longitude)	13	18.79	<2e-16
f(sampling programme)	2	259.29	<2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Prev 3 yr av. catch)	8.866	9.366	96.18	<2e-16

Deviance explained = 11.9%
Sample size = 26964

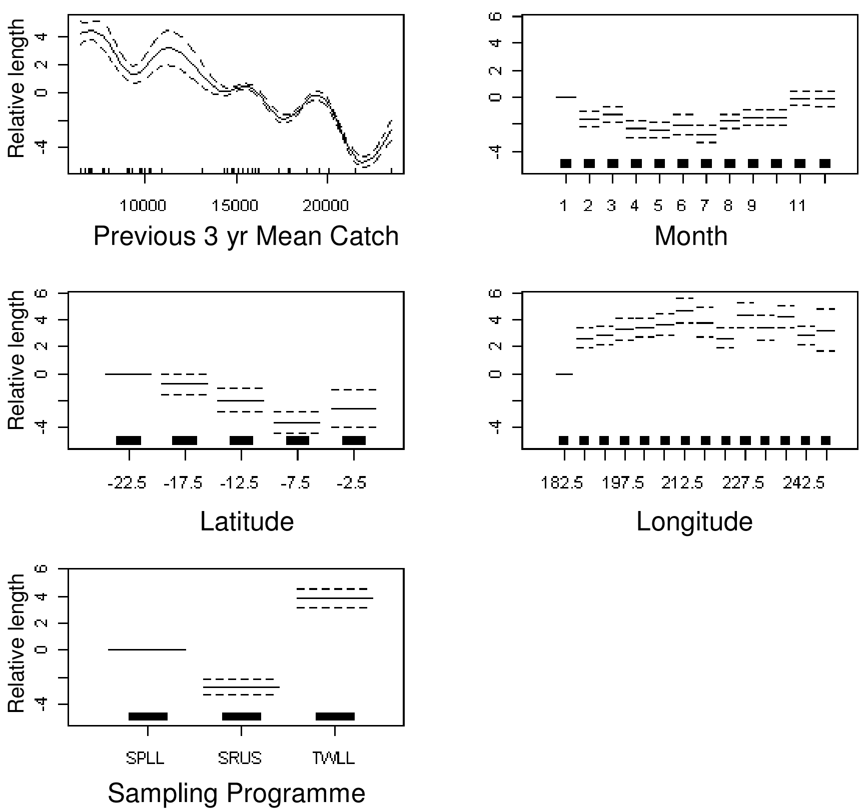


Figure 17– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Chinese Taipei** longline fishery that operated in **Region 2** between 1962 and 2008. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 2 – CHINESE TAIPEI – (PRE-2000)

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch)+ f(sampling programme)

Parametric Terms:

	df	**F**	**p-value**
f(month)	11	25.274	< 2e-16
f(latitude)	4	224.811	< 2e-16
f(longitude)	13	6.354	3.78e-12
f(sampling programme)	1	3.204	0.0735

Approximate significance of smooth terms:

	edf	**Ref.df**	**F**	**p-value**
s(as.numeric(llr2lag3))	8.606	9.106	104.4	<2e-16

Deviance explained = 20.6%
Sample size = 21836

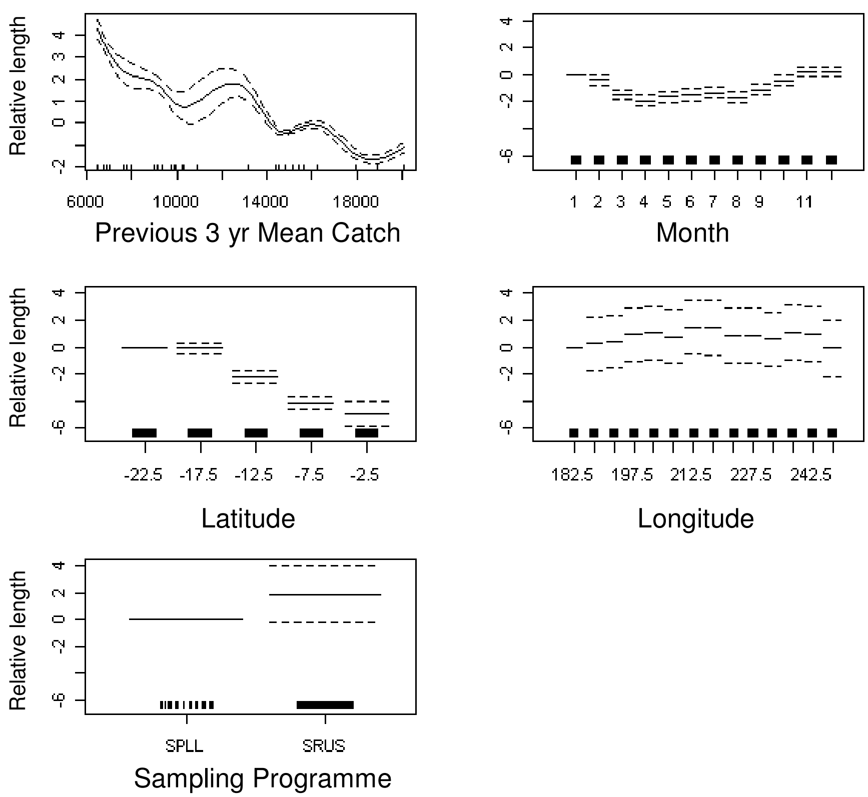


Figure 18 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Chinese Taipei** longline fishery that operated in **Region 2, prior to the year 2000** (when increased targeting of bigeye tuna started). Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 2 – KOREA (ALL PERIODS)

Model: len ~ f(month) + f(latitude)+ f(longitude)+ s(Prev 3 yr av. catch)+ f(sampling programme)

Parametric Terms:

	df	F	p-value
f(month)	11	32.24	<2e-16
f(latitude)	4	78.13	<2e-16
f(longitude)	13	21.77	<2e-16
f(sampling programme)	3	77.65	<2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Prev 3 yr av. catch)	8.792	9.292	138.2	<2e-16

Deviance explained = 17.4%
n = 25543

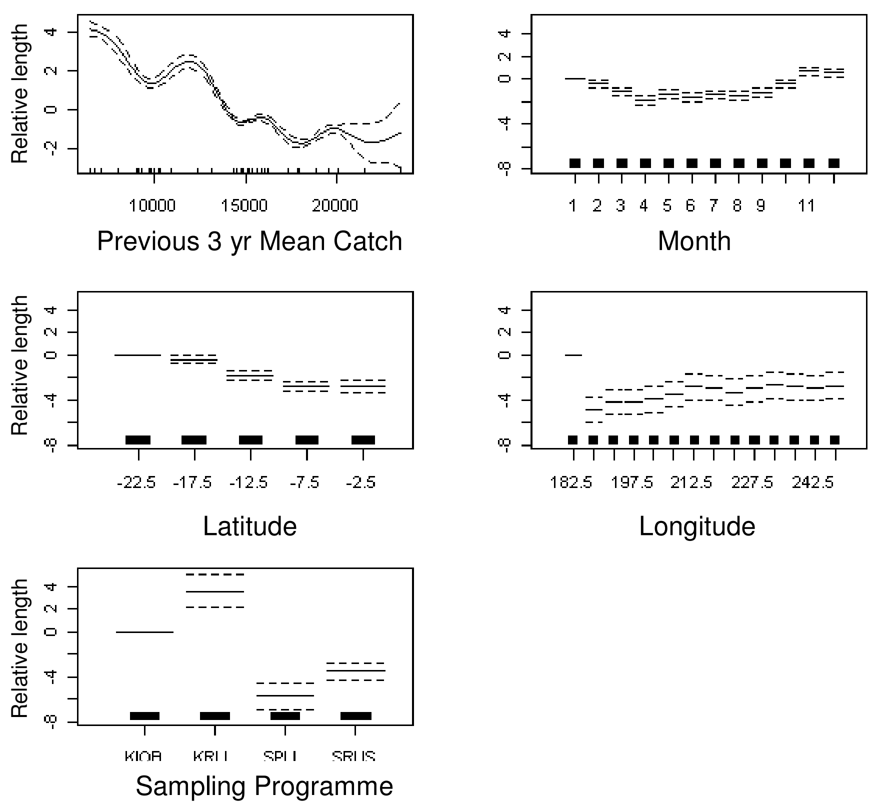


Figure 19 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Korean** longline fishery that operated in **Region 2** between 1962 and 2008. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 2 – KOREA (PRE-1991)

Model: len ~ f(month) + f(latitude)+ f(longitude)+ s(Prev 3 yr av. catch)

Parametric Terms:

	df	F	p-value
f(month)	11	34.90	<2e-16
f(latitude)	4	85.13	<2e-16
f(longitude)	12	19.53	<2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Prev 3 yr av. catch)	8.846	9.346	148.0	<2e-16

Deviance explained = 17.8%
n = 24764

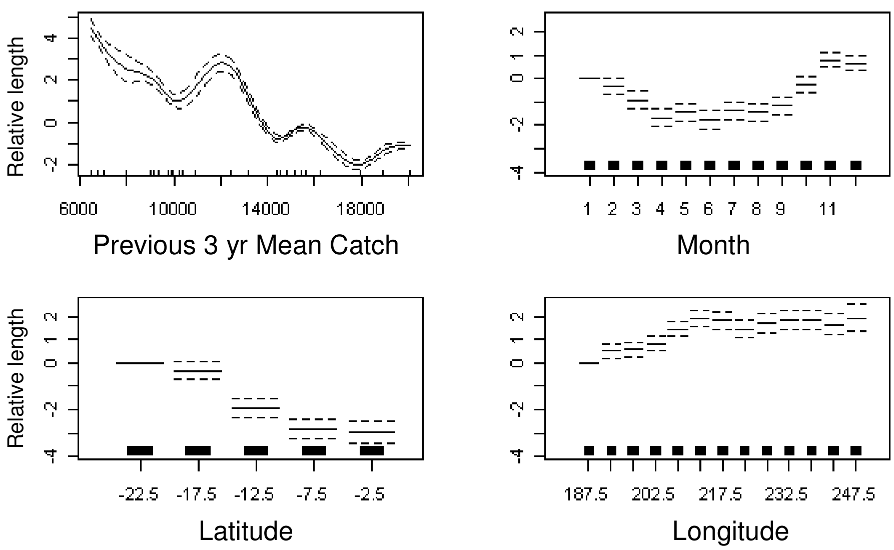


Figure 20– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Korean** longline fishery that operated in **Region 2 prior to 1991** (when the fleet switched to targeting bigeye tuna). Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 2- JAPAN

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch) + f(sampling programme)

Parametric Terms:

	df	**F**	**p-value**
f(month)	11	36.655	< 2e-16
f(latitude)	4	103.348	< 2e-16
f(longitude)	13	3.991	1.45e-06
f(sampling programme)	3	56.082	< 2e-16

Approximate significance of smooth terms:

	edf	**Ref.df**	**F**	**p-value**
s(Prev 3 yr av. catch)	8.718	9.218	37.12	<2e-16

Deviance explained = 11.9%
Sample size = 15641

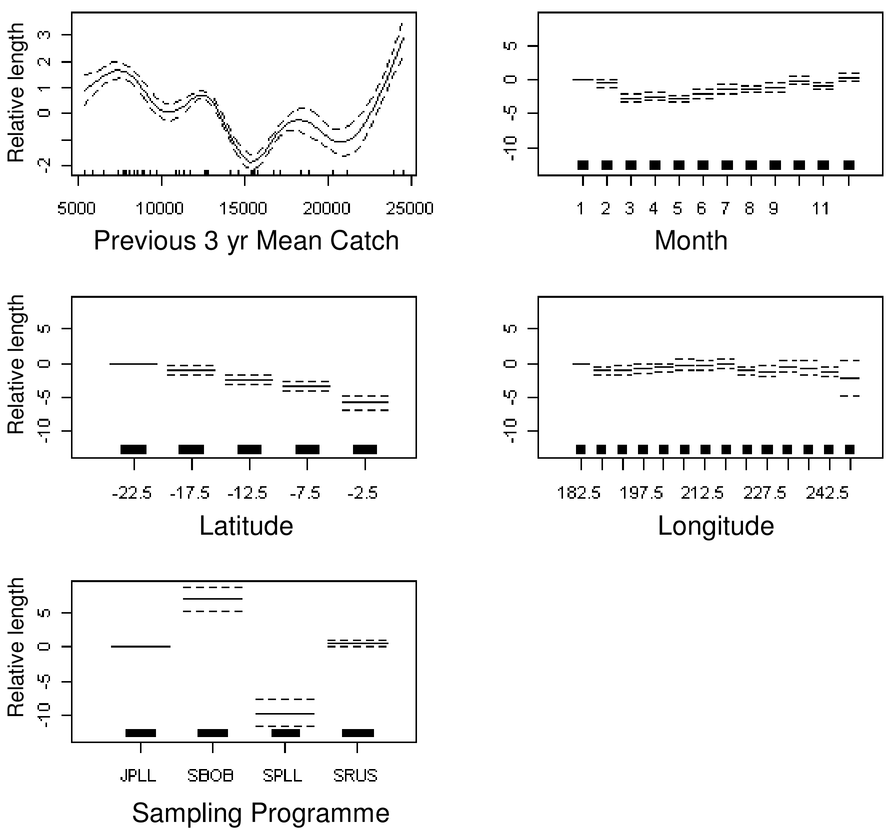


Figure 21– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Japanese** longline fishery that operated in **Region 2**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 3- CHINESE TAIPEI

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch) + f(sampling programme)

Parametric Terms:

	df	F	p-value
f(month)	9 10.	59 2.4	3e-16
f(latitude)	4	21.68	< 2e-16
f(longitude)	6	10.38	1.94e-11
f(sampling programme)	3	16.67	9.49e-11

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Prev 3 yr av. catch)	8.415	8.915	30.57	<2e-16

Deviance explained = 15.5%
Sample size = 3512

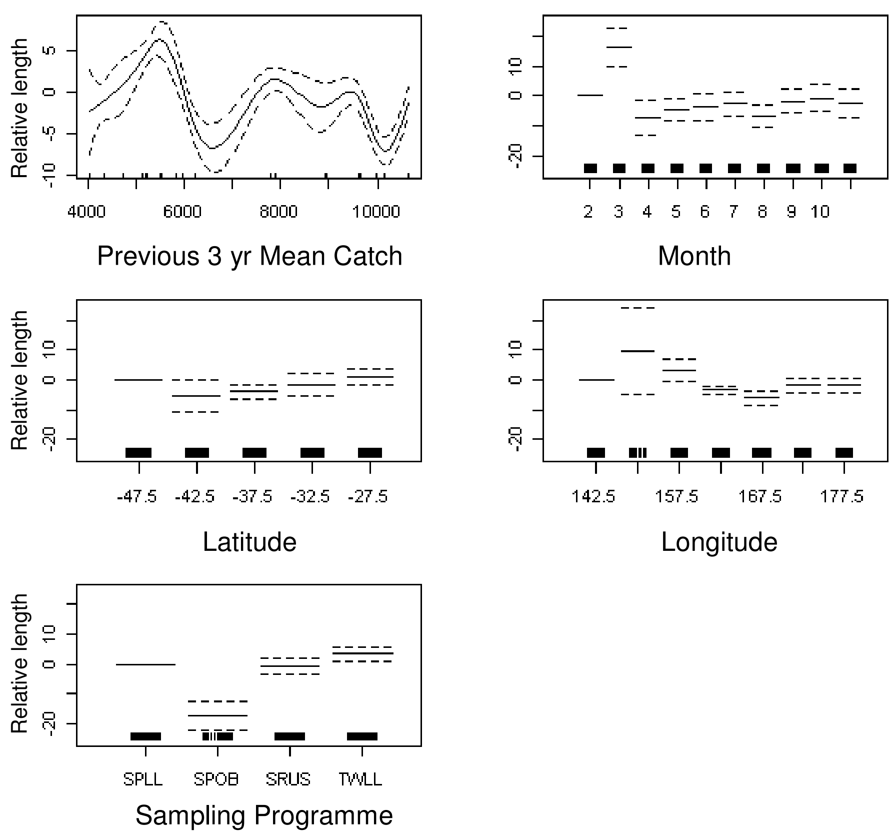


Figure 22 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Chinese Taipei** longline fishery that operated in **Region 3**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 3 - KOREA

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch)

Parametric Terms:

	df	F	p-value
f(month)	10	14.026	< 2e-16
f(latitude)	3	13.128	1.58e-08
f(longitude)	7	4.438	6.31e-05

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Prev 3 yr av. catch)	8.814	9.314	26.96	<2e-16

Deviance explained = 22.3%
Sample size = 4030

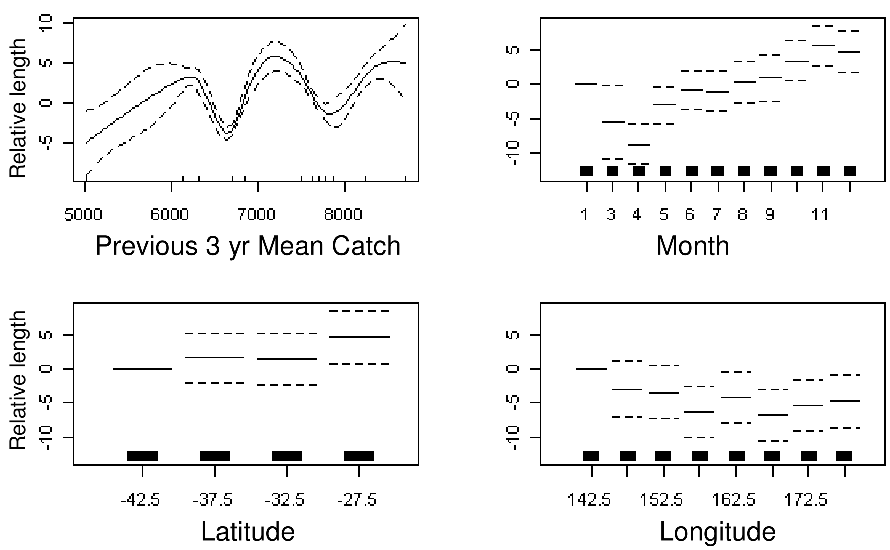


Figure 23 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Korean** longline fishery that operated in **Region 3**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 4 - CHINESE TAIPEI

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch)+ f(sampling programme)

Parametric Terms:

	df	**F**	**p-value**
f(month)	11	16.53	< 2e-16
f(latitude)	4	203.76	< 2e-16
f(longitude)	13	26.77	< 2e-16
f(sampling programme)	2	21.72	3.86e-10

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Prev 3 yr av. catch)	8.897	9.397	145.3	<2e-16

Deviance explained = 19.6%
Sample size = 10419

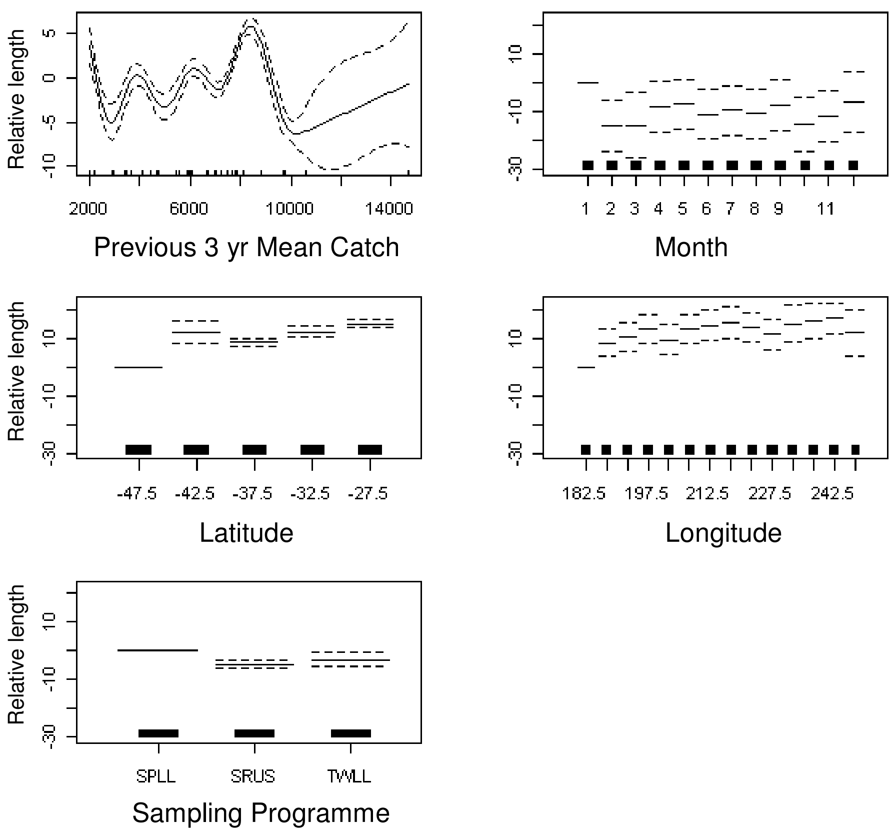


Figure 24– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Chinese Taipei** longline fishery that operated in **Region 4**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 4 - KOREA

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(as.numeric(llr4lag3))

Parametric Terms:

	df	F	p-value
f(month)	8	14.10	<2e-16
f(latitude)	3	161.46	<2e-16
f(longitude)	10	43.67	<2e-16

Approximate significance of smooth terms:

	edf	**Ref.df**	**F**	**p-value**
s(Prev 3 yr av. catch)	8.431	8.931	38.31	<2e-16

Deviance explained = 14.2%
Sample size = 8792

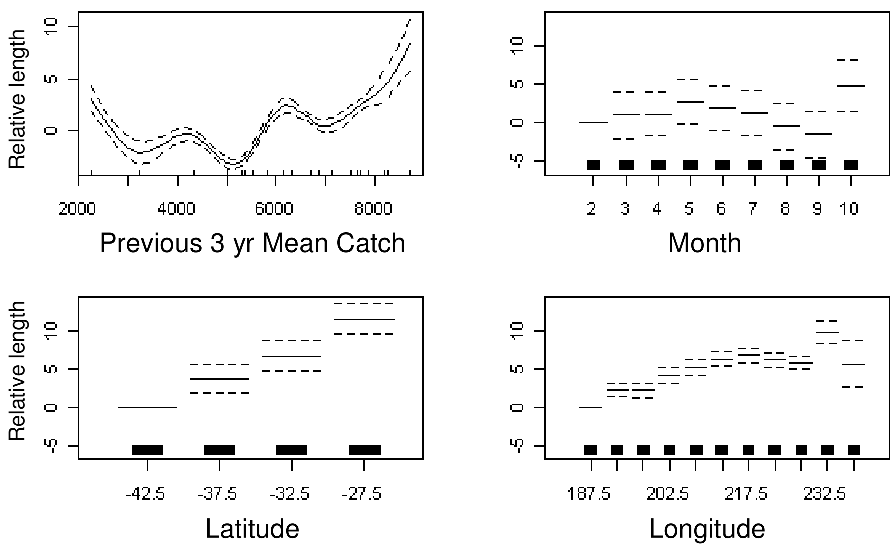


Figure 25 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Korean** longline fishery that operated in **Region 4**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

REGION 4 - JAPAN

Model: len ~ f(month) + f(latitude)+ f(longitude)+
s(Prev 3 yr av. catch)+ f(sampling programme)

Parametric Terms:

	df	**F**	**p-value**
f(month)	8	16.56	<2e-16
f(latitude)	3	257.28	<2e-16
f(longitude)	11	30.84	<2e-16
f(sampling programme)	2	110.11	<2e-16

Approximate significance of smooth terms:

	edf	**Ref.df**	**F**	**p-value**
s(Prev 3 yr av. catch)	8.294	8.794	23.72	<2e-16

Deviance explained = 39.7%
Sample size = 5679

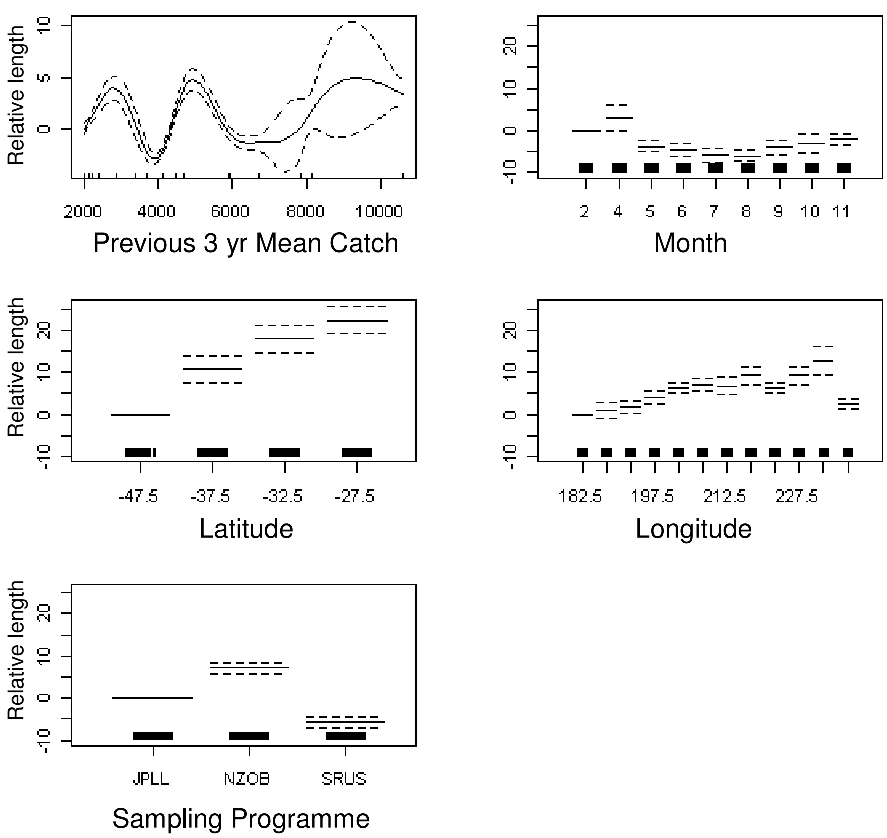


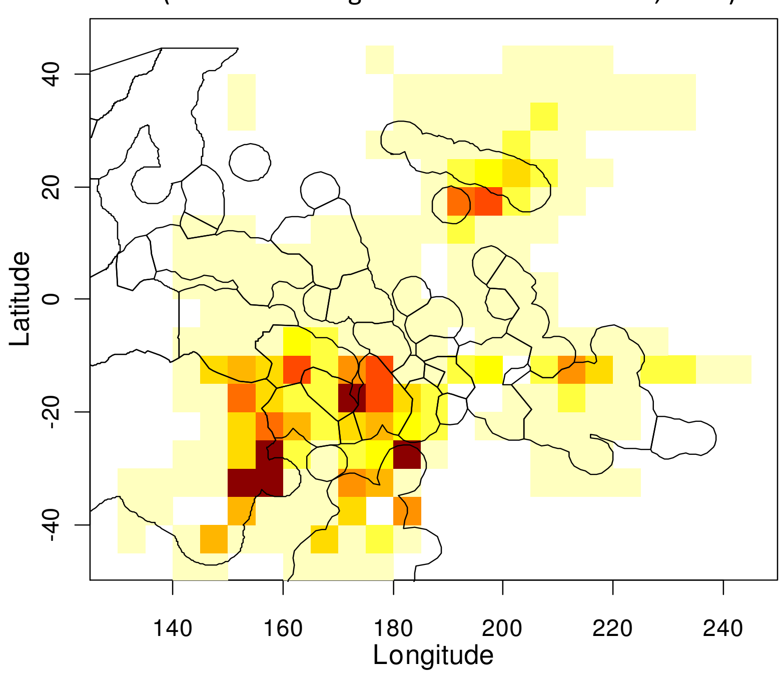
Figure 26 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on length frequency data collected from the **Japanese** longline fishery that operated in **Region 4**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

OBSERVER DATA

Table 3 – Number of observer trips by observer programme and year in the SPC Regional Observer Database. Grey highlight indicates observer programmes operating in the South Pacific. Note that this table contains only data uploaded to the main SPC database, and may not reflect all data received (some of which has yet to be uploaded).

YEARDEPART	AUOB	CKOB	FJOB	FMOB	HWOB	KIOB	MHOB	NCOB	NZOB	PFOB	PGOB	PWOB	SBOB	SPOB	TOOB	WSOB
1980	2															
1981	1															
1982	2															
1984	1															
1985	2															
1986	1															
1987	2								1							
1988	4								3							
1989	3								5							
1990	4								6							
1991	7								3							
1992	10			1					12					1		
1993	7			6					18					1		
1994	8			12	6				10					1		
1995	6			7	9		1		12				1	9		
1996	6			15	7				4					11		
1997	5			24	7		1		15					11		
1998	2			26	4				16				5	8		
1999				15	6	1			10		2	1	11	7		
2000				22	4				14				13	5		
2001	6	2		16	10		1	2	25		4		11	1		
2002	28	4	2	9	13	2		8	13	5	6		11			
2003	39	1	4	10	15			11	9	8	3		10			
2004	30		4	6	8		7	10	16	7	5	3	14		3	
2005	33		8	8		2	8	2	15	8	4	1			1	
2006	23		5	10		2	10	3	17	10	3				6	2
2007			3	8			10	5		11	1					
2008			3	1			2			7					3	

Figure 27 – Spatial distribution of albacore tuna length measures collected by observer programmes throughout the Convention Area (Source: SPC Regional Observer Database, 2009)



JAPAN in AUSTRALIA (JPAU) – WHOLE FISHERY – HPB20C

Model: Log(len) ~ s(Sea Surface Temperature) + s(Latitude) + s(Longitude) + f(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(HPB-Thermocline depth)

Parametric Terms:

	df	F	p-value
f(F(Climate state))	1	15.54	8.11e-05
f(Time of set)	4	19.06	1.15e-15
f(Year)	6	142.18	< 2e-16
f(HPB-Thermocline depth)	3	34.94	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.276	8.776	299.58	<2e-16
s(Latitude)	8.848	9.348	79.53	<2e-16
s(Longitude)	8.948	9.448	165.24	<2e-16
s(Moon phase)	8.961	9.461	96.06	<2e-16

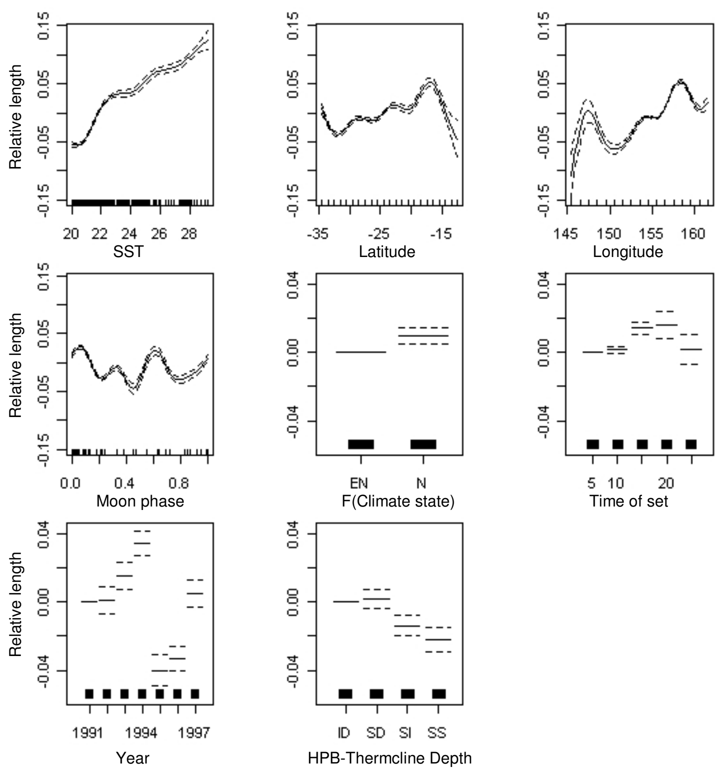


Figure 28– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Japanese** longline fishery that operated in the **Australian EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

JAPAN in AUSTRALIA (JPAU) – WHOLE FISHERY – HPB ONLY

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + s(Longitude) + f(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
F(Climate state)	1	35.82	2.18e-09
f(Time of set)	4	23.57	< 2e-16
f(Year)	6	201.68	< 2e-16
f(Hooks per basket)	8	41.77	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.641	9.141	305.76	<2e-16
s(Latitude)	8.739	9.239	55.96	<2e-16
s(Longitude)	8.979	9.479	159.38	<2e-16
s(Moon phase)	8.978	9.478	118.15	<2e-16

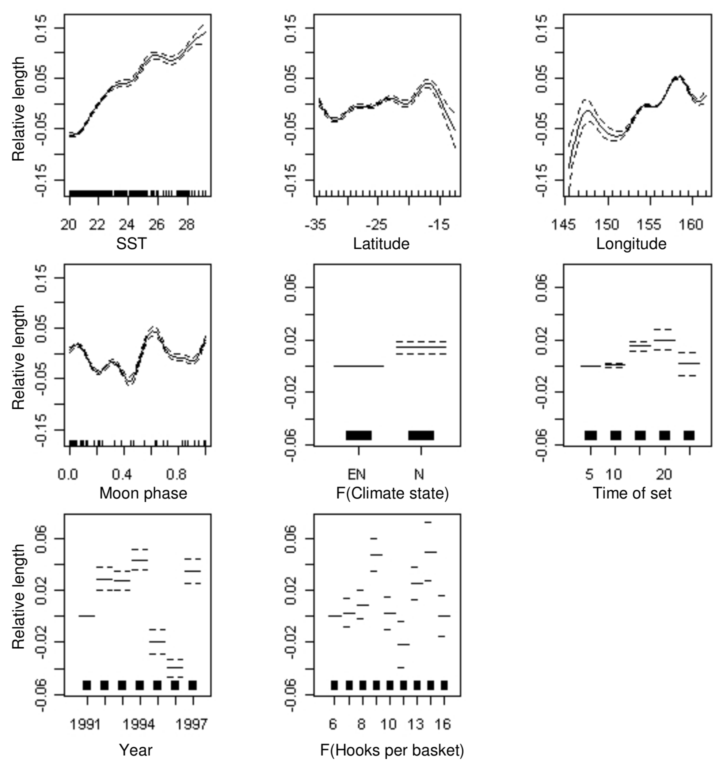


Figure 29 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Japanese** longline fishery that operated in the eastern **Australian EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

JAPAN in AUSTRALIA (JPAU) – NORTH AND SOUTH MODELS

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + f(Hooks per basket)

SOUTH

	df	F	p-value
f(Hooks per basket)	4	7.381	6.2e-06

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.708	9.208	116.85	<2e-16
s(Latitude)	8.996	9.496	81.95	<2e-16

Deviance explained = 21.9%
Sample size = 16068

NORTH

	df	F	p-value
F(Hooks per basket)	8	47.48	<2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.919	9.419	93.83	<2e-16
s(Latitude)	8.979	9.479	126.26	<2e-16

Deviance explained = 35.6%
Sample size = 13449

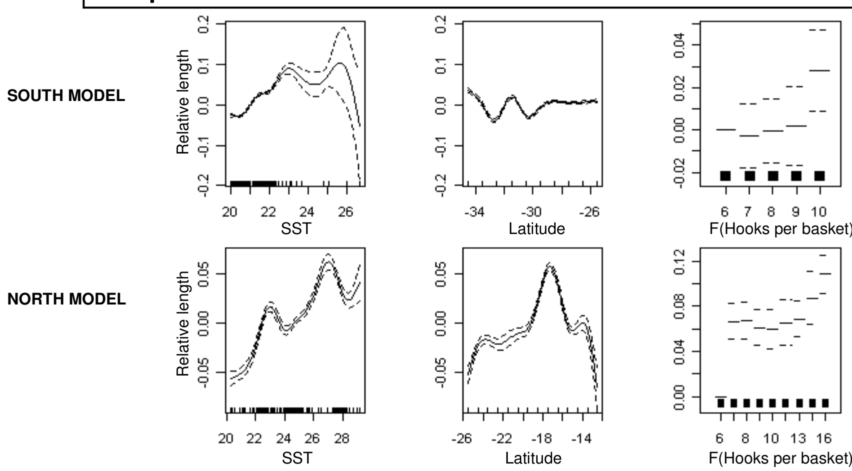


Figure 30 – Top panel: Analysis of variance statistics (top) derived from two simplified generalized additive models for albacore length, based on observer data collected from the **Japanese** longline fishery that operated in the **south-eastern Australian EEZ ("South model")** and in the **north eastern Australian EEZ ("North model")**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

CHINESE TAIPEI in SOLOMON ISLANDS (TWSB)

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + f(Longitude) + f(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Longitude)	17	4.509	1.79e-09
f(Climate state)	2	18.568	9.21e-09
f(Time of set)	4	40.690	< 2e-16
f(Year)	6	29.243	< 2e-16
f(Hooks per basket)	9	229.031	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.844	9.344	9.736	2.18e-15
s(Latitude)	8.794	9.294	15.564	< 2e-16
s(Moon phase)	8.899	9.399	25.073	< 2e-16

Deviance explained = 33.8%
Sample size = 5388

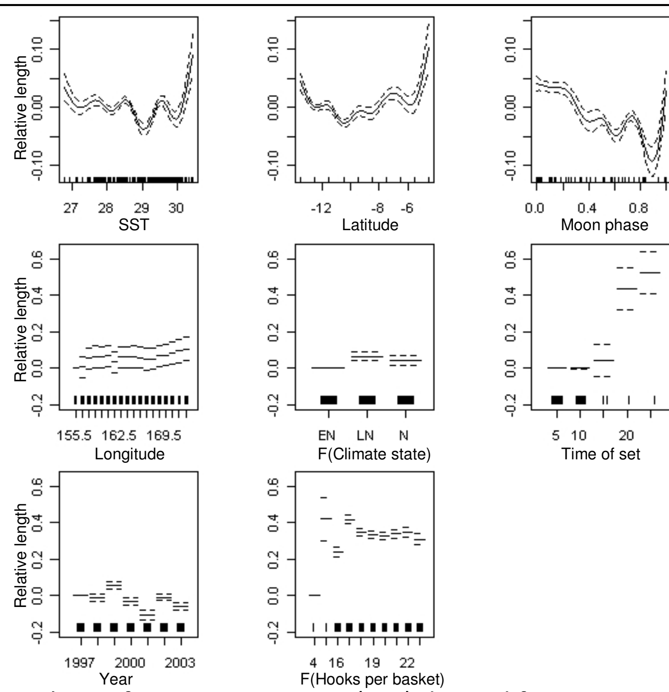


Figure 31– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Chinese Taipei** longline fishery that operated in the **Solomon Islands EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

TONGA in TONGA

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + f(Longitude) + F(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Longitude)	5	3.619	0.00286
f(Climate state)	2	6.530	0.00147
f(Time of set)	2	2.630	0.07215
f(Year)	7	19.233	< 2e-16
f(Hooks per basket)	18	9.376	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.900	9.400	19.730	< 2e-16
s(Latitude)	8.734	9.234	8.678	2.50e-13
s(Moon phase)	4.742	5.242	5.476	3.47e-05

Deviance explained = 23.5%
Sample size = 5933

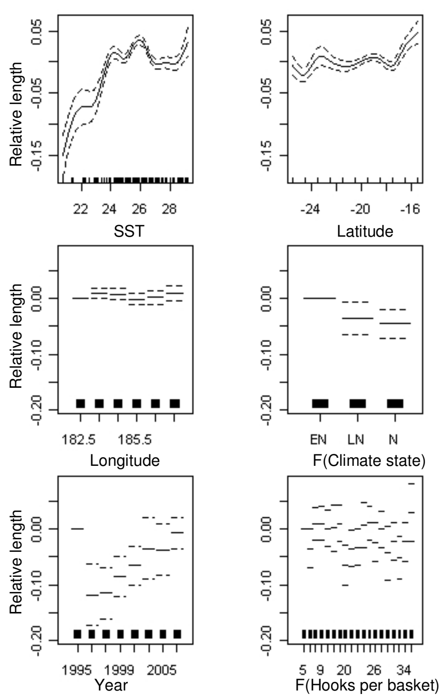


Figure 32 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Tongan** longline fishery that operated in the **Tongan EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

SOLOMON ISLANDS in SOLOMON ISLANDS EEZ

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + s(Longitude) + f(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Climate state)	2	100.11	< 2e-16
f(Time of set)	2	16.61	6.36e-08
f(Year)	7	34.94	< 2e-16
f(Hooks per basket)	11	27.80	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.326	8.826	18.16	<2e-16
s(Latitude)	8.816	9.316	18.97	<2e-16
s(Longitude)	8.899	9.399	41.75	<2e-16
s(Moon phase)	8.716	9.216	30.98	<2e-16

Deviance explained = 30.1%
Sample size = 6899

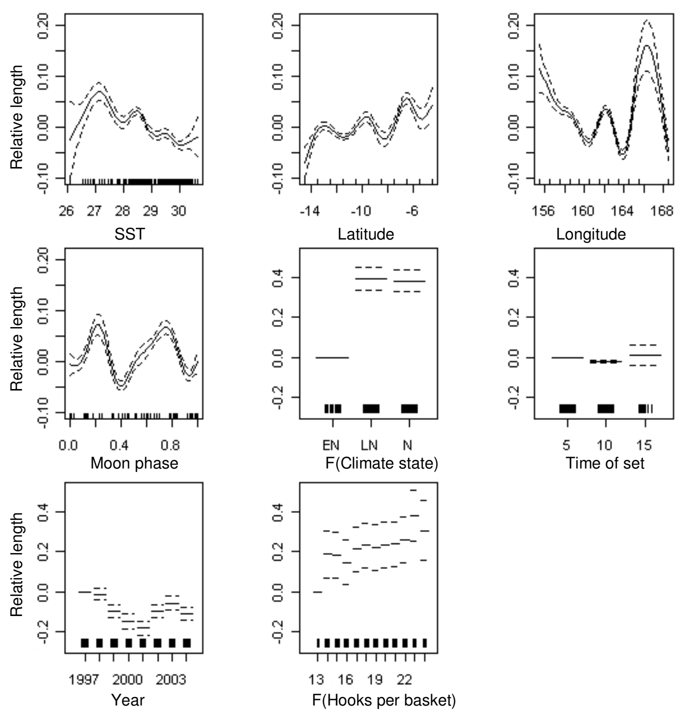


Figure 33– Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Solomon Islands** longline fishery that operated in the **Solomon Islands EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

FRENCH POLYNESIA in FRENCH POLYNESIA

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + s(Longitude) + F(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Climate state)	1	27.31	1.76e-07
f(Time of set)	4	119.66	< 2e-16
f(Year)	5	70.11	< 2e-16
f(Hooks per basket)	16	2392.47	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.715	9.215	40.09	<2e-16
s(Latitude)	8.799	9.299	37.43	<2e-16
s(Longitude)	8.798	9.298	19.33	<2e-16
s(Moon phase)	8.834	9.334	44.80	<2e-16

Deviance explained = 38.1%
Sample size = 13115

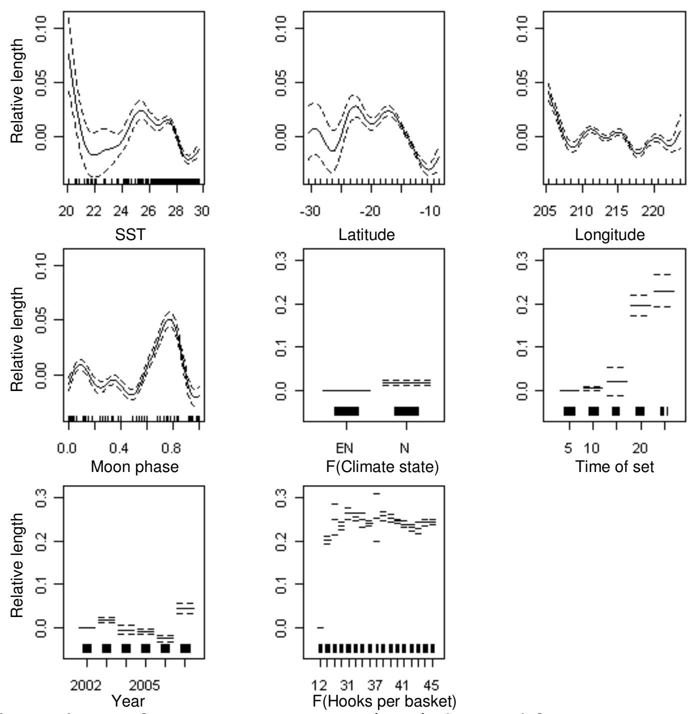


Figure 34 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **French Polynesia** longline fishery that operates in the **French Polynesia EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths (presented as relative length) and a rangle of explanatory variables. (Data source: SPC length frequency database).

NEW ZEALAND LL in NEW ZEALAND EEZ

Model: log(LEN) ~ s(Sea Surface Temperature) + f(Latitude) + s(Longitude) + F(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Latitude)	9	19.720	< 2e-16
f(Climate state)	2	12.314	4.54e-06
f(Time of set)	4	6.619	2.56e-05
f(Year)	11	54.760	< 2e-16
f(Hooks per basket)	13	326.666	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.579	9.079	11.62	<2e-16
s(Longitude)	8.093	8.593	34.43	<2e-16
s(Moon phase)	8.840	9.340	10.37	<2e-16

Deviance explained = 43.8%
Sample size = 13085

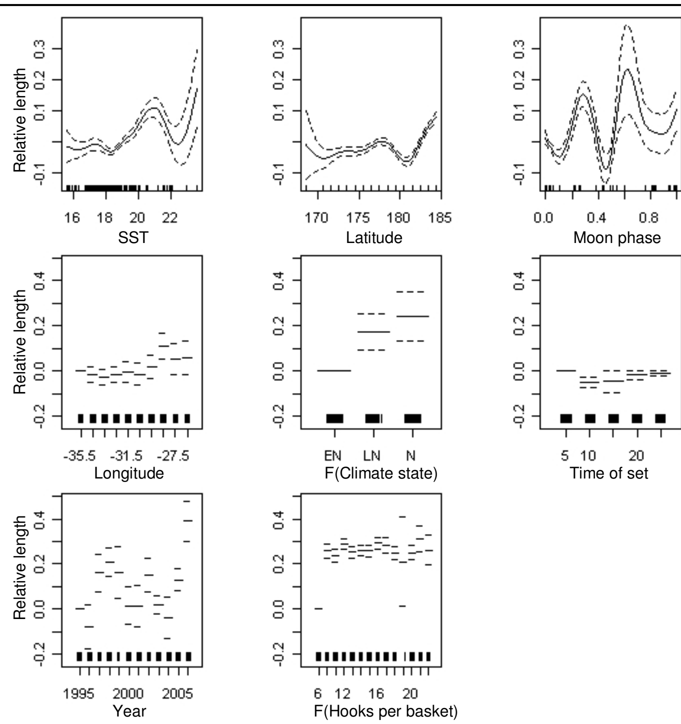


Figure 35 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **New Zealand** longline fishery that operates in the **New Zealand EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

NEW CALEDONIA in NEW CALEDONIA

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Longitude) + f(Latitude) + f(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Latitude)	8	5.840	1.85e-07
f(Climate state)	1	0.615	0.43309
f(Time of set)	1	2.108	0.14654
f(Year)	5	7.100	1.24e-06
f(Hooks per basket)	1	8.559	0.00345

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.243	8.743	9.273	9.04e-14
s(Longitude)	8.379	8.879	14.077	< 2e-16
s(Moon phase)	8.498	8.998	5.033	8.63e-07

Deviance explained = 14.6%
Sample size = 6565

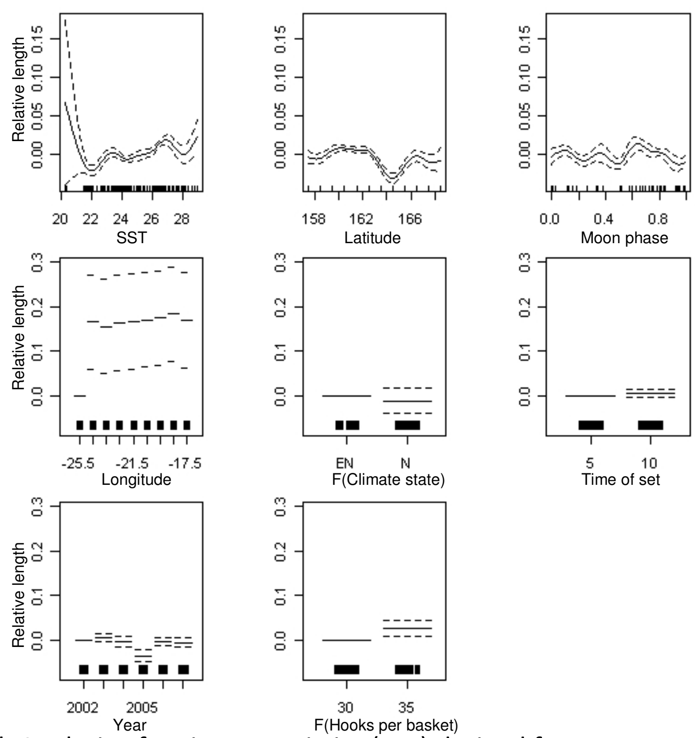


Figure 36 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **New Caledonia (NC)** longline fishery that operates in the **NC EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

FIJI in FIJI

Model: log(LEN) ~ s(Sea Surface Temperature) + s(Latitude) + s(Longitude) + F(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
as.factor(SOICAT)	1	1.542	0.214
as.factor(TIMECAT)	2	5.523	0.004
as.factor(yy)	5	15.576	2.44e-15
as.factor(HK_BT_FLT)	19	36.866	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Sea Surface Temperature)	8.428	8.928	19.57	<2e-16
s(Latitude)	8.922	9.422	91.33	<2e-16
s(Longitude)	8.930	9.430	45.87	<2e-16
s(Moon phase)	8.948	9.448	22.24	<2e-16

Deviance explained = 15.3%
Sample size = 30277

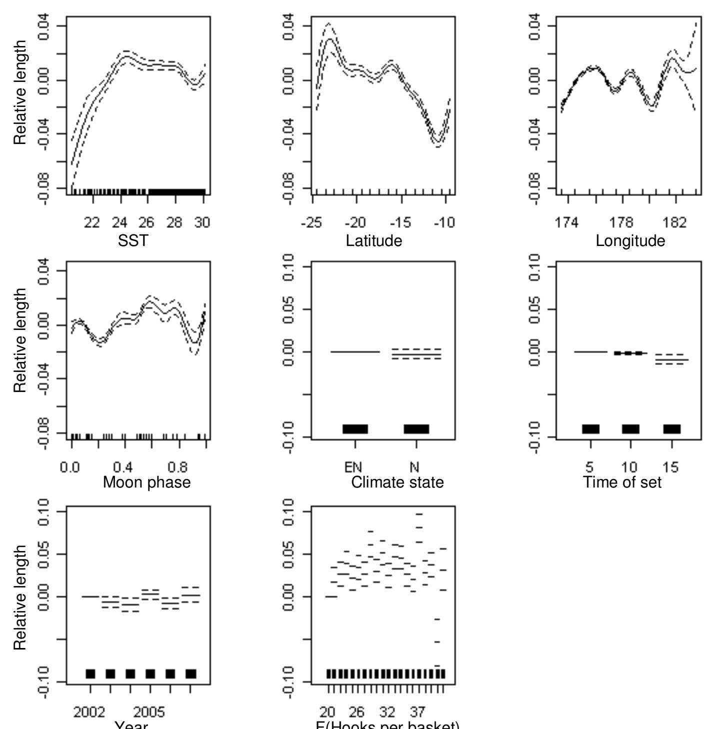


Figure 37 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Fiji** longline fishery that operates in the **Fiji EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

JAPAN IN NEW ZEALAND

Model: log(LEN) ~ f(Latitude) + s(Longitude) + f(Climate state) + s(Moon phase) + f(Time of set) + f(Year) + f(Hooks per basket)

Parametric Terms:

	df	F	p-value
f(Latitude)	19	65.521	< 2e-16
f(month)	5	31.055	< 2e-16
f(Climate state)	2	5.454	0.00428
f(Time of set)	4	9.745	7.12e-08
f(Year)	17	42.019	< 2e-16
f(Hooks per basket)	6	5.430	1.27e-05

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(Longitude)	8.820	9.320	14.01	<2e-16
s(Moon phase)	8.816	9.316	15.32	<2e-16

Deviance explained = 18.6%
Sample size = 25587

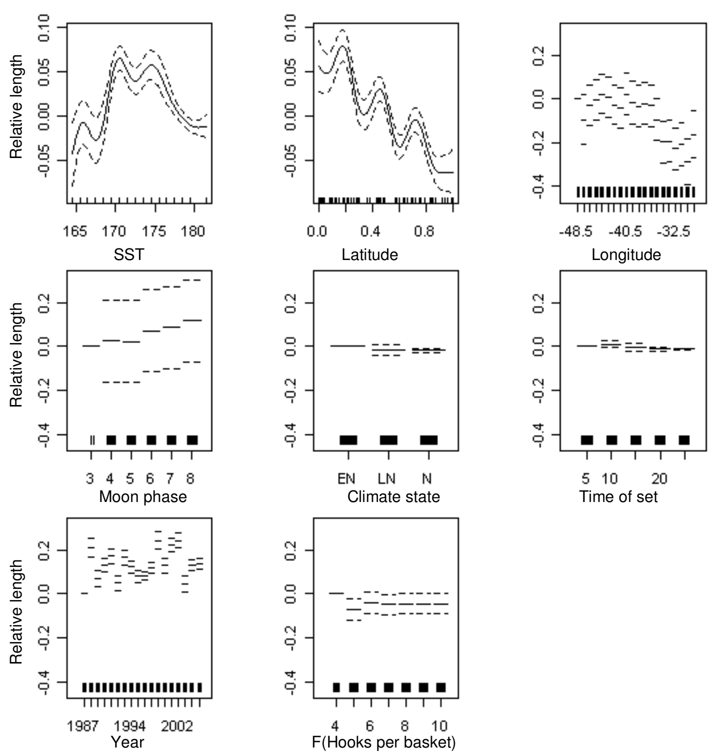


Figure 38 – Top panel: Analysis of variance statistics (top) derived from a generalized additive model for albacore length, based on observer data collected from the **Japanese** longline fishery that operated in the **New Zealand EEZ**. Bottom panels: Describe the predicted relationship between sampled albacore lengths and a rangle of explanatory variables. (Data source: SPC length frequency database).

Appendix 1

Proportion of logsheet level longline effort data (in days fished) collected by the US National Marine Fisheries Service (from Pago Pago, American Samoa) and by Chinese Taipei, as derived from the integrated dataset held by Chinese Taipei