CALCULATION OF ANNUAL ABUNDANCE INDICES FOR BIGEYE TUNA IN THE INDIAN OCEAN USING JAPANESE LONGLINE CATCH AND EFFORT DATA.

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ABSTRACT

*Document WPTT-01-14 presents several alternative methods for calculating annual indices of bigeye abundance using Japanese longline catch-and-effort data in the Indian Ocean. Three different 'core' bigeye fishing areas are used to limit the data used in the models and simple sum indices together with several GLM based indices are calculated. In calculating indices based on models which allow for Year*Area interactions a protocol is described for estimating catch rates in those areas which remain unfished in any year. The results show that the annual indices are relatively invariant to the core area used. Finally, a novel approach is described which allows for the spatial areas used in the models to vary from year to year. For this purpose, only the data within the top 49 catch squares in any year are used in an attempt to limit the analysis to a core habitat of bigeye each year. The annual indices were found to show temporal trends that were significantly different from those based on the more traditional approaches.*

INTRODUCTION

Further to the work done by Okamoto and Miyabe (1999) and Anon. (2001), we present several alternative methods for calculating annual abundance indices (or more correctly, indices of availability) for bigeye tuna in the Indian Ocean. The data file *JPNLLCE.xls*, provided by the IOTC and containing Japanese longline catch-effort data aggregated on a monthly, 5-degree basis from 1952 to 1999, was used for the analysis. However, as the fishery was in expansive phase during the 1950's and 1960's, for most models only the data from 1970 to 1999 was used.

CORE FISHING AREAS

Abundance indices are compared for three different "core bigeye fishing areas", each based on different criteria. The first core area definition was that of Okamoto and Miyabe (1999), who defined 7 sub-areas based on the geographic distribution of effort and bigeye tuna catch rates.

For the second core area definition, bigeye tuna catches within each 5-degree squares were ranked for each year and quarter. Those 5-degree squares that accounted for the top 95% of the total catch were considered to be in the core area for that year and quarter. The overall core area for a quarter across all years was then deemed to consist of those 5-degree squares that had been in an annual core area at least once and had been fished for at least 10 of the 40 years between 1960 and 1999. The union of the core areas for each quarter was then taken as the overall core area for the entire fishery.

The criteria for the third core area were more stringent. The core area for each year and quarter was calculated as above. However, for a given quarter a 5-degree square was considered to be in the overall core area for that quarter only if that square had been in the annual core area for at least 10 years (instead of only been fished for 10 years) of the 30 years between 1970 and 1999. Furthermore, instead of taking the union of these areas as before, the core areas for each quarter were considered separately.

Figures 1a-c show the proportion of the total bigeye catch in the Indian Ocean that is accounted for by each of the core areas by year and quarter. The first and second core areas contain at least 80% of the total bigeye catch in any year and quarter, while due to the more stringent conditions placed on the third core area the catch is less than 80% for some years.

Based on the geographical distribution of effort and catch rates, the second and third core areas were each divided into 7 sub-areas as per Okamoto and Miyabe (1999).

The three different core areas and their sub-areas are mapped below. Note that the third core area varies by quarter.

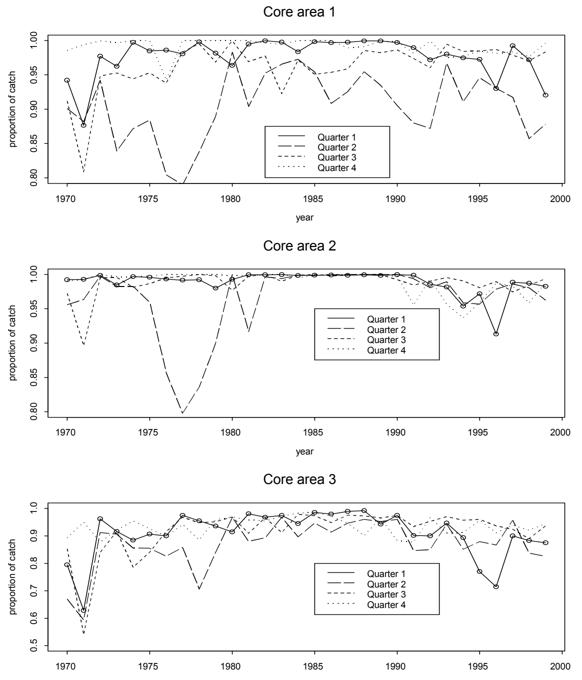

Figure 1a,c. Proportion of the total catch of bigeye in the Indian Ocean each year which is caught within each of the core bigeye areas.

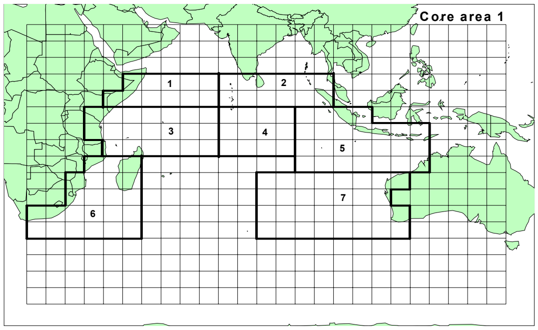

Figure 2a. Boundaries of the 7 regions defining Core Area 1.

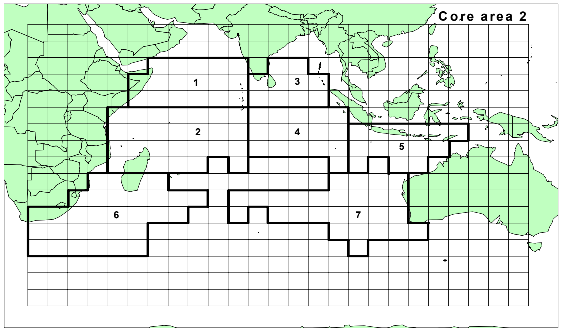

Figure 2b. Boundaries of the 7 regions defining Core Area 2.

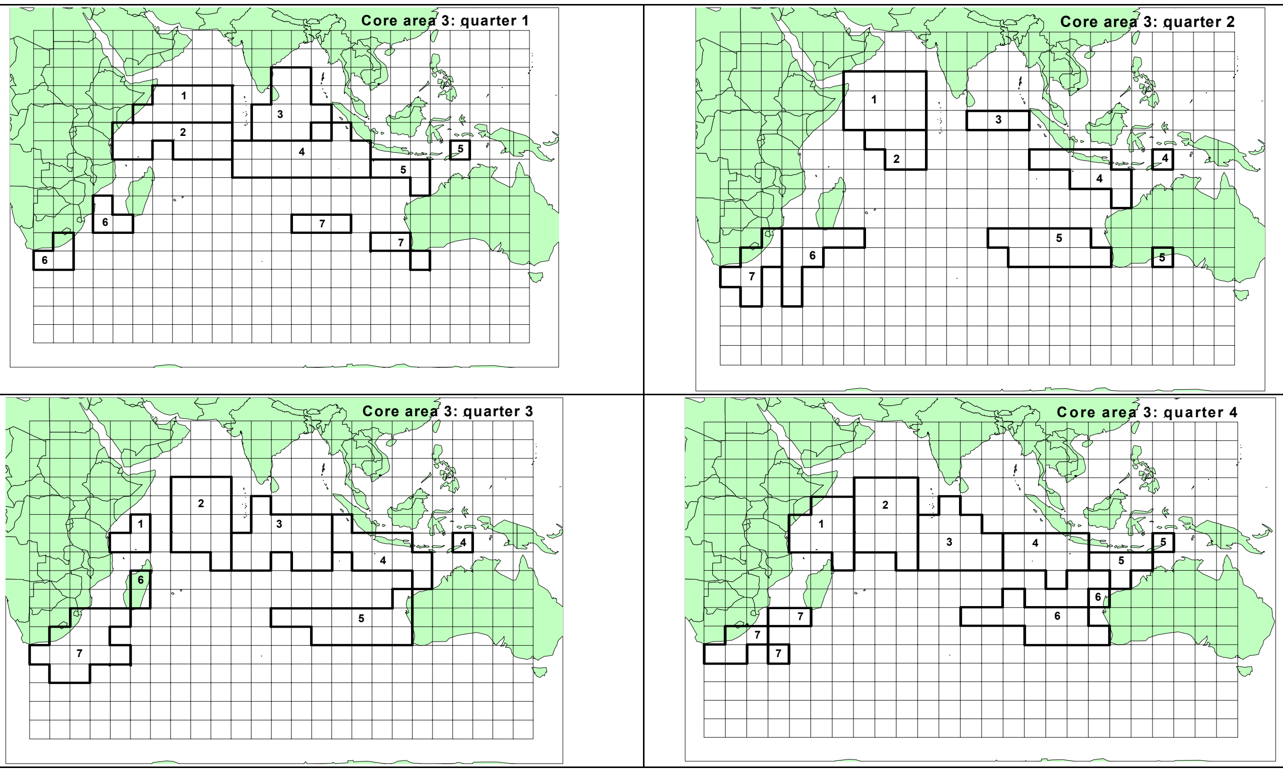

Figure 2c. Boundaries of the 7 regions defining Core Area 3.

CALCULATION OF ABUNDANCE INDICES

The traditional catch equation

$$C = qED$$

assumes that the expected or average catch in a given area is proportional to the average density of fish, *D*, and the amount of effort, *E* in that area. Thus the average density in the area is proportional to the expected catch rate (*C*/*E*). In order to account for spatial variations in fish density, the total fishery is divided into *n* different area. If it is assumed that catchability, *q*, is invariant across all areas fished, then an index of the biomass of fish available to the fishery, *B*, can be found by multiplying by the density of fish in each area by the size of that area, $Area_i$, and then summing over all areas:

$$B = \sum_{i=1}^{n} D_i * Area_i = \frac{1}{q}\sum_{i=1}^{n}[C/E]_i * Area_i$$

In the following analysis, each area to considered to consist of a number N_i of 5-degree squares, with each square considered to be of the same size A_5 (ignoring land and curvature of the earth). The above equation can therefore be written:

$$B = \frac{1}{q}\sum_{i=1}^{n}[C/E]_i * N_i * A_5$$

Given that all 5-degree squares have the same size, A_5, and re-scaling so that $(A_5/q)=1$, then the above index of abundance, *B*, can be written:

$$B = \sum_{i=1}^{n}[C/E]_i * N_i$$

Hence, given the catch rates, $[C/E]_i$, within each area of the fishery during any temporal period, the corresponding index of abundance can readily be calculated for that period. In this paper two different methods are employed to estimate the catch rates $[C/E]_i$:

i) GLM:

The catch rate in the i-th area $[C/E]_i$ is taken to be the standardised catch rate, SCR, for that region after fitting the data to a General Linear Model.

$$B_{GLM} = \sum_{i=1}^{n} SCR_i * N_i$$

A problem occurs, however, when a Year.Area interaction term is used in the GLM, as no estimate is given for the SCR in those year-areas which are not fished (and for which there is no data). In these situations a proxy SCR needs to be substituted. The following protocol was adopted: For each year, the ratio of the estimated biomass in the i-th area to the maximum estimated biomass in any area for that year was calculated. For each area, the average of this ratio for was taken across all years for which data existed. In a year for which an area was not fished, the biomass in that area was then assumed to be equal to the product of the average ratio for that area and the maximum biomass in any other area for that year.

ii) Simple Sum:

The catch rate in the i-th area $[C/E]_i$ is assumed to be equal to the mean catch rate across the N_i five-degree squares which make that area, ie.

$$C/E_i = \frac{1}{N_i}\sum_{j=1}^{N_i} CPUE_{ij}$$

where $CPUE_{ij}$ is the catch rate in the j-th 5-degree square in the i-th area. Substituting this expression into the above gives:

$$B_{SS} = \sum_{i=1}^{n}\sum_{j=1}^{N_i} CPUE_{ij}$$

Again a problem exists when not every 5-degree square within each region is fished each year and a proxy catch rate needs to be substituted for these unfished cells. Two alternative assumptions were made about the catch rate that would have been recorded had the squares been exploited (note that an "unfished square" refers only to a 5-degree square that has been exploited at some other point in time):

1. Fished squares are assumed to be a random selection of all squares in the area, implying that the average catch rates in the unfished squares would be similar to those in the fished squares. Thus in any of the seven areas making up the core fishery, the catch rates in the unfished 5-degree squares are assumed equal to the average of the catch rates across the fished 5-degree squares for that year and quarter. The resulting index is termed the Bavg index.
2. The catch rates in the unfished squares are set equal to the minimum catch rate in that area for that year and quarter. The resulting index is termed the Bmin index and can be interpreted as perhaps giving a lower bound to the likely biomass in that area.

Finally, when an entire area was not fished in a given year, the previously described protocol adopted for the B_{GLM} index was used.

Note that when there are unfished squares in an area, the data for the squares that are fished represent a sample of the catch rates across all N_i squares. If the squares fished are selected randomly then the biomass in the area should be represented by the Bavg index. However, if there is preferential targeting of those squares with higher catch rates (based on historical knowledge of the spatial distribution of catch rates in the area), then the catch rates in those squares which are fished may be upwardly biased relative to the mean across all squares. As such, the Bavg index may also be an upwardly biased estimate of the biomass in the area with the true biomass lying somewhere between the Bavg and Bmin indices. As such, the difference between the two indices gives some measure of the uncertainty associated with the biomass estimates for an area. Depending upon the distribution of catch rates across those squares that are fished, one may expect this measure of uncertainty to increase as fewer squares are fished.

Both the GLM and Simple Sum indices account for variation across years and areas. However, while the simple-sum indices also allow fine-scale changes at the 5-degree square level to be taken into account, unlike the GLM indices they do not account for any other factors that may influence the expected catch rates. In this regard, the influence of targeting practices and sea surface temperature were considered in the GLM models described below. For a full description of CPUE standardisation using GLMs refer to Campbell *et al.*(1996).

COMPARISON OF B_{GLM} INDICES FOR DIFFERENT MODELS

The B_{GLM} indices based on the models described in Table 1 were calculated for each quarter of the year. All models assumed a log-Normal error structure. Results were compared with year and area both as main effects ('a' models) and interaction terms ('b' models). Note that “area” refers to the seven sub-areas comprising the core fishery. For brevity, only the indices based on the third core area are used in the following comparisons.

Table 1. *Array of models used for comparison of the B_{GLM} indices.*

Model	**Model Structure: Main Effects only**	**Model**	**Model Structure: Interaction**
1a	log(CPUE+0.1*mean(CPUE)=year+area	**1b**	log(CPUE+0.1*mean(CPUE)=year*area
2a	log(CPUE+0.1*mean(CPUE)=year+area+YB.ratio(numeric)	**2b**	log(CPUE+0.1*mean(CPUE)=year*area +YB.ratio(numeric)
3a	log(CPUE+0.1*mean(CPUE)=year+area+YB.ratio(factor)	**3b**	log(CPUE+0.1*mean(CPUE)=year*area +YB.ratio(factor)
4a	log(CPUE+0.1*mean(CPUE)=year+area+YB.ratio(numeric)	**4b**	log(CPUE+0.1*mean(CPUE)=year*area +YB.ratio(numeric)
5a	log(CPUE+0.1*mean(CPUE)=year+area+YB.ratio(numeric)+SST+SST^2	**5b**	log(CPUE+0.1*mean(CPUE)=year*area +YB.ratio(numeric)+SST+SST^2
6a	log(CPUE+0.1*mean(CPUE)=year+area+YB.ratio(numeric)+SST:area	**6b**	log(CPUE+0.1*mean(CPUE)=year*area +YB.ratio(numeric)+SST:area
7a	log(CPUE+0.1*mean(CPUE)=year+area+SST+SST^2	**7b**	log(CPUE+0.1*mean(CPUE)=year*area+SST+ SST^2

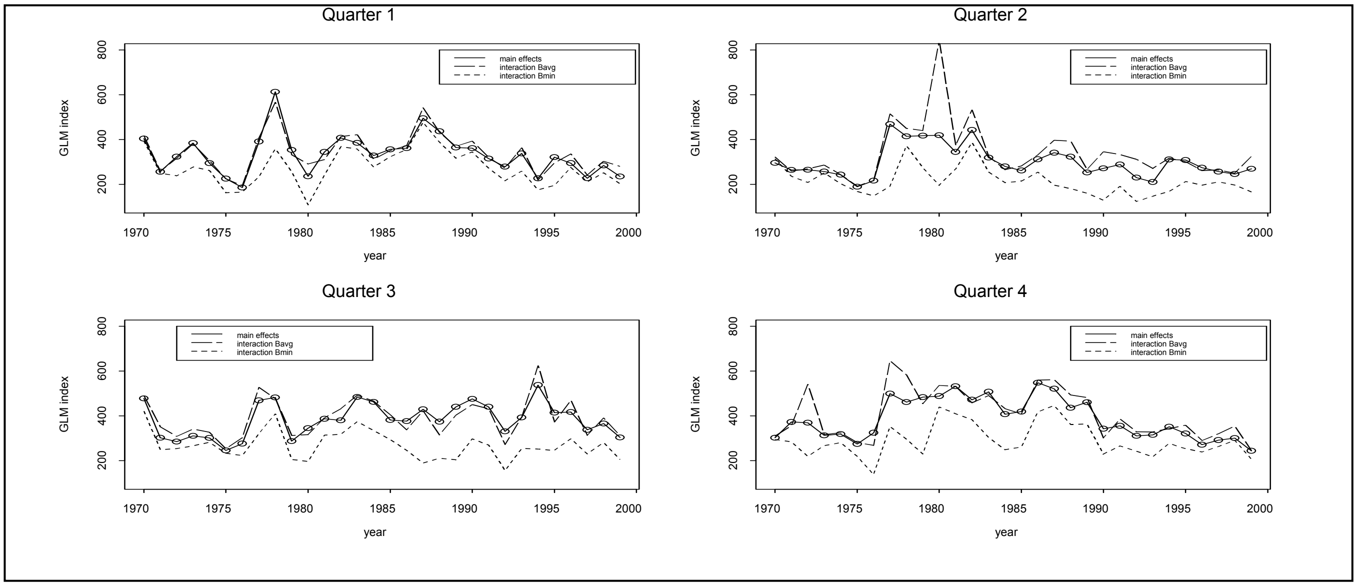

Figure 3. Comparison of B_{GLM} indices for each quarter for models 1a and 1b.

No modelled data (ie substitution of unfished 5-degree squares using the Bmin or Bavg methods) was used in the GLMs. For the interaction effects models, both Bmin and Bavg indices was calculated from the GLM results by multiplying the modelled indices by the number of fished squares, and the total number of squares in the core sub-area, respectively. Note: this Bmin index differs from that described earlier as it assumes no fish in areas not fished. Whilst this may be considered an unrealistic assumption, the index is nevertheless shown for comparison.

The YB.ratio is the ratio of the bigeye to bigeye and yellowfin catch, and is a targeting index that is a proxy for hooks-per-basket (Anon. 2001). In model 2, this ratio was included as a continuous numeric predictor variable, while in model 3 the ratio was incorporated as a factor with two levels (BET proportion in catch > 0.5 and below 0.5). Note that the YB.ratio may not be strictly an independent linear predictor, since BET catch is also used to calculate CPUE, the response variable. As such the results from models 2-6 should be treated with caution.

SST is the sea surface temperature (normalised for each quarter). This data was only available since 1982, so models 4-7 are only for 1982-1999. Thus, although models 2 and 4 are identical, the latter is done for the data subset 1982-1999.

The results for each quarter for the models 1a and 1b are shown in Figure 3. All indices display a high degree of inter-annual variability. Furthermore, for all quarters there is a large increase in the index between 1976 and 1977. The index for the first quarter in 1978 is also anomalously large. There also appears to be an unusually large degree of uncertainly associated with the interaction index for the second quarter in 1980 as seen by the large difference between the Bavg and Bmin indices.

The Bmin index for the interaction effects model provides a lower bound, and is seen to dampen some of the increase seen in the Bavg indices after the mid-1970s. The greater difference between the Bavg and Bmin indices after this time also indicates that greater degree of uncertainty associated with calculating abundance indices due to the fact that a smaller number of 5-degree squares are fished in areas after this time.

An example of ANOVA tables for models 1a and 1b are presented in Table 2 for quarter 2.

While all terms were statistically significant, the area term had the highest F value, suggesting that this factor accounted for the highest amount of residual deviance.

The QQ-plots of the residuals for models 1a (left panel) and 1b (right panel) are shown in Figure 4. While there is some negative skew, particularly for the interaction model (1b), and an few outliers on the right tails for the interaction model, the residuals for these log-normal models show a reasonably symmetric, normal distribution. However, the slight departures from normality in the tails probably results in overestimation of the p-values, and hence in the significance of terms. Thus, it is difficult to determine whether terms with lower F-values are statistically significant in the GLM.

Finally, in order to examine the relative contribution of each of the seven sub-areas to the overall index, Bavg and Bmin indices specific to each sub-area are plotted in Figure 5 for the interaction effects model for quarter 2

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Table 2. *ANOVA tables for models 1a and 1b for quarter 2.*

Model 1a					
	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Year	29	136.226	4.69746	9.4363	0
Area	6	399.100	66.51665	133.6191	0
Residuals	2300	1144.959	0.49781		

Model 1b					
	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Year	29	136.2265	4.69746	11.2416	0
Area	6	399.0999	66.51665	159.1819	0
Year:Area	160	250.7261	1.56704	3.7501	0
Residuals	2140	894.2325	0.41787		

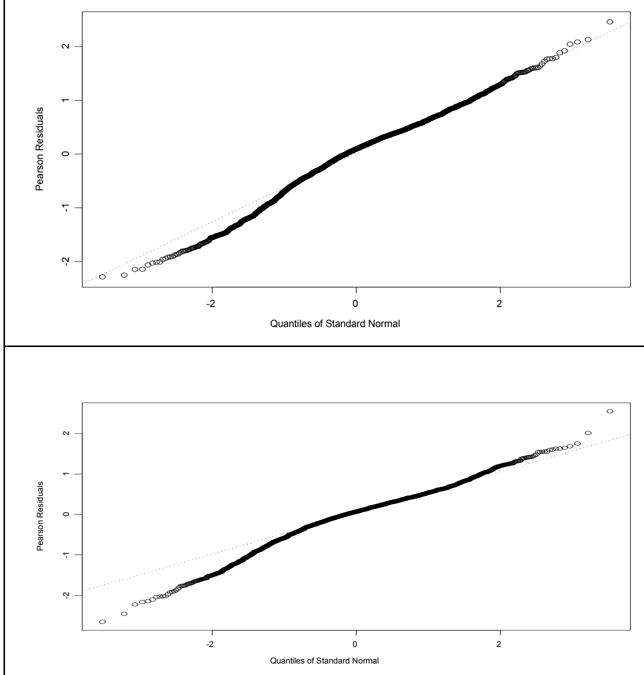

Figure 4. QQ-plots of the residuals for models 1a and 1b.

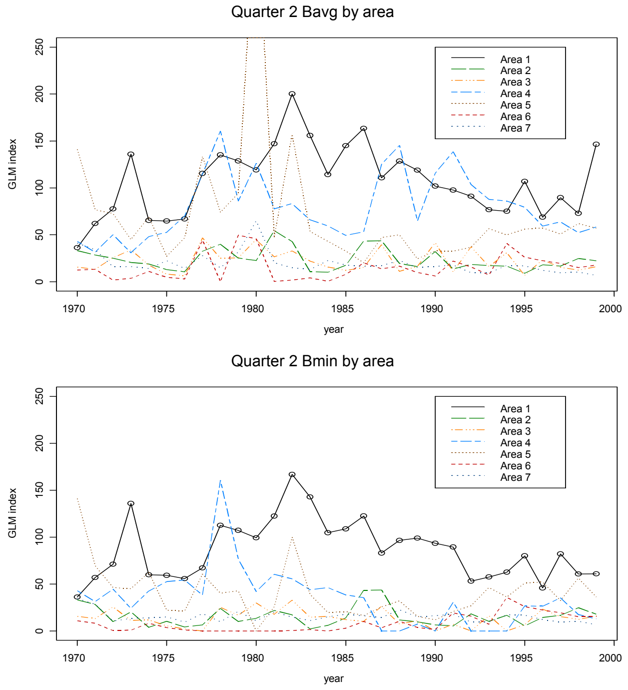

Figure 5. *Bavg$_{GLM}$ indices specific to each of the seven sub-areas of the core fishery.*

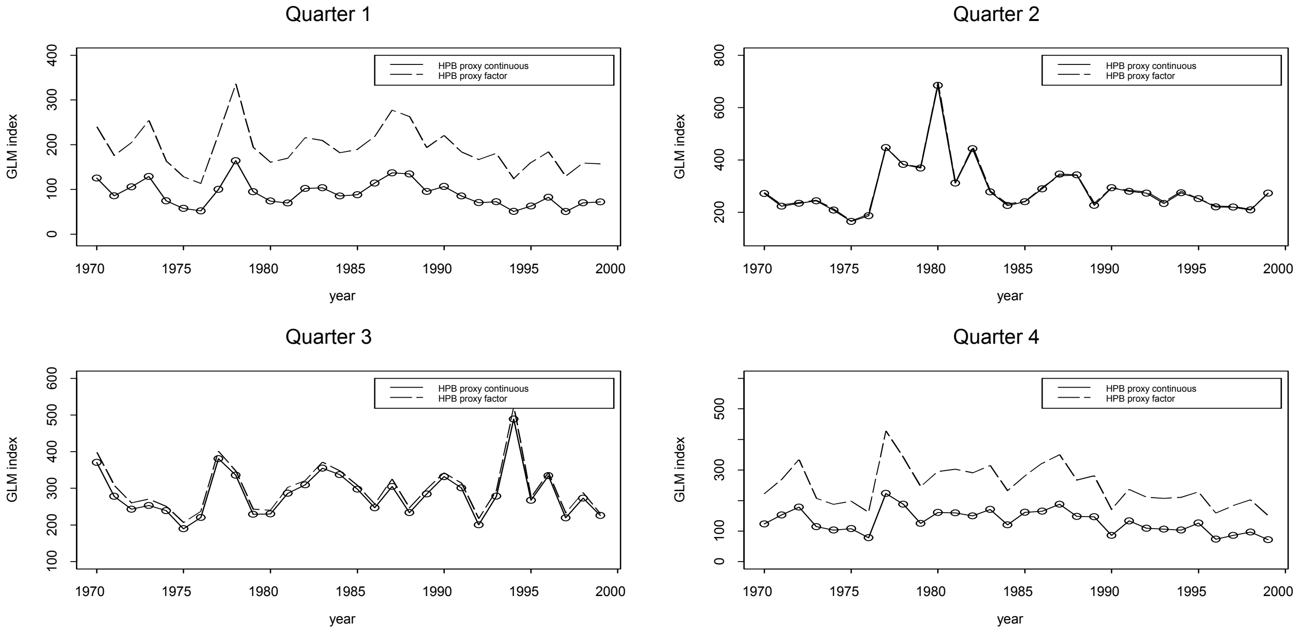

Figure 6a. *B$_{GLM}$ indices, by quarter, for models 2b and 3b.*

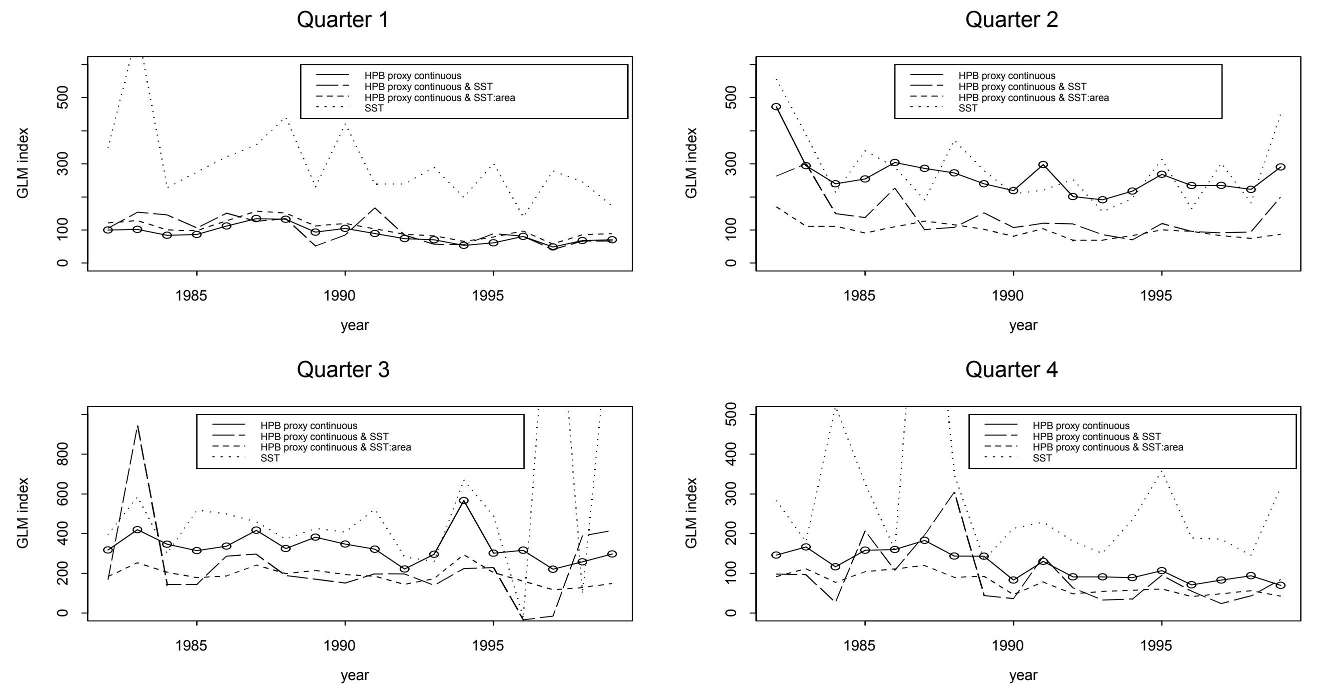

Figure 6b. *B_{GLM} indices, by quarter, for models 4b-7b*

These plots show that sub-areas 1, 4 and 5 are the main contributors to the overall index in quarter 2, and that the peak in 1980 for the Bavg index in quarter 2 was due mainly to the upscaling of the area 5 index. For quarter 2, sub-areas 1, 4 and 5 are the largest in terms of area (see maps above), so it is intuitively sensible that these make up the majority of the abundance index.

The indices for models 2b and 3b and 4b-7b are shown in Figure 6a,b. The temporal patterns for models 2b and 3b show very similar trends to those indices from model 1. However, the declines since the early 1980's observed for most quarters for the simple sum indices and for model 1 are not as strong in models 2b-7b.

In quarters 1 and 4, the difference in magnitude of the effect of the YB.ratio (or proxy for hooks per basket) as a numeric versus a factor predictor variable was marked, with a higher index associated with YB.ratio as a factor. However, in quarters 2 and 3, the form of the YB.ratio had minimal effect on the magnitude of the abundance index. In all quarters, the relative temporal trends were almost identical for both models.

In general, the temporal patterns for models 4b-7b also gave similar relative results to the earlier models. Model 4b gave almost identical results to model 2b, indicating that using the data subset 1982-1999 as opposed to data from 1970, made little difference to the abundance indices.

In quarter 1, models 4b-6b all yielded indices of similar magnitude, while model 7b, where SST was included in the absence of the YB.ratio term, gave a similar trend but with a higher magnitude. Models 5b and 6b, where SST or an SST-area interaction term were included together with the YB.ratio predictor, gave lower magnitude indices but a similar relative trend to models 4b and 7b in quarter 2.

In quarter 3, all models yielded similar relative temporal trends, except for model 7b from 1996 onwards, where the indices showed high interannual variability with a different pattern to that from the other models, and the 1983 peak for model 5b. Otherwise, the results were as for quarter 2, with models 5b and 6b yielding lower magnitude indices but similar relative trends to models 4b and 7b. The indices from model 7b were close in magnitude to those from model 4b.

Models 4b and 6b showed similar relative temporal patterns in quarter 4, while the indices for model 5b were similar in magnitude to those from models 4b and 6b, but showed stronger inter-annual variability. Model 7b, where SST was included in the absence of the YB.ratio term, gave a similar trend to model 5b, but with a higher magnitude.

ANOVA tables for quarter 2 for each of models 2b-7b are given in Table 3. The area term consistently explained a large proportion of the variability. Although the YB.ratio term had a reasonably high F-value, it was the least significant of all of the terms according to the Pr(F) values. Conversely, the year-area interaction term had the lowest F-value in all of the models, yet it was highly statistically significant according to the Pr(F) term. Note that the YB.ratio term explained more of the deviance and was more statistically significant when represented as a two-level factor rather than a numeric variable (model 2b compared with 3b). Sea surface temperature explained more of the variability than any other term (models 5b and 6b), and had a higher F-value when included as main effects term than as an interaction term with area (model 7b).

Table 3. ANOVA tables for models 2b-7d for quarter 2.

Model 2b

	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**Pr(F)**
Year	29	136.2265	4.69746	11.2947	0.000000e+000
area	6	399.0999	66.51665	159.9340	0.000000e+000
YB.ratio	1	16.2751	16.27507	39.1321	4.769458e-010
Year:area	160	239.0719	1.49420	3.5927	0.000000e+000
Residuals	2139	889.6117	0.41590		

Model 3b

	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**Pr(F)**
Year	29	136.2265	4.69746	11.3771	0.000000e+000
area	6	399.0999	66.51665	161.1013	0.000000e+000
YB.ratio.factor	1	27.7980	27.79797	67.3258	4.440892e-016
Year:area	160	233.9950	1.46247	3.5421	0.000000e+000
Residuals	2139	883.1657	0.41289		

Model 4b

	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**Pr(F)**
Year	17	55.6164	3.27155	8.5934	0.0000000000
area	6	308.2620	51.37701	134.9523	0.0000000000
YB.ratio	1	5.0224	5.02241	13.1924	0.0002921047
Year:area	93	105.4121	1.13346	2.9773	0.0000000000
Residuals	1291	491.4901	0.38070		

Model 5b

	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**Pr(F)**
Year	17	55.6164	3.2716	12.9670	0.000000e+000
area	6	308.2620	51.3770	203.6359	0.000000e+000
YB.ratio	1	5.0224	5.0224	19.9066	8.840926e-006
sst.norm.qtr	1	200.3180	200.3180	793.9727	0.000000e+000
sst.norm.qtr^2	1	10.8266	10.8266	42.9118	8.300000e-011
Year:area	93	60.5450	0.6510	2.5804	0.000000e+000
Residuals	1289	325.2126	0.2523		

Model 6b

	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**Pr(F)**
Year	17	55.6164	3.2716	11.6114	0.000000e+000
area	6	308.2620	51.3770	182.3473	0.000000e+000
sst.norm.qtr	1	148.3388	148.3388	526.4842	0.000000e+000
I(sst.norm.qtr^2)	1	7.6646	7.6646	27.2031	2.131691e-007
Year:fixed.core	93	82.4591	0.8867	3.1469	0.000000e+000
Residuals	1290	363.4622	0.2818		

Model 7b

	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**Pr(F)**
Year	17	55.6164	3.27155	13.5291	0.000000e+000
area	6	308.2620	51.37701	212.4632	0.000000e+000
YB.ratio	1	5.0224	5.02241	20.7695	5.673446e-006
Year:area	93	105.4121	1.13346	4.6873	0.000000e+000
sst.norm.qtr:area	7	180.9983	25.85690	106.9280	0.000000e+000
Residuals	1284	310.4918	0.24182		

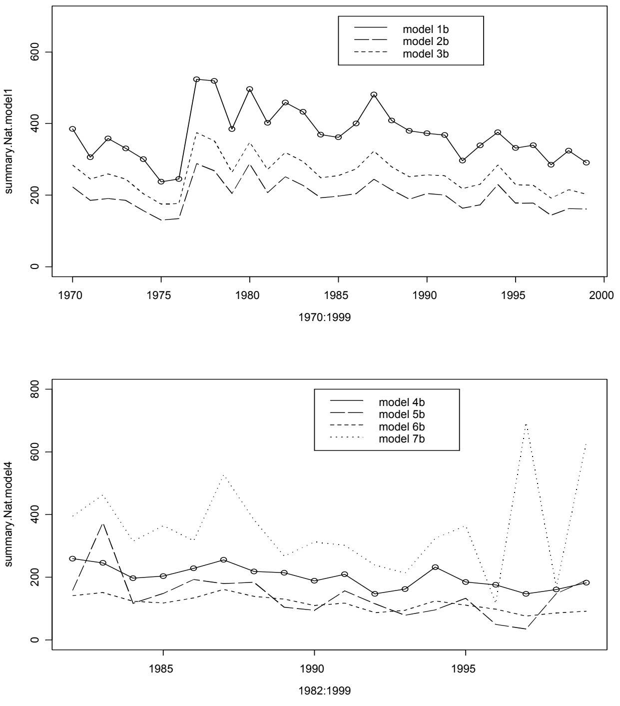

Figure 7. Annual B_{GLM} indices for models 1b-7b.

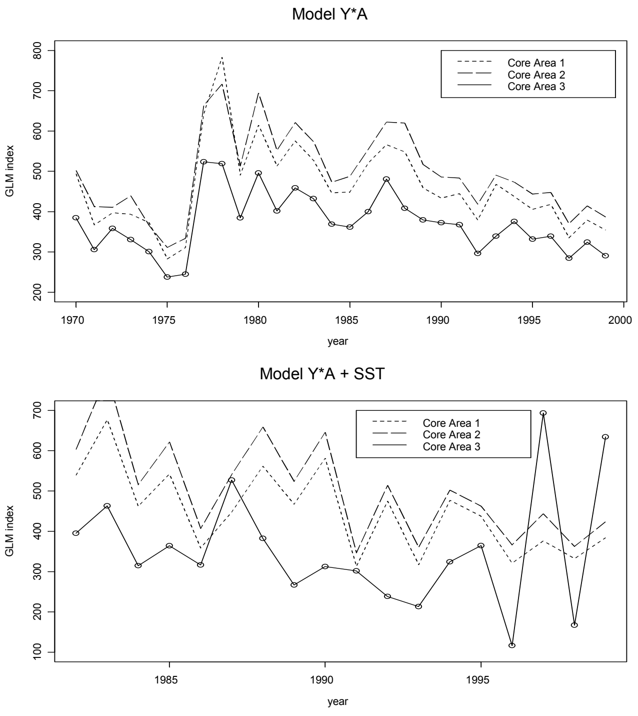

Figure 8. Comparison of the Bavg indices for the three different core fisheries.

The QQ plots for quarter 2 (not shown) were found to be similar across the models 2b-7b and to that for model 1b, showing a reasonably symmetric, normal distribution with some negative skew and one or two outliers in the upper tail. Again, the slight departures from normality in the tails probably results in overestimation of the p-values, and hence in the significance of term, warranting caution in the interpretation of the Pr(F) values presented in the ANOVA tables.

To provide a more concise visual summary, and to obtain an overall temporal trend, the results from each model are also plotted as annual indices obtained from the arithmetic means of the GLM indices across the 4 quarters. The results are shown in Figure 7.

It can be seen that the indices for all of the models except for model 7b show relatively similar temporal trends. The model 7b indices show similar trends until 1997, when large peaks occur in that year and in 1999. These peaks occurred in quarter 3 and dominate the other quarters in the calculation of the mean indices. The reason for these peaks currently remains unresolved and the unusual behaviour suggests that this index may be in error.

COMPARISON OF CORE AREA CHOICE

The Bavg indices resulting from the interaction effects models were used to compare the effect of choosing different core areas. To provide a more concise visual summary, the only results shown (Figure 8) are annual indices obtained from the arithmetic means of the GLM indices across the 4 quarters. As would be expected, the lowest magnitude indices correspond to core area 3, that with the most stringent selection criteria. The indices associated with core areas 1 and 2, being of similar sizes, are of comparable magnitude.

All of the models generally yielded similar temporal trends, though the 1977-78 peak in abundance, and thus the subsequent decline, is not as pronounced for core area 3. The annual indices are similar to those presented in Okomoto and Miyabe (1999) and Anon. (2001). The indices show a peak in 1977-78, followed by a general decline, with inter-annual oscillations and secondary peaks in 1980, 1982 and 1987.

COMPARISON OF TOTAL VS TROPICAL CORE AREA

Targeting issues in southern latitudes highlighted by Okamoto and Miyabe (1999) have suggested that it may be more appropriate to restrict the standardisation of bigeye CPUE to tropical latitudes. For core areas 1 and 2, five of the seven sub-areas are tropical, while for core area 3, four to five of the sub-areas (depending on the quarter) are tropical. Together these sub-areas form a tropical core area on which revised CPUE standardisations were performed. The resulting indices are compared with those derived using the full core areas. As with the comparison of the different core areas above, the Bavg indices resulting from the interaction effects models 1b and 7b were used, and the results shown are annual indices obtained from the arithmetic means of the GLM indices across the 4 quarters. The results are presented for each of the three core area definitions.

Our results suggest that the difference in the relative temporal trend for the abundance indices between the full and tropical core areas is negligible. As would be expected, the magnitude of the indices is lower for the tropical subset, but the pattern over time shows very little difference.

TEMPORALLY FIXED VS VARIABLE AREA APPROACH

The above analyses all include area effects that are fixed across all years. However, as tunas are highly migratory and are known to change their spatial distributions in response to large scale changes in oceanographic conditions, the abundance of these species in any fixed area can change significantly from year to year. Such changes result in significant Year.Area effects in the above GLMs. An alternative analytical approach for accounting such effects may be to allow the spatial areas fitted in the above models to change from year to year. For example, for any year one can rank the 5-degree squares by bigeye catch. One can then define sub-regions that are based on the collection of those squares having a given range of ranks.

In Campbell et al (2001) it was found that for many years 95 percent of the bigeye catch has been caught in around fifty 5-degree squares. Accordingly, each year we defined seven spatial areas based on the following criteria:

Area 1: Those 5-degree squares ranked 1-7 in bigeye catch

Area 2: Those 5-degree squares ranked 8-14 in bigeye catch

Area 3: Those 5-degree squares ranked 15-21 in bigeye catch

Area 4: Those 5-degree squares ranked 22-28 in bigeye catch

Area 5: Those 5-degree squares ranked 29-35 in bigeye catch

Area 6: Those 5-degree squares ranked 36-42 in bigeye catch

Area 7: Those 5-degree squares ranked 43-49 in bigeye catch

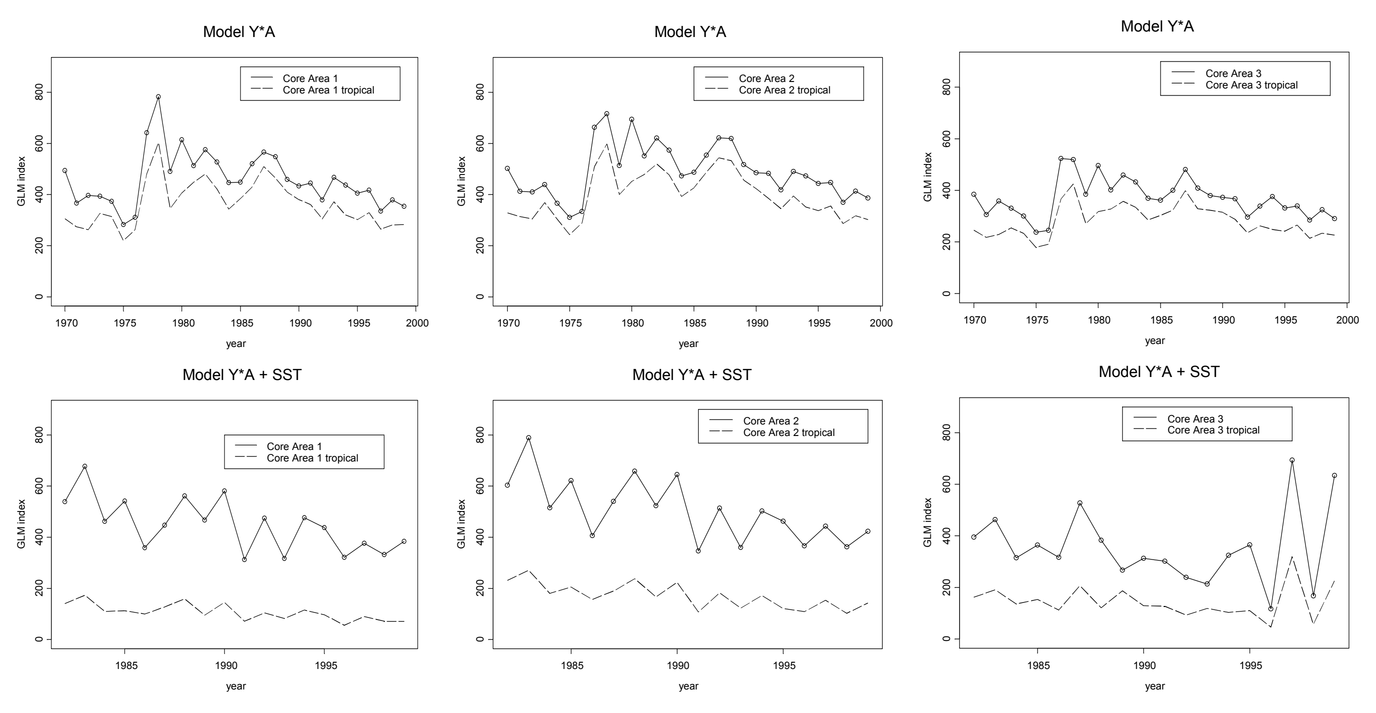

Figure 9. *Comparison of indices based on analysis of data for i) the entire core fishery and ii) tropical regions only.*

With these new area definitions, calculation of the GLM index together with the simple sum Bavg and Bmin indices for each quarter was undertaken as described previously. Annual indices were then calculated by taking the geometric mean of the indices for the four quarters. Results for three separate periods 1960-99, 1970-99, and 1982-99 are shown in Figures 10a,b and 11a,b. The indices based on the former models using areas which are the temporally fixed across all years are also shown. Note the following protocols were adopted for the analysis within each period:

Core Fishery and Areas

- Fixed Temporal Areas: Core fishery consists of the union across all quarters of those 5-degree squares which were in the annual core catch area for bigeye (defined as those squares with 95% of the catch) at least once during the period of interest and which were fished at least 10 years during that period (6 years for the period 1982-99). Seven areas were defined for the periods 1960-99 and 1970-99 with the former areas shown in Figure 2b. Nine areas were defined for the period 1982-99.

- Variable Temporal Areas: Core fishery consists of the top 49 bigeye catch squares each year, divided into 7 areas as described above.

Data Included in Analyses

- Only those catch and effort observations within the core fishery as defined above and excluding those observations based on less than 10,000 hooks.

GLM Model

- 1960-99 Log(CPUE+0.1(Mean CPUE)) = Year*Area

- 1970-99 Log(CPUE+0.1(Mean CPUE)) = Year*Area

- 1982-99 Log(CPUE+0.1(Mean CPUE)) = Year*Area+sst+sst^2

(Note: sst = Mean monthly Sea Surface Temperature associated with each 5-degree square, normalised across the entire data set).

The results shown in Figures 10a and 10b indicate that for a given model structure, the temporal trends in the annual indices are similar for the three periods analysed. However, there are seen to be large difference between the indices based on the two different model structures. In particular, the step-wise increase in the index based on the temporally fixed area model after 1976 is replaced by an large dip in 1976 in the index based on the temporally variable area model. Furthermore, the former index displays a decreasing trend both before and after the discontinuity between 1976 and 1977, while the latter index displays a highly variable but relatively flat trend up until 1980 with a decreasing trend only after this time. The overall decrease over the 40-year period for the temporally variable index is around 33 percent (from approx. 375 to 250).

Comparison of the GLM index with the simple sum indices for the temporally fixed area model (cf. Figure 11a) indicate that the GLM and Bavg indices are very similar. This is to be expected as both indices are based on the mean catch rate across those squares fished. On the other hand, the large jump after 1976 is dampened to a significant extent with the Bmin index. Instead of the 80 percent increase in the Bavg index between 1970 and 1977 the Bmin index has an 8 percent decline (though there is a 12 percent increase between 1970 and 1978). Indeed, in replacing the large jump after 1976 with a large dip between 1970 and 1977, the Bmin index is similar to the GLM index for the temporally variable area model. Finally, the GLM and simple sum indices based on the temporally variable area model are seen to be similar (cf. Figure 11b). This result is to be expected as there are only a few years when less than 49 5-degree squares were fished in the core area used in these models and as such proxy data had to be substituted for only a few squares.

In conclusion, significant differences have been found between several of the annual indices calculated above. The reasons for these differences are twofold: i) the manner in which the area (in particular the Year.Area) effect is modelled, and ii) whether or not the catch rates in fished 5-degree squares are deemed to be upwardly biased samples of catch rates in all squares within a given area. These differences indicate that close attention needs to be paid to manner in which the spatial-temporal distribution of catch rates is modelled. In particular, the significant difference between the above results suggests that the large area effects used in the temporally fixed models may not be adequate for capturing the large degree of inter-annual variation in catch rates that occur on fine-spatial scales within the Indian Ocean. Furthermore, the natural level of inter-annual variation in catch rates may have become confounded with spatial shifts in areas fished and the introduction of deeper longlining during the mid-1970s. The smaller and more spatially concentrated levels of fishing effort during the period in the mid-1970s also appears to be frustrating efforts to adequately account for the influence of each separate factor.

Further Work

The analyses presented in this paper are preliminary in that in most instances the observed catch rates have not been standardised for factors other than year and area (and quarter). In this regard the paper should be viewed primarily as exploring various methodological approaches for analysing CPUE data and calculating annual indices of abundance rather than providing a standardised index to be used in further assessment work. When more suitable data sets become available, aspects of the above analyses can be repeated. In particular, catch rates should be standardised for changes in fishing strategies and gear efficiencies, as well as for environmental and oceanographic influences. Some thought should also be given to how best to incorporate such effects into the model, as the response of the fish populations to many of these effects may vary significantly within different areas across the Indian Ocean. Further work also needs to be undertaken to find the most suitable area effects for inclusion in the models. More and smaller areas are probably required to adequately account of the spatial changes in catch rates mentioned above. Finally, comparison of indices based on data from both the temperate and tropical regions of the Indian Ocean with indices based on data from the tropical regions only should be further investigated.

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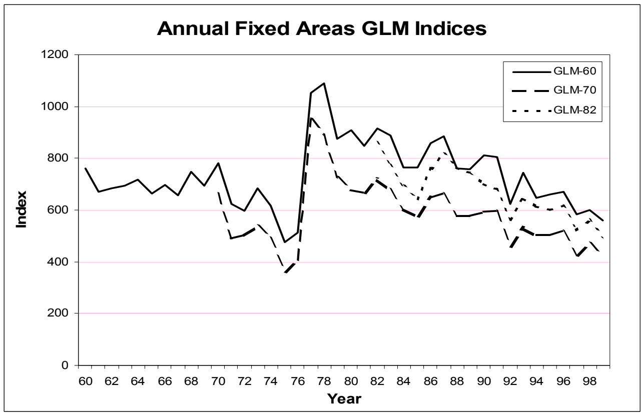

Figure 10a. *Comparison of B_{GLM} indices based on models using temporally fixed areas for the periods 1960-99, 1970-99, and 1982-99.*

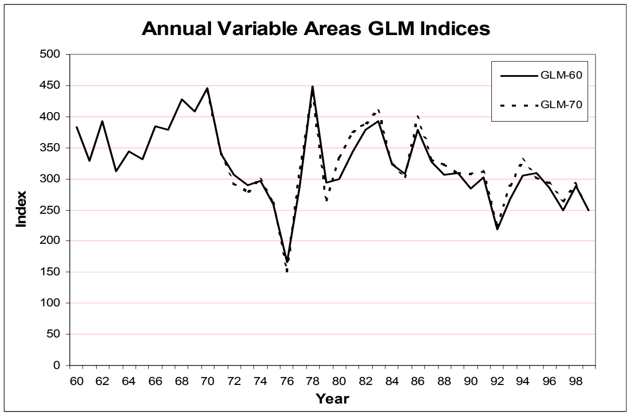

Figure 10a. *Comparison of B_{GLM} indices based on models using temporally variable areas for the periods 1960-99 and 1970-99.*

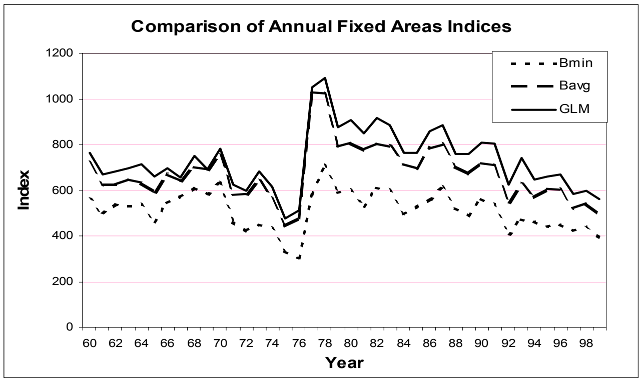

Figure 11a. *Comparison of the B_{GLM} and Bavg and Bmin simple sum indices, based on models using temporally fixed areas, for the period 1960-99.*

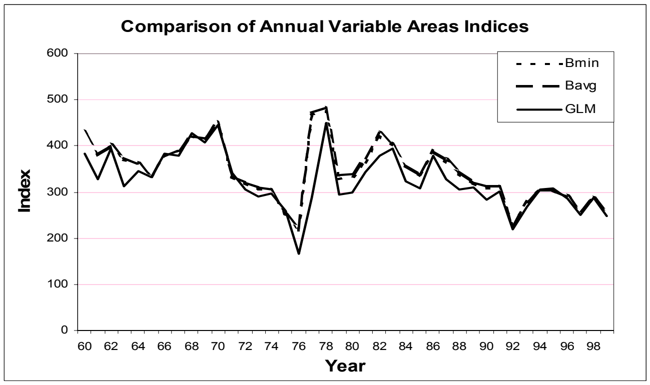

Figure 11b. Comparison of the BGLM and Bavg and Bmin simple sum indices, based on models using temporally variable areas, for the period 1960-99.