 Collect. Vol. Sci. Pap. ICCAT, 62(2): 372-396 (2008)

STANDARDIZED CATCH PER UNIT EFFORT OF BIGEYE TUNA (*THUNNUS OBESUS*) FOR THE TAIWANESE LONGLINE FISHERY IN THE ATLANTIC OCEAN BY GENERAL ADDITIVE MODEL

Chien-Chung Hsu[1]

SUMMARY

Abundance index of bigeye tuna (Thunnus obesus) *in the Atlantic Ocean from Taiwanese longline fishery are presented for the period 1981-2006 by general additive model. The index (number caught per 1,000 hooks) was generated from numbers of bigeye tuna caught and reported in the logbooks submitted by commercial fishermen since 1981. Variables used in standardization are year, area, season, targets that are represented as quantiles of ratios of albacore and yellowfin tuna in total catches of these three species and their interactions. Thus, a step-wise regression procedure was used to select the set of systematic factors and interactions that significantly explained the observed variability, and deviance analysis was used to select the most appropriate factors in the standardization for the proportion positive observations and the deviance for the positive catch rates. Final selection of explanatory factors was conditioned to the significance of chi-square test and the relative percentages of deviance explained by adding the factor in evaluation and normally, factors that explained more than 5 were selected. Consequently, factors of year, area, target on albacore, target on yellowfin tuna and year-area interaction were used in both models. The results of abundance index were obtained from multiplying positive catch rate, which was generated from a general linear mixed model (GLMM) with delta-lognormal error structure, and proportion of positive catch sets, which was obtained by GLMM with binomial error structure. Then two data sets were applied and the result obtained from monthly aggregated data by vessels and by 5-degree square are more reasonable. Different results obtained by different regions were also presented in the report. However, since the quarter factor is not significant, the quarterly standardized catch-per- unit-effort for regions were not available.*

RÉSUMÉ

*Ce document présente l'indice d'abondance du thon obèse (*Thunnus obesus*) de la pêcherie palangrière du Taïpei chinois dans l'Océan Atlantique pour la période 1981-2006, réalisé par modèle additif généralisé. Cet indice (nombre capturé par 1.000 hameçons) a été généré d'après le nombre de thons obèses capturés et déclarés dans les livres de bord soumis par les pêcheurs commerciaux depuis 1981. Les variables utilisées dans la standardisation sont l'année, la saison, les cibles, qui sont présentées comme quantiles des ratios du germon et de l'albacore en prises totales de ces trois espèces et leurs interactions. Une procédure de régression pas à pas a donc été utilisée pour sélectionner le jeu de facteurs systématiques et les interactions qui expliquent largement la variabilité observée. Une analyse de déviance a été utilisée pour sélectionner les facteurs les plus appropriés dans la standardisation pour la proportion des observations positives et la déviance pour les taux de capture positifs. La sélection finale des facteurs explicatifs dépendait de l'importance du test du chi-deux et des pourcentages relatifs de déviance, expliqués en rajoutant le facteur dans l'évaluation ; les facteurs qui en expliquaient plus de cinq ont généralement été sélectionnés. On a donc utilisé, dans les deux modèles, les facteurs année, zone, ciblage du germon, ciblage de l'albacore, et l'interaction année-zone. Les résultats de l'indice d'abondance ont été obtenus en multipliant le taux de capture positif, qui a été généré d'après un modèle linéaire généralisé mixte (GLMM) avec une structure d'erreur delta-lognormale et une proportion d'opérations de pêche positives, obtenues par GLMM avec une structure d'erreur binomiale. Deux jeux de données ont alors été appliqués et le résultat obtenu des données regroupées par mois et par carrés de 5 degrés est plus raisonnable. Le présent rapport inclut aussi différents résultats obtenus par différentes régions. Toutefois, étant donné que le facteur trimestre n'est pas important, la capture par unité d'effort standardisée par trimestre pour ces régions n'était pas disponible.*

[1] Institute of Oceanography, National Taiwan University, P. O. Box 23-13, Taipei, Taiwan 106; E-mail: hsucc@ntu.edu.tw

RESUMEN

Se presentan los índices de abundancia de patudo (Thunnus obesus) *en el océano Atlántico para la pesquería palangrera de Taipei Chino durante el periodo 1981-2006, mediante un modelo generalizado aditivo. Se obtuvo el índice (número capturado por 1.000 anzuelos) a partir del número de ejemplares de patudo capturados y comunicados en los cuadernos de pesca presentados por los pescadores comerciales desde 1981. Las variables utilizadas en la estandarización fueron año, zona, temporada, especie objetivo, representada como cuantiles de ratios de atún blanco y rabil en las capturas totales de estas tres especies, y sus interacciones. Por tanto, se utilizó un procedimiento de regresión gradual para seleccionar un conjunto de interacciones y factores sistemáticos que explicaban en gran medida la variabilidad observada. Se utilizó el análisis de devianza para seleccionar los factores más apropiados en la estandarización para la proporción de observaciones positivas y la devianza para las tasas de captura positivas. La selección final de factores explicativos estuvo condicionada por la importancia de la prueba de chi cuadrado y los porcentajes relativos de devianza que se explicaban al añadir el factor a la evaluación y se seleccionaron los factores que explicaban más de 5. Por consiguiente, los factores año, zona, estrategia de pesca dirigida al atún blanco, estrategia de pesca dirigida al rabil e interacción zona-año se utilizaron en ambos modelos. Los resultados del índice de abundancia se obtuvieron multiplicando la tasa de captura positiva, que se generó a partir de un modelo lineal mixto generalizado (GLMM) con una estructura de error delta-lognormal, y la proporción de lances de captura positivos, que se obtuvo mediante un GLMM con una estructura de error binomial. A continuación se aplicaron dos conjuntos de datos y los resultados obtenidos de los datos agregados mensualmente por buques y por cuadrículas de 5º fueron más razonables. En este documento se presentan también los diferentes resultados obtenidos para las diferentes regiones. Sin embargo, dado que el factor trimestre no es significativo, la captura por unidad de esfuerzo estandarizada trimestralmente no estaba disponible.*

KEYWORDS

Bigeye tuna (Thunnus obesus)*, abundance index, GLMM, longline, delta lognormal distribution, binomial distribution, deep longline fishing pattern, logbook*

1. Introduction

Bigeye tuna (*Thunnus obesus*), is the most valuable and cosmopolitan scombridae, distributing in the tropical and temperate waters between 45°N and 45°S (Collette and Nauen, 1983). In the Atlantic Ocean, the species has been targeting by many fisheries including Taiwanese longline fishery mainly since 1990, although significant catches before 1989 were also reported previously (Hsu and Chen, 1996) as non-targeted. The annual production by all fleets in the entire Atlantic bigeye tuna stock has exceeded 100,000 tons since 1995, and Taiwanese catches have been limited to 16,500 tons since 1998.

The stock status was first evaluated in 1997 using only the standardized catch per unit effort of the Japanese longline fishery (Satoh *et al.* 2003). The results obtained indicated that the stock was fully exploited, especially the spawning stock biomass, which has declined since the early 1990s (Anon., 2003). The previous standardized catch per unit effort for Taiwanese series (Hsu, 1999; Hsu and Lee, 2003) showed a great variation from year to year and stratified sub-area, because of the non homogeneous distribution of logbook recovery in the early 1990s in space and time.

Information on the relative abundance is always necessary to tuna stock assessment models. Catch per unit effort (CPUE) from commercial fisheries has been used to derive indices of relative abundance or to estimate fishing effort for many world fisheries (Gulland, 1956; Robson, 1996; Large, 1992; Stefansson, 1996; Griffin *et al.*, 1997; Goni *et al.*, 1999). However, the use of catch rates in constructing abundance indices requires standardization to take into account changes in the ability to catch fish, fleet composition, and to adjust catch rate estimates for other factors that may affect the catch rates such as year, month, boat type, or abundance of other target species in the catch (Hilborn and Walters, 1992). The generalized additive modeling (GAM) technique with general linear mixed models (GLMM) and delta log-normal distribution for the positive catch rate and binomial distribution for the proportion of positive bigeye tuna catch, respectively, is used because (1) GLMM extends from generalized linear model (GLM) which allows identification of the factors that influence catch rates as well as computation of standardized catch rates, represented by the year effect factor. The factor levels in GLMM are considered as randomly selected from a population of all possible factor levels and the model does not allow only one source of randomness from error structure; and (2) the delta log-normal distribution avoids problems with contagion by zero data and treats zero and nonzero data separately (Lo *et al.*, 1992).

This study is an attempt to address the above two issues in standardizing catch rates of bigeye tuna: (1) to identify factors that have significant effects on catch rates of this species; and (2) to produce a time series of standardized catch rate estimates that can be used for stock assessments.

2. Materials and methods

2.1 Data used

Two data sets were used in the present analysis. First, the 5x5 squared catch-effort data for bigeye tuna were compiled from logbooks of Taiwanese longline fishery in the Atlantic Ocean for the period 1981 to 2006. And second, the aggregated data set from pooling daily records of logbooks, i.e. the logbook data were pooled vessel by vessel for monthly 5x5 square data. The second dataset was very similar to TASKII without raising to TASK I. For convenience, the new dataset was called "TASKII" hereinafter.

There were many changes either in the fishery or in the statistical system during the previous two decades for Taiwanese longline fishery. Those changes may provide different information on the interpretation of standardized abundance index, which include: first, the fishery has been starting to target bigeye tuna since 1990 (about 12,000 t). The catch was found notable from 1994 (about 20,000 t) with historical high level appeared in 1996 (about 22,000 t), but has then declined significantly in 1998 due the catch limit of 16,500 t annually set specifically to the fishery, and an abrupt quota reduction to 4,500 t in 2006. Those quotas had been shared to both bigeye vessels (mainly) and albacore vessels (partially), so some of the albacore vessels may have reported a significant bigeye tuna catch which the information may be involved in the analysis of the bigeye tuna abundance index.

Second, the responsible organization for logbook compilation has changed in 1995 on the logbook data from 1994 onwards, from Institute of Oceanography, National Taiwan University (IONTU) to Oversea Fisheries Development Council (OFDC). Logbook of 1991-1993 has been revised after that time in the consideration to increase very low logbook coverage (originally less than 5%). But even with such revision, the coverage of 1991-93 is still low comparing to the current coverage level of 40-60%.

2.2 Stratification of sub-area

Sub-area defined for bigeye tuna (**Figure 1**) used in this study is assigned as in the "Bigeye tuna work plan: year 2002," which is stratified the bigeye tuna fishing area in the Atlantic Ocean into 12 strata. Each area is assumed to approximately have homogeneous species density with the investigation of nominal catch per unit effort by 5x5 squared area catch records and those stratified sub-areas were used in the following standardized process as the area factor. Also a larger sub-area was stratified as in **Figure 1** for trying to develop a new abundance index for MULTIFAN-CL analysis.

2.3 Model used for standardization

Relative indices of abundance for bigeye tuna were generated by Generalized Linear Mixed Model (GLMM) approach assuming a delta-lognormal error distribution for the positive catch rates. The delta model fits separately the proportion of positive sets assuming a binomial error distribution and the mean catch rate of sets if at least one fish was caught assuming a lognormal error distribution. The standardized index is the product of these two independent model-estimated components. The estimated proportion of successful sets per stratum is assumed to be the result of r positive sets of a total n number of sets, and each one is an independent Bernoulli-type realization. The estimated proportion is a linear function of fixed effects and interactions. The logit function was used as a link between linear factor components and binomial errors. For positive observations, which were defined as at least one bigeye tuna caught, the estimated CPUE rate was assumed to follow a lognormal error distribution (lnCPUE-nominal) of a linear function of fixed factors and random effect interactions, particularly when the $year$ effect was within the interaction.

A step-wise regression procedure was used to determine the set of systematic factors and interactions that significantly explained the observed variability. Then the Chi-square (χ^2) distribution was used to test the difference of deviance between two consecutive models, that is, this statistic was used to test significance of an additional factor in the model and the number of additional parameters associated with the added factor minus one corresponds to the number of degree of freedom in the χ^2 test (McCullagh and Nelder, 1989). Deviance analysis tables are presented for both data series, each table includes the deviance for the proportion of positive observations (i.e. positive sets/total sets), and the deviance for the positive catch rates. Final selection of explanatory factors was conditional to (1) the relative percentage of deviance explained by adding the factor in evaluation (normally factors that explained more than 5 to 10 % were selected); (2) significance of the χ^2 test; and (3) the type III test of significance within the final specified model.

Once a set of fixed factors was specified, possible interactions were evaluated, in particular interactions between the $year$ effect and other factors. Relative indices for the delta model formulation were calculated as the product of the year effect least square means (LSMeans) from the binomial and the lognormal model components. The LSMeans estimates use a weighted factor of the proportional observed margins in the input data to account for the un-balanced characteristics of the data. All models using the stepwise approach were fitted with the SAS GEBNOD procedure, whereas the final model was run with the SAS GLIMMIX and MIXED procedures (SAS Inst. Inc.). The detail of GLMM statistical algorithm of standardization for catch per unit effort was described in Lo et al. (1992).. For the model, the average positive catch rate was for instance; a logarithmic transformation of observed positive catch rate is represented by factors of year, sub-area, targets and their interaction as:

$$\log(\mu_{y,a,f}) = \alpha_0 + \alpha_y + \alpha_a + \alpha_f + \alpha_{y,a} + \alpha_{f,a} + \alpha_{y,f} + z \qquad (1)$$

And the probability that at least catch one fish is a log-normal density:

$$z_{y,a,f,t} \sim LogNorm(u_{y,a,f}, \sigma^2_{a,f}) \qquad (2)$$

Further, the proportion of positive catch can be expressed as:

$$\log\left(\frac{\rho_{y,a,f}}{1-\rho_{y,a,f}}\right) = \beta_0 + \beta_y + \beta_a + \beta_f + \beta_{y,a} + \beta_{f,a} + \beta_{y,f} + w \qquad (3)$$

with a binomial density:

$$w_{y,a,f} \sim Bin(n_{y,a,f}, \rho_{y,a,f}) \qquad (4)$$

The computation was pursued by SAS version 8.2.

3. Results

3.1 Nominal catch per unit effort

Nominal catch per unit effort series (number of fish per 1,000 hooks) of bigeye tuna caught by the Taiwanese longline fleets was estimated by the total number of catch divided the total number of hooks summing up from daily logbooks and from the TASKII data sets, and is illustrated in **Figure 2**. The nominal catch per unit depicts that a flat trend till 1989, an increasing trend from 1990 to 1996, then a sharp decline to 2000, and a slight increasing trend since then with a little drop in 2004. The nominal series obtained from TASKII dataset was coincident with the series obtained from daily logbooks. Both series almost have the same value before 1990; however, the TASKII series has significantly lower values than the logbook series.

3.2 Standardization of catch per unit effort

3.2.1 Logbook databases

As shown in **Table 1**, the analysis of deviance explains that factors of year, sub-area, catch of albacore, catch of yellowfin tuna and year-sub-area interaction are significant for Chi-square test (p <0.0001) and percentage of deviance on standardizing positive catch rate; and factors of year, sub-area, catch of albacore and yellowfin tuna are significant for Chi-square test (p <0.0001) and percentage of deviance for proportion positive sets. Then, these mentioned factors were selected in GLMM model to standardize catch per unit effort of bigeye tuna caught by Taiwanese longline fishery in the Atlantic from 1981 to 2006. The quarter factor was not significant for both of positive catch rate and positive proportion analyses.

Thus, for logbook dataset the standardized positive catch rate, standardized proportion of positive catch and the standardized catch per unit effort were shown in **Figures 3, 4** and **5**, respectively. For validating the standardization, a normal residual frequency distribution, QQ plot to detect the relation between residuals and normal quantiles, residual distribution with year and residuals of the binomial distribution for the proportion of positive sets by years was illustrated in **Figures 6, 7** and **8**, respectively. All the error structures were investigated and followed the lognormal distribution for standardizing positive catch rate and following binomial distribution for the proportion of positive catch. Therefore, the standardization of catch per unit effort of bigeye tuna for Taiwanese longline fishery using daily logbook data and applying to GAM is validated.

The standardized positive catch rate shows decreasing trend from 1981 to1992, abrupt increase to 1994, then declined continuously to 2001, then increased to about 1990' level in 2001 and maintained fluctuated in this level (**Figure 3**). The proportion of positive catch was maintained in 0.5-0.6 level before 1995, and dropped to below 0.4 in 1998, then increased to the 0.5-06 level then after (**Figure 4**). And the integrate standardization of abundance index (**Figure 5**) shows decreasing trend from 1981 to 1992, and increases to the highest level for the series in 1995, then declines to the lowest level in 1998 and 1999, and increased again to the level of 1990's.

3.2.2 Task II dataset

For Task II dataset the standardized positive catch rate, standardized proportion of positive catch and the standardized catch per unit effort were shown in **Figures 9, 10** and **11,** respectively. For validating the standardization, a normal residual frequency distribution, QQ plot to detect the relation between residuals and normal quantiles, residual distribution with year and residuals of the binomial distribution for the proportion of positive sets by years was illustrated in **Figures 12, 13** and **14**, respectively. All the error structures were investigated and followed the lognormal distribution for standardizing positive catch rate and following binomial distribution for the proportion of positive catch. Therefore, the standardization of catch per unit effort of bigeye tuna for Taiwanese longline fishery using aggregated daily logbook data (Task II) and applying to GAM is validated.

The standardized positive catch rate shows decreasing trend from 1981 to1988 with great fluctuation, kept flat to 1991 and slightly decreased in 1992, increased to 1994, then declined slightly to 1996 and continuously and abruptly to 1998, then increased slightly in a historical low level to 2001 and slightly increased and maintained fluctuated in this level (**Figure 9**) then after. The proportion of positive catch was maintained in 0.6-0.8 level for the entire series (**Figure 10**). And the integrate standardization of abundance index (**Figure 11**) shows slight fluctuation with decreasing trend from 1981 to 1992 with a incident peak in 1987, and increases to 1994, then declines to the lowest level in 1998, and increased again to 2002, decreases in 2003 and increases further to 2006 with the level of mid-1990s.

3.2.3 Regional standardized catch per unit effort using Task II dataset

The region stratification was mapped in **Figure 2**. Since the factors examined by step-wise regression and deviance analysis showed different factors significant in different regions **(Table 1b)**, a different factors was used in standardization for different regions. The validation using examination of error structure assumption was presented. For region I, QQ plot to detect the relation between residuals and normal quantiles, a normal residual frequency distribution, residual distribution with year was illustrated in **Figures 15, 16** and **1**7, respectively. And residuals of the binomial distribution for the proportion of positive sets by years were not available, since none of the examined was significant **(Table 1b)**.

For region II, QQ plot to detect the relation between residuals and normal quantiles, a normal residual frequency distribution, and residual distribution with year and residuals of the binomial distribution for the proportion of positive sets by years was illustrated in **Figures 18, 19** and **20,** respectively.

For region III, QQ plot to detect the relation between residuals and normal quantiles, a normal residual frequency distribution, and residual distribution with year and residuals of the binomial distribution for the proportion of positive sets by years was illustrated in **Figure**s **21, 22** and **23**, respectively.

Consequently, the time series of abundance index for bigeye tuna estimated by entire Atlantic with logbook and TASKII data sets and by regions by TASKII data set shows in **Figure 24**. Standardized catch per unit effort of region II shows much fluctuated and of region III shows decreasing trend from 2005.

4. Discussion

There were several trials (e.g., Hsu 1999; Hsu and Liu 2000; 2001; Hsu and Lee 2002) to standardize bigeye tuna abundance index using Taiwanese longline catch and effort data from Atlantic Ocean. However, those trials need to be verified for their fitness to the fishery, and the results are uncertain due to the possible effects from the changes that have been mentioned in the Material and Methods section, in particular, the change of target species in early 1990s (Hsu and Lin 1996), the change of logbook compilation system and the setting of catch limit since 1998. Further investigations will be needed for deriving more reliable abundance index.

Further, information of a number of hooks per basket (between two floats, NHPB) was added in the logbooks for all Taiwanese distant waters longline vessels from 1995 onward, however, the percentages of returned logbooks with NHPB information were still very low. So the information seemed not useful in standardization. Lin (1998), Yeh *et al.* (2001) and Lee *et al.* (2004) have attempted to use a learning data set, which is built from the returned logbooks with NHPB, to separate the daily set in the returned logbooks without NHPB into either deep or regular longline pattern. The separation result was said about 67.7% being classified correctly in according to Lee-Nishida. method (Lee *et al.* 2004). However, if we do this so by Lin method (Lin 1998) and by Yeh method (Yeh *et al.* 2001), which almost look like Lee-Nishda method (Lee et al. 2004), the result was still not satisfactory (Hsu and Lee 2002). Consequently, the separation of fishing patterns seems not helpful on the standardization of bigeye tuna for Taiwanese longline fishery in the Atlantic. As the result, a general additive model (GAM) was used in the present study to avoid separating fishing patterns. Thus, the proportion of positive catch and positive catch rate were applied to daily sets collected from logbooks of Taiwanese longline fishery and their aggregated by vessel and by 5-degree block (TASKII data set) for GAM. And GAM may solve the problem of fishing patterns, particularly for the TASKII data set.

However, due to unbalance allocation of collection of logbooks, which were from deep longline vessels or regular longline vessels, the estimation of proportion positive catch (a probability to catch at least one bigeye tuna) may be biased. The obvious condition was occurred as in 2006, which almost all return logbooks are from deep longline vessels because followed ICCAT recommendation (05-01).

During the analysis, some daily sets were collected from small-scaled longline fishery. And the analysis was incorporated with those small-scaled longline fishery data without expelling those data out, because it is not possible to separate those data out at this moment. But this needs to be done in future study.

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Table 1. Deviance analysis table of explanatory variables in the delta lognormal model for bigeye tuna catch rates (in number per 1,000 hooks) for Taiwanese longline fishery from 1981 to 2004. Percentages of total deviance refer to the deviance explained by the full model, and p values indicate the 5% Chi-square probability between consecutive models.

(a) ALL AREAS for data of logbooks

Model factors positive catch rate values	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	181363	240671.3665		
Year	181338	187727.6568	52943.7097	28.2 <0.0001
Year Area	181327	141331.5447	46396.1121	32.8 <0.0001
Year Area Quar	181324	138941.6175	2389.9272	1.7 <0.0001
Year Area Quar Ralbrank	181321	106566.0179	32375.5996	30.4 <0.0001
Year Area Quar Ralbrank Ryftrank	181318	99088.8559	7477.1620	7.5 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	181073	94160.8485	4928.0074	5.2 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Quar	181243	96589.7378	2499.1181	2.6 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	181243	97857.9718	1230.8841	1.3 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	181245	98310.1056	778.7503	0.8 <0.0001
Year Area Quar Ralbrank Ryftrank Area*Quar	181285	96238.6604	2850.1955	3.0 < 0.0001

Model factors proportion positives	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	3541	183887.9169		
Year	3516	149415.9093	34472.0076	23.1 <0.0001
Year Area	3505	88109.1955	61306.7138	69.6 <0.0001
Year Area Quar	3502	84547.7466	3561.4489	4.2 <0.0001
Year Area Quar Ralbrank	3499	50437.7394	34110.0072	67.6 <0.0001
Year Area Quar Ralbrank Ryftrank	3496	27450.8801	22986.8593	83.7 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	3241	17471.4437	9979.4364	57.1
Year Area Quar Ralbrank Ryftrank Year*Quar	3421	25120.5009	2330.3792	9.3 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	3421	25982.1258	1468.7543	5.7
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	3423	26009.2458	1441.6343	5.5
Year Area Quar Ralbrank Ryftrank Area*Quar	3463	24841.3998	2609.4803	10.5 <0.0001

(b) ALL AREAS for data aggregated monthly from logbooks

Model factors positive catch rate values	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	29363	71809.2684		
Year	29338	55762.5459	16046.7225	22.3 <0.0001
Year Area	29327	37677.7116	18084.8343	32.4<0.0001
Year Area Quar	29324	37245.8906	431.8210	1.1 <0.0001
Year Area Quar Ralbrank	29321	25442.9913	11802.8993	31.7 <0.0001
Year Area Quar Ralbrank Ryftrank	29318	24054.4142	1388.5771	5.5 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	29072	22044.1227	2010.2915	8.4 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Quar	29243	23063.9174	990.4968	4.5 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	29244	23583.5659	470.8483	2.0 <0.0001

Year Area Quar Ralbrank Ryftrank Year*Ryftrank	29250	23795.2109	259.2033	1.1 <0.0001
Year Area Quar Ralbrank Ryftrank Area*Quar	29285	22973.5003	1080.9139	4.5 <0.0001

Model factors proportion positives	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	2369	14878.8903		
Year	2344	13494.1874	1384.7029	9.3 <0.0001
Year Area	2333	8347.3994	5146.7880	38.1<0.0001
Year Area Quar	2330	8006.1635	341.2359	4.1 <0.0001
Year Area Quar Ralbrank	2327	6339.7448	1666.4187	20.8 <0.0001
Year Area Quar Ralbrank Ryftrank	2324	4767.7765	1571.9683	24.8 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	2066	3011.0310	1756.7455	36.8
Year Area Quar Ralbrank Ryftrank Year*Quar	2249	4357.8093	409.9672	13.6<0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	2250	4467.7254	300.0511	6.9
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	2255	4485.2486	282.5279	6.3
Year Area Quar Ralbrank Ryftrank Area*Quar	2291	4278.8781	488.8984	10.9 <0.0001

Region 1

Model factors positive catch rate values	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	2889	3184.0669		
Year	2868	3036.6333	147.4336	4.6 <0.0001
Year Area	2867	2918.3629	118.2704	3.9 <0.0001
Year Area Quar	2864	2907.9125	10.4504	0.4 0.0157
Year Area Quar Ralbrank	2861	2739.0185	168.8940	5.8 <0.0001
Year Area Quar Ralbrank Ryftrank	2858	2733.7303	5.2882	0.2 0.01336
Year Area Quar Ralbrank Ryftrank Year*Area	2839	2635.6065	98.1238	3.6 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Quar	2806	2585.3672	148.3631	5.6 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	2837	2625.6401	108.0902	4.2 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	2851	2687.6236	46.1067	1.8 <0.0001
Year Area Quar Ralbrank Ryftrank Area*Quar	2855	2650.1563	83.5740	3.1 <0.0001

Model factors proportion positives	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	177	592.4833		
Year	152	286.1474	306.3359	51.7
Year Area	151	282.0012	4.1462	1.4
Year Area Quar	148	275.3409	6.6603	2.4
Year Area Quar Ralbrank	145	267.9128	7.4281	2.7
Year Area Quar Ralbrank Ryftrank	142	259.7279	8.1849	3.1
Year Area Quar Ralbrank Ryftrank Year*Area	123	212.3077	47.4202	18.3
Year Area Quar Ralbrank Ryftrank Year*Quar	80	120.4929	139.2350	65.6
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	118	210.3203	49.4076	41.0
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	133	232.0885	27.6394	13.1

Year Area Quar Ralbrank Ryftrank Area*Quar	139	256.7889	2.9390	1.3

Region 2

Model factors positive catch rate values	*DF*	*Deviance*	*Change deviance*	*% total deviance*
Intercept	17094	32518.3483		
Year	17069	21275.6327	11242.7156	34.6 <0.0001
Year Area	17064	18053.1495	3222.4832	15.1 <0.0001
Year Area Quar	17061	17613.1283	440.0212	2.4 <0.0001
Year Area Quar Ralbrank	17058	11167.6678	6445.4605	36.6 <0.0001
Year Area Quar Ralbrank Ryftrank	17055	10010.7448	1156.9230	10.4<0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	16946	9504.1208	506.6240	5.1 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Quar	16984	9555.0781	455.6667	4.8 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	16990	9655.4809	355.2639	3.7 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	16990	9842.0716	168.6732	1.7 <0.0001
Year Area Quar Ralbrank Ryftrank Area*Quar	17040	9844.9520	165.7928	1.7 <0.0001

Model factors proportion positives	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	1418	8092.7857		
Year	1393	6537.5460	1555.2397	19.2 <0.0001
Year Area	1388	4893.2311	1644.3149	25.2 <0.0001
Year Area Quar	1385	4787.6613	105.5698	2.2 <0.0001
Year Area Quar Ralbrank	1382	3516.8803	1270.7810	26.5 <0.0001
Year Area Quar Ralbrank Ryftrank	1379	1731.8764	1785.0039	50.8 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	1263	1279.3787	452.4977	26.1
Year Area Quar Ralbrank Ryftrank Year*Quar	1304	1425.1868	306.6896	24.0
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	1313	1470.0782	261.7982	18.4
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	1313	1533.7799	198.0965	13.5
Year Area Quar Ralbrank Ryftrank Area*Quar	1364	1674.6554	57.2210	3.7 <0.0001

Region 3

Model factors positive catch rate values	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	9378	16004.1855		
Year	9353	14678.0886	1326.0969	8.3 <0.0001
Year Area	9350	13546.5324	1131.5562	7.7 <0.0001
Year Area Quar	9347	12994.9489	551.5835	4.1 <0.0001
Year Area Quar Ralbrank	9344	10111.0831	2883.8658	22.2 <0.0001
Year Area Quar Ralbrank Ryftrank	9341	9893.4122	217.6709	2.2 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Area	9269	9161.0803	732.3319	7.4 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Quar	9270	9403.1266	490.2856	5.4 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	9277	9635.5172	257.8950	2.7 <0.0001
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	9302	9759.6057	133.8065	1.4 <0.0001

Year Area Quar Ralbrank Ryftrank Area*Quar	9332	9761.7723	131.6399	1.3 <0.0001

Model factors proportion positives	*DF*	*Deviance*	*Change deviance*	*% total deviance (<P)*
Intercept	772	3651.5647		
Year	747	3221.5233	430.0414	11.8 <0.0001
Year Area	744	2568.9964	652.5269	20.3 <0.0001
Year Area Quar	741	2139.4928	429.5036	16.7 <0.0001
Year Area Quar Ralbrank	738	1750.6740	388.8188	18.2 <0.0001
Year Area Quar Ralbrank Ryftrank	735	1729.7163	20.9577	1.2
Year Area Quar Ralbrank Ryftrank Year*Area	662	1234.8402	494.8761	28.6
Year Area Quar Ralbrank Ryftrank Year*Quar	663	1341.5182	388.1981	31.4
Year Area Quar Ralbrank Ryftrank Year*Ralbrank	670	1614.8960	114.8203	8.6
Year Area Quar Ralbrank Ryftrank Year*Ryftrank	691	1612.5490	117.1673	7.3
Year Area Quar Ralbrank Ryftrank Area*Quar	726	1649.6827	80.0336	5.0 <0.0001

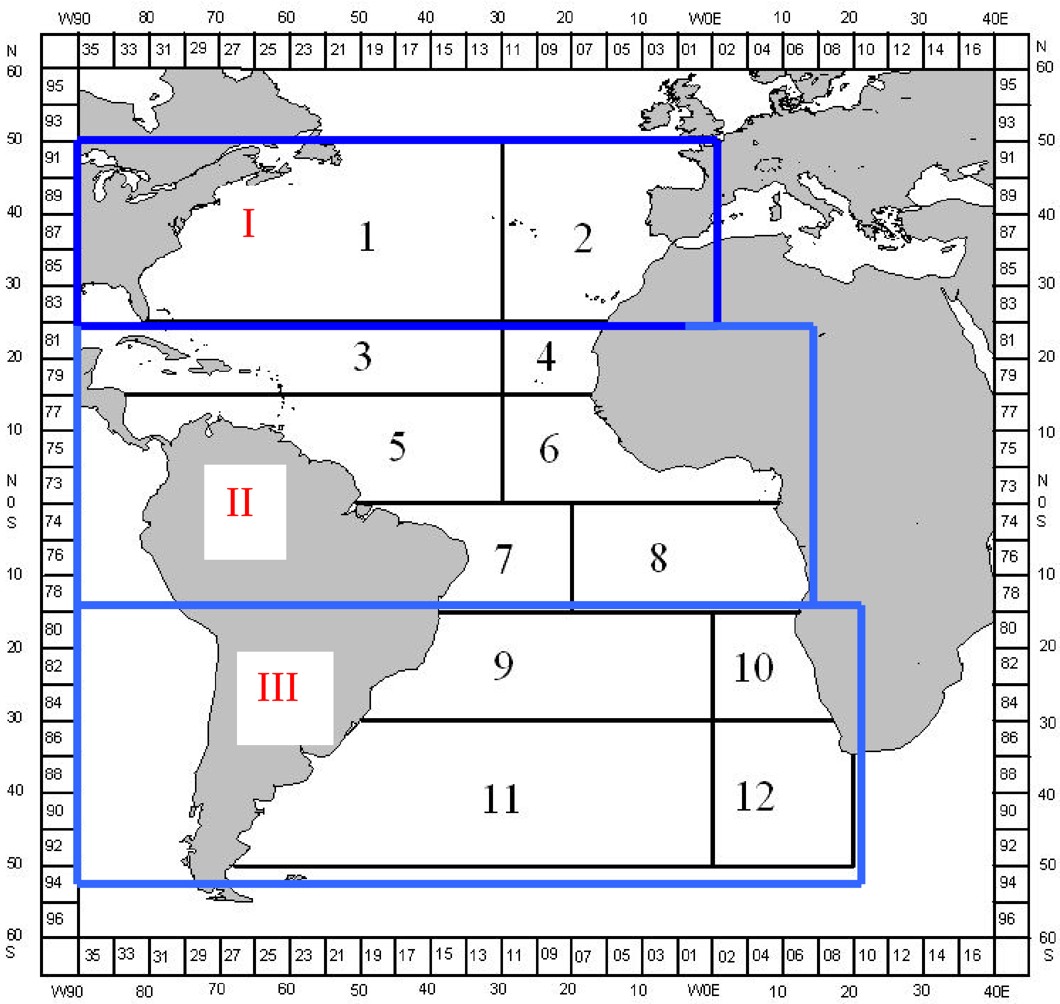


Figure 1. Area stratification of Atlantic for standardizing bigeye tuna catch per unit effort.

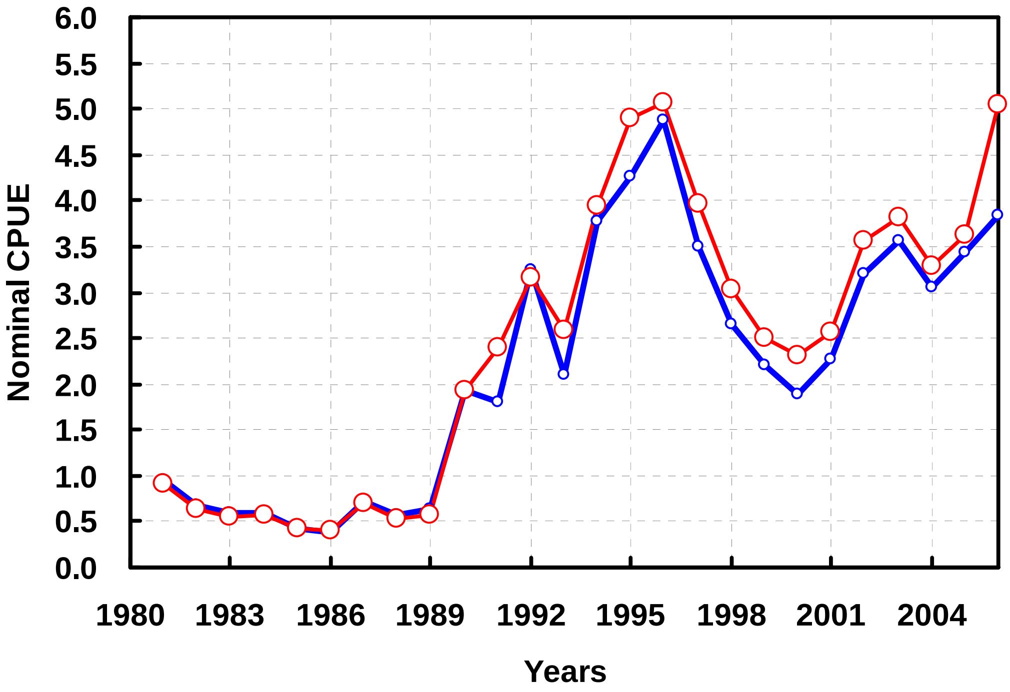


Figure 2. Nominal CPUE of bigeye tuna for Taiwanese longline fishery in the Atlantic from 1981 to 2006, estimated from logbooks (red curve) and monthly aggregated data (blue curve) for positive catch.

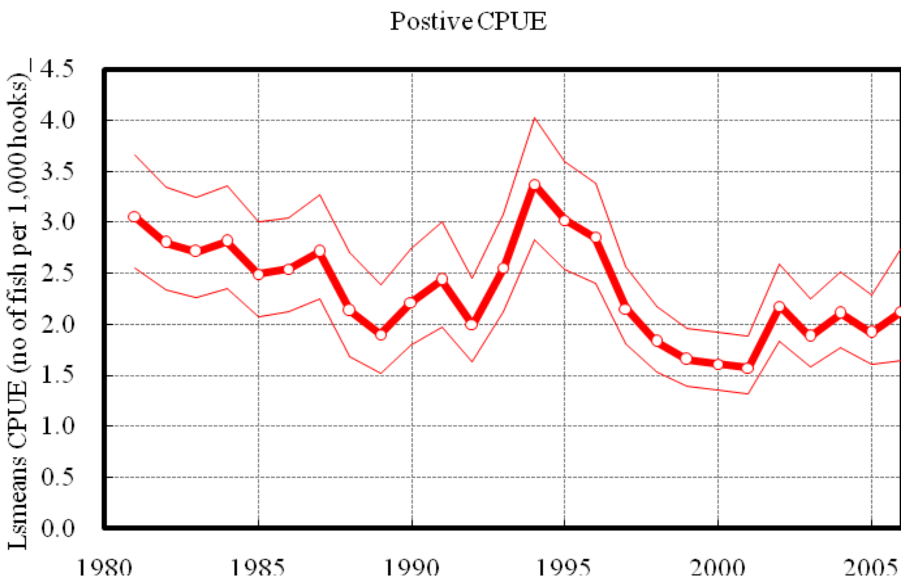


Figure 3. Standardized CPUE of bigeye tuna for Taiwanese longline fishery in the Atlantic from 1981 to 2006, estimated from logbooks for positive catch.

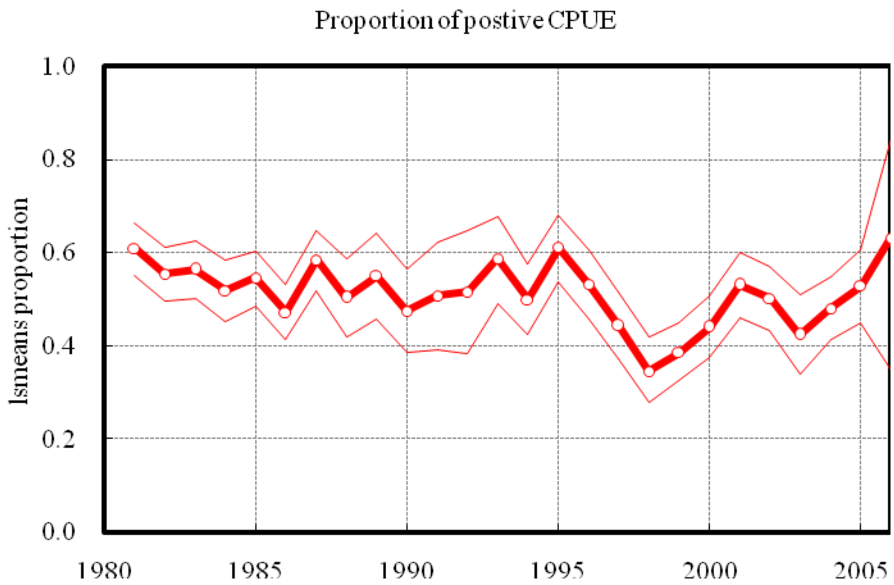


Figure 4. Observed probability of positive sets to catch bigeye tuna for Taiwanese longline fishery in the Atlantic, estimated from daily records of logbooks from 1981 to 2006.

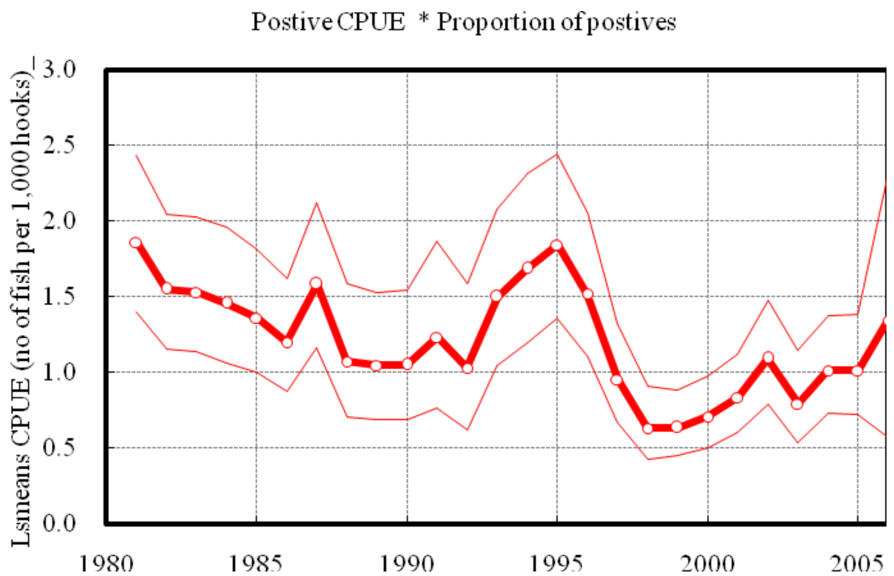


Figure 5. Standardized CPUE of bigeye tuna for Taiwanese longline fishery in the Atlantic from 1981 to 2006, estimated from daily logbooks.

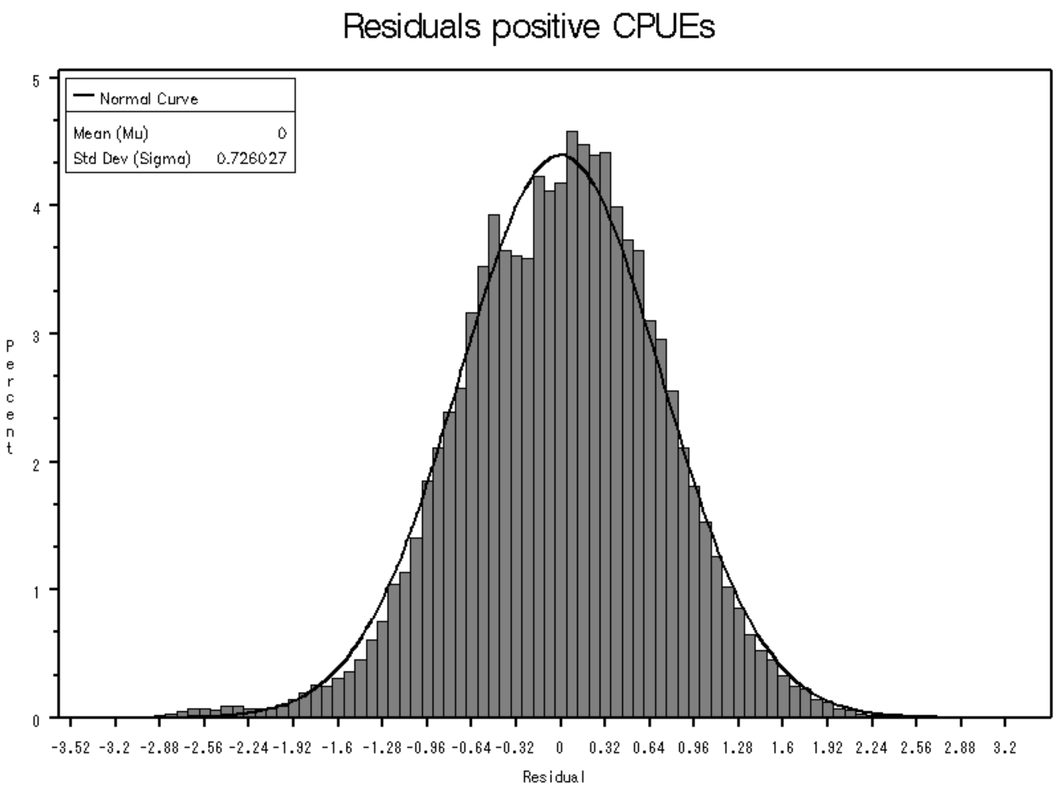


Figure 6. Residual frequency distribution of positive catch rate sets with delta lognormal errors for bigeye tuna caught by Taiwanese longline fleets in the Atlantic from 1981 to 2006.

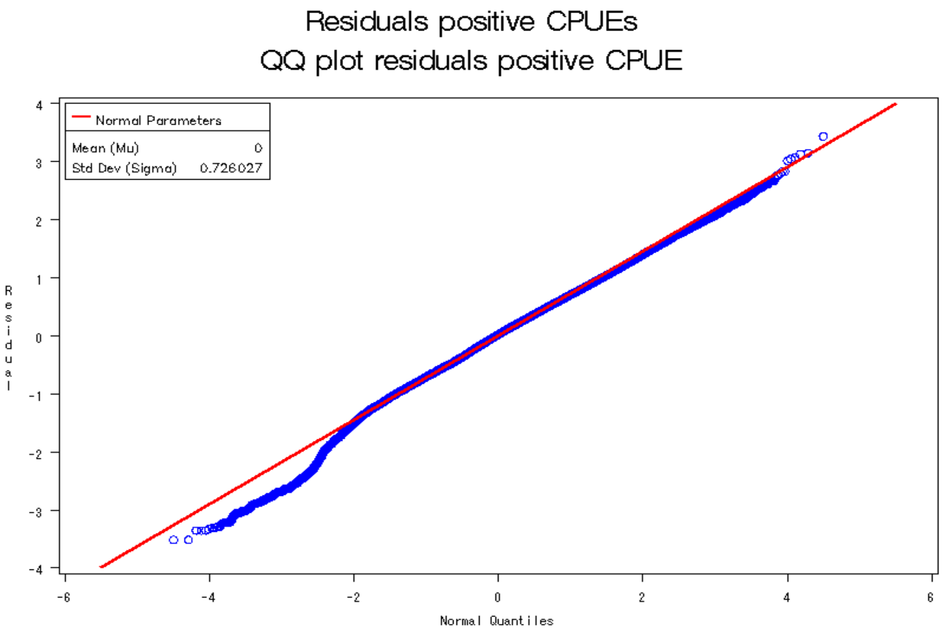


Figure 7. The Q-Q plot for the residuals of using general linear mixed model with delta log-normal error structure to standardize observed positive catch rate of bigeye tuna caught by Taiwanese longline fishery in the Atlantic from 1981 to 2006.

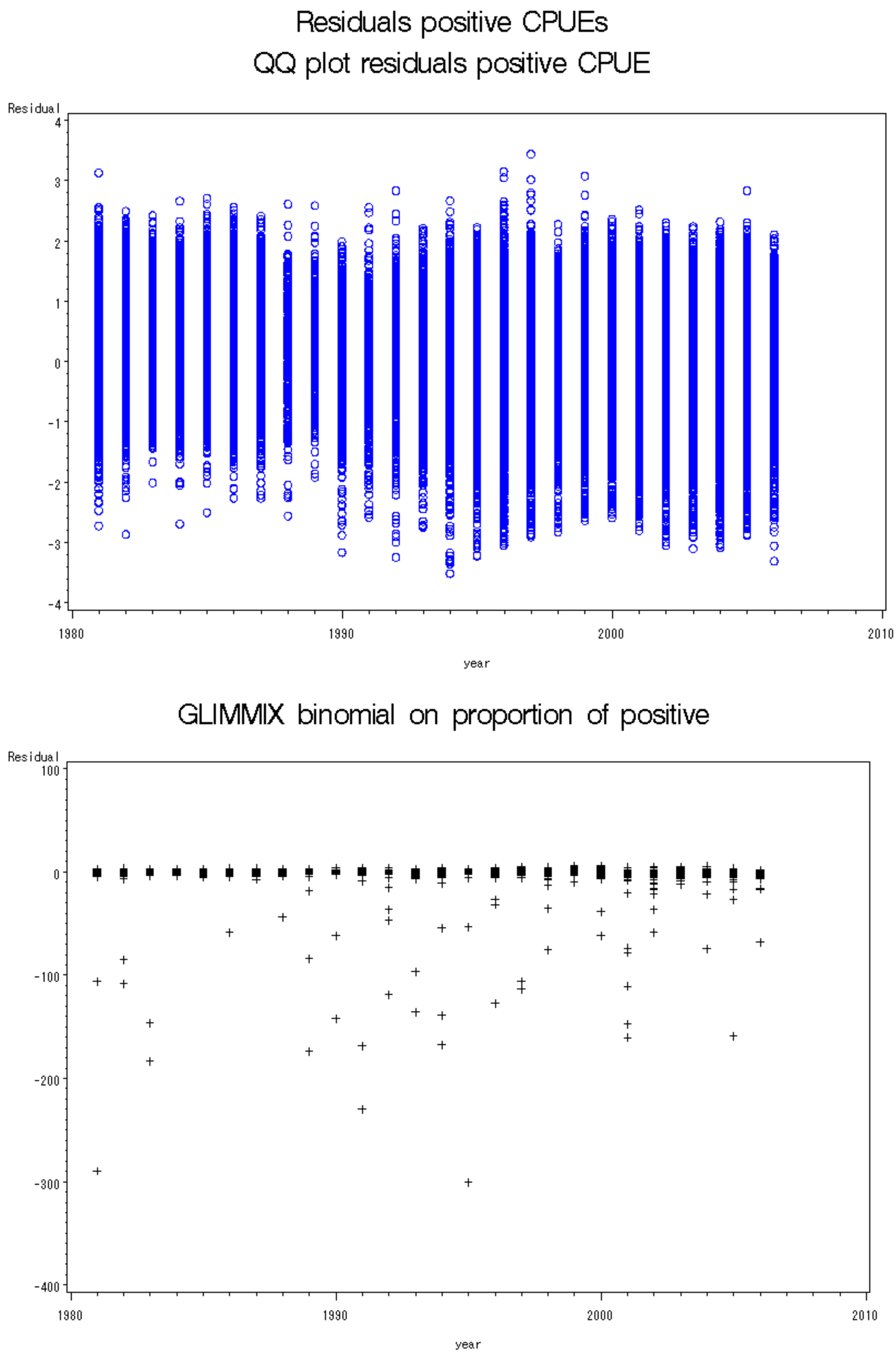


Figure 8. Diagnostic plot: Chi-square residuals of the residuals of the lognormal assumed error distribution for the positive sets (upper), and binomial assumed error distribution for the proportion of positive sets of bigeye tuna (lower).

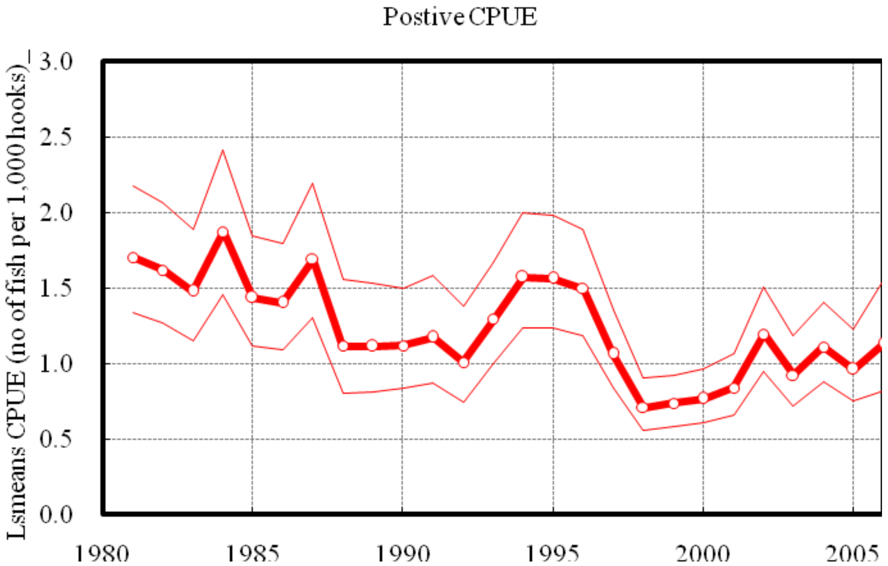


Figure 9. Standardized CPUE of bigeye tuna for Taiwanese longline fishery in the Atlantic from 1981 to 2006, estimated from monthly aggregated data of logbooks for positive catch.

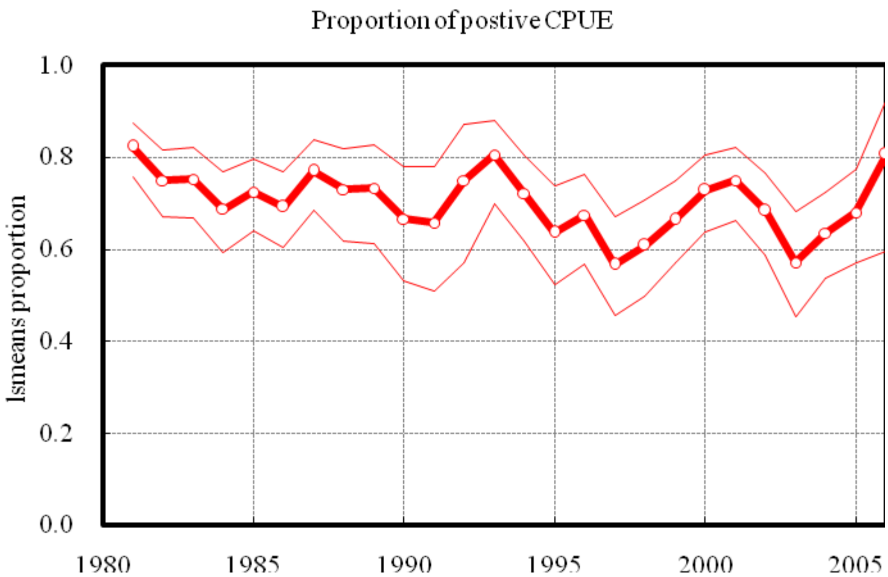


Figure 10. Observed probability of positive sets for Taiwanese longline fishery in the Atlantic, estimated from monthly aggregated data of daily records of logbooks from 1981 to 2006.

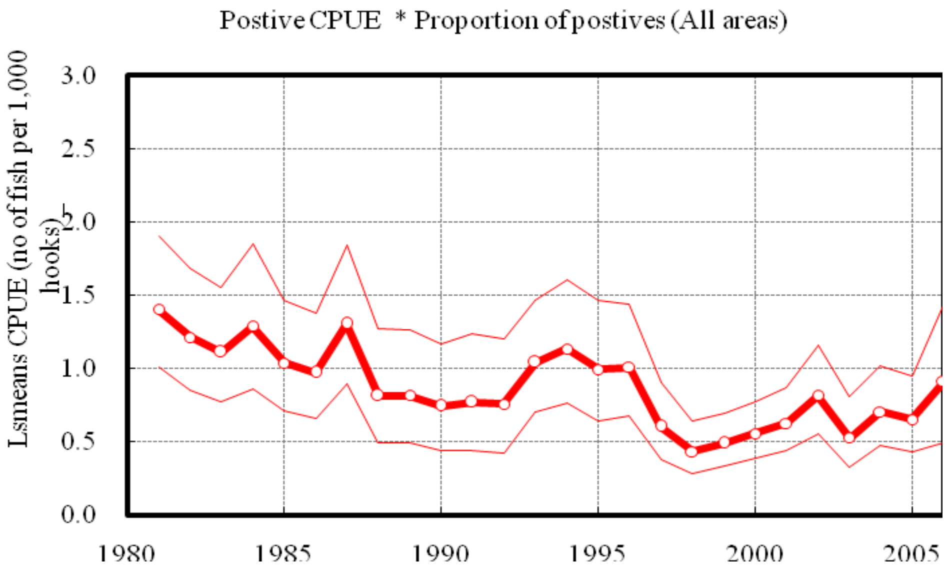


Figure 11. Standardized CPUE of bigeye tuna for Taiwanese longline fishery in the Atlantic from 1981 to 2006, estimated from monthly aggregated data of logbooks.

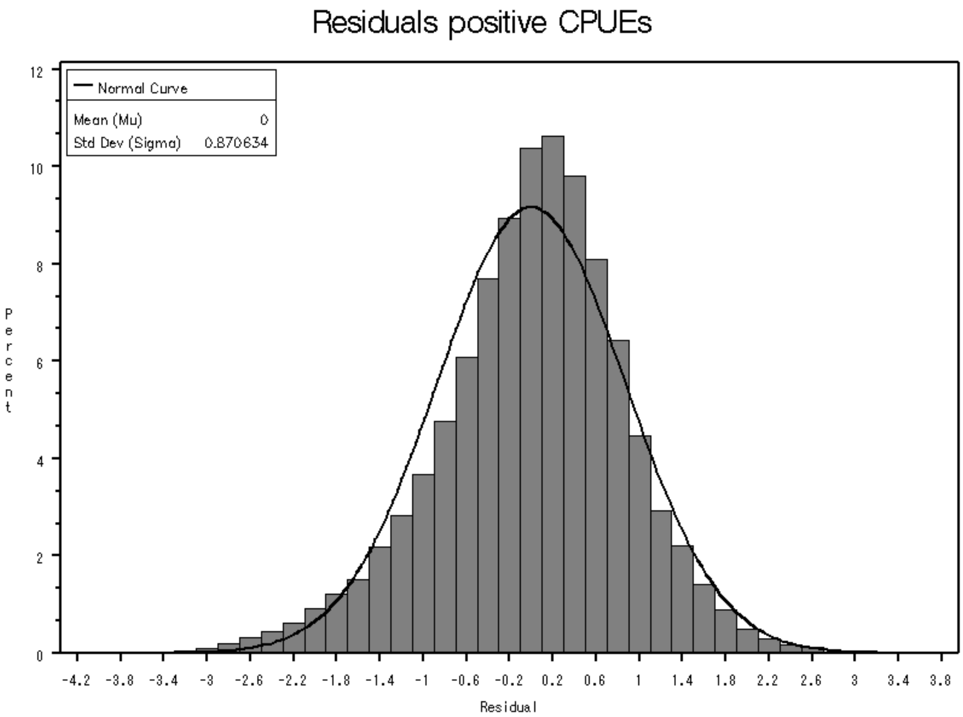
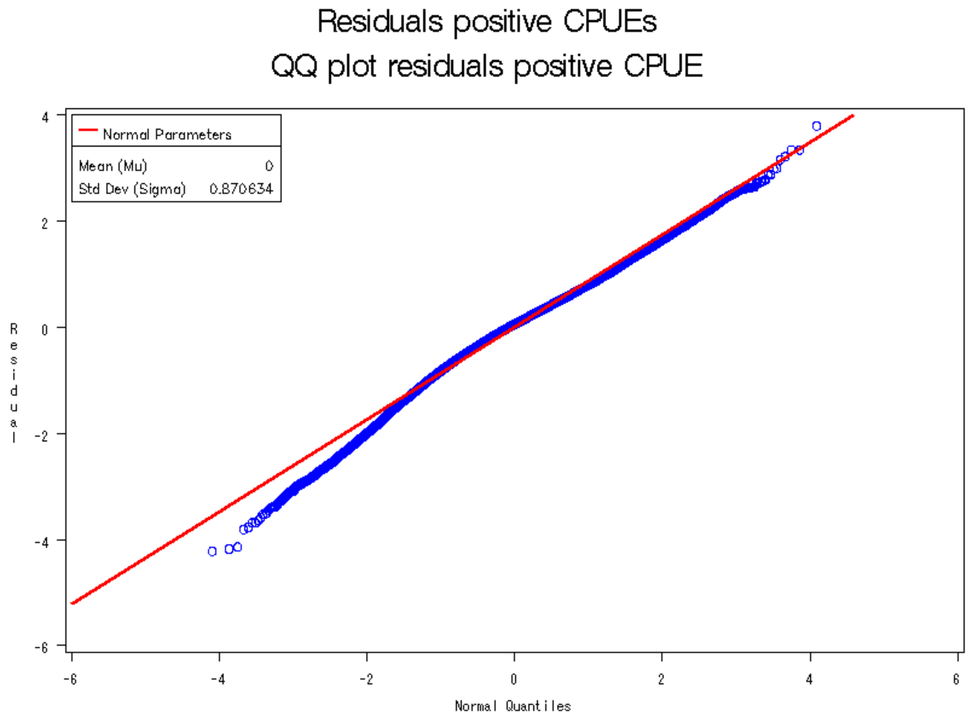


Figure 12. Residual frequency distribution of positive catch rate sets with delta lognormal errors for bigeye tuna caught by Taiwanese longline fleets in the Atlantic from 1981 to 2006.



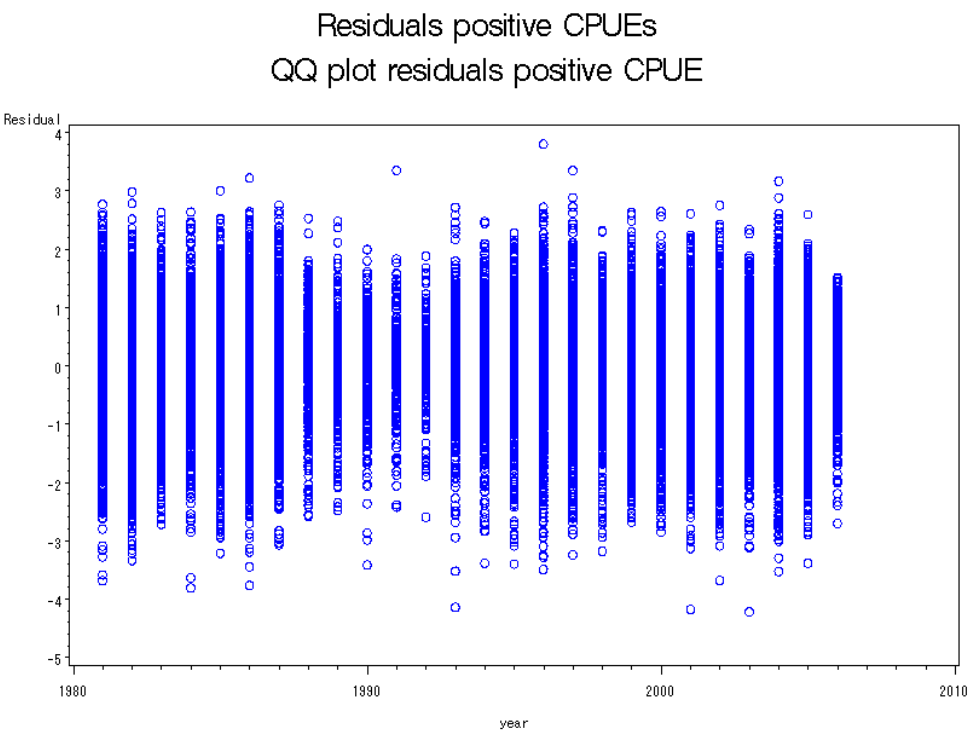


Figure 13. The Q-Q plot for the residuals of using general linear mixed model with delta log-normal error structure to standardize observed positive catch rate of bigeye tuna caught by Taiwanese longline fishery in the Atlantic from 1981 to 2006.

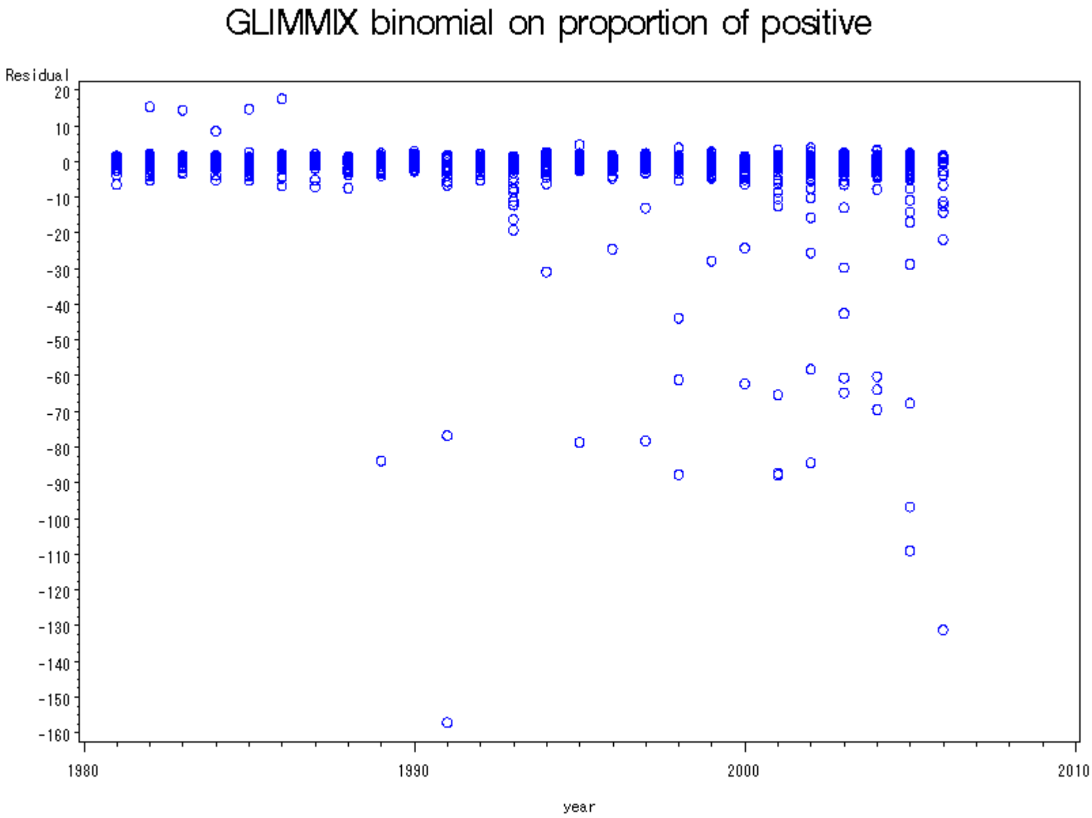


Figure 14. Diagnostic plot: Chi-square residuals of the binomial assumed error distribution for the proportion of positive sets of bigeye tuna (upper), and residuals of the lognormal assumed error distribution for the positive sets (lower).

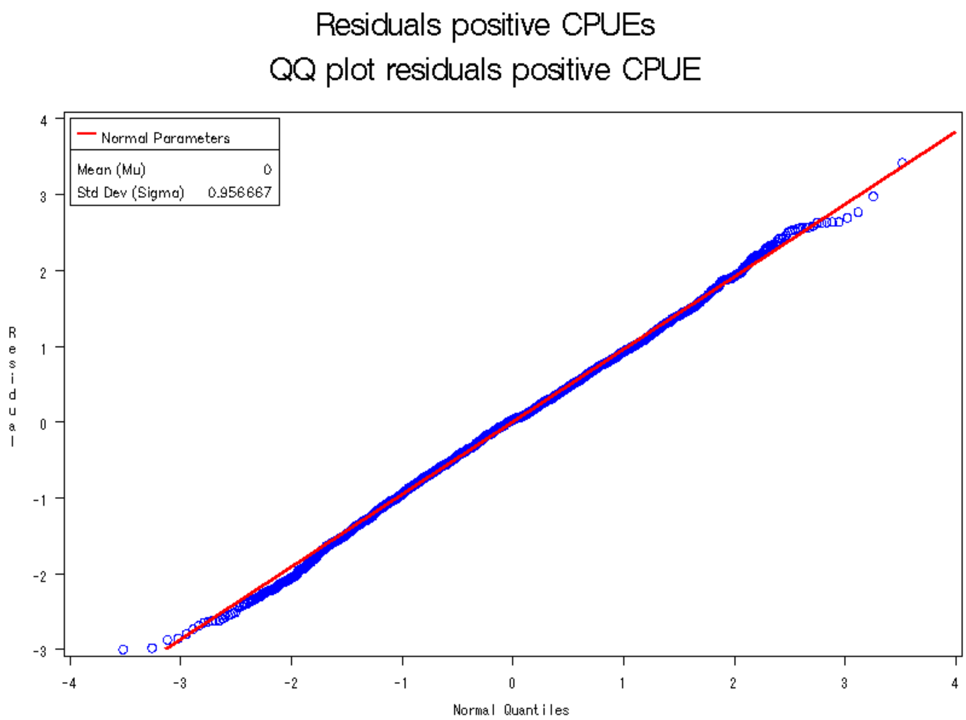


Figure 15. The Q-Q plot for the residuals of using general linear mixed model with delta log-normal error structure to standardize observed positive catch rate of bigeye tuna caught by Taiwanese longline fishery in the Atlantic from 1981 to 2006 for region I.

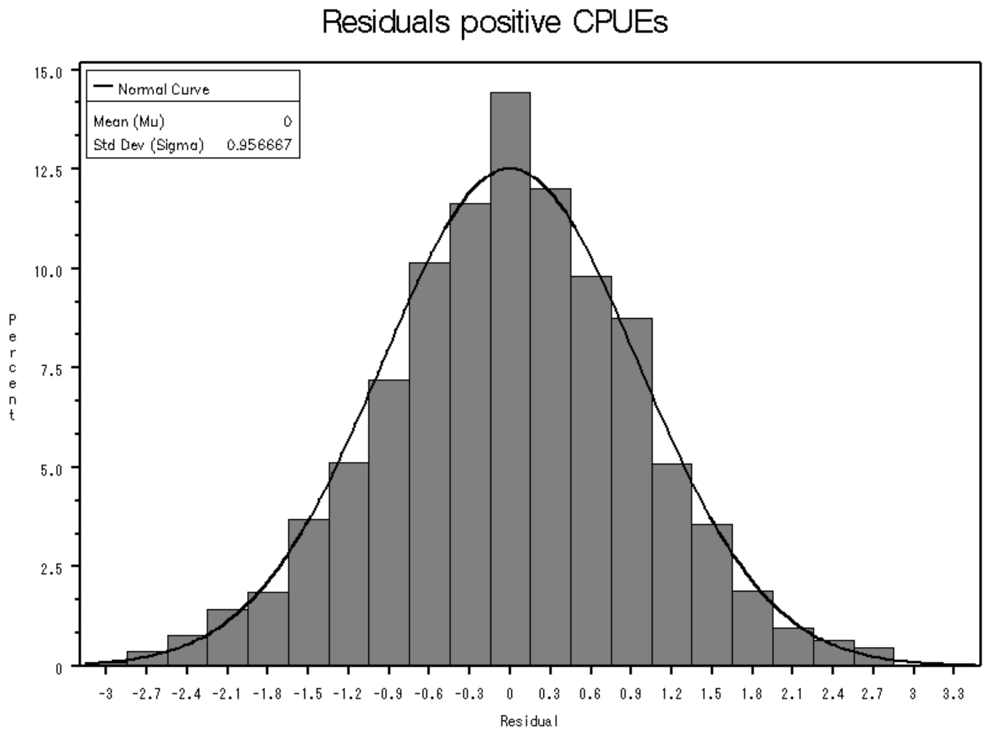


Figure 16. Residual frequency distribution of positive catch rate sets with delta lognormal errors for bigeye tuna caught by Taiwanese longline fleets in the Atlantic from 1981 to 2006 for region I.

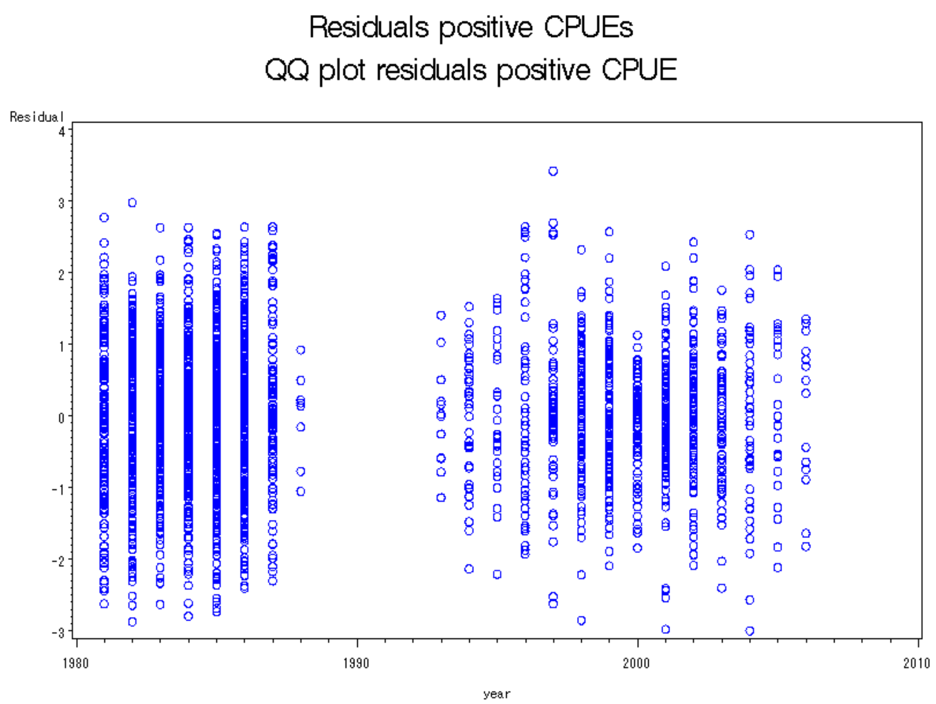


Figure 17. Diagnostic plot: Chi-square residuals of the residuals of the lognormal assumed error distribution for the positive sets (upper), and binomial assumed error distribution for the proportion of positive sets of bigeye tuna (lower) for Region I..

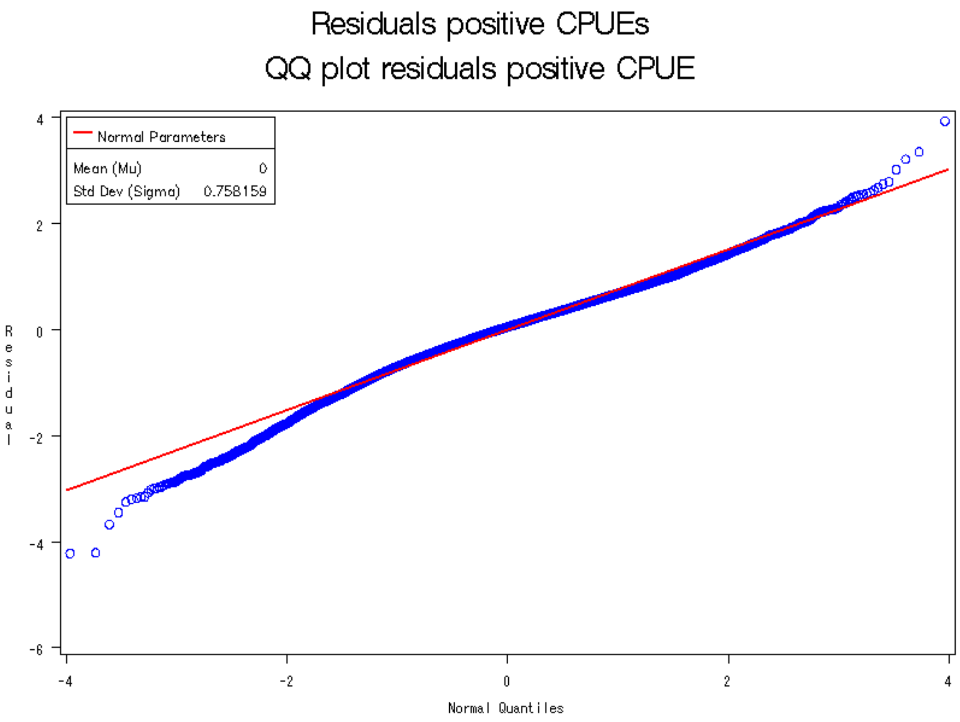


Figure 18. The Q-Q plot for the residuals of using general linear mixed model with delta log-normal error structure to standardize observed positive catch rate of bigeye tuna caught by Taiwanese longline fishery in the Atlantic from 1981 to 2006 for region II.

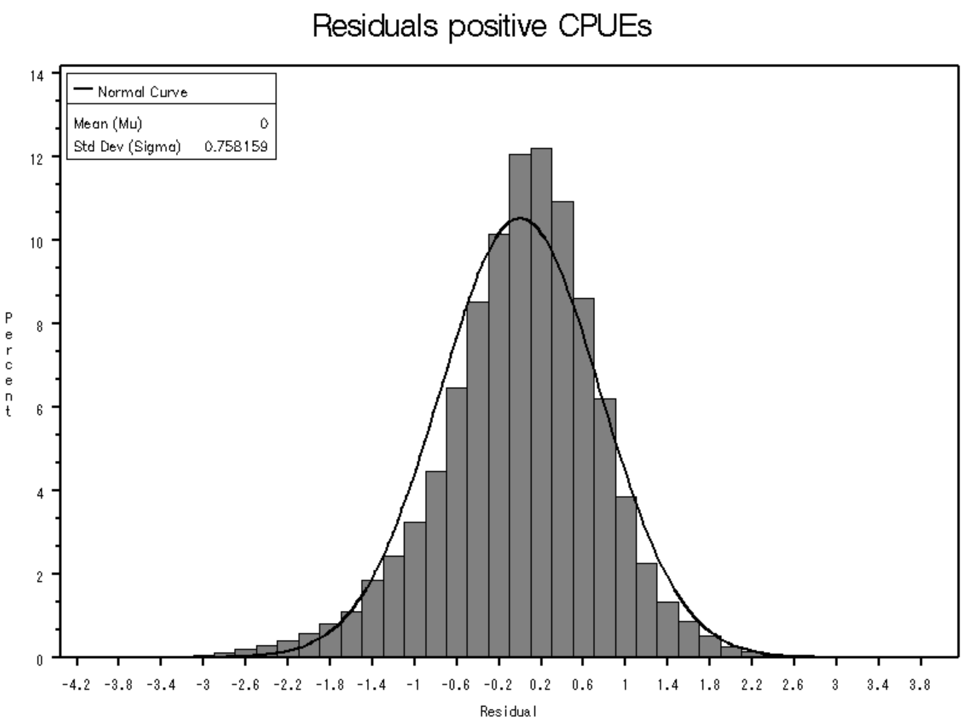
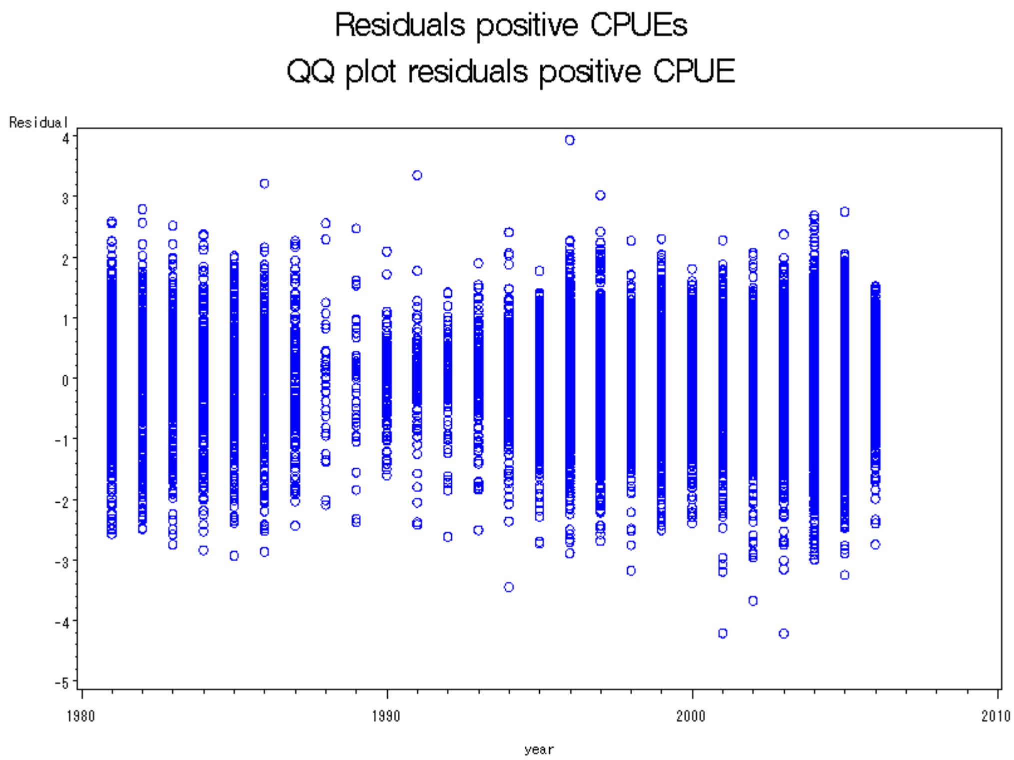


Figure 19. Residual frequency distribution of positive catch rate sets with delta lognormal errors for bigeye tuna caught by Taiwanese longline fleets in the Atlantic from 1981 to 2006 for region II.



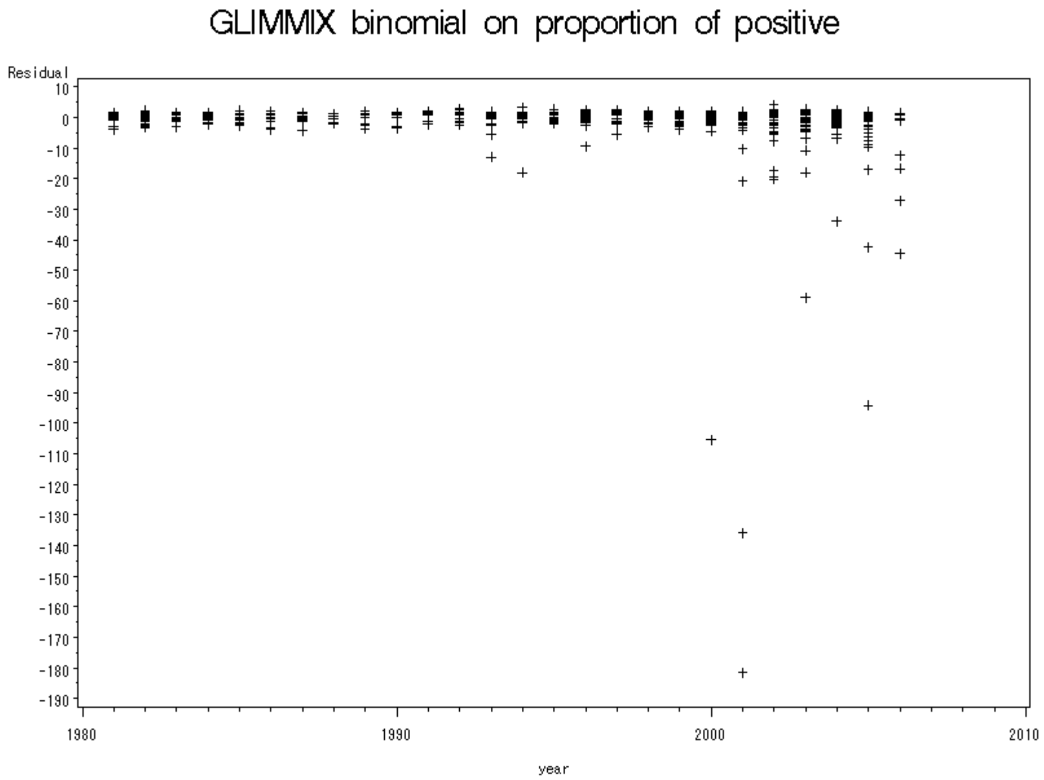


Figure 20. Diagnostic plot: Chi-square residuals of the residuals of the lognormal assumed error distribution for the positive sets (upper), and binomial assumed error distribution for the proportion of positive sets of bigeye tuna (lower) for Region II.

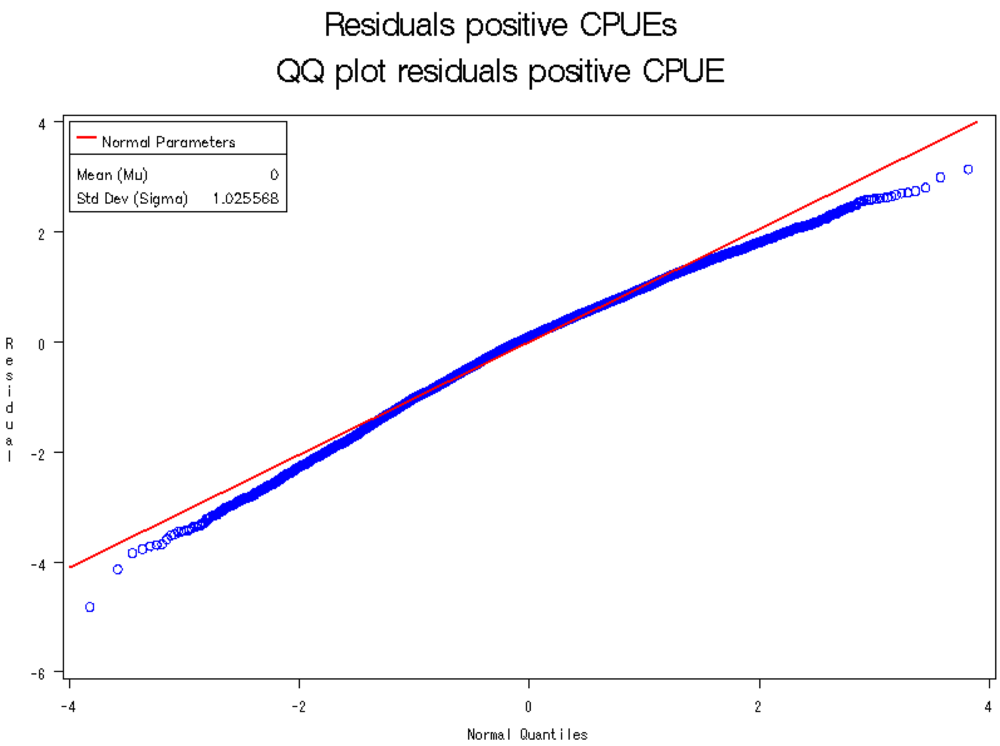


Figure 21. The Q-Q plot for the residuals of using general linear mixed model with delta log-normal error structure to standardize observed positive catch rate of bigeye tuna caught by Taiwanese longline fishery in the Atlantic from 1981 to 2006 for region III.

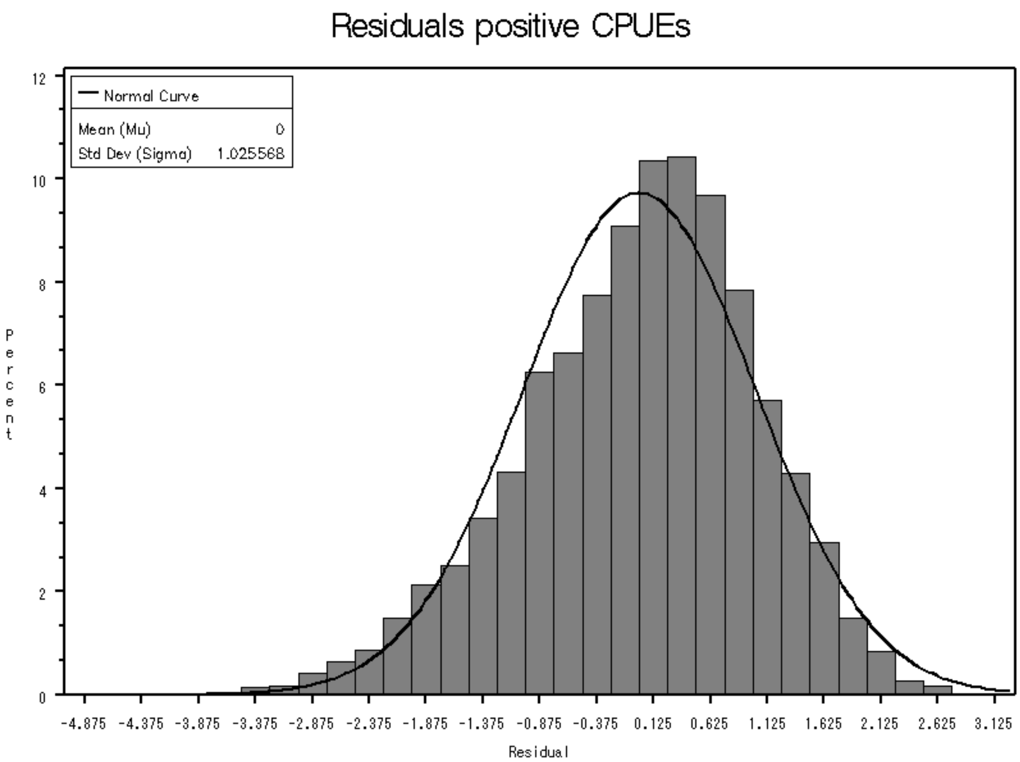
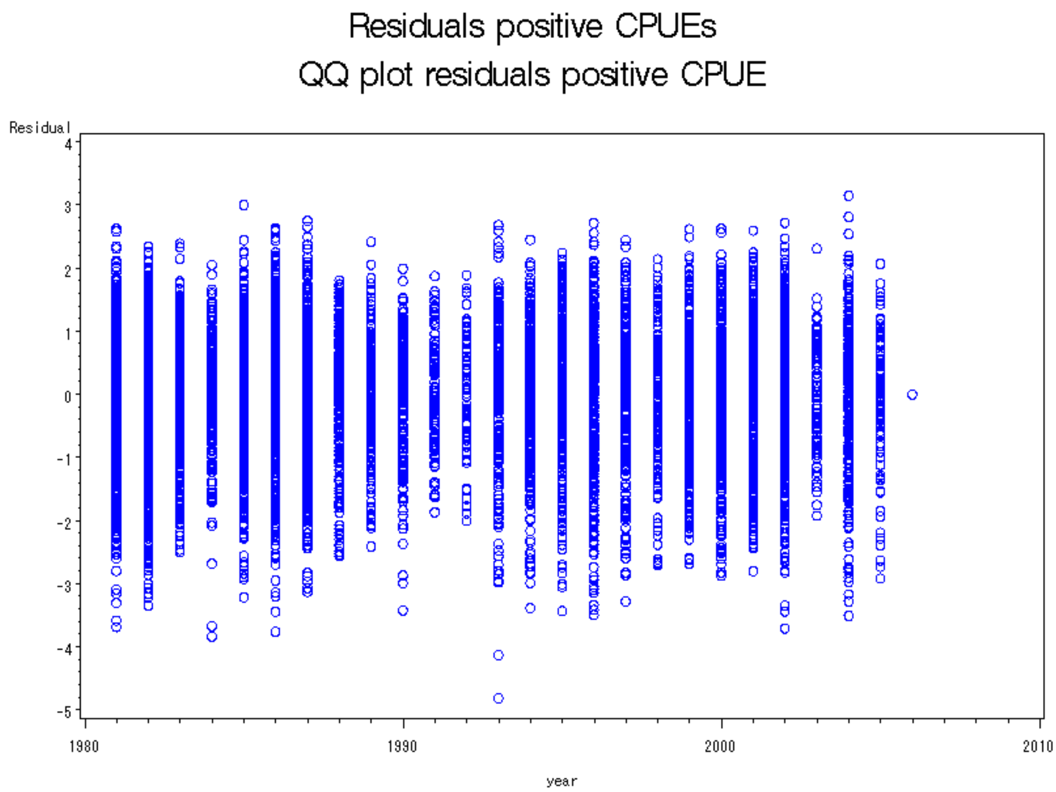


Figure 22. Residual frequency distribution of positive catch rate sets with delta lognormal errors for bigeye tuna caught by Taiwanese longline fleets in the Atlantic from 1981 to 2006 for region III.



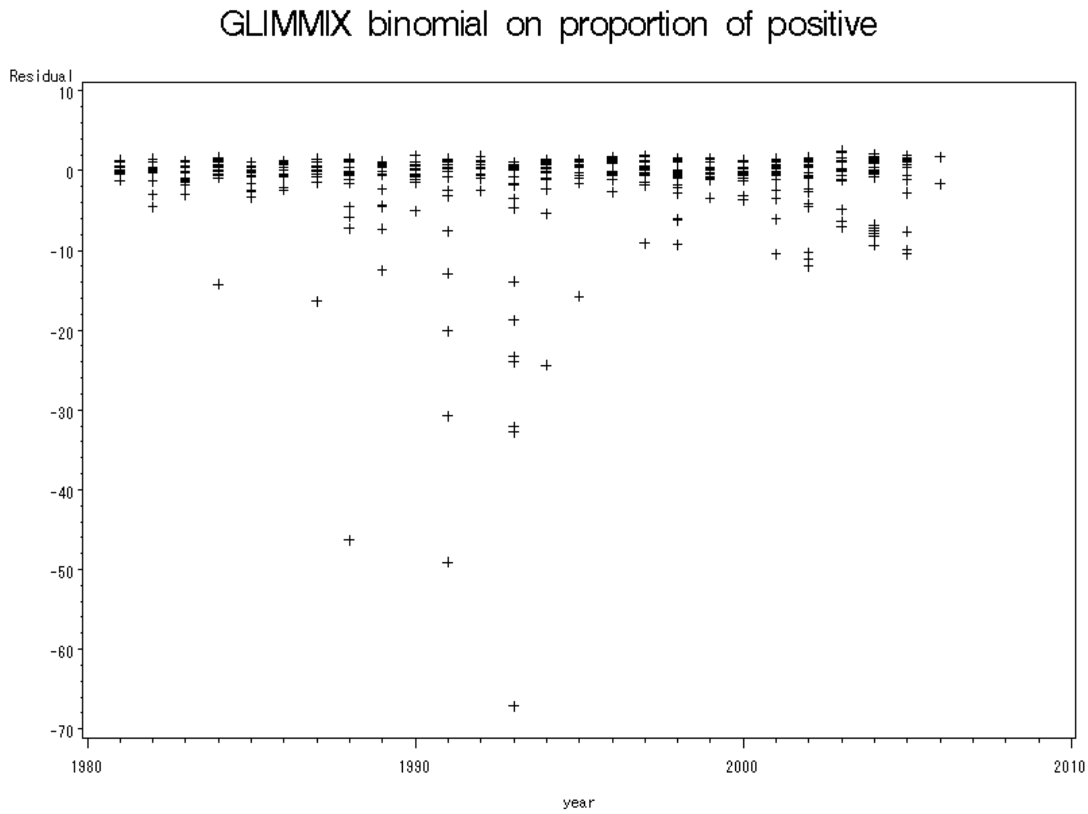


Figure 23. Diagnostic plot: Chi-square residuals of the residuals of the lognormal assumed error distribution for the positive sets (upper), and binomial assumed error distribution for the proportion of positive sets of bigeye tuna (lower) for Region III.

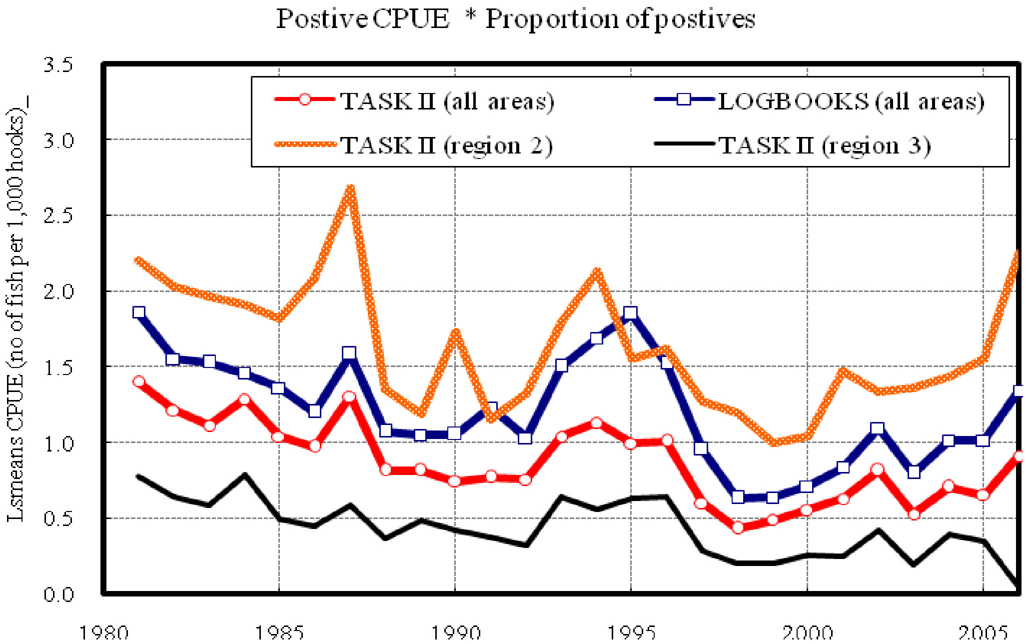


Figure 24. Time series of standardized abundance indices of bigeye tuna by Taiwanese longline fishery, estimated by integrating the results from the binomial and lognormal error models for Taiwanese longline fishery from 1981 to 2006 for the entire Atlantic by different data sets and by regions.