UPDATED STANDARDIZED CATCH RATES OF SHORTFIN MAKO (*Isurus oxyrinchus*) INFERRED FROM THE SPANISH SURFACE LONGLINE FISHERY IN THE INDIAN OCEAN DURING THE PERIOD 2001-2022

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ABSTRACT

This paper provides an updated of the standardized catch rates per unit of effort (CPUE) in number and in biomass for the shortfin mako in the Indian Ocean stock using Generalized Linear Models. A total of 2,828 trips (80.3 millions of hooks) which represents around 90% of the total effort deployed by the Spanish surface longline fleet targeting swordfish, were analyzed for the period 2001-2022. The main factors considered in the final models were year, quarter, area, and the targeting criteria of skippers. The results indicate that the year regularly was the most important factor explained the CPUE variability. However, the ranking and the relative importance of each main factor are depending on whether capture rates are considering in number or weight. The model explained 33% and 26% of CPUE variability in number and weight, respectively. Both standardized CPUE show stable trends until 2008 with an increasing trend until 2021 and a slightly decreasing in the last year of the series.

Key words: shortfin mako, sharks, CPUE, GLM, longline**.**

1. INTRODUCTION

The shortfin mako, *Isurus oxyrinchus*, is a highly mobile marine predator widely distributed mainly off-shore in temperate, subtropical and tropical areas worldwide. It is a common, extremely active, and highly migratory species with occasional inshore movements from the deeper water over the continental slopes (Compagno 2001). Shortfin mako is one of the most abundant and common shark species caught as bycatch in pelagic longline and driftnet fisheries in the Indian Ocean. In some cases, is also a catch of other gear such as purse seiners, hand lines, recreational and charter fisheries. The complexity of the horizontal and vertical behavior of shortfin mako (a 3-dimensional habitat) has been described in literature related to conventional and electronic tagging. This species spends a great deal of time near the surface layers (Abascal *et al*. 2011, Vaudo *et al*. 2024). The analyzes suggest not only behavioral changes of this species between different thermal areas-habitats but also high levels of inter- and intra-individual variability in the pelagic environment related to prey patches located in the horizontal and vertical dimensions. The behaviour can be also directly related in order to minimize energetic costs and the depth distribution could be significant related to the body size, water column characteristics and behavioural state. However, the studies available to date do not allow identify common and generalized behavioral patterns and a high diversity is described in literature.

The most common method for standardizing catch rates (CPUE) is the application of generalized linear models (GLM) (Robson 1966, Gavaris 1980, Kimura 1981) which removes the effects of factors other than abundance that bias the index. Indirect factors such as operational changes, technological improvements, including changes in the target species or the targeting criteria of the skippers over time, could be a good alternative to be considered in some cases. Modeling approaches should be adapted to each fishery case, data availability and the respective historical circumstances of each fishery.

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The Spanish surface longline fishery has been developed since the late 1970's in the North Atlantic areas targeting mainly swordfish (*Xiphias gladius*) and has been operating in the Indian Ocean since 1993. During the period analyzed in the present paper, the commercial fishing areas of this fleet in the Indian Ocean remained fairly constant, and the monofilament 'American style' gear was largely introduced on most vessels and it became essentially the only gear style present.

This document is an update of the standardized CPUE series of shortfin mako (*Isurus oxyrinchus*) for the Spanish longline fishery targeting swordfish in the Indian Ocean that was presented to the IOTC Working Party on Ecosystems and Bycatch (WPEB16) in 2020 (Ramos-Cartelle *et al. 2*020). Descriptive about this fishery and sensitivity scenarios already tested in previous analysis are not reiterated in the present paper for procedural economy.

2. MATERIAL AND METHODS

The data used in this analysis were voluntarily reported and taken for scientific purposes from the Spanish surface longline fleet targeting swordfish and from scientific observers onboard in the Indian Ocean, during the period 2001-2022. The nominal effort was defined by thousands of hooks. The nominal catch per unit of effort (CPUE) was obtained as number of fish and kilograms round weight per thousand hooks.

The standardized log-normal CPUE analyses were performed using generalized linear model (GLM) procedures of *SAS 9.4* assuming a log-normal distribution of catch rates. A base case GLM (in number of fish and in round weight) and sensitivity analyses (in weight) were carried out. The models took into consideration the results of deviance obtained, including the main factors and factor-interactions that reduce the overall deviance ≥ 5% of the full model in weight.

The response variable lnCPUE measured in number and in weight per 1000 hooks and the following explanatory variables were considered for the analysis: year, quarter, area, gear, bait, ratio and interactions:

$$\text{Ln (CPUE)} = u + Y + Q + A + G + B + R + \text{(interactions)} + e$$

Where: u = overall mean, Y = *year* effect, Q = *quarter* effect (Q1 = January-March; Q2 = April-June; Q3 = July-September; Q4 = October-December), A= *area* effect (**Figure 1**), G = *gear* style effect (traditional multifilament or American-monofilament style), B = *bait* type (mackerel, squid or unknown), R= *ratio* or targeting effect (defined in order to categorize each type of trip record based on the percentage of swordfish in weight related to the catches of swordfish and blue shark combined, broken down into ten ratio categories at 10% intervals) and e = logarithm of the normally distributed error term.

An alternative run was considered as a sensitivity analysis using a generalized linear mixed model (GLMM) procedure, which allows some of the parameters in the linear predictor to be treated as random variables (Maunder and Punt 2004).

3. RESULTS AND DISCUSSION

A total of 2,828 trip records (80.3 millions of hooks) were available for the analysis between 2001 and 2022. The spatial and temporal coverage of the observations were highly representative of the whole activity of this Spanish feet during the period analyzed. The percentage of effort that was included in the analysis was the 90% of the total effort during this period. **Figure 1** shows the geographical areas stratification used in the GLM models. They were the same areas used in previous analyses of shortfin mako (Ramos-Cartelle *et al.* 2020). The number of observations as well as catch and effort coverage per spatial-temporal strata can be considered satisfactory, except for area 56 where few observations were available because the commercial fishing was very rare or sporadic. Therefore, 7 areas were considered in the final runs. Area 56 was merged with area 57.

Table 1 provides the results of deviance analysis of the factors tested in the analysis for standardized the catch rates of the shortfin mako in the Indian Ocean. Factors that reduce the overall deviance more than 5% of the full model in weight were used as base case. Some interactions with the area factor, such as area-ratio and area-quarter, although they reduced the deviance more than 5%, were not considered in the runs due to convergence problems in the models. The final base case GLM model was: Ln (CPUE) = u + Y + Q + A + R + e.

Table 2 provides the ANOVA summary obtained from the GLM base case analysis, including R-square, mean square error (root), F statistics and significance level, as well as the Type III SS for each factor considered. The base case models explained the 33% and the 26% of the CPUE variability in number and weight respectively. All the explanatory variables tested contributed significantly to explaining part of the deviance.

In the case of the CPUEn (in number), the variability (Type III SS) can be attributed mainly to the *year* and *area* factors. The targeting criteria (*ratio*) and *quarter* were also significant but less important. The ranking for factors changes for the CPUEw analysis (in round weight). The variability was in the last case mainly attributed to the *year* and *area* factors and less to *ratio* and *quarter* factors. The results obtained in this case suggest that the skipper's targeting criteria (the *ratio* factor) although significant, was much less important than when the main or targeting species are analyzed (swordfish and blue shark), probably because the shortfin mako is a “pure” bycatch in this fleet (García-Cortés and Mejuto 2005, Ramos-Cartelle *et al.* 2008, 2009).

Tables 3 and **4** provide information on estimated parameters lsmean, standard error, CV%, standardized CPUE and upper and lower 95% confidence limits, in number and in weight, respectively. **Figure 2** shows the frequency distribution of standardized residuals and normal probability qq-plot in number of fishes and in weight for the years 2001 to 2022 combined. The variability box-plot for the standardized residuals obtained by the main factors considered in the base case runs is shown in number (**Figures 3)** and in weight (**Figures 4)**.

Figure 5 shows the base case standardized CPUE in number and weight as well as the standardized mean round weight obtained by year and their respective 95% confidence intervals. Both trends of standardized CPUE in number and weight are similar. Both standardized CPUE shows a stable trend until 2008 followed by an increasing trend since then until 2021 and been a decreasing trend in the last year of the series. In the case of the standardized mean weight, this shows a slight decrease in the weight at the beginning of the series until 2007, followed by a stable trend until the current years, with a mean round weight above the 70 Kg in all years.

A sensitivity analysis was carried out using a Generalized Linear Mixed Model (GLMM) in which some of the factors are treated as random variables (interactions year-quarter, year-area and year-ratio). Some interactions with the area factor, such as area-ratio and area-quarter, reduced the deviance by more than 5% (**Table 1**), but were not included in the runs due to convergence problems in the model. The final GLMM model was: Ln (CPUE) = Y + A + Q + R + random (Y*Q + Y*A + Y*R).

Figure 6 shows a comparative between standardized CPUE performed in the base case in weight and the sensitivity analyzes. The CPUE were scaled to their respective average values to be compared. Overall, the trends obtained are similar with a small difference between the base case and the GLMM for some of the years analyzed. The updated index is in line with the one presented in the previous document in 2020 (Ramos-Cartelle *et al*. 2020).

It is recognized by many scientists as almost impossible to avoid some degree of model misspecification due to complexity and heterogeneity in the fishery operations among very different fleets. A first step is to determine in each fleet which explanatory variables should be a priori considered that they may influence catchability of the species. The empirical information obtained from the fishing actors is one of the keys. In each fleet, methodology to standardize catch rates is often developed and adapted to their respective casuistry in terms of the history of the fishery (the greater or lesser knowledge of the fishery and information recorded from fishermen), the deficiencies or lacks of the historical data available (Kai 2023, Walter *et al.* 2014), the fishing practices and changes over time (Cardoso *et al.* 2023); among other factors considering their respective particularities for different authors.

The coefficients of variation (CV) provided could be relatively shorter than those reported in other fleets. The CV is a statistical measure that tells us about the relative dispersion around the mean of the dataset analyzed. But dispersion of the data could be affected by many factors. It is convenient to put in context the meaning of the CVs obtained in the different studies considering the respective fleets, gear-styles modeled, model approach, volume of data used and the representativeness of each dataset, area-time definitions, quality of the observations and filtering implemented before modeling, and of course the aggregation degree of the respective observations modeled. For instance, the standardization of catch rates carried out on shortfin mako based on data from observers at sea using a relative low data coverage it regularly have produced broader confidence intervals and higher CVs (range 19-47%) than those obtained using mandatory logbooks data (range 7-13%) with a much higher coverage, using in both cases set-by-set data of the same fleet; even although mandatory logbook data could be affected by misreports of catches for some years (Cortés 2017). In a similar way, studies carried out in a fleet for swordfish CPUE standardization achieved lower CV (range 3-51%) when shallow sets were separately analyzed versus much higher CV values (168-269%) when deep sets considered (Sculley *et al*. 2018). Different ranges of CVs could be also obtained depending of the dataset used and the model factors considered for the same fleet (Walter *et al.* 2014). Lower CVs do not necessarily mean that they better represent the abundance of the whole stock it doesn't mean either the opposite. For instance, a very low amount of records used from restricted areas-times and with low variability in the fishing practices observed could achieve relatively lower CVs (Tsai and Liu 2017) than those obtained in other fleets with highly amount of data and much greater representativeness. The assessment of each index -and weights considered in the stock assessment models- should be evaluated case by case based on *qualitative* and *quantitative* merits of the data used, the credibility of each dataset, the spatial coverage of each fleet data in relation to the stock area-distribution and habitats, as well as (inter alia) the biological plausibility of the inter-annual CPUE variability obtained in the analyses since abrupt changes in the total abundance should not be biologically plausible in this type species during short time scenarios (Ramos-Cartelle *et al.* 2011).

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Table 1. Deviance table of the factors tested for log CPUE (in weight) for the shortfin mako of the Indian Ocean. Highlighted are the factors with ≥ 5.0% of deviance explained.

Model factors	d.f.	Residual deviance	Change in deviance	% of total deviance	*p*	chi-sq
1	_	1758.4478				
Year	21	1528.9533	229.4945	38.7%	< 0.001	5.20E-37
Year Quarter	3	1492.1963	36.7570	6.2%	< 0.001	5.18E-08
Year Quarter Area	6	1363.0797	129.1166	21.8%	< 0.001	1.97E-25
Year Quarter Area Gear	1	1356.3958	6.6839	1.1%	0.010	9.73E-03
Year Quarter Area Gear Bait	2	1341.1022	15.2936	2.6%	< 0.001	4.78E-04
Year Quarter Area Gear Bait Ratio	9	1280.708	60.3942	10.2%	< 0.001	1.13E-09
Year Quarter Area Gear Bait Ratio Year*Gear	1	1280.437	0.2710	0.0%	0.603	6.03E-01
Year Quarter Area Gear Bait Ratio Gear*Ratio	3	1279.5579	1.1501	0.2%	0.765	7.65E-01
Year Quarter Area Gear Bait Ratio Quarter*Gear	2	1278.0177	2.6903	0.5%	0.261	2.61E-01
Year Quarter Area Gear Bait Ratio Quarter*Bait	4	1274.8572	5.8508	1.0%	0.211	2.11E-01
Year Quarter Area Gear Bait Ratio Area*Bait	7	1273.0022	7.7058	1.3%	0.359	3.59E-01
Year Quarter Area Gear Bait Ratio Area*Gear	4	1272.3212	8.3868	1.4%	0.078	7.84E-02
Year Quarter Area Gear Bait Ratio Year*Bait	19	1270.9867	9.7213	1.6%	0.959	9.59E-01
Year Quarter Area Gear Bait Ratio Bait*Ratio	13	1268.7789	11.9291	2.0%	0.533	5.33E-01
Year Quarter Area Gear Bait Ratio Quarter*Ratio	26	1252.9561	27.7519	4.7%	0.371	3.71E-01
Year Quarter Area Gear Bait Ratio Area*Ratio	43	1221.8243	58.8837	9.9%	0.054	5.39E-02
Year Quarter Area Gear Bait Ratio Year*Quarter	63	1208.7763	71.9317	12.1%	0.206	2.06E-01
Year Quarter Area Gear Bait Ratio Quarter*Area	17	1208.4661	72.2419	12.2%	< 0.001	8.84E-09
Year Quarter Area Gear Bait Ratio Year*Ratio	148	1189.0369	91.6711	15.5%	1.000	1.00E+00
Year Quarter Area Gear Bait Ratio Year*Area	83	1165.3508	115.3572	19.4%	0.011	1.09E-02

Table 2. Summary of ANOVA for the base case CPUE analysis, in number (upper table) and in weight (lower table).

CPUEn (in number of fish)

Source	DF	Sum of Squares	Mean squared	F value	Pr>F
Model	39	611.94504	15.690898	35.48	<.0001
Error	2788	1232.972765	0.442243		
Corrected Total	2827	1844.9178			

R-Squared	Coeff Var	Root MSE	Mean CPUEn
0.331692	194.3004	0.665013	0.34226

Source	DF	Type III SS	Mean squared	F value	Pr>F
year	21	103.9391754	4.9494845	11.19	<.0001
quarter	3	58.8990224	19.6330075	44.39	<.0001
area	6	164.604726	27.434121	62.03	<.0001
ratio	9	34.6187631	3.8465292	8.7	<.0001

CPUEw (in round weight)

Source	DF	Sum of Squares	Mean squared	F value	Pr>F
Model	39	454.366098	11.650413	24.91	<.0001
Error	2788	1304.081727	0.467748		
Corrected Total	2827	1758.447825			

R-Squared	Coeff Var	Root MSE	Mean CPUEw
0.25839	15.18185	0.683921	4.504861

Source	DF	Type III SS	Mean squared	F value	Pr>F
year	21	98.62725289	4.69653585	10.04	<.0001
quarter	3	46.82081567	15.60693856	33.37	<.0001
area	6	98.33555645	16.38925941	35.04	<.0001
ratio	9	58.99798928	6.55533214	14.01	<.0001

Table 3. Estimated parameters (lsmean), standard error (stderr), standardized CPUE in number (CPUEn) of shortfin mako, upper and lower 95% confidence limits and CV for the Spanish longline fleet in the Indian Ocean during the period analyzed 2001-2022.

YEAR	LSMEAN	STDERR	UCPUEn	CPUEn	LCPUEn	CV (%)
2001	-0.4005	0.0866	0.7968	0.6725	0.5676	8.67
2002	-0.2748	0.0610	0.8579	0.7611	0.6753	6.11
2003	-0.3370	0.0573	0.8001	0.7151	0.6391	5.74
2004	-0.4114	0.0595	0.7461	0.6639	0.5908	5.96
2005	-0.3488	0.0672	0.8067	0.7071	0.6199	6.73
2006	-0.4860	0.0556	0.6870	0.6161	0.5525	5.56
2007	-0.4068	0.0688	0.7637	0.6674	0.5832	6.88
2008	-0.4988	0.0725	0.7018	0.6089	0.5282	7.26
2009	-0.3955	0.0724	0.7781	0.6751	0.5858	7.25
2010	-0.1600	0.0930	1.0269	0.8559	0.7133	9.32
2011	-0.0636	0.0839	1.1100	0.9417	0.7988	8.41
2012	0.0005	0.0750	1.1623	1.0033	0.8661	7.51
2013	-0.1979	0.0696	0.9427	0.8224	0.7175	6.97
2014	-0.0726	0.0687	1.0665	0.9322	0.8148	6.88
2015	-0.2076	0.0873	0.9679	0.8156	0.6873	8.75
2016	-0.0687	0.0933	1.1258	0.9377	0.7810	9.35
2017	0.1282	0.0967	1.3805	1.1421	0.9448	9.70
2018	-0.0119	0.1029	1.2155	0.9934	0.8119	10.32
2019	-0.0885	0.0849	1.0850	0.9186	0.7778	8.51
2020	0.0428	0.0518	1.1568	1.0451	0.9443	5.18
2021	0.3009	0.0762	1.5732	1.3550	1.1671	7.63
2022	0.1458	0.0801	1.3579	1.1607	0.9921	8.02

Table 4. Estimated parameters (lsmean), standard error (stderr), standardized CPUE in weight (CPUEw) of shortfin mako, upper and lower 95% confidence limits and CV for the Spanish longline fleet in the Indian Ocean during the period analyzed 2001-2022.

YEAR	LSMEAN	STDERR	UCPUEw	CPUEw	LCPUEw	CV (%)
2001	3.8442	0.0890	55.8484	46.9075	39.3980	8.92
2002	3.9455	0.0628	58.5846	51.8021	45.8048	6.28
2003	3.9804	0.0590	60.2051	53.6335	47.7793	5.90
2004	3.8389	0.0612	52.4970	46.5622	41.2983	6.13
2005	3.8307	0.0691	52.9123	46.2072	40.3517	6.92
2006	3.7086	0.0572	45.7093	40.8628	36.5301	5.72
2007	3.7413	0.0707	48.5397	42.2573	36.7880	7.08
2008	3.6499	0.0745	44.6443	38.5765	33.3334	7.46
2009	3.7876	0.0745	51.2305	44.2717	38.2581	7.46
2010	3.9778	0.0956	64.7029	53.6455	44.4778	9.58
2011	4.0631	0.0863	69.1274	58.3687	49.2845	8.65
2012	4.1458	0.0772	73.7039	63.3579	54.4642	7.73
2013	4.0322	0.0716	65.0432	56.5274	49.1265	7.17
2014	4.1532	0.0706	73.2648	63.7930	55.5458	7.07
2015	4.0407	0.0898	68.0856	57.0949	47.8783	9.00
2016	4.0810	0.0960	71.7856	59.4791	49.2824	9.62
2017	4.2732	0.0995	87.6318	72.1059	59.3308	9.97
2018	4.1785	0.1059	80.7736	65.6376	53.3379	10.62
2019	4.1397	0.0874	74.7901	63.0214	53.1047	8.75
2020	4.2314	0.0533	76.4962	68.9138	62.0831	5.33
2021	4.4396	0.0783	99.1107	85.0050	72.9069	7.85
2022	4.3196	0.0823	88.6177	75.4109	64.1723	8.25

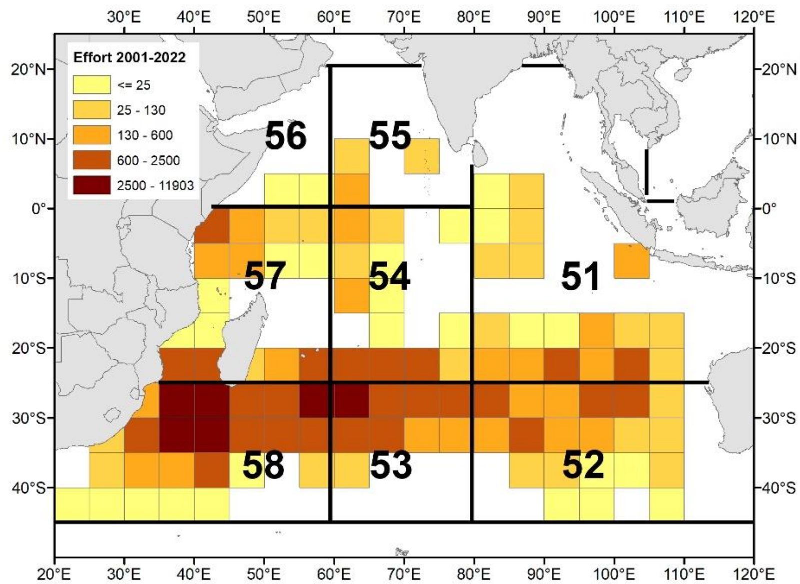

Figure 1. Area definition used for the GLM runs. Color scale represents the total nominal effort of this fleet (thousands of hooks) per 5x5 squares during the combined period 2001-2022.

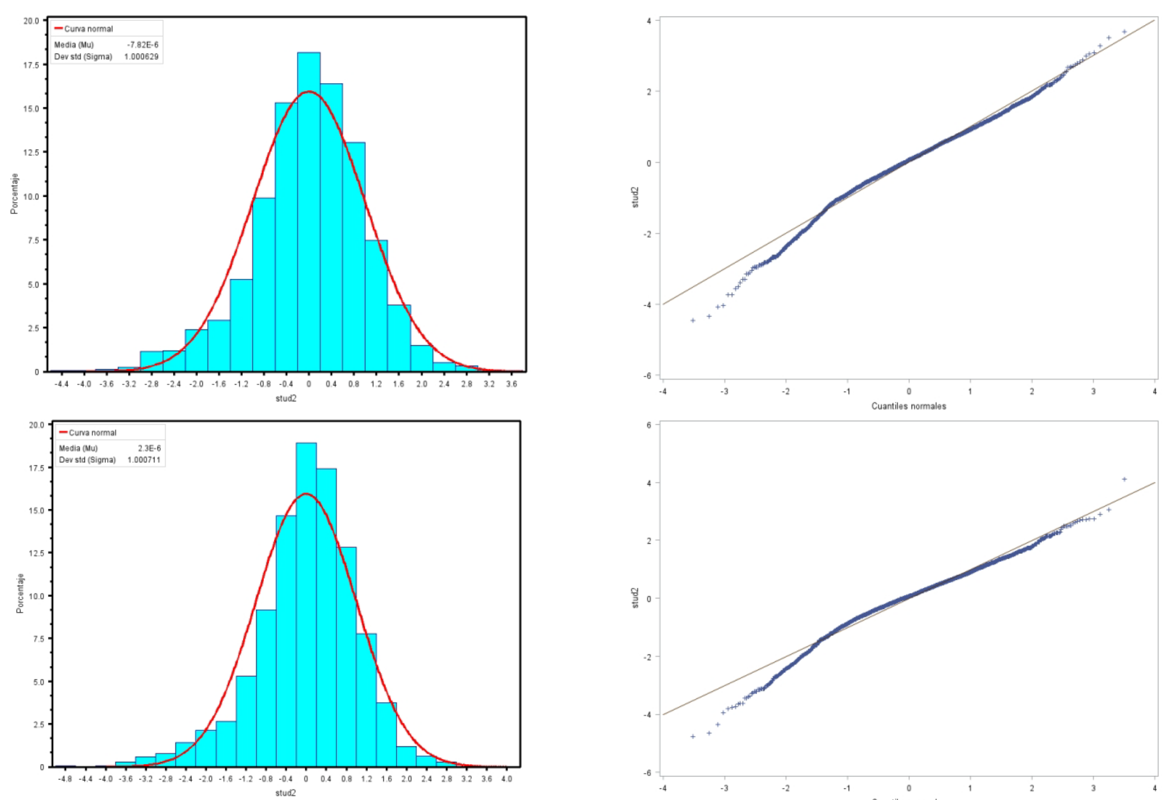

Figure 2. Diagnosis of the GLM runs for standardized CPUE in number of shortfin mako (upper) and in round weight (lower) for Indian Ocean: frequency distribution of the standardized residuals years combined (left panels) and normal probability qq-plot (right panels).

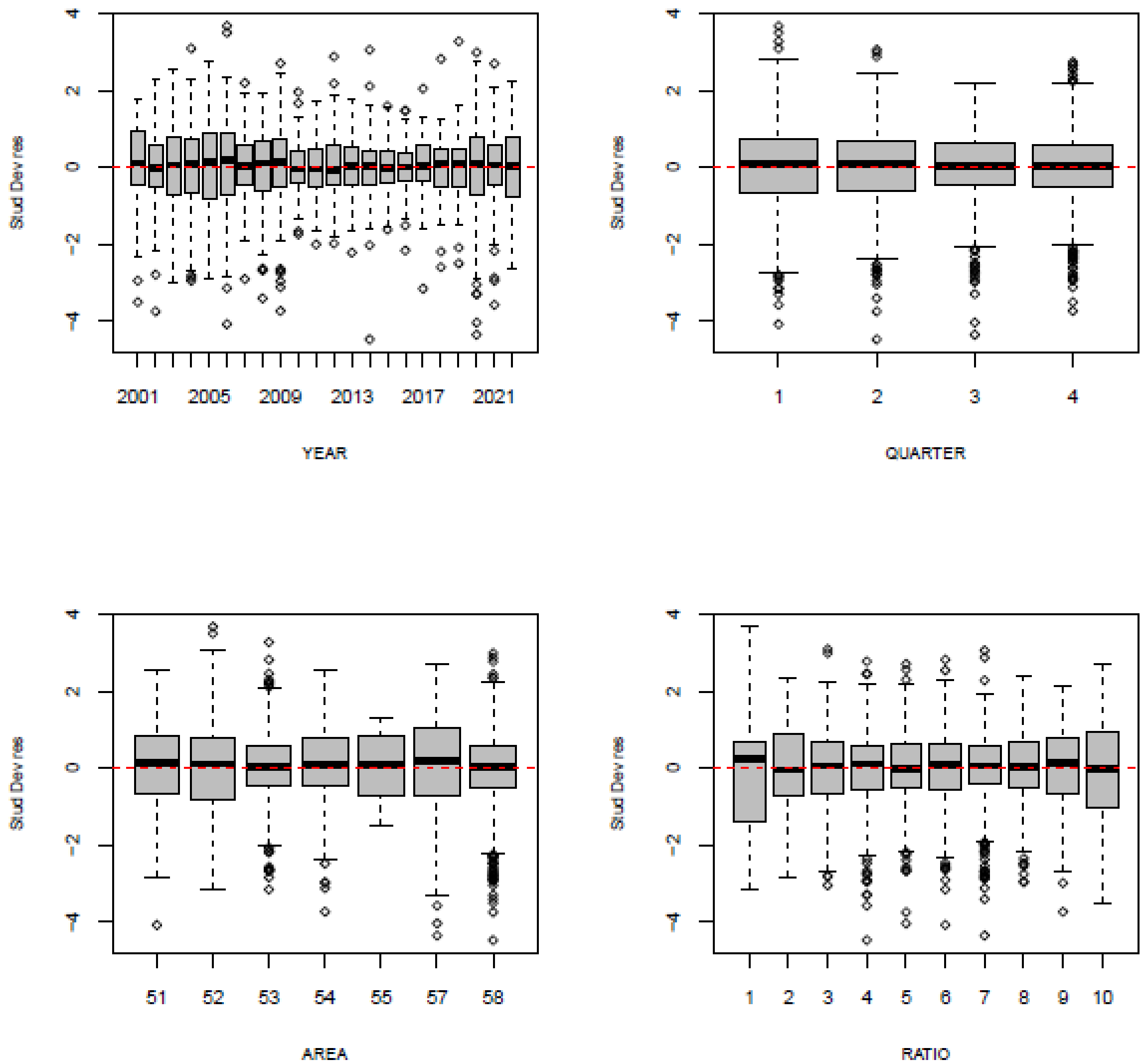

Figure 3. Box-plots of the standardized deviance residuals by explanatory variables obtained from the GLM base case in number of shortfin mako for the Indian Ocean.

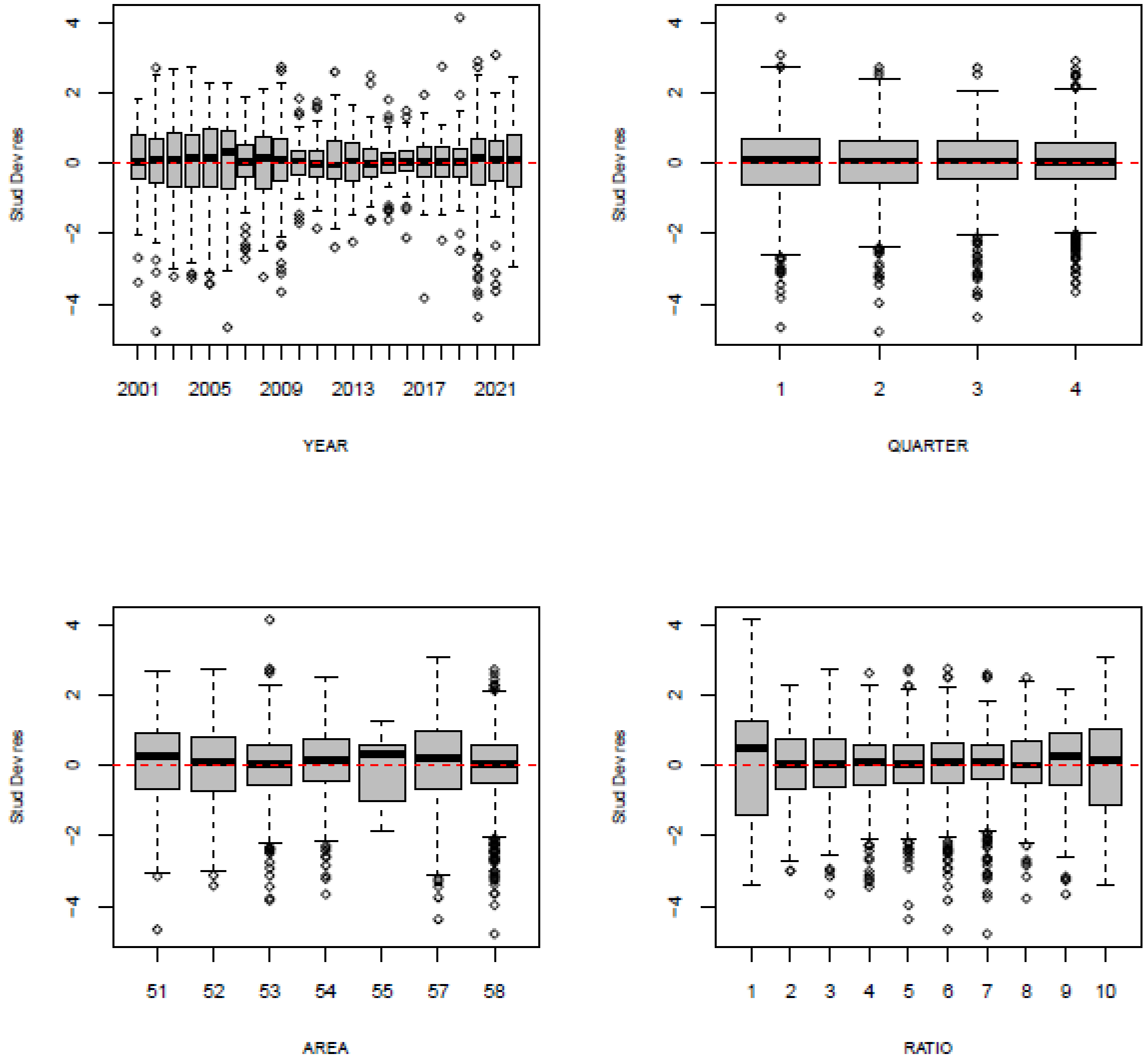

Figure 4. Box-plots of the standardized deviance residuals by explanatory variables obtained from the GLM base case in weight of shortfin mako for the Indian Ocean.

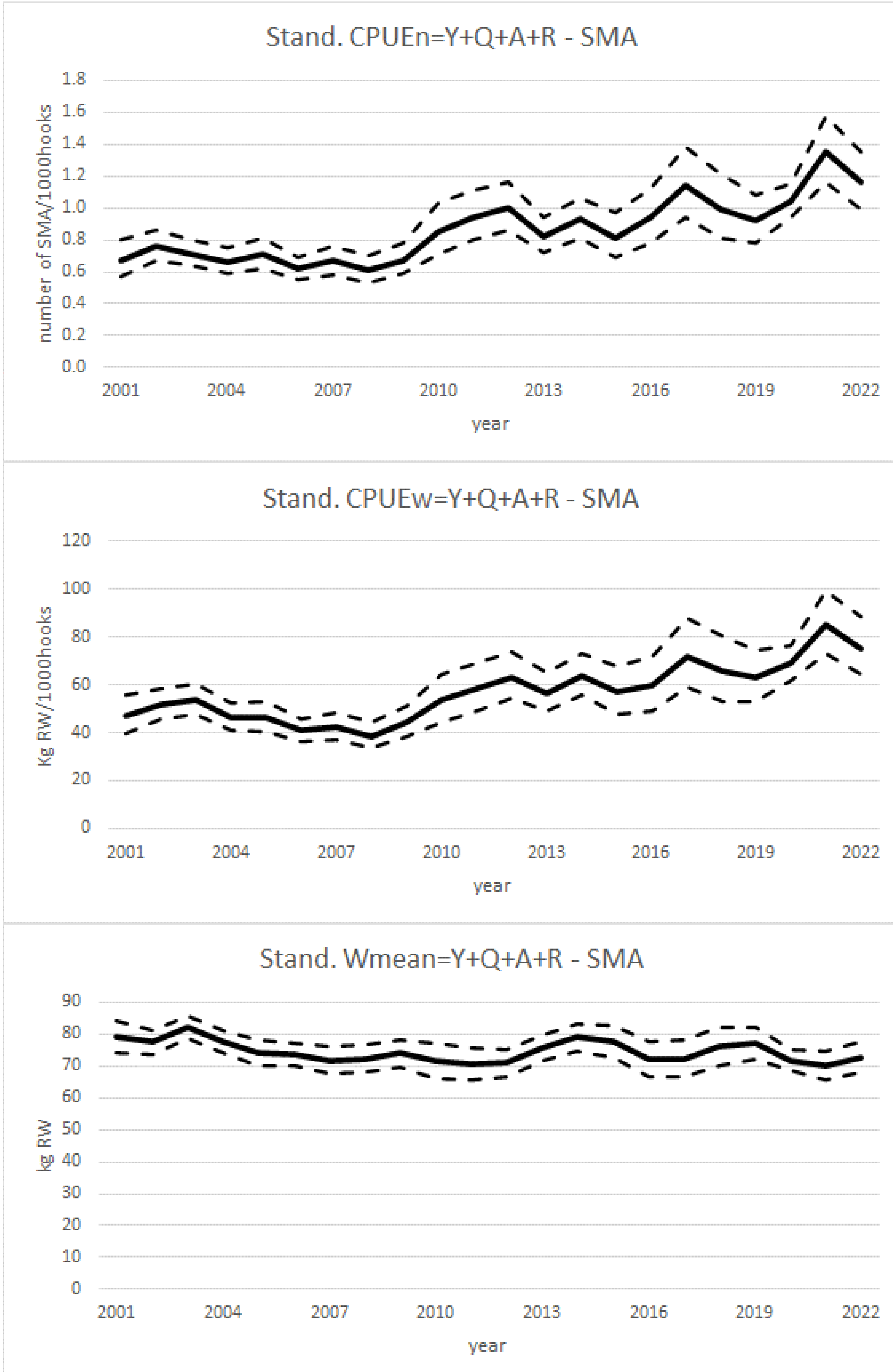

Figure 5. Standardized CPUEs per thousand hooks, in number of fish (upper), in kilograms round weight (middle) and standardized mean round weight in kilograms (lower) of shortfin mako and their respective confidence intervals (95%) observed in the Spanish surface longline fleet during the period analyzed (2001-2022) in the Indian Ocean.

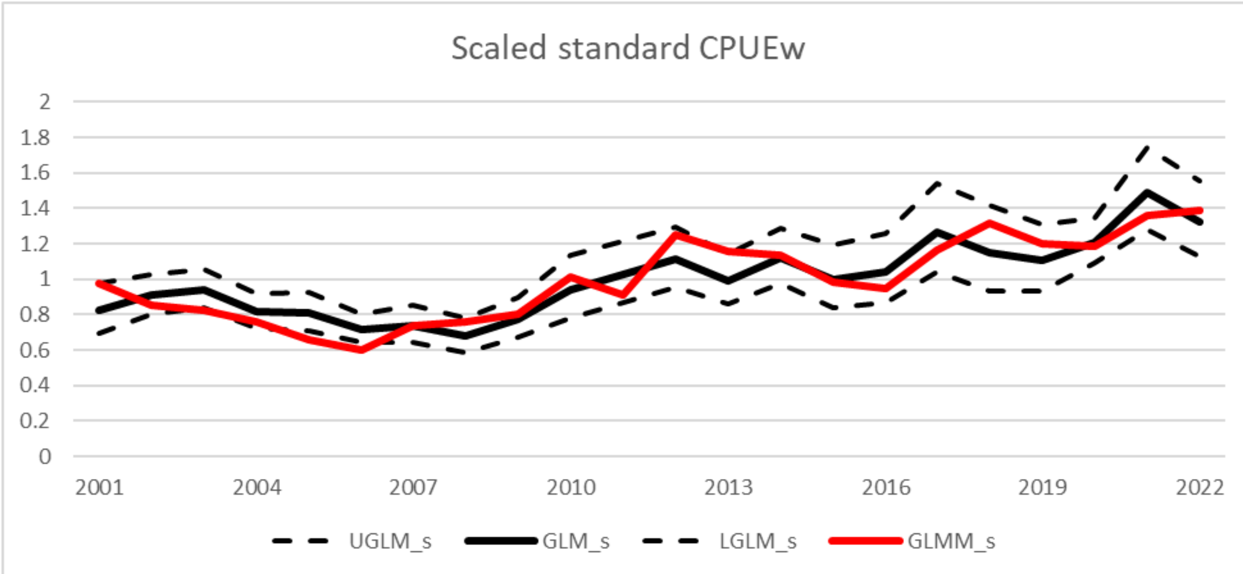

Figure 6. Comparative scaled standardized CPUE in weight, GLM *versus* GLMM (MIXED), obtained in the Indian Ocean for the period 2001-2022. Both series are scaled from their respective mean value.