Received: 30 June & 28 July 2014

REUNION ISLAND PELAGIC LONGLINE FISHERY CHARACTERIZATION AND STANDARDIZATION OF ALBACORE CATCH RATES

Rui Coelho[1,*], Natacha Nikolic[2], Hugues Evano[2], Miguel N. Santos[1]
Jérôme Bourjea[2]

SUMMARY

This document presents a characterization of the Reunion Island pelagic longline fishery, with a first description of the albacore catches, catch-at-size, and the standardized catch per unit of effort (CPUE) series for the period 1992-2013. The spatial catch and effort analysis revealed the major areas of operation of the fishery, and the identification of the fishery core region closer to the Reunion Island area. The trends in the albacore catch-at-size were analyzed annually, and compared between the seasons and regions of operation of the fishery. The albacore nominal CPUEs were calculated as number of fish per 1000 hooks, and were standardized using Generalized Linear Models (GLMs). Four different modeling approaches were used (including Tweedie, lognormal, Negative Binomial and Delta-method models) and compared in a sensitivity analysis. The models were compared with goodness-of-fit measures, and validated with residual analysis. The results presented in this paper, in particular the proposed albacore annual index of abundance, is a further contribution by the European Union to contribute for the assessment of the species in the Indian Ocean.

KEYWORDS: Albacore, catch and effort, catch at size, CPUE standardization, longline fisheries, SW Indian Ocean, *Thunnus alalunga*.

1: IPMA, I.P. - Instituto Português do Mar e da Atmosfera. Av. 5 de Outubro s/n, 8700-305 Olhão, Portugal.
2: IFREMER, Délégation Océan Indien, Laboratoire Ressources Halieutiques. Rue Jean Bertho BP 60, 97822 Le Port Cedex, La Reunion.
*: Corresponding author e-mail: rpcoelho@ipma.pt

1. Introduction

Fisheries management is usually based on stock assessment models that require data on the abundance of the species under assessment (Hilborn and Walters 1992). Ideally, data for such models should be fishery-independent but, when assessing pelagic and migratory species that cover wide geographical areas (e.g. tunas, billfishes and pelagic sharks) this type of fisheries-independent data is usually not available. Therefore, most stock assessments currently carried out for pelagic species are based on fishery-dependant data, available from the commercial fisheries that capture those species. The data usually gathered from the commercial fisheries and analyzed is the Catch per Unit of Effort (CPUE, either in number or biomass), and it is important to standardize those CPUE trends to account for effects (consequence of the fishery-dependence) other than the annual variations in the abundance of the species being analyzed (Maunder and Punt 2004). The primary objective of the CPUE standardization process is therefore to estimate a time series of relative abundance of a species, from which the fishery-dependant effects have been removed, and that can therefore be used as an annual index of abundance for stock assessment purposes.

The Reunion Island semi-industrial pelagic longline fishery started in 1991 and has operated most consistently in the vicinity of Reunion Island. However, in some years, particularly in the earlier years of the fishery, substantial operations were undertaken farther away in the Mozambique Channel and northward in the Seychelles region. This fishery targets as a primary resource swordfish (*Xiphias gladius*) and therefore fishing operation (i.e. sets) occurs during the night. However, even considering that the fishery did not majorly change its fishing strategy over time, it started in the 1900s with a species composition of catches largely dominated by swordfish (70%), and 30% of tuna and tuna-like species), while this ratio changed in the last years to catches dominated by tuna species (70%) and only 30% of swordfish. Descriptions of the fishery, especially during the earlier years of the development stage of the fishery were described in detail by Poisson and Rene (1999) and Poisson and Taquet (2001).

In the Indian Ocean, the previous albacore (ALB) stock assessment was carried out in 2012, with the current management advice based on an age-structured production model (ASPM) described by Nishida et al. (2012). For that assessment three standardized Catch per Unit of Effort (CPUE) indexes from pelagic longline fisheries were available, specifically the Japanese series between 1966-2010 (Matsumoto et al. 2012), the Korean series between 1986-87 and 1990-2010 (Lee et al. 2012) and the Taiwanese series between 1980-2010 (Lee et al. 2012). However, only the Taiwanese series and a combined CPUE (weighted average of the Japan and Taiwan series) were used in the models. The assessment results showed that the more recent albacore catches were above the MSY level with the fishing mortality exceeding F_{MSY} (F_{2010}/F_{MSY} = 1.33), and the spawning biomass was considered to be at or very near the SB_{MSY} level (SB_{2010}/SB_{MSY} = 1.05). Thus, the last IOTC albacore assessment carried out in 2012 indicated that the stock was subject to overfishing, but not overfished at that time.

As a new albacore stock assessment is schedule for 2014 during the WPTmT5, the main goal of this study was to present information from the Reunion Island pelagic longline fishery that may be relevant and used in that evaluation process. Particularly, the specific objectives of this paper were to: 1) analyze the Reunion Island pelagic longline fishery effort distribution; 2) analyze the spatial and seasonal variability in the albacore catches; 3) analyze the albacore catch-at-size distribution in the fishery, and 4) standardize the Reunion Island pelagic longline albacore CPUE time series for potential use as an annual index of abundance.

2. Material and methods

2.1. Data collection

Four distinct datasets were available for the Reunion Island French longline fishery, maintained by Ifremer (La Reunion), which are summarized in **Table 1**.

The first dataset covers the period between 1992 and 2001, and derives from a voluntary logbook program (Poisson and Taquet, 2001), which covered the majority of sets during that period in the early stages of the fishery. This dataset includes several operational factors that may be important for the CPUE standardization analysis. The number of observations in 1992, 1993 (low number of boats in activity) and 2001 was very low, making their use within the CPUE standardization process of marginal value, and as such those years were excluded from the CPUE standardization models.

The second dataset covers data between 2001 and 2004, with the data grouped by fishing trips. This dataset does not have individual fishing sets information with date or locations, nor the conventional unit of longline effort (i.e. number of hooks). Given the clustered nature of the data and the lack of set-specific catch, effort and location information, it was not possible to integrate this dataset with the rest of the analysis and therefore it was not further analyzed.

The third and fourth datasets covers data between 2005 and 2013, and were obtained from the more recent mandatory logbook program. Between 2005 and 2011 the program used the traditional logbooks directly reported by the skippers. In 2012 the program started to use electronic logbooks and VMS (Vessel Monitoring System) data to determine the fishing locations. However, in the more recent years (2012 and 2013) the skippers no longer reported the effort in number of hooks and, as such, those were estimated using the known total annual effort and the effective fishing set time calculated from the VMS system. Some data fields that were reported in the original dataset (1992-2001 period) were missing in this dataset (e.g. lightstick use, temperature), which only makes those two periods partly compatible. Still, some other variables as the vessel ID (and corresponding characteristics such as size and year of construction) are compatible between the two periods and datasets, and could therefore be used in the CPUE standardization models.

Table 1. Summary of Reunion Island longline fishery datasets characteristics, available for albacore CPUE standardization.

Dataset Characteristic	**Dataset period**			
	(1992-2001)	**(2001-2004)**	**(2005-2011)**	**(2012-2013)**
Logbook Programme	Voluntary	-	Mandatory (traditional)	Mandatory (electronic)
Detail level	Set	Trip	Set	Set
Set time	Yes	No	Yes	Yes
Location	Yes (cords. by set)	No	Yes (1x1 squares)	Yes (VMS)
Effort Units	Hooks per set	Sets per trip	Hooks per set	Hooks per set (estimated from set time)
Light sticks reported	Yes	No	No	No
Vessel ID	Yes	Yes	Yes	Yes
Other species catch	Yes	Yes	Yes	Yes
Catch units	Numbers	-	Estimated biomass	Estimated biomass
Other variables	Gear configuration, vessel characteristics, temperature, lightsticks use.		Vessel characteristics	Vessel characteristics
Number of observations	7970 sets	1773 trips	19003 sets	6255 sets

2.2. Exploratory data analysis

The spatial catch and effort was mapped and plotted in order to identify the major areas of operation of the Reunion Island pelagic longline fleet. This analysis was carried out separately for the two fishing periods (1992-2000 and 2005-2013) in order to understand eventual shifts in the spatial distribution of the fishery between the periods. The CPUE, measured in number of albacore (ALB) per 1000 hooks (N/1000 hooks), were plotted in each of the regions and along the months/seasons of the year, in order to describe the patterns of the catches of this species by the fleet in those regions/seasons.

The percentages of fishing sets with zeros (fishing sets with ALB catch = 0) were analyzed and plotted along the years of the time series and in the various regions and seasons. These patterns helped identify areas/seasons where the fishery was mainly targeting tunas as albacore, as opposed to other regions/seasons where there were no albacore catches and as such, the fleet was more likely targeting other species (i.e. swordfish) fishing with night sets. The statistical analysis was carried out with contingency tables and chi-square tests, comparing the proportion of zeros between years. A Cochran–Mantel–Haenszel test (CMH) was also used to compare the proportions of zeros in the main regions of operation of the fishery, taking into account the seasonal effects.

The available ALB catch-at-size data were analyzed in terms of the mean values and catch-at-size distribution along the period of the time series. This data was available between 2001 and 2014 (except for 2011), and helped to identify how the albacore sizes varied in the fishery along the period. The sizes for the years 2001-2003 and 2007-2014 were recorded in fork length (FL), while during the period 2004-2006 the sizes were recorded in pectoral fork length (PFL). For those years, and in order to make the comparisons possible, the PFL sizes were converted to FL using the Ifremer equation for the Reunion fishery albacore:

FL = 1.0612*PFL + 27.2; $R^2 = 0.7071$; N=422 specimens.

The size distribution between years in the time series were compared with Kruskal-Wallis non-parametric rank sum tests, chosen instead of parametric approaches (e.g. ANOVA) because the data were not normally distributed (tested with Kolmogorov Smirnov tests with Lilliefors correction) and were heterogeneous between groups (tested with Levene's tests).

2.3. CPUE standardization

For the CPUE standardization models, the response variable considered was the CPUE in number of specimens (N) captured per 1000 hooks. As the more recent data (2005-2013) was reported in biomass, the set-specific biomass was converted to numbers using the mean yearly albacore catch-at-size recorded by Ifremer in the Reunion Island longline fishery. The year-specific means were used for all years, except for 2005 and 2006 given the uncertainties in the size data that was recorded in PFL instead of FL, and for 2011 because no catch-at-size data was available for that year. For those specific years the overall mean sizes were used for the conversions. On all cases, we used the "*Length (cm) & weight (kg) conversion equations used for IOTC species"*:

Albacore FL-W parameters: a=0.000013718, b=3.0793.

The standardized CPUE series was estimated with Generalized Linear Models (GLM) assuming various types of distributions that were compared in a sensitivity analysis. The models were built considering the information per fishing set. The explanatory variables considered and tested for the models were:

- Year: analyzed between 1994-2000 (voluntary logbook program) and between 2005-2013 (mandatory logbook program);
- Seasonality: Month (12 months of the year), Season (warm = Oct-Mar, cold = Apr-Sep) or Quarter (1 = Jan-Mar; 2 = Apr-Jun; 3 = Jul-Sep; 4 = Oct-Dec). The

choice of the seasonal variable used (i.e. month, season or quarter) depended on each specific model and the quantity of data available;

- Regions: using the areas defined in the results in **Figure 1** for the models with data from all regions, and using regional squares (NW, NE, SW, and SE) for the models specific to the core area (REU region, as defined in the results in **Figure 2**). This has been applied previously in the Reunion SWO longline fishery (Kolody et al. 2010);
- Vessel ID: to take into account vessel effects such as the vessel characteristics, and the skipper/crew experience;
- Interactions between pairs of variables, particularly Spatial: Seasonal effects.

The significance of the explanatory variables was assessed with likelihood ratio tests (LRT) comparing each univariate model to the null model, and by analyzing the deviance tables. Once a full simple effects model was built, possible pairs of interactions were tested with LRT tests to compare the complete simple effects model with the models with interactions, and if significant, the interactions were included in the final models. Model goodness-of-fit was carried out by calculating and comparing the coefficient of determination (R^2) and AIC values for each different candidate model. Model validation was carried out with a residual analysis.

Comparative models were run for the different available CPUE time series, specifically for the earlier (1994-2000) and later (2005-2013) periods. Additionally, models were also run for the entire time series combined, pooling the information from both data periods and sources. In terms or areas, comparative models were run for the entire fishery locations (data from all the regions) and also for the specific Reunion Island (REU) region, in an attempt to compare and model only the core region where the fishery and most catches took place. Finally, with the best final model selected, a comparison was made with a quarterly CPUE index; in that particular case taking into account the interactions between years and quarters. The various model specification considered in this comparative approach are listed in detail in **Table 2**, as well as some model results (goodness-of-fit values) that are discussed later in the results section.

Table 2. Specifications of the candidate models run for each dataset for standardizing the ALB CPUE in the La Reunion Island pelagic longline fishery. On all cases, the model considered were Generalized Linear Models (GLM) using the CPUE (N/1000 hooks) as the response variable and considering a Tweedie error distribution. The best models within each dataset (considering the AIC and R^2) are in bold and underlined. For each model some comments are also provided, including the number of estimated parameters (pars.) and the percentage of zeros in each specific dataset.

Data	Model	Explanatory variables	AIC	R^2	Comments
1994-2000: Voluntary logbooks, all data (7864 obs.); 25.1% zeros	Mod1	Year + Month + Region	37023	38.7	Early data simple effects model (21 pars.)
	Mod2	Year + Month + Region + Vessel	36365	43.2	Model with vessel effects (59 pars.)
	Mod3	Year + Season + Region + Vessel + Season:Region	38309	30.2	Model with interactions. Using season instead of month due to lack of monthly-regional info. (52 pars.)
1994-2000: Voluntary logbooks, REU core region (6937 obs.); 20.5% zeros	Mod4	Year + Month + Area	34214	34.6	Early data simple effects model, REU core region only (21 pars.)
	Mod5	Year + Month + Area + Vessel	33588	39.4	Model with vessel effects (59 pars.)
	Mod6	Year + Month + Area + Vessel + Month:Area	33457	40.5	Model with interactions (92 pars.)
2005-2013: Mandatory logbooks, all data (22009 obs.); 25.3% zeros	Mod7	Year + Month + Region	105242	30.5	Later years data, simple effects model (22 pars.)
	Mod8	Year + Month + Region + Vessel	103726	34.2	Model with vessel effects (62 pars.)
	Mod9	Year + Season + Region + Vessel + Season:Region	106717	26.9	Model with interactions. Using season instead of month due to lack of monthly-regional info. (54 pars.)
2005-2013: Mandatory logbooks, REU core region (20533 obs.); 24.2% zeros	Mod10	Year + Month + Area	99350	31.0	Later years data, simple effects model (23 pars.)
	Mod11	Year + Month + Area + Vessel	97968	34.5	Model with vessel effects (63 pars.)
	Mod12	Year + Month + Area + Vessel + Month:Area	97697	35.3	Model with interactions (96 pars.)
1994-2000 & 2005-2013: All data (29873 obs.); 25.3% zeros	Mod13	Year + Month + Region	142652	31.9	All years, simple effects model (30 pars.)
	Mod14	Year + Month + Region + Vessel	140843	35.2	Model with vessel effects (94 pars.)
	Mod15	Year + Season + Region + Vessel + Season:Region	145486	26.7	Model with interactions. Using season instead of month due to lack of monthly-regional info (87 pars.)
1994-2000 & 2005-2013: REU core region (27470 obs.); 23.2% zeros	Mod16	Year + Month + Area	133841	31.3	All years, simple effects model for REU core region (30 pars.)
	Mod17	Year + Month + Area + Vessel	132056	34.8	Model with vessel effects for the REU core region (94 pars.)
	Mod18	Year + Month + Area + Vessel + Month:Area	131771	35.4	All years, REU core region only and with interactions (127 pars.)

As there were several fishing sets with zero ALB catches, which results in a response variable of CPUE=0, and as those zeros can cause mathematical problems for fitting the models, various model methodologies were applied in a sensitivity analysis. The following types of distributions and models were considered:

1) Tweedie model: This was the primary approach used in the comparative runs of the various models, as the quantity of zeros varied depending on the specific data used (i.e. years and regions considered). The Tweedie distribution is a generalization of the exponential family and is highly flexible in terms of the quantity of zeros explained, being defined by a mean, a dispersion parameter (φ) and an index parameter (p). When p takes values between 1 and 2, the distribution is continuous for positive real numbers but has an added discrete mass at 0, which seems appropriate to model CPUE data directly (continuous data with an added mass of zeros). The index parameter for this specific work was calculated by maximizing the likelihood profile function of possible values of p. This distribution has been increasingly used for CPUE standardization studies when the proportion of zeros is relatively high (e.g. Candy 2004; Coelho et al. 2012, 2013);
2) Lognormal model adding a small constant: Another tested option was to add a small constant (c) to the CPUE, so that the response variable was transformed into CPUE+c and becomes a continuous positive variable no longer containing zeros. The choice of the constant value to be added can be somewhat subjective (Campbell, 2004), but in this case we added the value 1, which seems to be a common approach in fisheries biology studies (e.g. Punt et al. 2000). When the proportion of zeros is high this approach may introduce significant bias in the analysis, as demonstrated by Shono (2008). In our study, the proportion of zeros was relatively high and as such this model was used only for comparative purposes;
3) Delta-method approach using binomial and lognormal models: With this approach two separate models are fitted in this particular case - a binomial (logistic) distribution to model the proportion of fishing sets with positive catches and a lognormal distribution to model the nominal CPUE of the positive sets (Maunder and Punt 2004). This is a relatively common used technique to standardize CPUE series when part of the data contains zeros (e.g. Ortiz and Arocha 2004; Cortés 2009; Pons et al. 2009);
4) Negative Binomial: Negative Binomial model was used to fit the ALB catches in number (N) and the effort (number of hooks) was used as an offset variable functioning as an exposure variable. This indicates the number of times the event (i.e. catches in number) can occur given the opportunities (i.e. number of hooks used). This type of model has been applied in CPUE standardization of albacore in the Atlantic and Indian Oceans (e.g. Hazin et al. 2008; Matsumoto et al. 2012; Uosaki and Shono, 2008), as well as to model bycatch groups such as sea-turtles and sharks (Pradhan and Leung 2006; Carvalho et al. 2009). In our study an initial attempt was also made with a Poisson model, but given that the data was overdispersed the Negative Binomial was chosen instead.

The final standardized CPUEs were estimated by least square means (LSMeans also called marginal means) for the effects of year averaged over the effects of the other variables. For the Delta method the LSMeans were calculated as the yearly probability of having a positive set multiplied by the expected catch rate conditional to the set being positive. The final estimated indexes of abundance were compared by scaling the annual standardized CPUE values by the mean standardized CPUE in the time series.

All statistical analysis for this paper was carried out with the R Project for Statistical Computing version 2.15.3 (R Core Team, 2013) using several additional libraries (Becker et al., 2013a, 2013b; Bivand, 2013; Bivand and Lewin-Koh, 2013; Dunn, 2012; Fox and Weisberg, 2011; Gerritsen, 2013; Højsgaard et al., 2013; Lenth, 2013; Neuwirth, 2011; Stabler, 2013; Venables and Ripley, 2002; Warnes, 2012; Wickham, 2009, 2012; Wood, 2006, 2011).

3. Results and Discussion

3.1. Catch and effort

3.1.1. Spatial distribution

The historical areas of operation in terms of fishing effort for the Reunion Island pelagic longline fleet are shown in **Figure 1** for the periods 1992-2001 and 2005-2013. Overall, it was possible to observe that most of the effort took place relatively close to the Reunion Island (REU core region), with some effort also occurring in farther away areas as the Mozambique Channel and the Seychelles region, especially in the earlier years of the fishery (**Figure 1**). For the more recent time period the distribution of the effort showed no effort in the most northern Seychelles region, and lower effort in the Mozambique Channel, with the fishery tending to be more restricted to the REU core region (**Figure 1**). Such trend is a consequence of the size of the boats (<24m) associated to exploitation costs (e.g. diesel) and the economic crisis of the fishery sector in Reunion Island during the last 10 years. The areas where the fleet catches more albacore is shown in **Figure 2** for the 1992-2001 (reported by voluntary logbooks) and 2005-2013 (reported with mandatory logbooks) periods. It is possible to observe that most albacore catches takes place in the area closer to the Reunion Island.

Considering the effort distribution and the areas of albacore catches' concentration, three distinct sub-regions were defined, specifically the core Reunion Island region (REU) where most of the effort and albacore catches took place; the Mozambique Channel (MZB) and Seychelles (SEZ) regions that show much less effort and catches. The effort and catches in the MZB and SEZ regions were minimal in many years, and as such only the REU region was considered when attempting to model the fishery core region.

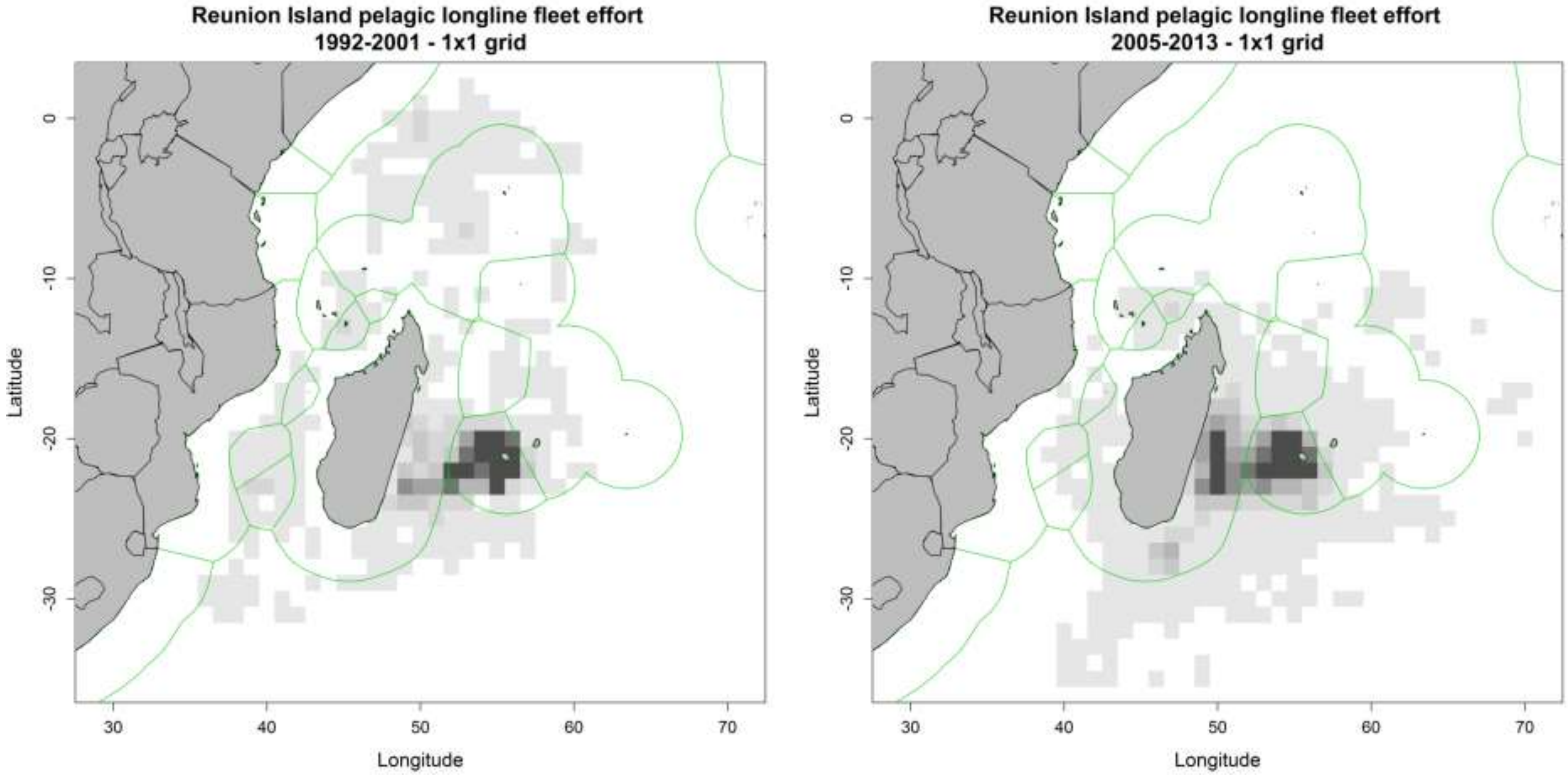


Figure 1. Effort distribution of the Reunion Island pelagic longline fleet for the 1992-2001 (map on the left) and 2005-2013 (map on the right) periods. The effort is represented in 1x1 degree grids, with darker and lighter colors representing respectively areas with more and less effort in number of hooks.

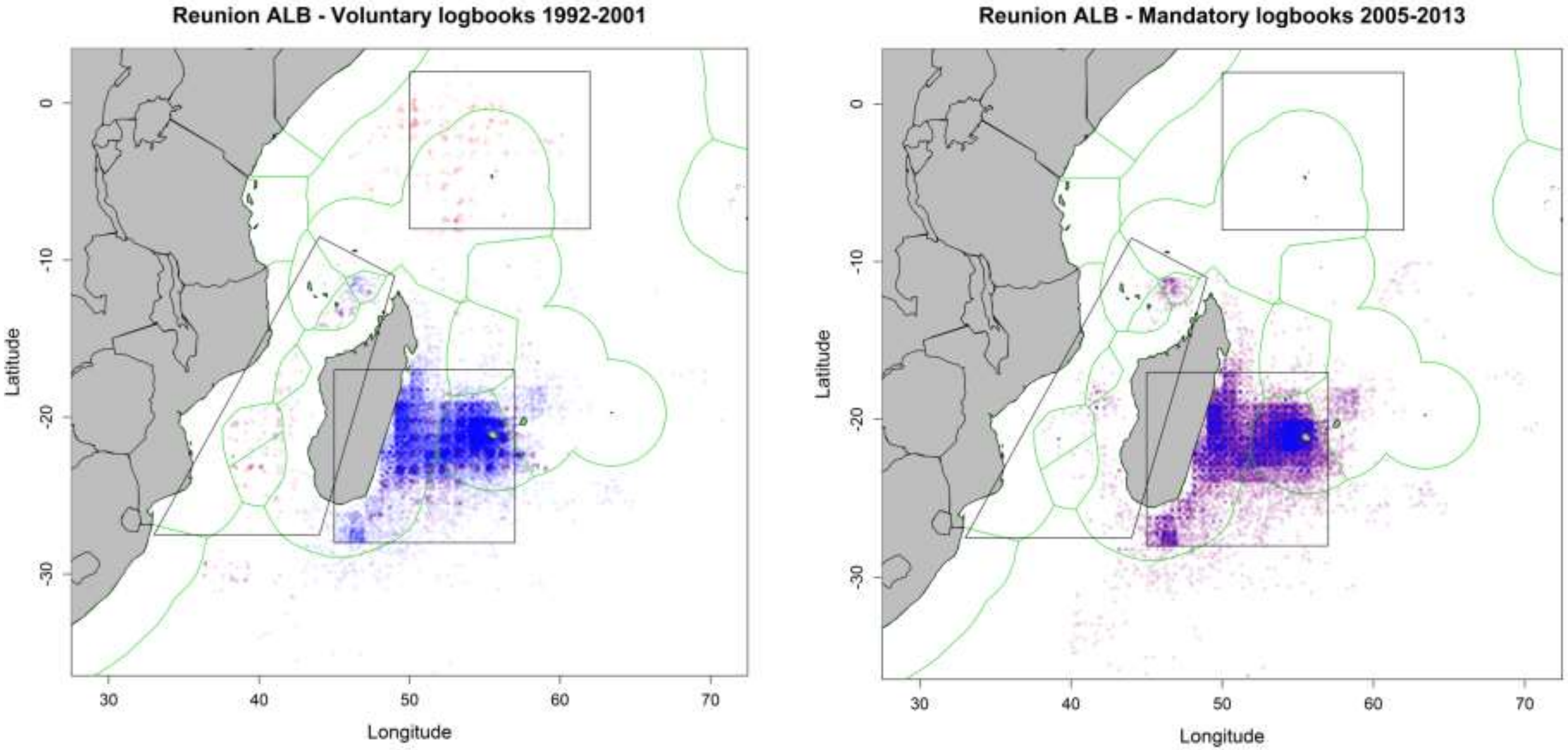


Figure 2. Location of the Reunion Island pelagic longline sets reported by the fleet with the voluntary logbooks between 1992 and 2001 (map on the left) and with the mandatory logbooks between 2005 and 2013 (map on the right). Full color saturation indicates more ALB catches while the lighter red color represent sets with zero ALB catches. Locations are jittered +/- 1 degree using a Uniform distribution to better illustrate repeated observations within the same 1x1 square. The boxes indicate the three main regions of operation of the fleet: Seychelles (SEZ), Mozambique Channel (MZB) and Reunion Island (REU).

3.1.2. Annual, seasonal and regional variability in the catches

A pattern in the Albacore CPUE was observed along the months of the year, with higher catches tending to be reported in the warmer months, particularly from October to March (**Figure 3**). Even though the CPUE values varied inter-annually, this type of pattern tended to be common for most years analyzed (**Figure 3**). When considering the regional factor, this seasonal pattern was most evident in the REU, as in that region the CPUEs tended to be much higher and there were reports for all the years in the time series (**Figure 4)**. In this particular case, the season 2 refers to the warmer period, assigned to the period between October and March.

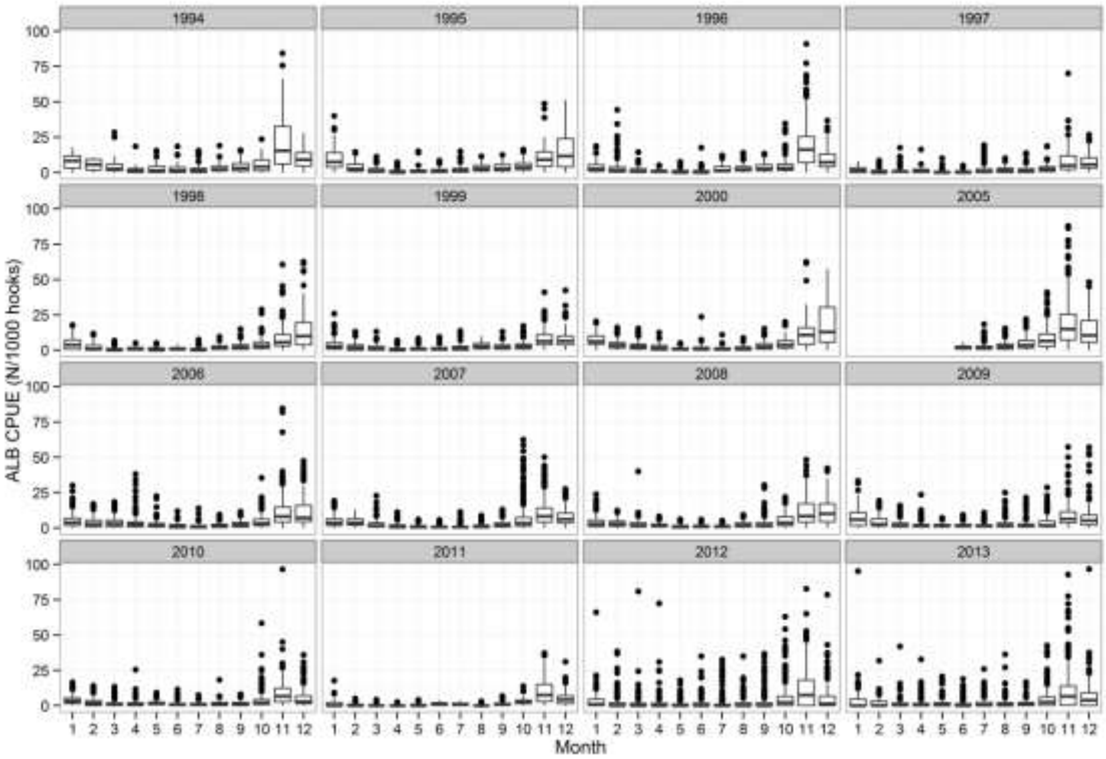


Figure 3. Monthly albacore CPUE (N/1000 hooks) in the Reunion Island pelagic longline fishery per year. Note a break in the time series between 2000 and 2005, for which no set-specific information was available, and that in 2005 the data only started to be collected in June.

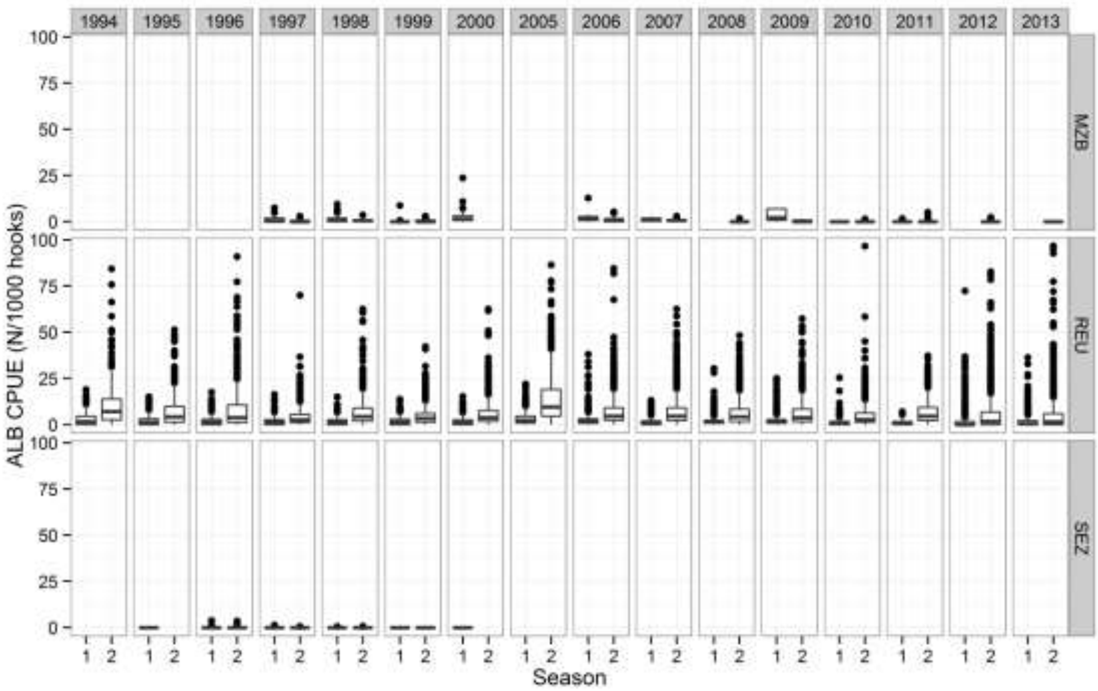


Figure 4. Albacore CPUEs (N/1000 hooks) in the Reunion Island pelagic longline fishery per year, region and season of the year. The regions correspond to the three main areas of operation of the fleet: MZB = Mozambique Channel, REU = Reunion Island area and SEZ = Seychelles area. The seasons were defined as 1 = colder period (months 4, 5, 6, 7, 8 and 9), and 2 = warmer period (months 10, 11, 12, 1, 2 and 3). Note a break in the time series between 2000 and 2005, for which no set-specific information is available.

3.1.3. Distribution of sets with positive and zero catches

The overall percentage of sets with zero ALB catches in the 1992-2000 and 2005-2013 datasets was 25.3%. However, significant inter-annual variability was observed in the percentages of sets with zero catches (proportion test: chi-square = 2382.4, df (degrees of freedom) = 15, p-value < 0.001), with those varying between the minimum of 9.7% in 2005 and the maximum of 50.5% in 2012 (**Figure 5**).

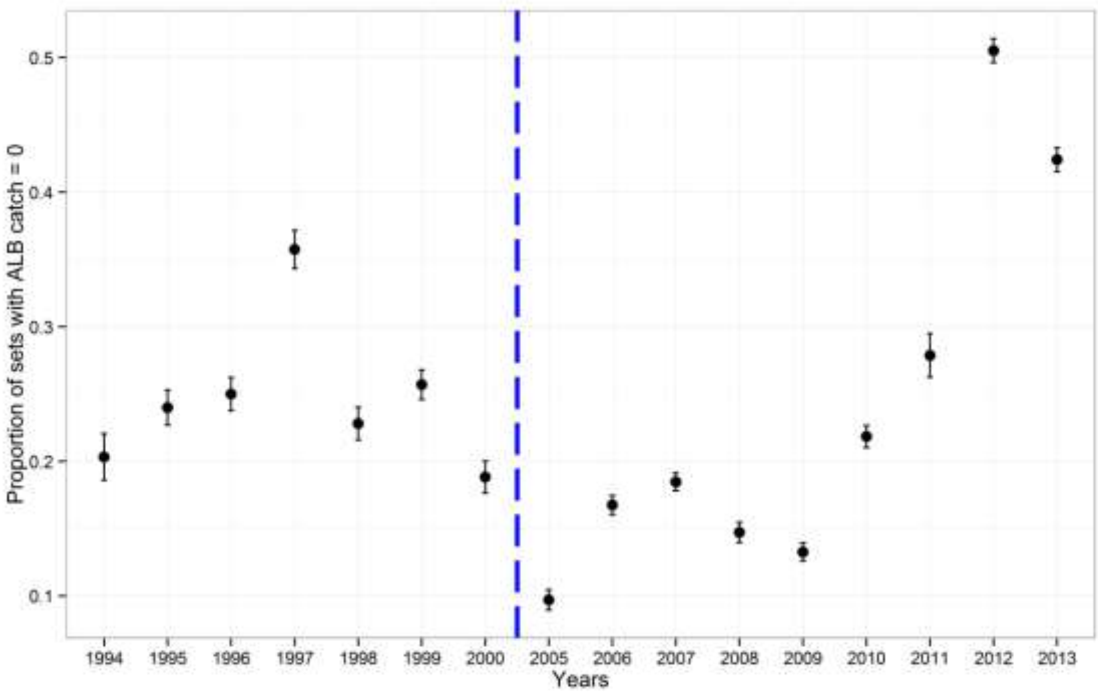


Figure 5. Proportion of sets with zero albacore catches (catch=0) reported in the Reunion Island pelagic longline fishery. Note that there is a break in the time series between 2000 and 2005, for which no set-specific data is available. The error bars represent ± 1 standard error.

The proportion of sets with zero ALB catches also varied significantly when comparing the three main areas of operation of the fishery, even when the seasonal effects were taken into account (CMH proportion test: chi-square = 1417.9, df = 2, p-value < 0.001). Specifically, in the Reunion Island region (REU) the percentage of sets with zero ALB catches was the lowest, varying between 31.4% in the colder season and 15.0% in the warmer period (**Figure 6**). In the other regions, the percentages of fishing sets with ALB catches were much higher, specifically 59.8% in the Mozambique Channel and 94.7% in the Seychelles regions (**Figure 6**).

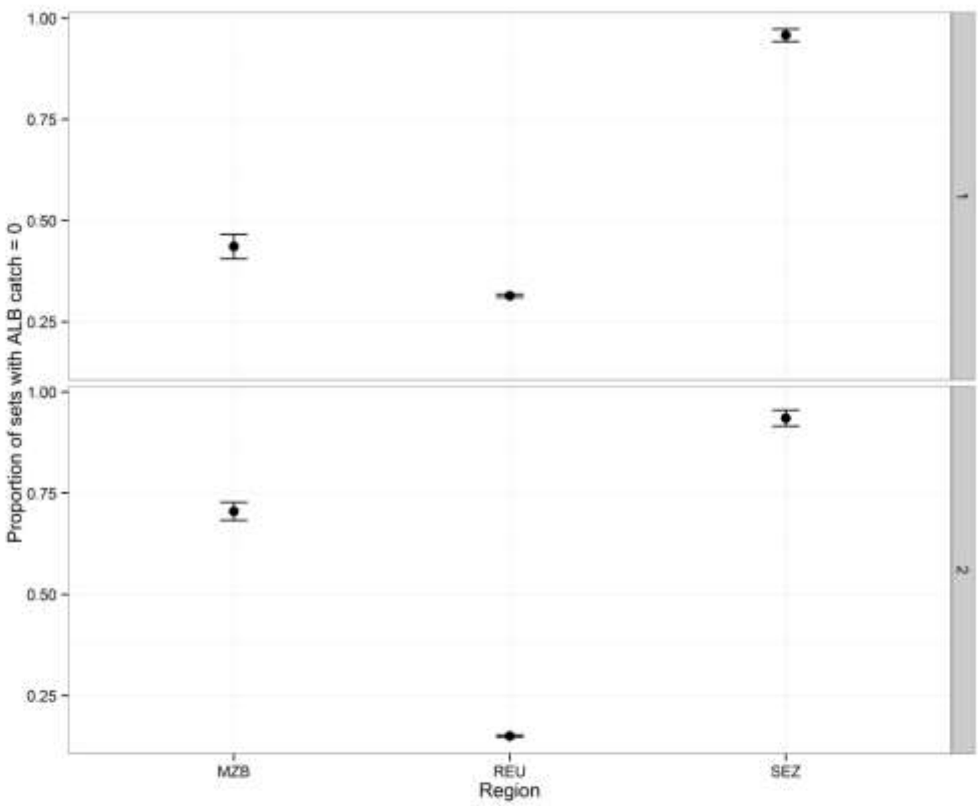


Figure 6. Proportion of sets with zero albacore catches (catch=0) reported by the Reunion Island pelagic longline fleet, for the three main regions of operation of the fleet: MZB = Mozambique Channel, REU = Reunion Island area and SEZ = Seychelles. The seasons were defined as: 1 = colder period (months 4, 5, 6, 7, 8 and 9); 2 = warmer period (months 10, 11, 12, 1, 2 and 3). The error bars represent ± 1 standard error.

3.2. Catch-at-size

The catch-at-size distribution of the albacore reported by the Reunion Island pelagic longline fishery in the Indian Ocean remained relatively stable throughout most of the study period with some yearly oscillations (**Figure 7**), and with significant differences detected between the years (Kruskal-Wallis: chi-square = 354.7, df = 12, p-value < 0.001). In terms of seasonal variability some differences were also detected, but in general both seasons followed the same general size trend along the time series (**Figure 8**).

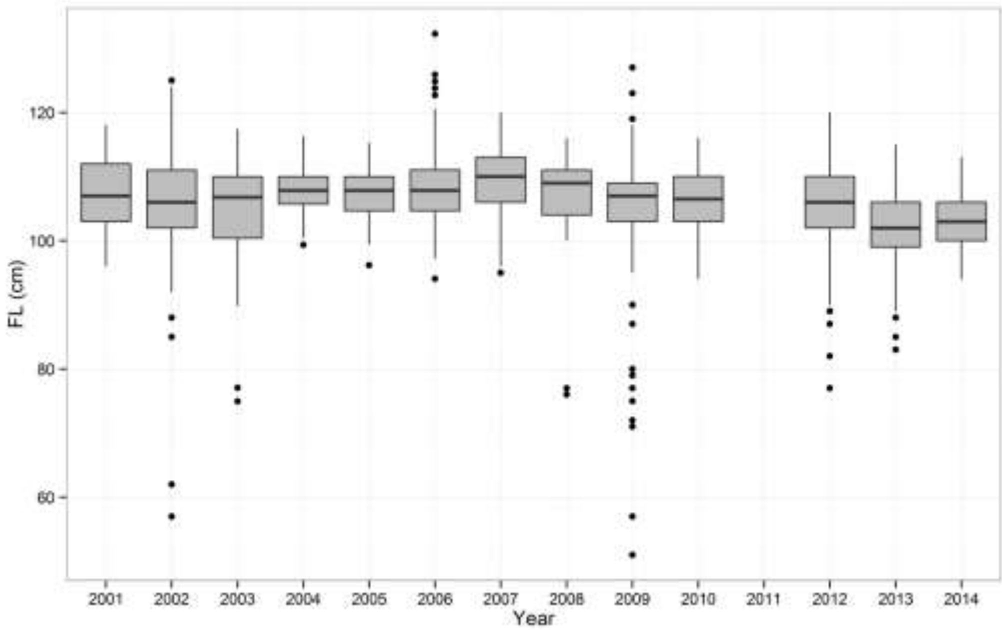


Figure 7. Yearly boxplots with the catch-at-sizes for the albacore reported by the Reunion Island pelagic longline fleet operating in the Indian Ocean. In the boxplots the middle lines represents the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

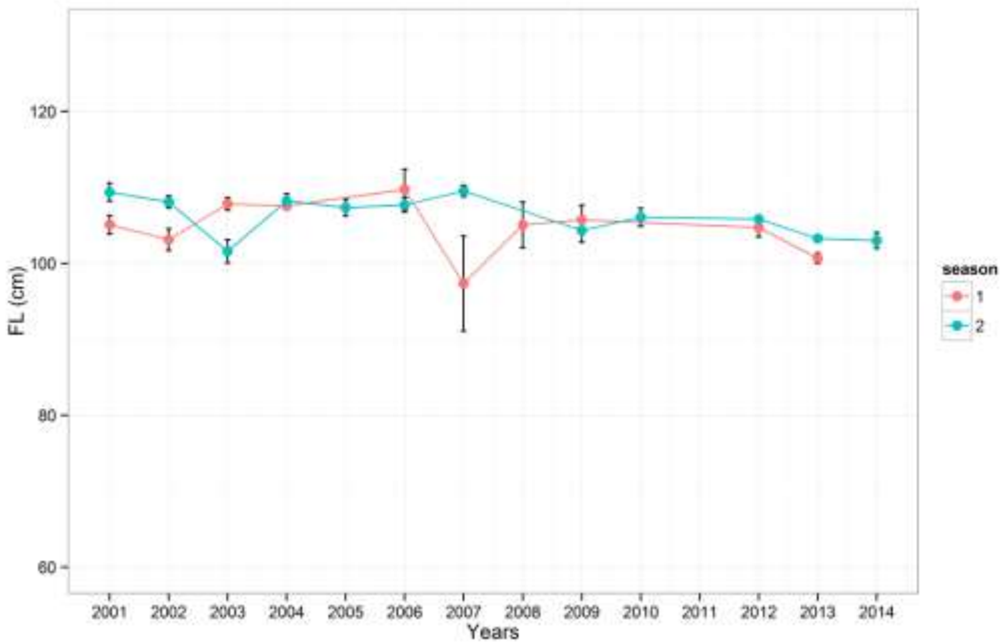


Figure 8. Mean yearly catch-at-size for the albacore reported by the Reunion Island pelagic longline fleet operating in the Indian Ocean in each season. The seasons were defined as 1 = colder period (months 4, 5, 6, 7, 8 and 9), and 2 = warmer period (months 10, 11, 12, 1, 2 and 3). The error bars represent the 95% confidence intervals.

3.3. CPUE standardization process

3.3.1. Nominal CPUE series

The total nominal albacore CPUE for the Reunion Island pelagic longline fishery is presented in **Figure 9**, both for the entire fishing area and the REU core region alone. In both cases the nominal CPUE tended to decrease in the initial time period (1994-1997), but when all regions are considered there was a slight increase from 1997 to 2000, while in the REU core region a general decrease was noted until 2000. The highest CPUE for the entire time series (both for all regions and for the REU data only) were recorded immediately after the period for which no set specific data was available (2001-2004), followed by a general decreasing trend until 2013, with an intermediate peak in the CPUEs during 2011 (**Figure 9**).

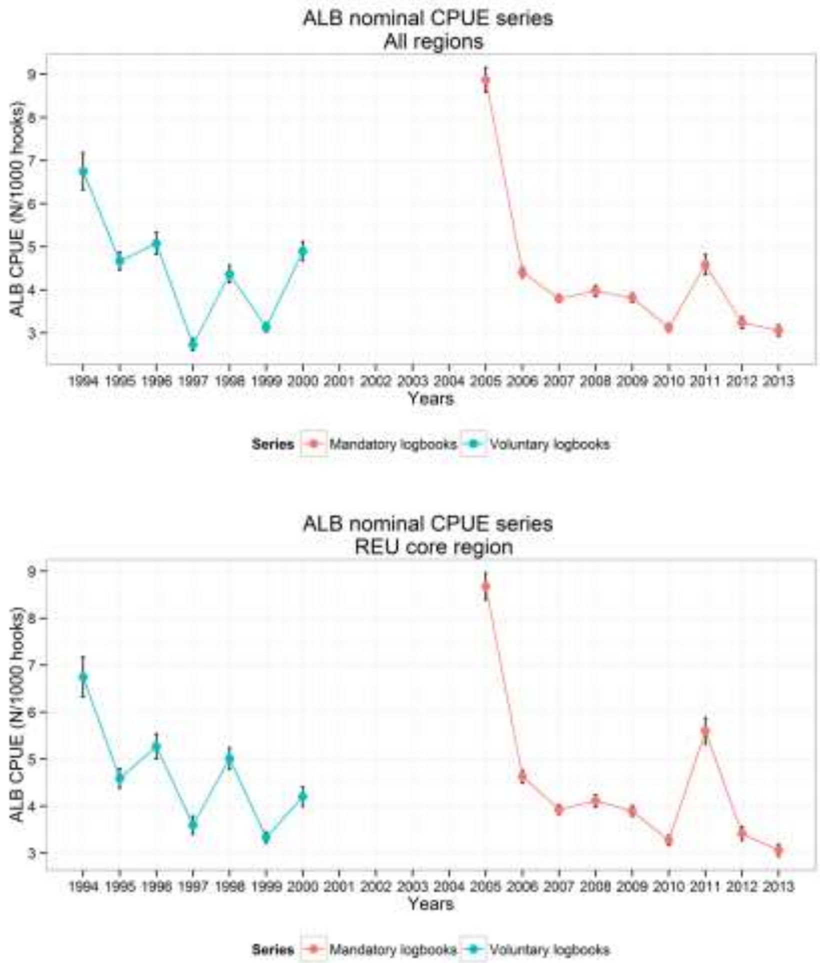


Figure 9. Nominal albacore CPUE series (N/1000 hooks) for the Reunion Island pelagic longline fishery in the Indian Ocean (all areas and REU core region) between 1994 and 2013. The periods between 1994-2000 and 2005-2013 were compiled from voluntary and mandatory logbooks, respectively. Note that there is a break in the time series between 2001-2004, for which no set-specific data is available. The error bars represent ± 1 standard error.

3.3.2. Data distribution

The distribution of the nominal albacore CPUE data was highly asymmetrical and skewed to the right, with a relatively high percentage of zeros (25.3%). After adding a constant (in this case c=1) and log-transforming the data, the CPUE distribution become more Normal-shaped, even though there were still some problems due to the high percentage of zeros (**Figure 10**). When considering only the positive sets, and after log-transforming the data, the CPUEs became much more Normal-shaped. This later result is particularly important when considering the Delta-method approach, as it is the specific data that is modeled with the lognormal component for the positive sets.

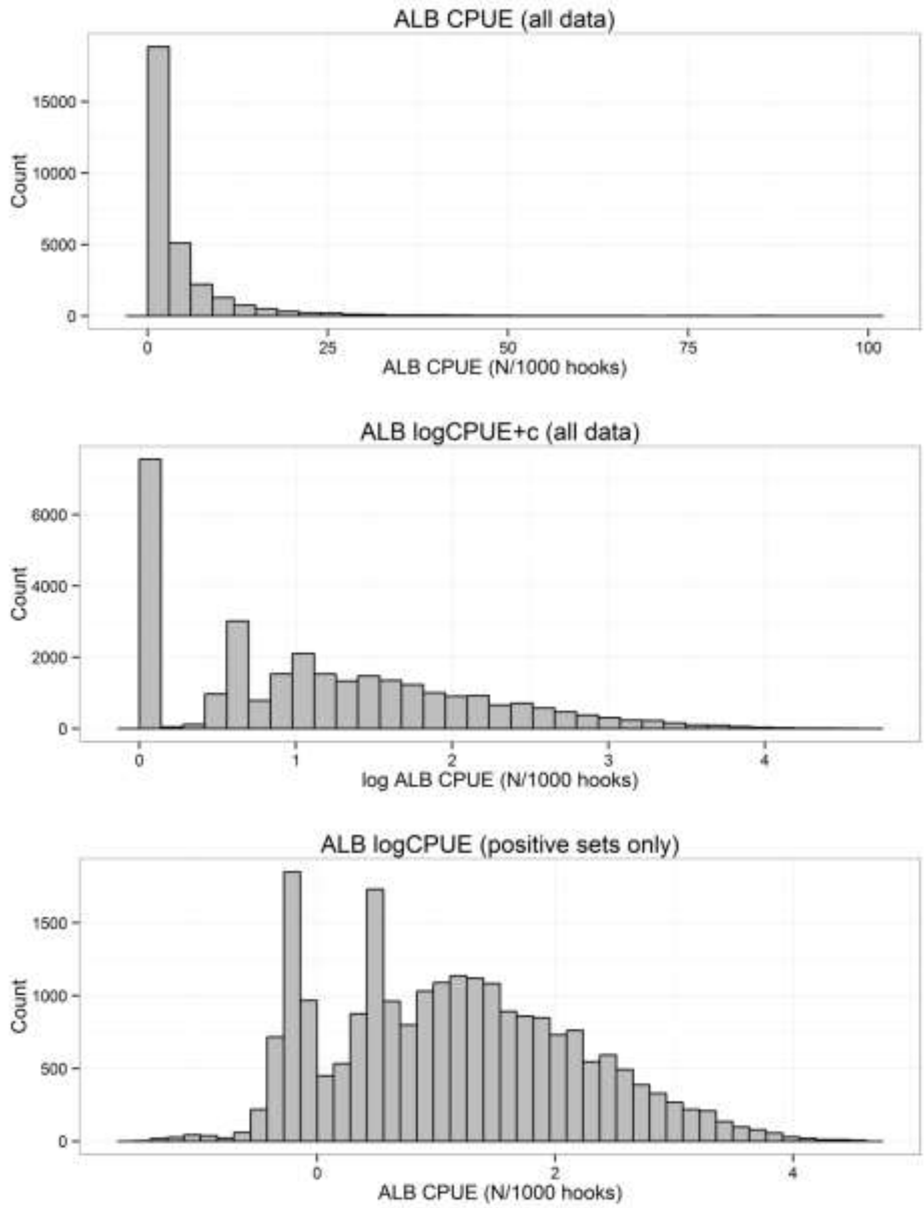
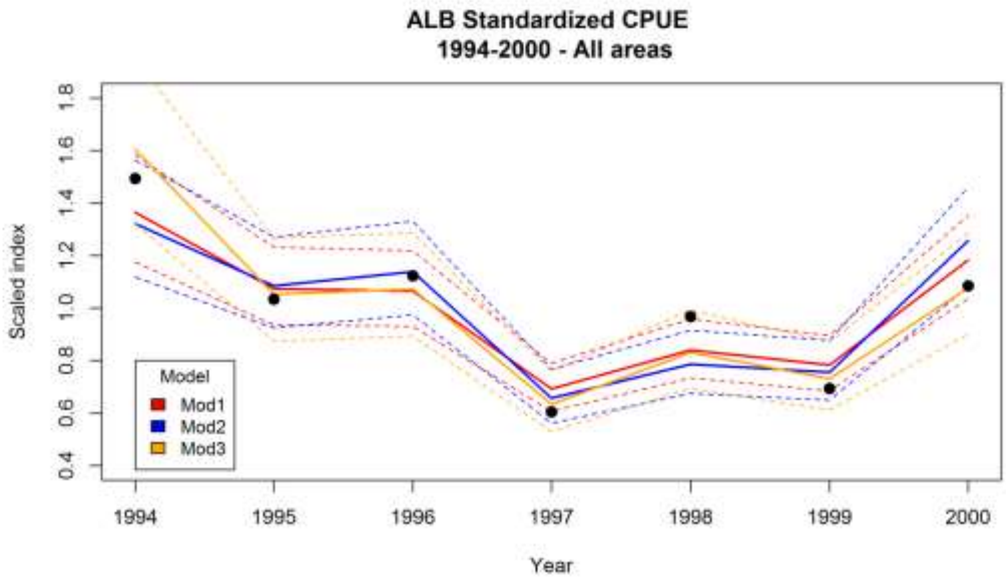


Figure 10. Distribution of the albacore nominal CPUE data (N/1000 hooks) in non-transformed and log-transformed scales (all sets and positive sets only), from logbooks reported between 1992-2000 and 2005-2013 in the Reunion Island pelagic longline fishery.

3.3.3. CPUE modeling: 1994-2000 data (voluntary logbooks)

The standardized albacore CPUE between 1994 and 2000 showed a general initial decreasing trend, followed by an increase in the later years, which is consistent with the nominal CPUE series (**Figure 11**). Not many differences were observed with the various models considered, even when considering the entire dataset from all regions combined *versus* the REU core region.



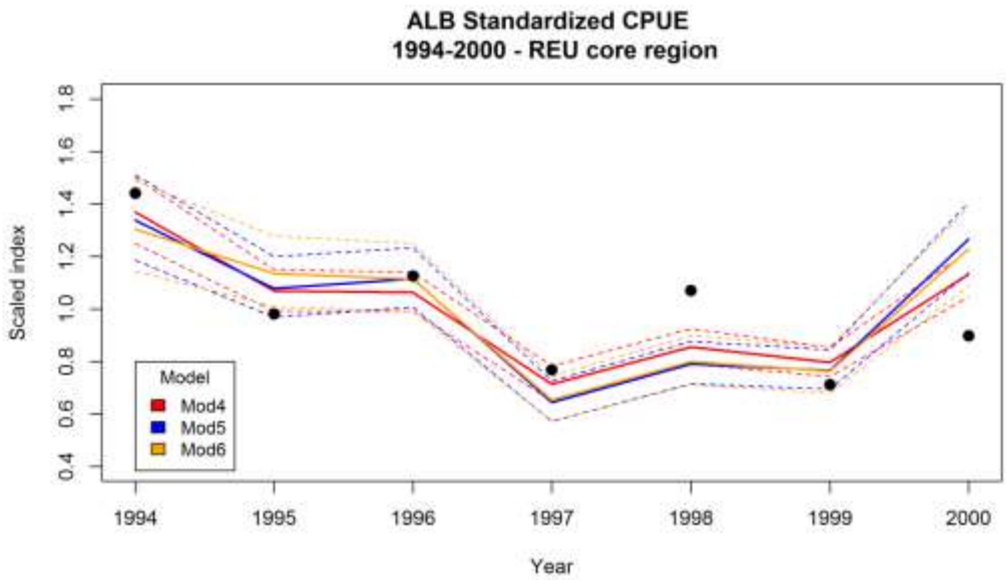


Figure 11. Standardized albacore CPUE indexes for the 1994-2000 data period (voluntary logbooks) of the Reunion Island pelagic longline fishery, considering the catches on all regions combined and in the REU core region. The black circles represent the nominal CPUE, the solid lines the standardized CPUE and the dotted lines the 95% confidence intervals of the various models. The various model specifications are listed in detail in **Table 2**.

In terms of model goodness-of-fit, the best model when considering data from all regions combined was the model **using Year + Month + Region + Vessel but without interactions – Mod 2** (higher R^2 and lower AIC values), while for the REU core region the best model was similar but also considered the **Month:Area interaction – Mod 6** (**Table 2**). On both cases (i.e. both datasets), and considering only the best models with each dataset, seasonality was the variable explaining most of the deviance, in this case using month or quarter, followed by the vessel effects, and then the year and spatial effects, respectively (**Table 3**).

Table 3. Deviance table for the explanatory variables used in theReunion Island pelagic longline fishery for the albacore CPUE standardization of the 1994-2000 dataset, referring to the best candidate models considering all regions combined and the REU core region. The residual deviance (Df and Dev) refer to the specific degrees of freedom and deviance explained by each additional explanatory variable included sequentially in the models.

Model / Data	**Variables**	**Df**	**Dev.**	**Resid Df**	**Resid. Dev**	**F-stat.**	***p-value***
Mod 2: Voluntary logbooks (1994-2000), All regions	Intersept only			7863	33141		
	Year	6	1216	7857	31925	77.8	< 0.001
	Year + Month	11	10515	7846	21411	366.9	< 0.001
	Year + Month + Region	3	1157	7843	20253	148.1	< 0.001
	Year + Quarter + Region + Vessel	38	1554	7805	18699	15.7	< 0.001
Mod 6: Voluntary logbooks (1994-2000), REU core region	Intersept only			6936	27234		
	Year	6	723	6930	26511	54.7	< 0.001
	Year + Month	11	8665	6919	17846	357.3	< 0.001
	Year + Month + Area	3	74	6916	17771	11.3	< 0.001
	Year + Month + Area + Vessel	38	1401	6878	16370	16.7	< 0.001
	Year + Month + Area + Vessel + Month:Area	33	383	6845	15987	5.3	< 0.001

In terms of residual analysis of those two best models for this time period, no major outliers were detected, with the residuals tending to be randomly distributed along the data (**Figure 12**). However, it was possible to note that the residuals for the REU core region seemed better, especially when considering the dispersion of the quantile residuals along the fitted values and the Q-Q Plot (**Figure 12**).

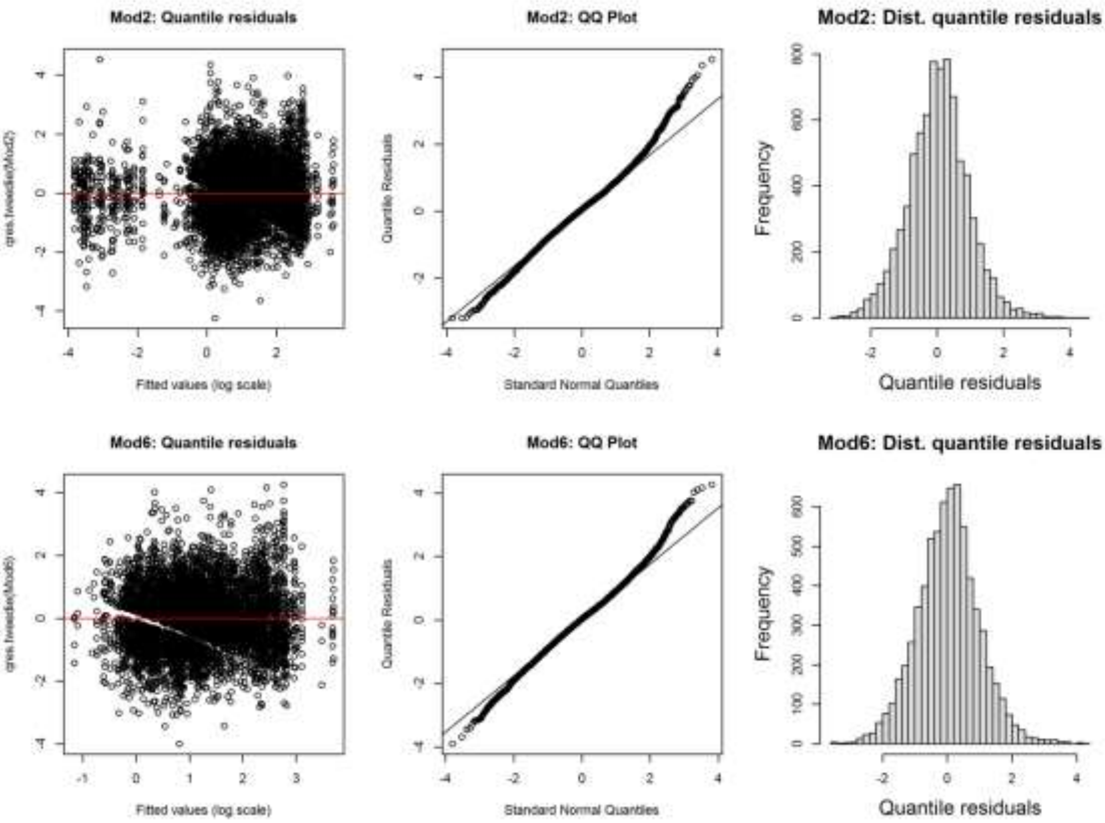
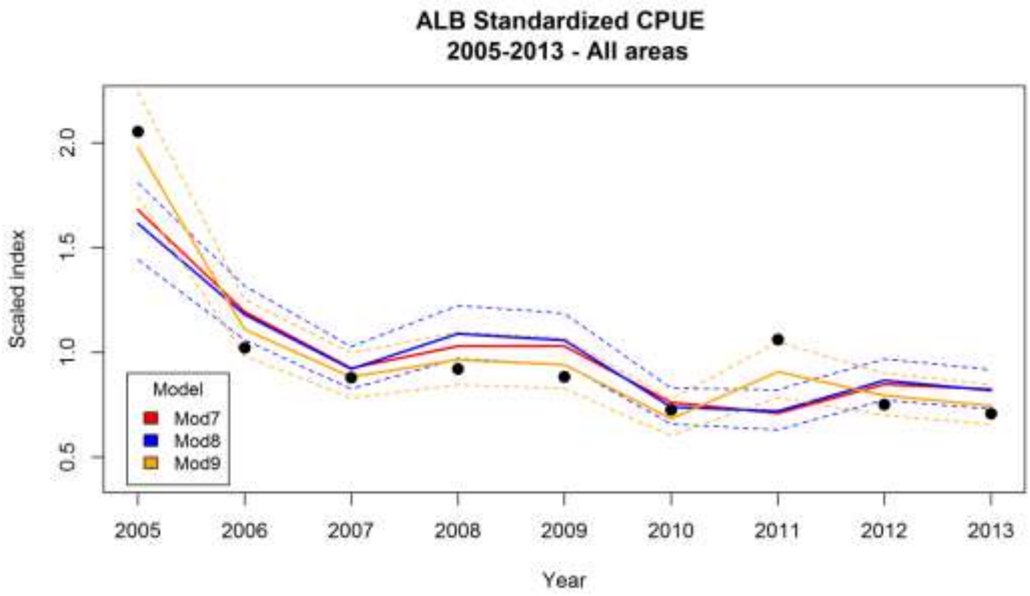


Figure 12. Residual analysis for the Reunion Island pelagic longline fishery albacore CPUE standardization of the 1994-2000 dataset, referring to the best candidate models considering all regions combined (Mod2) and the REU core region (Mod6). The plots on the left represent the quantile residuals along the predicted values (log scale), the plots in the middle represent the Q-Q Plot and the plots on the right the histogram with the residuals frequency distribution.

3.3.4. CPUE modeling: 2005-2013 data (mandatory logbooks)

The standardized CPUE for the mandatory logbooks for the period 2005 to 2013 showed a general decreasing trend along the entire period (**Figure 13**). This decrease was particularly evident during the initial years of the series (2005 to 2007), while it remained relatively stable at lower values thereafter. Like in the previous time period, not many differences were detected between the various candidate models considered (**Figure 13**).



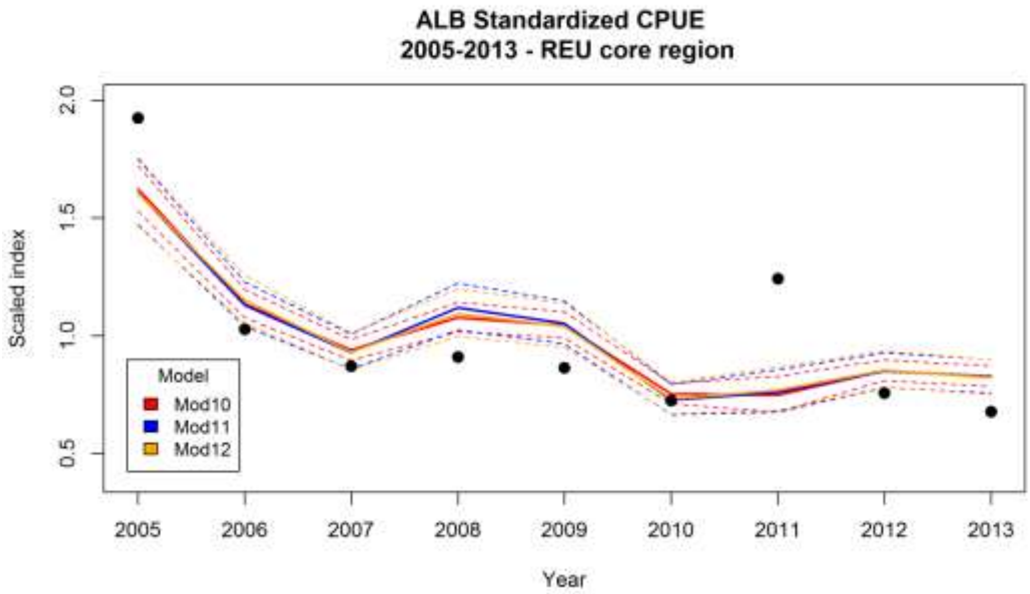


Figure 13. Standardized albacore CPUE indexes for the 2005-2013 data period (mandatory logbooks) of the Reunion Island pelagic longline fishery, considering the catches on all regions combined and in the REU core region. The black circles represent the nominal CPUEs, the solid lines the standardized CPUEs and the dotted lines the 95% confidence intervals of the various models. The various model specifications are listed in detail in **Table 2**.

In terms of model goodness-of-fit, the best model when considering data from all regions was the same as the previous time series, **the model using Year + Month + Region + Vessel but without interactions – Mod 8** (higher R^2 and lower AIC values), while for the REU core region the best model was similar but also considered the **Month:Area interaction – Mod 12** (**Table 2**). Like in the previous dataset, on both cases (i.e. using all data or the REU core region only), and considering only the best models within each dataset, the variables explaining most of the deviance was the seasonality, in this case always using month. However, and contrary to the previous time period, in this case the years were explaining more of the deviance than the vessel effects, that were then followed by the spatial effects (**Table 4**)

Table 4. Deviance table for the explanatory variables used in the Reunion Island pelagic longline fishery for the albacore CPUE standardization of the 2005-2013 dataset, referring to the best candidate models considering all regions and the REU core region only. The residual deviance (Df and Dev) refer to the specific degrees of freedom and deviance explained by each additional variable included sequentially in the models.

Model / Data	**Variables**	**df**	**Dev.**	**Df**	**Dev**	**F-stat.**	***p-value***
Mod 8: Mandatory logbooks (2005-2013), All regions	Intersept only			22017	91597		
	Year	8	4364	22009	87233	164.6	< 0.001
	Year + Month	11	22710	21998	64522	622.8	< 0.001
	Year + Month + Region	2	973	21996	63550	146.7	< 0.001
	Year + Month + Region + Vessel	40	3481	21956	60069	26.3	< 0.001
Mod 12: Mandatory logbooks (2005-2013), REU core region	Intersept only			20547	85583		
	Year	8	3930	20539	81653	159.4	< 0.001
	Year + Month	11	22113	20528	59540	652.3	< 0.001
	Year + Month + Area	3	591	20525	58949	63.9	< 0.001
	Year + Month + Area + Vessel	40	3091	20485	55859	25.1	< 0.001
	Year + Month + Area + Vessel + Month:Area	33	718	20452	55140	7.1	< 0.001

In terms of residual analysis of those two best models for this time period a few outliers were detected, but in general the residuals tended to be randomly distributed along the data and showed a Normal shaped distribution (**Figure 14**).

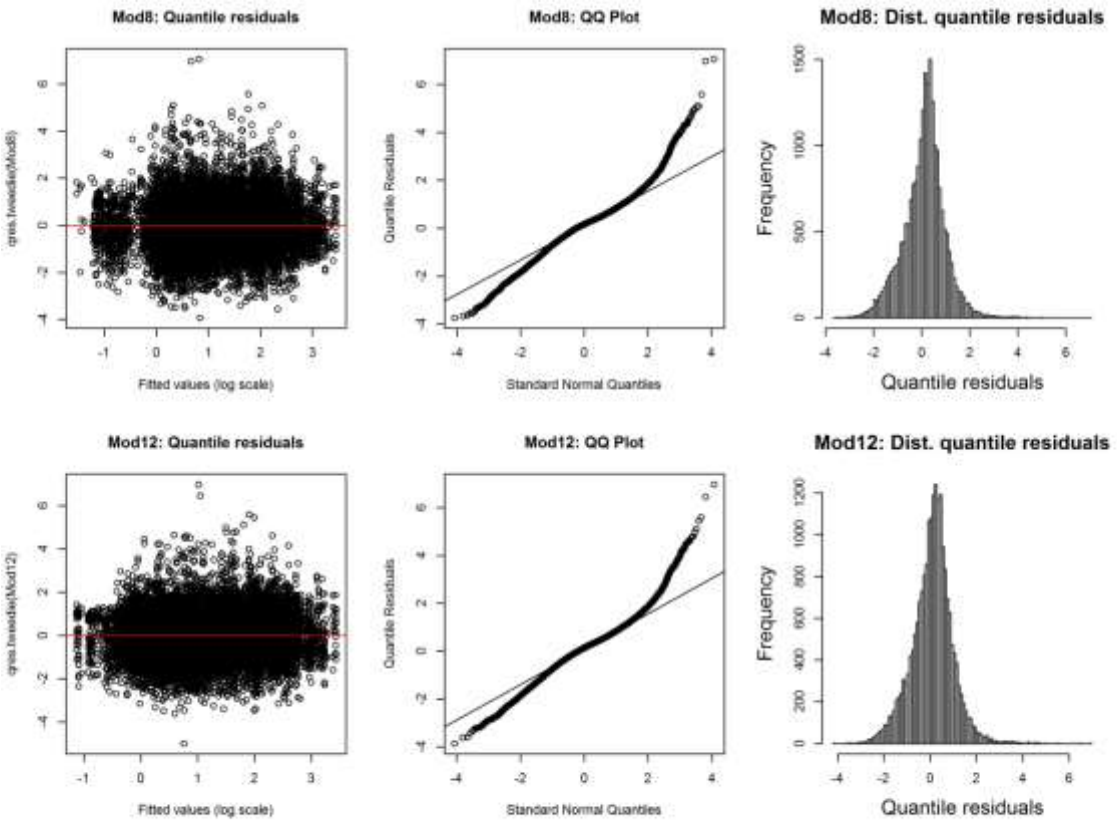
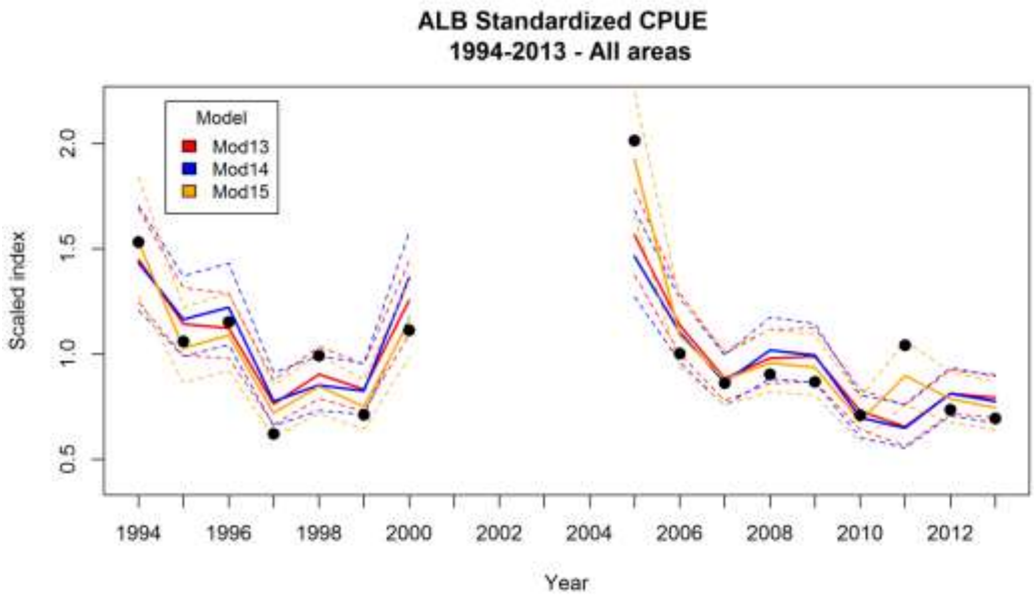


Figure 14. Residual analysis for the Reunion Island pelagic longline fishery albacore CPUE standardization of the 2005-2013 dataset, referring to the best candidate models considering all regions combined (Mod8) and the REU core region (Mod12). The plots on the left represent the quantile residuals along the predicted values (log scale), the plots in the middle represent the Q-Q Plot and the plots on the right the histogram with the residuals frequency distribution.

3.3.5. CPUE modeling: All data (1994-2000 & 2005-2013)

When combining the two datasets from the two time periods (1994-2000 and 2005-2013), the standardized albacore CPUEs showed an initial decreasing between 1994-1997, followed by an increase until 2000. Although the data gap did not allow to analyze the CPUE trend during the mid 2000's, there was a peak in 2005 that was followed by a general decreasing trend thereafter, which was less pronounced for the later period of the time series (i.e. after 2010) (**Figure 15**). Like with the models for each period separately, the different candidate models using various model specifications and explanatory variables did not produce any major differences. Likewise, the patterns of using the entire fishery data and the REU core region were also very similar (**Figure 15**).



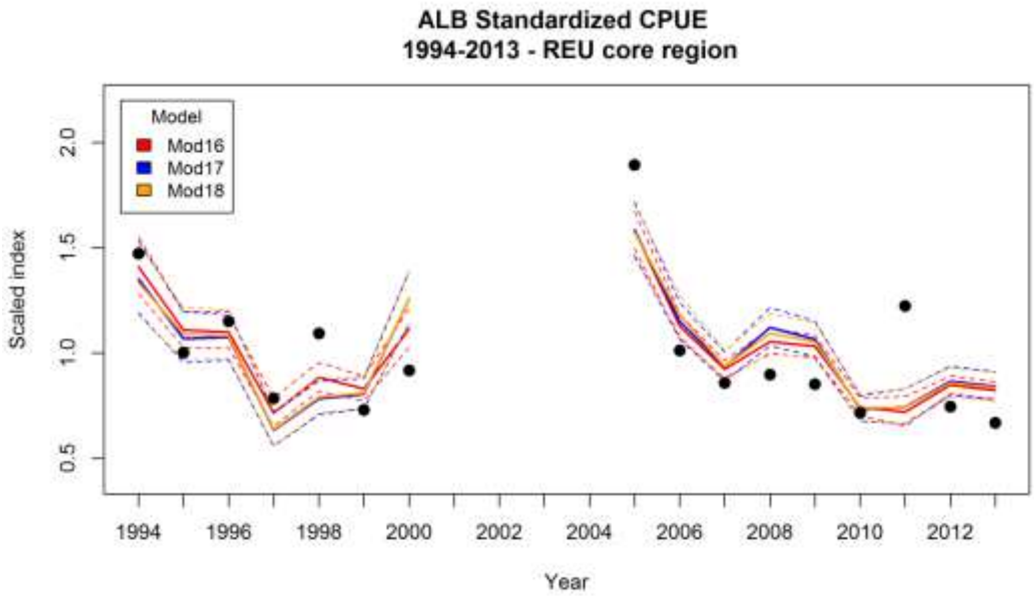


Figure 15. Standardized albacore CPUE indexes for the entire 1994-2000 and 2005-2013 data periods (voluntary and mandatory logbooks) of the Reunion Island pelagic longline fishery, considering the catches on all regions combined and in the REU core region. The black circles represent the nominal CPUE, the solid lines the standardized CPUE and the dotted lines the 95% confidence intervals of the various models. The various model specifications are listed in detail in **Table 2**.

For this entire time period, and in terms of model goodness-of-fit, the best models when considering all regions were obtained **using Year + Month + Region + Vessel – Mod 14**. For the data from the REU core region the best model was similar but also considered the **Month:Area interaction – Mod 18** (**Table 2**). When considering only the best models for the entire region and for the REU core region, the variables explaining most of the deviance were seasonality, in this case using month, followed by the year, vessel and the regional effects (**Table 5**).

Table 5. Deviance table for the explanatory variables used in the Reunion Island pelagic longline fishery for the albacore CPUE standardization of the 1994-2000 and 2005-2013 datasets, referring to the best candidate models considering all regions combined and the REU core region. The residual deviance (Df and Dev) refer to the specific degrees of freedom and deviance explained by each additional variable included sequentially in the models.

Model / Data	**Variables**	**df**	**Dev.**	**Df**	**Dev**	**F-stat.**	***p-value***
Mod14: All data (1994-2013), All regions	Intersept only			29881	123987		
	Year	15	5568	29866	118419	114.1	< 0.001
	Year + Month	11	32142	29855	86277	898.5	< 0.001
	Year + Month + Region	3	1941	29852	84336	199.0	< 0.001
	Year + Month + Region + Vessel	64	4298	29788	80038	20.7	< 0.001
Mod18: All data (1994-2013), REU core region	Intersept only			27484	112510		
	Year	15	4722	27469	107788	105.3	< 0.001
	Year + Month	11	30130	27458	77658	916.1	< 0.001
	Year + Month + Area	3	480	27455	77178	53.5	< 0.001
	Year + Month + Area + Vessel	64	4086	27391	73092	21.4	< 0.001
	Year + Month + Area + Vessel + Month:Area	33	736	27358	72355	7.5	< 0.001

In terms of residual analysis of those two best models for the entire time period, the residuals for the model corresponding to the core region (Mod18) seemed to be better than when considering all the regions, as they were more evenly distributed along the fitted values and with a more Normal-shaped distribution (**Figure 16**). Only a few outliers were detected, but in general the residual analysis did not detect any major problems with the models (**Figure 16**).

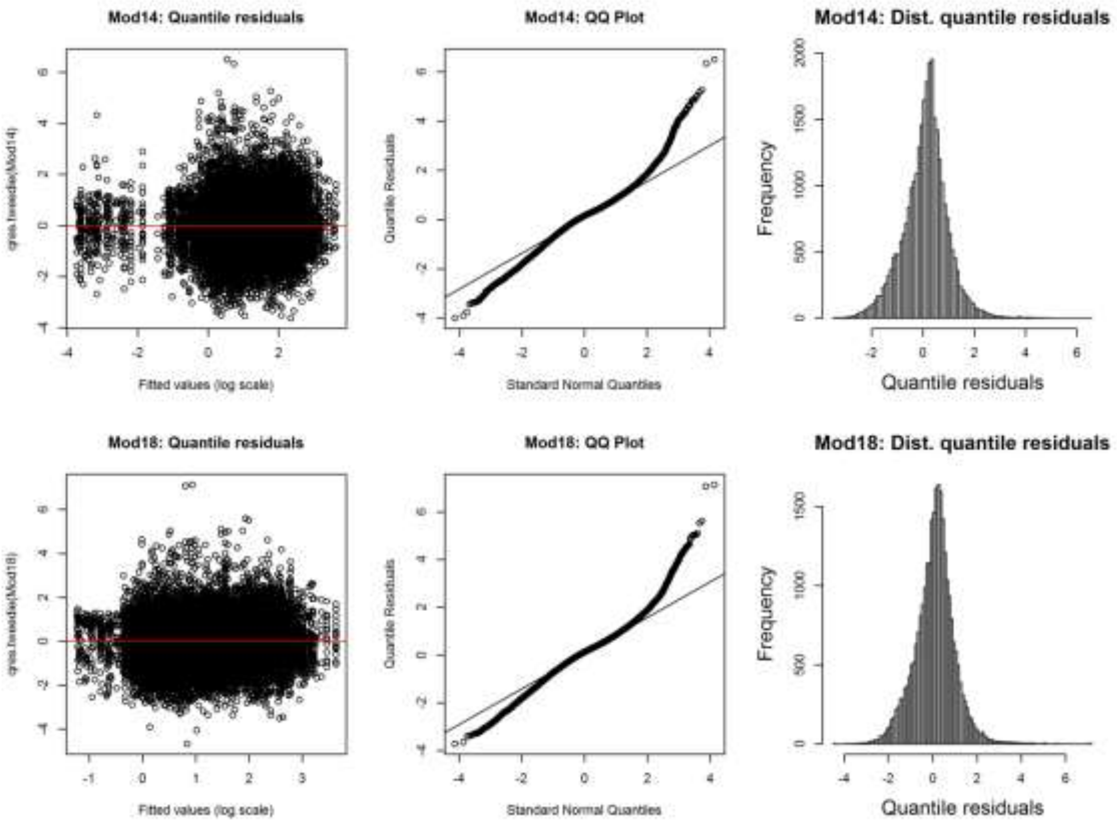


Figure 16. Residual analysis for the Reunion Island pelagic longline fishery albacore CPUE standardization of the 1994-2000 and 2005-2013 combined datasets, referring to the best candidate models considering all regions combined (Mod14) and the REU core region (Mod18). The plots on the left represent the quantile residuals along the predicted values (log scale), the plots in the middle represent the Q-Q Plot and the plots on the right the histogram with the residuals frequency distribution.

3.3.6. Sensitivity analysis

The sensitivity analysis in terms of the chosen error distribution revealed that the Tweedie and the Negative Binomial models produced almost identical standardized indices. The lognormal model was also very similar but with some slight differences, while the Delta-method approach produced the largest differences between these four tested approaches (**Figure 17**). However, the decreasing trend between 1994-1997, followed by an increase until 2000, and then a general decrease for the later period (2005-2013), was similar for all tested models, despite the detail differences noted between the models (**Figure 17**). In fact, the Tweedie and the Negative Binomial models resulted in practically identical indexes, with only some very minor differences. With regards to the Tweedie and the Lognormal models most of the indices was very similar, with the main differences detected especially for the most recent years, with the index obtained with the Lognormal model decreasing more than with the Tweedie model in those later years (**Figure 17**). By the contrary, with the Delta-method, larger differences were detected both in the initial and in the later time periods, and those differences were common to all other models. In terms of goodness-of-fit, the R^2 values obtained were also very similar, specifically 35.4% for the Tweedie, 35.2% for the Lognormal and 36.1% for the Negative Binomial model. With the Delta-method the R^2 values obtained were 37.8% for the positives-only Lognormal model and 14.8% for the Negative Binomial model with the proportion of positives. However, the values obtained with the Delta-method cannot be compared directly to the other models, as only part of the data (positives only) is modeled with one of the components (lognormal component), while with the Binomial model the component modeling the expected proportion of positive sets and not the CPUE.

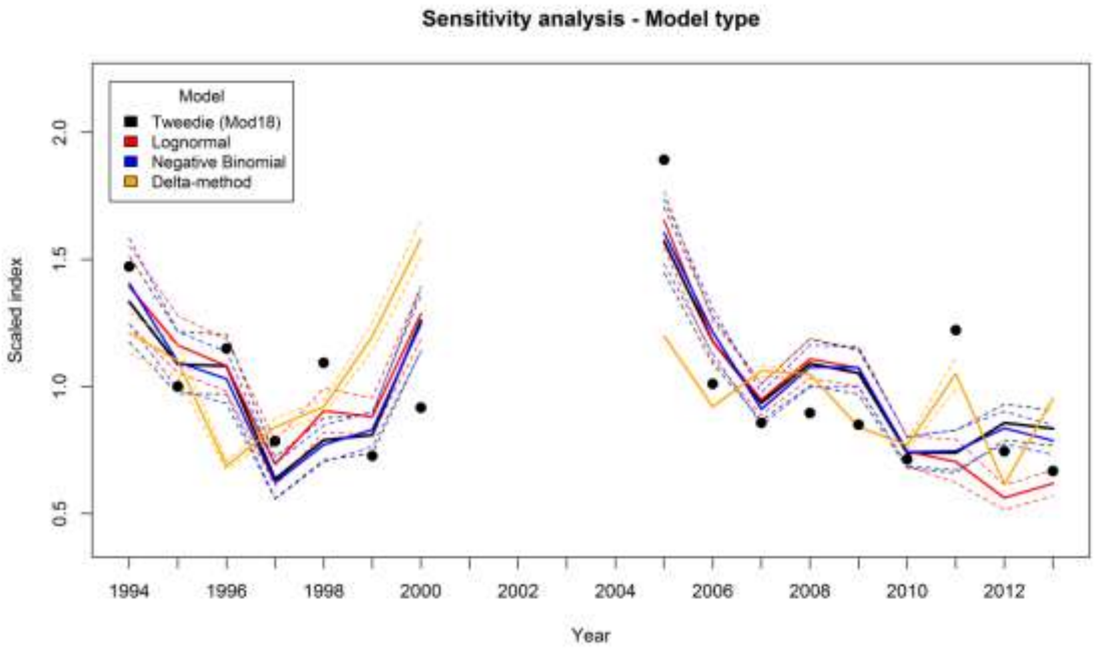


Figure 17. Sensitivity analysis to the model type (error distribution), for comparing the standardized albacore CPUE indexes obtained with the final Tweedie model (Mod 18), with a Lognormal model (adding *c*=1 to the CPUE), a Negative Binomial (modeling catches in N and using number of hooks as offset) and with the Delta-method approach (modeling separately the positive CPUE with a lognormal and the proportion of positives with a binomial logistic). The scaled annual indexes of abundance are represented as lines (with the 95% confidence intervals as dotted lines), and the black circles represent the nominal scaled CPUE.

3.3.7. Quarterly CPUE model

The quarterly index CPUE model was also applied to the two combined datasets, using the run Mod18 specifications (best model selected from the REU core region with the entire time series), in that particular case using the quarterly seasonal effects instead of the monthly effects, and taking into account the interactions between years and quarters. In that model it was possible to observe the strong quarterly effects in the albacore catch rates, which were consistently capturing more fishes during the warmer periods of the year, particularly during the 4th quarter of each year (**Figure 18**). This helps to highlight the high seasonality of the albacore catches in this fishery, as the albacores are only present in the fishing grounds and taken by this fishery during part of the year.

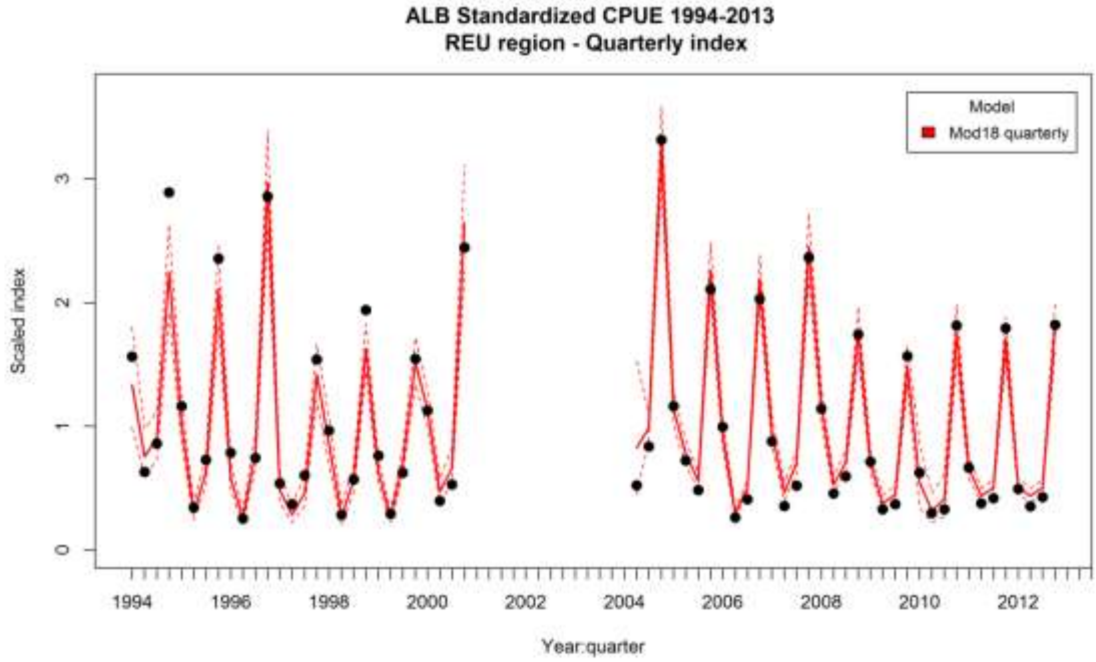


Figure 18. Standardized quarterly albacore CPUE indexes for the 1994-2000 and 2005-2013 data periods (voluntary and mandatory logbooks) of the Reunion Island pelagic longline fishery, considering the catches in the REU core region. The black circles represent the nominal CPUE, the solid red lines the standardized CPUE and the dotted red lines the 95% confidence intervals.

4. Conclusions

After testing the various available datasets for the two different time periods, comparing the use of the entire region *versus* the REU core area and performing a sensitivity analysis to the model type used, we concluded that run **Mod 18** (as specified in **Table 2**, with the index plotted in **Figures 15 and 17**, the residuals plotted in **Figure 16**, and the deviance table presented in **Table 5**, seemed to be the best approach to standardize the annual albacore CPUE index from the Reunion Island pelagic longline fishery. It should be noted that **Mod6** is also very well fitted to the data, however that specific model is only using the initial years of the time series and not all the available datasets.

The final annual standardized CPUE index values for the Reunion Island pelagic longline fishery with the respective confidence intervals and coefficients of variation, which represents a further contribution for the future stock assessment of the species in the Indian Ocean, are presented in **Table 6**.

Table 6. Standardized albacore CPUE index (N/1000 hooks) for the Reunion Island pelagic longline fishery in the Indian Ocean between 1994 and 2013, suggested to be used in future stock assessments, including the index value, the 95% confidence intervals (CI) and the coefficient of variation (CV, %).

Year	Estimate	Upper 95%CI	Lower 95%CI	CV (%)
1994	3.80	4.31	3.35	6.3
1995	3.10	3.47	2.77	5.7
1996	3.08	3.43	2.77	5.4
1997	1.81	2.06	1.60	6.4
1998	2.25	2.50	2.03	5.2
1999	2.31	2.53	2.10	4.6
2000	3.59	3.97	3.25	5.0
2001	-	-	-	-
2002	-	-	-	-
2003	-	-	-	-
2004	-	-	-	-
2005	4.48	4.86	4.13	4.1
2006	3.36	3.63	3.11	3.9
2007	2.67	2.88	2.47	3.8
2008	3.11	3.38	2.86	4.2
2009	3.00	3.25	2.76	4.1
2010	2.11	2.29	1.94	4.2
2011	2.11	2.36	1.88	5.7
2012	2.44	2.65	2.25	4.1
2013	2.38	2.58	2.19	4.1

The presented index has the advantages of using the entire time series period available (1994 to 2013, with missing years between 2001 and 2004). Furthermore by using a Tweedie model, the CPUE can be modeled directly and there is no need to add a constant to the CPUE to remove the zeros (as has to be done with the lognormal model) or to combine two different models (as has to be done with the Delta-method). As was shown by Shono (2008), adding a constant to the CPUE seems to be a good approach when the percentage of zeros is relatively low (<10%), but may produce biased results for datasets with larger percentages of zeros, as was the case of the present datasets with 20.5-25.3% of zeros (depending on the dataset).

An alternative approach with very similar results would be to use a Negative Binomial model, with the only shortcoming of this approach the fact that the Negative Binomial being a discrete distribution and therefore being limited to modeling the catches in numbers (counts). However, we would not recommend applying this approach if the catches would have been modeled in biomass. In this specific case, the Tweedie distribution (as a continuous distribution) can model the CPUE directly, while the

Negative Binomial used was modeling the catches in counts (N) and using the effort (number of hooks) as an offset variable in the model. Additionally, a Poisson model was also tested instead of the Negative Binomial, but not used due to the fact that the albacore CPUE data was overdispersed (dispersion parameter = 5.89).

In terms of using the all three regions *versus* the core region of the fishery (Reunion - REU) and albacore catches, one limitation when using only the core region is the possible loss of information on eventual spatial changes in the population (e.g. range contraction). However, when the standardized CPUEs were compared between the all combined areas of operation of the fishery with the REU core area only, the major CPUE trends were very similar indicating that such possible spatial changes were not being lost when modeling only the core region. In that way, the models for the REU core region seem to be able to reflect the changes in the albacore population in the entire region of the fishery.

Another tested option was to use a quarterly model, and it was interesting to note the seasonal variability in the quarterly CPUE index, with higher albacore catch rates during the warmer period, particularly in quarter 4. This quarterly model is reflecting the dynamics of the species and the albacore catches within the fishery along the quarters, while in the proposed annual standardized index (as presented in Mod18) those seasonal effects were removed from the annual index, as in that model the seasonal factors (in that particular case using months) were considered. Additionally, in the proposed final annual index the interactions between month and area were also considered, meaning that if the seasonal effects were different between the various regions those were also taken into account in the final annual CPUE index.

Another issue that has some influence in the results of this work is the FL-W relationship used to convert from catch in biomass to catch in numbers, and in this study we used the "*Length & weight conversion equations used for IOTC species"*. However, it should be noted that the relationships currently used for IOTC albacore comes from South Atlantic ICCAT data (equation from Penney 1994) but with an error introduced in IOTC (b= 3.0973 and not 3.0793). As such, and also considering other relationships available specifically for the Indian Ocean (e.g. Setyadji et al. 2012; Xu and Tian 2011; Zhu et al. 2008; Hsu 1999; Huang et al. 1990), this relationship currently accepted by IOTC might not be the most appropriate one for the Indian Ocean albacore. An albacore biological revision is currently being carried out by Ifremer, and will be presented in a separate document during the IOTC-WPTmT5.

Finally, one possibly important shortcoming of this work is the fact that targeting effects were not directly included in the models, but it is possible that the relative importance of the species in the fishery may have changed over time. For future research, it would be recommended to compile and collect additional data, especially operational details that could be used as proxy indicators for the fishery targeting effects, such as setting depth, bait and hook type used, and any other factors that the skippers identify as relevant. However, the final models used included a vessel identification factor and those may, to some extent, also be accounting for possible species targeting effects (i.e. swordfish *versus* albacore) that vary between the different vessels. Additionally, the fact that the models for the core region of the catches (were the targeting effects are likely to be less important, particularly during the warmer season when the albacore catches are higher) were producing similar results to the models for the entire fishery, which seems to suggest that the presented models were not majorly influenced by possible unaccounted targeting effects or, that the vessel effects already included are taking into account those possible targeting effects.

5. Acknowledgments

This work was carried out as part of project GERMON, GEnetic stRucture and Migration Of albacore tuna (GERMON Project) funded by the Fond Européen pour la Pêche – FEP and Ifremer (Ref n°39704/DMSOI/2013). The authors are grateful to Dale Kolody (CSIRO Marine and Atmospheric Research, Hobart, Tasmania, Australia) for providing help in the initial development stages of this work in terms of database management and R-code scripts.

6. References

Becker, R.A., Wilks, A.R., Brownrigg, R. 2013a. mapdata: Extra Map Databases. R package version 2.2-2. http://CRAN.R-project.org/package=mapdata

Becker, R.A., Wilks, A.R., Brownrigg. R., Minka, T.P. 2013b. maps: Draw Geographical Maps. R package version 2.3-6. http://CRAN.R-project.org/package=maps

Bivand, R. 2013. classInt: Choose univariate class intervals. R package version 0.1-21. http://CRAN.R-project.org/package=classInt

Bivand, R., Lewin-Koh, N. 2013. maptools: Tools for reading and handling spatial objects. R package version 0.8-27. http://CRAN.R-project.org/package=maptools

Campbell, R.A. 2004. CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research*, 70: 209–227.

Candy, S.G. 2004. Modeling catch and effort data using generalized linear models, the tweedie distribution, random vessel effects and random stratum-by-year effects. *CCAMLR Science*, 11: 59-80.

Carvalho, F., Hazin, H., Hazin, F.H.V., Wor, C., Murie, D., Travassos, P., Burgess, G. 2009. Catch trends of blue and mako sharks caught by Brazilian longliners in the Southwestern Atlantic Ocean (1978-2007). *Collective Volume of Scientific Papers ICCAT*, 64(5): 1717-1733.

Coelho, R., Santos, M.N., Lino, P.G. 2012. Update of the standardized CPUE series for major shark species caught by the Portuguese pelagic longline fishery in the Indian Ocean. *IOTC Working Document*, IOTC–2012–WPEB08–29.

Coelho, R., Lino, P.G., Santos, M.N. 2013. Standardized CPUE for the shortfin mako (*Isurus oxyrinchus*) caught by the Portuguese pelagic longline fishery. *Collective Volume of Scientific Papers ICCAT*, 69(4): 1591-1604.

Cortés, E. 2009. Standardized catch rates for blue and mako sharks from the U.S. pelagic longline logbook and observer programs. *Collective Volume of Scientific Papers ICCAT*, 64(5): 1595-1613.

Dunn, P.K. 2012. tweedie: Tweedie exponential family models. R package version 2.1.3.

Fox, J., Weisberg, S. 2011. An {R} Companion to Applied Regression, Second Edition. Thousand Oaks CA: Sage.

Gerritsen, H. 2013. mapplots: Data visualisation on maps. R package version 1.4. http://CRAN.R-project.org/package=mapplots

Hazin, H., Frédou, T., Travassos, P., Hazin, F., Carvalho, F. 2008. Standardization CPUE series of albacore (Thunnus alalunga) caught by Brazilian longliners in the Atlantic Ocean. *Collective Volume of Scientific Papers ICCAT*, 62(3): 934-943.

Hilborn, R., Walters, C.J. 1992. *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. Chapman and Hall, New York. 570 pp.

Hsu, CC. 1999. The length-weight relationship of Albacore, *Thunnus alalunga*, from the Indian Ocean. Fisheries Research 41: 87-92

Huang, C.-S., Wu, C.-L., Kuo, C.-L., Su, W.-C., 1990. Age and growth of the Indian Ocean albacore, *Thunnus alalunga*, by scales. IPTP Working Paper, FAO IPTP/TWS/90/53, pp.

Højsgaard, S., Halekoh, U., Robison-Cox, J., Wright, K., Leidi, A.A. 2013. doBy: doBy - Groupwise summary statistics, general linear contrasts, population means (least-squares-means), and other utilities. R package version 4.5-9. http://CRAN.R-project.org/package=doBy

Kolody, D., Poisson, F., Bourjea, J. 2010. Reunion Longline Swordfish Catch Rate Standardization. *IOTC Working Document*, IOTC–2010–WPB–03.

Lee, L-K., Chang, F-C., Chen, C-Y., Wang, W-J., Yeh, S-Y. 2012. Standardized CPUE of Indian albacore (*Thunnus alalunga*) based on Taiwanese longline catch and effort statistics dating from 1980 to 2011. *IOTC Working Document*, IOTC–2012–WPTmT04–18.

Lee, S., Kim, Z.G., Nishida, T., Lee, M.K. 2012. Standardization of albacore catch rates of Korean tuna longline fisheries in the Indian Ocean (1986-2010). 2012. *IOTC Working Document*, IOTC–2012–WPTmT04–17_Rev 1.

Lenth, R.V. 2013. lsmeans: Least-squares means. R package version 1.06-05. http://CRAN.R-project.org/package=lsmeans

Matsumoto, T., Nishida, T., Okamoto, H. 2012. Standardization of albacore CPUE by Japanese longline fishery in the Indian Ocean. *IOTC Working Document*, IOTC–2012–WPTmT04–10 Rev_1.

Maunder, M.N., Punt, A.E. 2004. Standardizing catch and effort data: a review of recent approaches. *Fisheries Research*, 70: 141–159.

Neuwirth, E. 2011. RColorBrewer: ColorBrewer palettes. R package version 1.0-5. http://CRAN.R-project.org/package=RColorBrewer

Nishida, T., Matsumoto, T., Kitakado, T. 2012. Stock and risk assessments on albacore (*Thunnus alalunga*) in the Indian Ocean based on AD Model Builder implemented Age-Structured Production Model (ASPM). *IOTC Working Document*, IOTC–2012–WPTmT04–21 Rev_4.

Ortiz, M., Arocha, F. 2004. Alternative error distribution models for standardization of catch rates of non-target species from a pelagic longline fishery: billfish species in the Venezuelan tuna longline fishery. *Fisheries Research*, 70: 275-297.

Penney, A.J., 1994. Morphometric relationships, annual catches and catch-at-size for south African caught south Atlantic albacore (*Thunnus alalunga*). International Commission for the Conservation of Atlantic Tunas, Coll. Vol. Sci. Pap. 42(1): 371-382.

Poisson F., Taquet. M. (Eds). 2001. L'espadon : de la recherche à l'exploitation durable. Programme Palangre Réunionnais, Rapport final, 248pp.

Pons, M., Travassos, P., Domingo, A., Hazin, H., Hazin, F. 2009. Standardized CPUE of yellowfin tuna (*Thunnus albacares*) caught by the Uruguayan and Brazilian pelagic longline fleets (1980-2006). *Collective Volume of Scientific Papers ICCAT*, 63(3): 977-987.

Pradhan, N.C., Leung, P. 2006. A Poisson and negative binomial regression model of sea turtle interactions in Hawaii's longline fishery. *Fisheries Research*, 78: 309–322.

Punt, A.E., Walker, T.I., Taylor, B.L., Pribac, F. 2000. Standardization of catch and effort data in a spatially-structured shark fishery. *Fisheries Research*, 45: 129-145.

R Core Team, 2013. A language and environment for statistical computing. Version 2.15.3. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Setyadji, B., Novianto, D., Nugraha, B., Sadiyah, L. 2012. Catch and size distribution of albacores (*Thunnus alalunga*) in the Eastern Indian Ocean. IOTC-2012-WPTmT04-13.

Shono, H. 2008. Application of the Tweedie distribution to zero-catch data in CPUE analysis. *Fish. Res.*, 93: 154–162.

Stabler, B. 2013. shapefiles: Read and Write ESRI Shapefiles. R package version 0.7. http://CRAN.R-project.org/package=shapefiles

Uosaki, K., Shono, H. 2008. Standardized CPUE for albacore using lognormal and negative binomial models for the Japanese longline in the Atlantic Ocean. *Collective Volume of Scientific Papers ICCAT*, 62(3): 911-933.

Venables, W.N., Ripley, B.D. 2002. *Modern Applied Statistics with S*. 4th Edition. Springer, New York.

Warnes, G.R. 2012. gmodels: Various R programming tools for model fitting. R package version 2.15.3. http://CRAN.R-project.org/package=gmodels

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Wickham, H. 2012. scales: Scale functions for graphics.. R package version 0.2.3. http://CRAN.R-project.org/package=scales

Wood, S.N. 2006. Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC.

Wood, S.N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (B)*, 73(1): 3-36.

Zhu, G., Liuxiong, X., Yingqi, Z., Dai, X. 2008. Length-frequency compositions and weight-length relations for big-eye tuna, yellowfin tuna, and albacore (Perciformes: Scombridae) in the Atlantic, Indian, and Eastern Pacific Oceans. *Acta Ichthyologica et Piscatoria*, 38(2): 157-161.