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Catch rates and size composition of blue sharks (*Prionace glauca*) caught by the Brazilian pelagic longline fleet in the southwestern Atlantic Ocean

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Abstract – Distribution and relative abundance of blue sharks (*Prionace glauca*) in the southwestern Atlantic Ocean was modeled based on catch-per-unit-effort (CPUE) per 1000 hooks and length frequencies of blue sharks caught by the Brazilian pelagic tuna longline fleet. As a measure of relative abundance, CPUE of blue sharks caught in 58 238 fishing sets by the Brazilian pelagic tuna longline fleet (national and chartered), from 1978 to 2009, was standardized by a Generalized Linear Model (GLM) using three different approaches: i) a negative binomial error structure (log link); ii) the traditional delta lognormal model; and iii) the Tweedie distribution, recently proposed to adjust models with a high proportion of zeros. A cluster analysis using the K-means method was used to identify target species and incorporate it as a factor into the GLM. Cluster analysis grouped the data into six different fishing clusters according to the percentage of target species. Target factor (cluster) was the most important factor explaining the variance in all three CPUE models. The Tweedie model showed a relatively better fit compared to the other models. Blue shark nominal and standardized CPUE showed a relatively stable trend from 1978 to 1995. From 1995 onwards, however, there was an increasing trend in the standardized CPUE, up to a maximum value in 2008. In general, nominal CPUE and standardized CPUE tracked well up until 2000, after which standardized CPUE's values were at a noticeably lower level than nominal CPUE. Length frequency data were analyzed for 11 932 blue sharks measured as part of the Brazilian onboard observer program operating on the pelagic tuna longline fleet between 2006 and 2008, with sizes ranging from 91 to 224 cm fork length. Overall, blue shark size data showed clear spatial and seasonal distributions for males and females in the southwestern Atlantic Ocean, with juveniles predominantly concentrated in the most southerly latitudes.

Key words: Pelagic shark / Fishing strategy / CPUE standardization, and spatial distribution

1 Introduction

Most of the world's catches of sharks are taken incidentally by various types of fishing gear, constituting bycatch that is either discarded as sea or landed for sale. Over the past decade there has been a growing global concern regarding bycatch of sharks in fishing operations (Coelho et al. 2003; Megalofonou et al. 2005; Baum and Blanchard 2010). However, the historically low economic value of shark products compared to other fishes has resulted in research and conservation of sharks being given a lower priority than traditionally higher-value fish species (Barker and Schleussel 2005).

The blue shark (*Prionace glauca*) is one of the widest ranging sharks, having a circumglobal distribution in tropical, subtropical, and temperate seas, including the Mediterranean (Compagno 1999). The blue shark's relatively high abundance, plus its cosmopolitan distribution and presence in multiple and widespread fisheries, has resulted in it being a relatively well-studied elasmobranch and there is considerable information available on its biology in the North Atlantic Ocean (e.g., Skomal and Natanson 2003) and in South Atlantic Ocean (Hazin et al. 1990, 1994a,b, 2000a,b; Amorim 1992). Little is yet known, however, about the stock structure of blue sharks in the world's oceans (Aires-da-Silva and Gallucci 2007). In the South Atlantic, the hypothesis of a single stock

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for management and stock assessment purposes is debatable (Amorim 1992; Hazin et al. 1994a; Castro and Mejuto 1995; Legat 2001; Azevedo 2003; Mejuto and García-Cortéz 2004).

In 2008, the International Commission for the Conservation of Atlantic Tunas (ICCAT) carried out a stock assessment for Atlantic blue sharks using the single stock hypothesis for the Southern Atlantic Ocean. Although the general conclusion of the assessment was that the blue shark stock in the South Atlantic Ocean was not overfished, the results were interpreted with considerable caution due to data deficiencies and the resulting uncertainty in the assessment (Anon. 2008).

Recently, the ICCAT working group on assessment methods also expressed concern that some CPUE-series used in the assessments might be misleading because of changing fishing strategies within the fishery. Specifically, several changes in both gear design and structure, as well as in fishing operation and targeting strategies, have been observed over the time series, which could strongly influence the catch rates of target and nontarget species (Anon. 2009). One way to overcome this lack of standardized fishing is to use clustering methods to categorize fishing effort based on the proportion of several species in the catches, which can provide a method to detect changes in targeting strategies in various fisheries (Ward et al. 1996; He et al. 1997; Wu and Yeh 2001; Alemany and Álvarez 2003). This "targeting strategy", along with other factors that are known to influence catchability, may then be included in the standardization of the CPUE-series using a Generalized Linear Model (GLM) (Gulland 1983).

Catch and effort databases, however, often include a high proportion of records in which the catch is zero, even though effort is recorded to be non-zero. This is particularly the case for bycatch species (Maunder and Punt 2004), such as blue sharks. In these cases, in order to standardize the CPUE using a GLM, a delta-lognormal model has traditionally been used, assuming different error distributions for the positive catches and for the proportion of positives. Another, less common, method is to assume a negative binomial distribution using CPUE as a discrete variable rounded to integer values (Minami et al. 2007). Recently, Shono (2008) proposed the use of the Tweedie distribution to adjust models with a high proportion of zeros. Functionally, different fisheries may require different models to obtain the best model fits.

An understanding of the structure of a specific stock is another crucial factor in fisheries population dynamics, in the allocation of catch among competing fisheries, in the recognition and protection of nursery and spawning areas, and for the development of optimal harvest and monitoring strategies (Begg et al. 1999). Catch composition data have been used in determination of the abundance and spatial distribution of age classes and cohorts, as well as the current mortality rate in the stock (Hogarth et al. 2006). In the case of blue sharks caught by the Brazilian pelagic longline fishery, information about catch composition is still very limited (Anon. 2008). It is therefore essential to learn how this species is spatially distributed in the southwestern Atlantic Ocean in relation to potential stock identification and reproductive patterns.

The goal of this study was to quantify the abundance and distribution of blue sharks in the southwestern Atlantic Ocean, including: a) categorizing the Brazilian longline fishery between 1978-2008 using cluster analysis based on similarities in catch composition. Clusters generated by this analysis can then be used as a factor reflecting fishing strategy and target species in the generation of a standardized CPUE-series; b) analyzing catch trends of blue sharks caught by the pelagic longline fleets of Brazil in the southwestern Atlantic Ocean over three decades by standardizing catch rates comparing three different approaches commonly used to standardize a CPUE-series of pelagic sharks (delta lognormal, negative binomial and Tweedie distributions); and c) analyze length-frequency composition of blue sharks caught by the Brazilian longline fleet between 2006-2008 in a spatially explicit comparison between female and male adult and subadult sharks.

2 Material and methods

2.1 Fisheries catch and effort data

Catch data were obtained from 58 238 longline sets made by the Brazilian pelagic tuna longline fleet, including both national and chartered vessels, fishing from 1978 to 2009. Logbooks were made available by the Ministry of Fisheries and Aquaculture within the Brazilian government. Logbooks were filled out by the captain of the vessel after each set. Logbook data included individual records for each fishing set that included the vessel identification, date, location of fishing ground (latitude and longitude), hour of the longline set, effort (number of hooks), and number and species of fish caught in each fishing set.

2.2 Fishing area

Longline sets were distributed throughout a wide area of the southwestern Atlantic Ocean, ranging from 0°W to 60°W longitude and from 10°N to 60°S latitude (Fig. 1). To perform the GLM analysis, the fishing area was split at 15°S based on differences in the oceanographic characteristics. The sub-area north of 15°S is mainly under the influence of the south Equatorial Current, which is a broad, westward flowing current that extends from the surface to a depth of 100 m. Its northern boundary is usually near 3°N, while the southern boundary is usually found between 15°–20°S (Mayer et al. 1998). This area is characterized also by the presence of seamounts (North Chain of Brazil) and oceanic islands (Fernando de Noronha Archipelago and Atol da Rocas), and upwelling driven by the equatorial convergence (Mayer et al. 1998). The sub-area south of 15°S is characterized mainly by the presence of the convergence zone between two current systems: 1) the warm, coast-hugging, southward-flowing Brazil Current; and 2) the cold, northward-flowing Malvinas (Falkland) Current (Garcia 1997; Seeliger et al. 1997).

2.3 Cluster analysis

In order to classify the 58 238 longline sets made by the Brazilian longline fleet between 1978 and 2009, a matrix containing the proportion of each specie or group of species to the

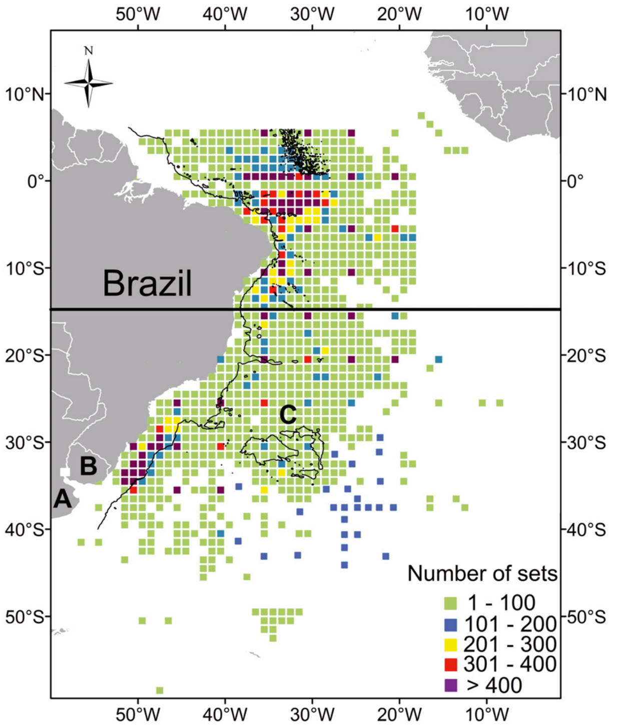

Fig. 1. Distribution of the fishing sets carried out by the Brazilian pelagic longline fleet in the southwestern Atlantic Ocean from 1978 to 2009. (A) Uruguay, (B) Argentina, (C) Rio Grande rise. Black lines indicate the isobaths of 3000 m.

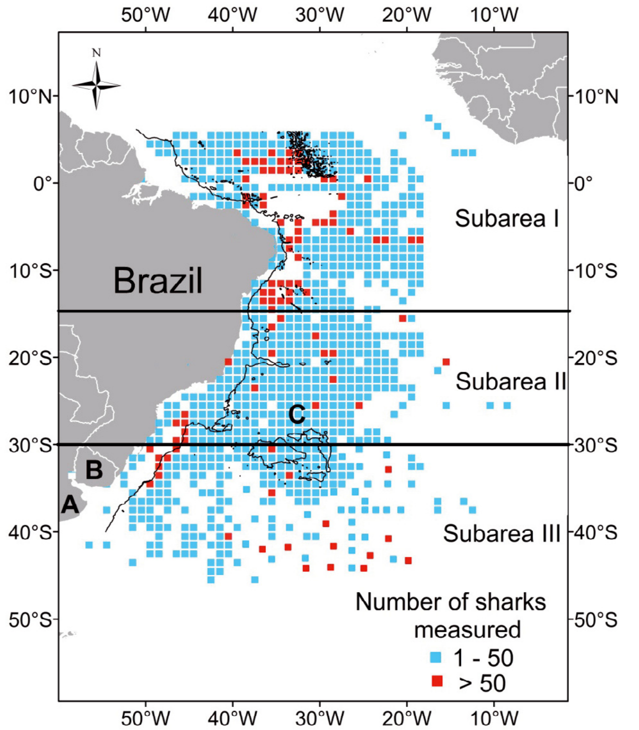

Fig. 2. Location and density of blue sharks measured by onboard observers on Brazilian pelagic longliners operating by subarea (I, II, and III) in the equatorial and southwestern Atlantic Ocean, from 2006 to 2008: (A) Uruguay, (B) Argentina, (C) Rio Grande rise. Black line indicates the isobaths of 3000 m.

total catch of the set was used in the cluster analysis. Clusters were developed in SAS software in two steps because the large number of observations precludes a direct hierarchical cluster analysis for the whole data set (He et al. 1997). For this reason, firstly we fitted a non- hierarchical cluster analysis (K-means method, Johnson and Wichern 1988) in order to identify the ideal number of clusters as well as the "outliers". The main advantage of such a method, as opposed to using the percentage of a single species as an expression of the targeting strategy, is that the frequency distribution of all species in each set is used, thus providing a more reliable estimation. After identifying the number of clusters a hierarchical cluster analysis (Ward method, Ward 1963) was also applied to evaluate the distance between the clusters initially considered in the non- hierarchical cluster analysis through a dendrogram. A total of 17 species or groups of fish species were included in the dataset. Once the cluster analysis was performed, catch compositions (mean percentages of the species) were calculated for each cluster and compared among clusters, and fishing operation characteristics for the clusters were summarized.

Characteristics of fishing operations for each set included number of hooks, fishing location depth, type of longline (monofilament or multifilament), duration of set, and the diurnal and lunar periodicity of fishing effort. Diurnal periodicity was characterized following the methodology proposed by He et al. (1997).

2.4 Standardization of CPUE

Relative abundance indices were estimated by a GLM developed using S-Plus, and using three different approaches: a traditional delta-lognormal model, a negative binomial error structure (log link), and a Tweedie distribution. For all models, five factors: year ($n = 32$), quarter of the year ($n = 4$), distance of the catch location from the Brazilian coast or oceanic islands, area ($n = 2$, <15°S or >15°S), target species ($n = 6$ clusters, see results below), and their interactions were considered. The distance of the catch location from the Brazilian coast or oceanic islands was calculated according to the methodology proposed by Damalas et al. (2007). This is based on locating the nearest land pixel (bottom depth > 0) on a grid map and then estimating the distance between the two points in kilometers, after correcting for the spheroid shape of the Earth.

The delta model fits separately the proportion of positive sets assuming a binomial error distribution (binomial model) and the mean catch rate of sets where at least one blue shark was caught assuming a lognormal error distribution (lognormal model). The negative binomial model is a discrete probability distribution that indicates the number of trials that are necessary to obtain k successes of equal probability θ at the end of n fishing sets (Minami et al. 2007). To estimate the power-parameter (p) and examine what is the best distribution to be used (e.g. Poisson, gamma), the scaled residuals from quasi-likelihood fits for the log-link function and variance as a power function (where $p = 0$ Gaussian, $p = 1$ Poisson, $1 < p < 2$

compound Poisson-gamma and $p = 2$ gamma) were plotted. The Tweedie model is expressed as a compound Poisson-gamma distribution, if $1 < p < 2$, then the Tweedie model seems to be appropriate for CPUE analysis (Shono 2008).

The selection of predictors was evaluated exclusively on AIC and total deviance explained. An F test was also computed to determine whether predictors yielded significant ($p < 0.05$) reductions in the residual deviance upon entry into the GLM. The accuracy of the three models was evaluated using n-fold cross-validation that: (1) divided all data into nth sub-datasets randomly; and (2) calculated the predicted values concealing the observed ones of each sub-dataset on purpose. The correlation coefficient between the observed and the corresponding predicted values was used for cross-validation of the candidate models. The dispersion parameter, used to capture the extra-variation observed in the data, was obtained through the function "summary" on the GLM model as proposed by Chambers and Hastie (1993).

2.5 Shark length frequencies

Blue sharks were measured through an onboard fishery observer program operating from January 2006 to December 2008. During this time period, a total of 11 932 blue sharks (6774 females and 5158 males) captured over a broad fishing area (Fig. 2) were externally sexed and measured to the nearest cm fork length (FL), the FL ranged from 96 to 224 for females and 91 to 223 for males (Fig. 3). For the length-frequency analysis, blue sharks were grouped into four size categories previously designated by Mejuto and García-Cortéz (2004) as juveniles (70–119 cm FL), subadults (120–169 cm FL), adults (170–209 FL) and large-adults (>210 cm FL). Data were also partitioned into three major fishing areas: 1) Subarea I, located in the Atlantic Equatorial Zone between 10°N and 15°S, the major fishing zone for vessels based in the coastal cities of northeast Brazil, including Recife, Natal, and Cabedelo; 2) Subarea II, between 16°S-30°S, the major fishing zone for vessels based in Santos, southeast Brazil; and 3) Subarea III, located between 31°S–45°S, an important fishing zone for vessels based in the coastal cities of Itajaí and Rio Grande (Fig. 2). Mean FL of sharks sampled by blocks of 5° latitude for the whole study area, by quarter of the year, were calculated and checked for normality and homoscedasticity in order to meet the assumptions of an ANOVA. A non-parametric Kruskal-Wallis test was used to compare FL means among blocks of 5° latitude and subareas in the cases where these assumptions were not met. In order to investigate significance of the difference of blue shark catches among quarters of the year by blocks of 5° latitude and the three major fishing areas, a mean of the nominal CPUE per set was calculated using only the onboard fishery observer dataset from January 2006 to December 2008. The significance of the difference of mean nominal CPUE was tested by ANOVA, with logarithmic transformation of the data (Sokal and Rohlf 1995). The non-parametric Kruskal–Wallis test was used in cases where the assumptions of an ANOVA were not met.

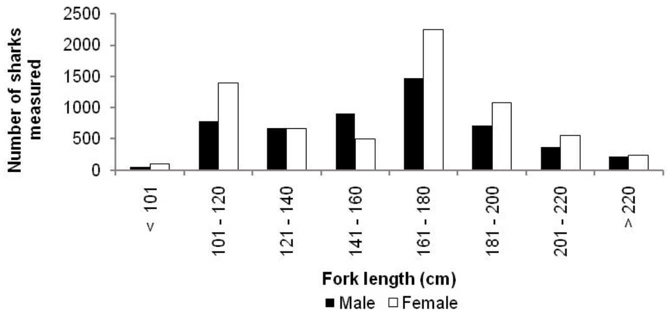

Fig. 3. Number of female (6774) and male (5158) blue sharks measured per fork length size class by observers onboard the Brazilian pelagic longline fleet between 2006 and 2008.

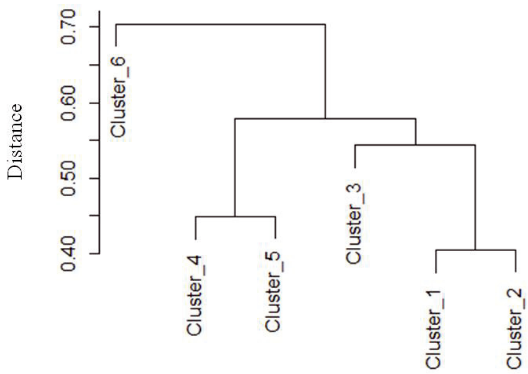

Fig. 4. Dendrogram of six clusters of longline sets from the Brazilian pelagic tuna longline fishery showing Euclidian distance between clusters. Cluster 1 = albacore; Cluster 2 = yellowfin tuna; Cluster 3 = other teleosts; Cluster 4 = swordfish; Cluster 5 = blue shark; and Cluster 6 = bigeye tuna.

3 Results

3.1 Cluster analysis

The cluster analysis grouped the data into six different fishing clusters according to the percentage of target species (Fig. 4), including: Cluster 1 = albacore (74.3%); Cluster 2 = yellowfin tuna, together with albacore and bigeye tuna (44.8%, 13.4%, and 13.6%, respectively); Cluster 3 = other teleosts, together with other sharks and swordfish (24.1%, 11.7%, and 10.4%, respectively); Cluster 4 = swordfish, along with blue shark (54.3% and 10.7%, respectively); Cluster 5 = blue shark (68%); and Cluster 6 = bigeye tuna (72%) (Table 1).

Comparison of fishing strategies among clusters (Table 2) indicated that operational characteristics of Cluster 5 sets (mostly blue sharks) included: (1) the latest mean time of deployment and (2) the highest percentage of sets using monofilament longline. Cluster 4 sets (mostly swordfish along with blue sharks) had similar characteristics of Cluster 5, although the cluster showed a slightly larger percentage of night sets, in fact, the greatest percentage of all clusters. Cluster 1 appeared to have the most similar percentage of sets between day and night, however, this cluster presented the earliest mean time of fishing. Clusters 2, 3, and 6 appeared to have similar fishing strategies, with the mean time of deployment being early in the afternoon.

Table 1. Distribution of 58, 238 longline sets by the Brazilian tuna longline fishery in the Southwestern Atlantic Ocean, from 1978 to 2009, by cluster (Asterisks indicates the target species in each cluster).

Species		Cluster 1	2	3	4	5	6
Yellowfin tuna	*Thunnus albacares*	5.6	44.8*	9.4	8.2	2.4	6.3
Albacore	*Thunnus alalunga*	74.3*	13.4	6.8	5.4	4.8	3.1
Bigeye tuna	*Thunnus obesus*	5.8	13.6	5.2	9.8	1.4	72.1*
Swordfish	*Xiphias gladius*	3.1	7.5	10.4	54.3*	8.3	9.0
Sailfish	*Istiophorus albicans*	1.3	2.4	2.1	1.9	0.8	1.0
White marlin	*Tetrapturus albidus*	0.7	1.2	1.4	0.9	0.5	0.5
Blue marlin	*Makaira nigricans*	0.5	1.3	0.7	2.3	0.4	0.9
Other billfishes		0.1	0.1	2.4	0.3	0.3	0
Wahoo	*Acanthocybium solandri*	0.7	2.9	2.1	0.4	0.3	0.3
Dolphin	*Coryphaena hippurus*	0.4	0.7	5.7	1.3	3.3	0.4
Blue shark	*Prionace glauca*	1.3	2.8	8.2	10.7	68.4*	1.9
Hammerhead shark	*Sphyrna* sp.	0	0.2	2.1	0.4	1.6	0
Bigeye thresher	*Alopias superciliosus*	0	0.1	0.1	0.1	0.3	0
Mako shark	*Isurus* sp.	0.3	0.3	1.8	0.8	2.8	0.1
Silky shark	*Carcharhinus falciformis*	0	0.1	5.8	0.1	0.2	0.1
Oceanic whitetip	*Carcharhinus longimanus*	0	0	0.1	0	0	0
Other Sharks		2.0	1.5	11.7	1.2	2.5	2.7
Other Teleosts		3.9	7.1	24.1*	1.9	1.8	1.7
Number of Sets		11 098	15 038	9 786	13 951	3 601	4 764
% of Sets		18.7	27.2	16.5	23.5	6.1	8.0

Table 2. Characteristics of fishing operations for the six clusters of sets from the Brazilian pelagic tuna longline fleet, from 1978 – 2009. Set duration is the interval between the beginning of deployment and the beginning of retrieval. Values in parentheses are ±1SE of the mean.

Operational characteristics	Cluster 1	2	3	4	5	6
Number of sets	11 098	15 038	9786	13 951	3601	4764
Mean initial time of deployment	9:30 (0.04)	13:00 (0.08)	13:00 (0.06)	17:00 (0.08)	17:30 (0.09)	12:00 (0.04)
Mean location depth (m)	3950 (11.4)	3613 (16.5)	3627 (17.7)	3299 (22.6)	3587 (20.4)	3175 (15.7)
Mean duration of sets (h)	22 (0.07)	19 (0.02)	19 (0.08)	17 (0.03)	18 (0.09)	19 (0.07)
Mean number of hooks per basket	10 (0.03)	7 (0.05)	7 (0.04)	4 (0.03)	6 (0.07)	8 (0.05)
% time of fishing at night	52	74	75	81	75	70
% per set where mainline is:						
monofilament	59	69	70	69	82	54
multifilament	41	31	30	31	18	46

In relation to the time series, the proportion of Cluster 4, was high in the early 1980's and in more recent years, with the maximum values reaching 67% and 66% in 2007 and 2009, respectively. The proportion of Cluster 5 was <5% for most of the earlier time period but increased to 14% in 2002 and remained around 5–10% up to 2009 (Fig. 5).

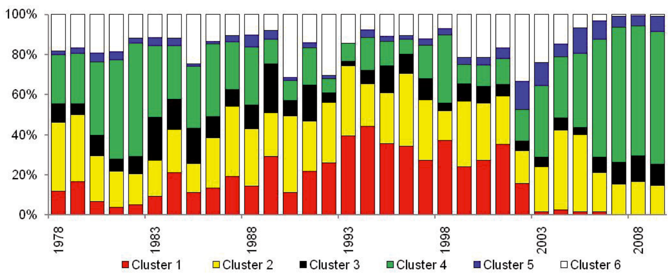

Fig. 5. Yearly frequency distribution of the 6 clusters reflecting the targeting strategy in the Brazilian pelagic tuna longline fleet from 1978 to 2009. Cluster 1 = albacore; Cluster 2 = yellowfin tuna; Cluster 3 = other teleosts; Cluster 4 = swordfish; Cluster 5 = blue shark; and Cluster 6 = bigeye tuna.

3.2 Catch models

The delta-lognormal distribution model explained 64.7% of the variance in CPUE and 75.0% for the proportion of positives sets (Table 3). The main factor explaining the variance for both the CPUE and the proportion of positive sets was the target species (cluster), accounting for 52.2% and 47.5%, respectively. The negative-binomial model explained 33.4% of the variance and target species was the most important factor, explaining 73.1% of the variance. The Tweedie model explained 60.1% of the catch rate variability for blue shark. Similarly to the previous models, the target species was the main factor explaining the variance for blue shark catches (46.8%).

In the cross-validation, the Tweedie model showed the highest correlation between the predicted and observed values

Table 3. Deviance analysis of explanatory variables in the delta lognormal (positive catch rates and proportion of positive), negative binomial, and Tweedie models of blue shark caught by Brazilian pelagic tuna longline fleet in the southwestern Atlantic Ocean, from 1978–2009.

Model factors - Positive catch rates	Degrees of freedom	Deviance	Residual difference	Residual deviance	Explained deviance (%)	Explained model (%)
NULL			24403	16567		
Year	26	2829	24377	13738	26.4	17.1
Quarter	3	75	24374	13663	0.7	17.5
Area	1	1980	24373	11683	18.5	29.5
Target	5	5592	24368	6092	52.2	63.2
Year*Quarter	77	179	24291	5912	1.7	64.3
Quarter:Area	3	62	24288	5851	0.6	64.7
Model factors - Proportion positive						
NULL			1038	28793		
Year	26	7360	1012	21432	34.1	25.6
Quarter	3	705	1009	20727	3.3	28.0
Area	1	1464	1008	19263	6.8	33.1
Target	5	10255	1003	9008	47.5	68.7
Year:Quarter	78	1559	925	7449	7.2	
Ouarter:Area	3	256	922	7193	1.2	
Model factors - Negative binomial						
NULL			57561	67220		
NULL			57561	67220		
Year	26	1338	57535	65882	6.0	2.0
Quarter	3	465	57532	65417	2.1	2.7
Area	1	2788	57531	62629	12.4	6.8
Target	5	16395	57526	46234	73.1	31.2
Year:Quarter	78	1201	57448	45034	5.4	33.0
Quarter:Area	3	238	57445	44795	1.1	33.4
Model factors - Tweedie						
NULL			57561	51122		
Year	26	8864	57535	42257	28.9	17.3
Quarter	3	700	57532	41558	2.3	18.7
Area	1	5980	57531	35577	19.5	30.4
Target	5	14384	57526	21194	46.8	58.5
Year:Quarter	78	335	57448	20859	1.1	59.2
Quarter:Area	3	439	57445	20419	1.4	60.1

Table 4. Model comparison based on the results of Pearson's correlation for the 5-fold cross validation, dispersion parameter (*m*) and average standard error of the predicted CPUEs (SE).

Models	*m*	*SE*	Correlation
Delta lognormal			
(Proportion of positive)	2.38	0.77	0.53
Negative Binomial	2.91	0.85	0.41
Tweedie	1.02	0.43	0.74

compared to the other models (0.74 for Tweedie versus 0.53 and 0.41 for the delta lognormal and negative binomial, respectively). The mean SE and dispersion parameter (*m*) for the Tweedie model (SE = 0.43; m= 1.02) were also smaller than those for the delta lognormal model (proportion of positive) (SE = 0.77; m = 2.38) and negative binomial (SE = 0.85; m = 2.91) (Table 4). In addition, the power-parameter (p) was approximately estimated at 1.2 (compound gamma-Poisson distribution) (Fig. 6). As discussed by Shono (2008) the Tweedie model can express the Poisson, Gamma and inverse Gaussian distributions if the power-parameter (p) is 1, 2, and 3, respectively, indicating that the Tweedie distribution might be a better option for the standardization of CPUE for this species.

Residual diagnostic plots for all of the models and QQ-normal plots (Fig. 7) showed that the residual distribution for the Tweedie model was close to normal compared with the delta-lognormal and negative binomial models. This suggested that relatively good fits were obtained and that the assumed error structures were satisfactory for the Tweedie model.

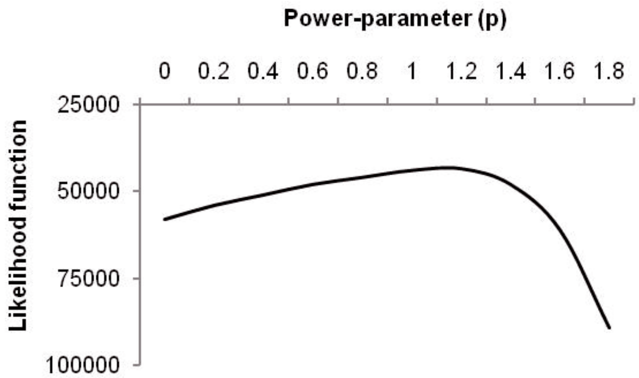

Fig. 6. Value of likelihood function changing the power-parameter (p) of the Tweedie model for CPUE standardization of blue sharks caught by Brazilian pelagic tuna longline fleet in the southwestern Atlantic Ocean, from 1978–2009.

Blue shark nominal CPUE and standardized CPUE using a Tweedie GLM (Fig. 8) showed a relatively stable trend from 1978 to 1995, oscillating from 0.5 to 1.0. From 1995 onwards, however, there was an increasing trend in the standardized

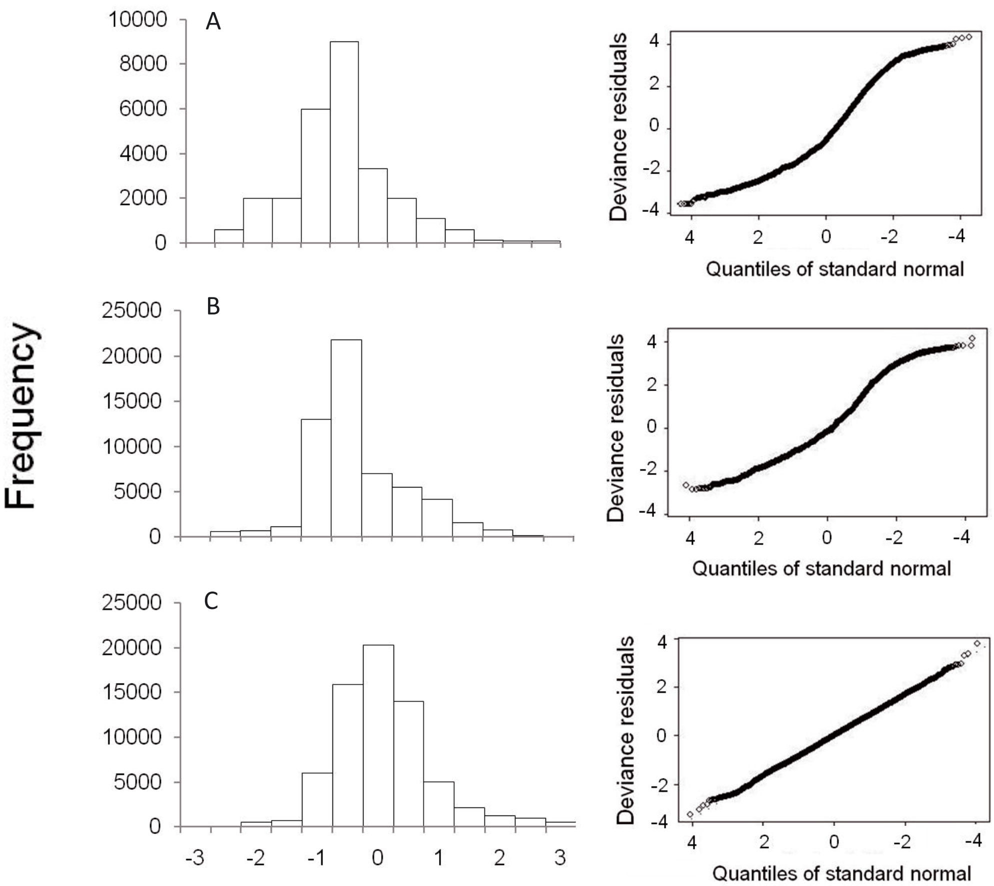

Fig. 7. Histogram of standard residuals (left panel) and quantile–quantile (QQ) plots of the deviance residuals (right panel) of the models fitting blue shark catches. Delta lognormal (A), Negative binomial (B) and Tweedie (C) models.

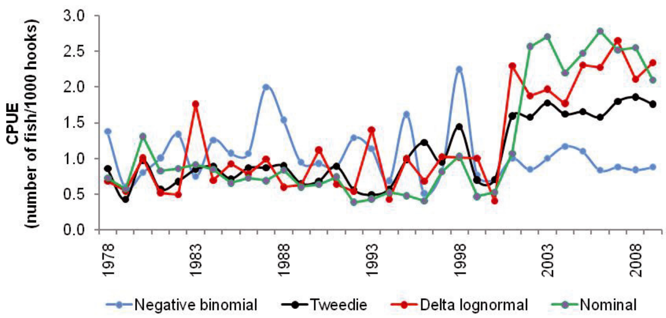

Fig. 8. Nominal and standardized CPUE of blue shark caught by the Brazilian pelagic tuna longline fleet, from 1978–2009, using Delta lognormal, Negative binomial, and Tweedie distributions.

CPUE, up to a maximum value in 2008 of 1.8. In general, nominal CPUE and standardized CPUE using a Tweedie GLM tracked well up until 2000, after which the standardized CPUE was at a markedly lower level than nominal CPUE.

3.3 Length-frequency composition and seasonal variation of CPUE

The assumptions of the ANOVA were not met for analysis of the present data. Then, all statistical comparisons regarding length-frequency composition and seasonal variation of CPUE were performed using the non-parametric test of Kruskal-Wallis.

Females

Overall, the length-frequency analysis showed that females of all fork length FL-classes, from juveniles to large-adults, occurred within the fishing area (Fig. 9). In Sub-area I, the mean FL indicated the presence of adults and large-adult females during the whole year. A significant difference in mean FL by quarter of the year was found for latitudes between 5°N – 0°S ($p = 0.014$), 1°S – 5°S ($p = 0.009$), and 6°S – 10°S ($p = 0.011$), with large-adults being more common during the second quarter of the year. In the southern portion of Sub-area I, between 11°S – 15°S, only adults were observed and no significant difference was found in the quarterly mean FL.

In Sub-area II, mean FL of females was significantly larger in the first and fourth quarters of the year, for all latitudinal

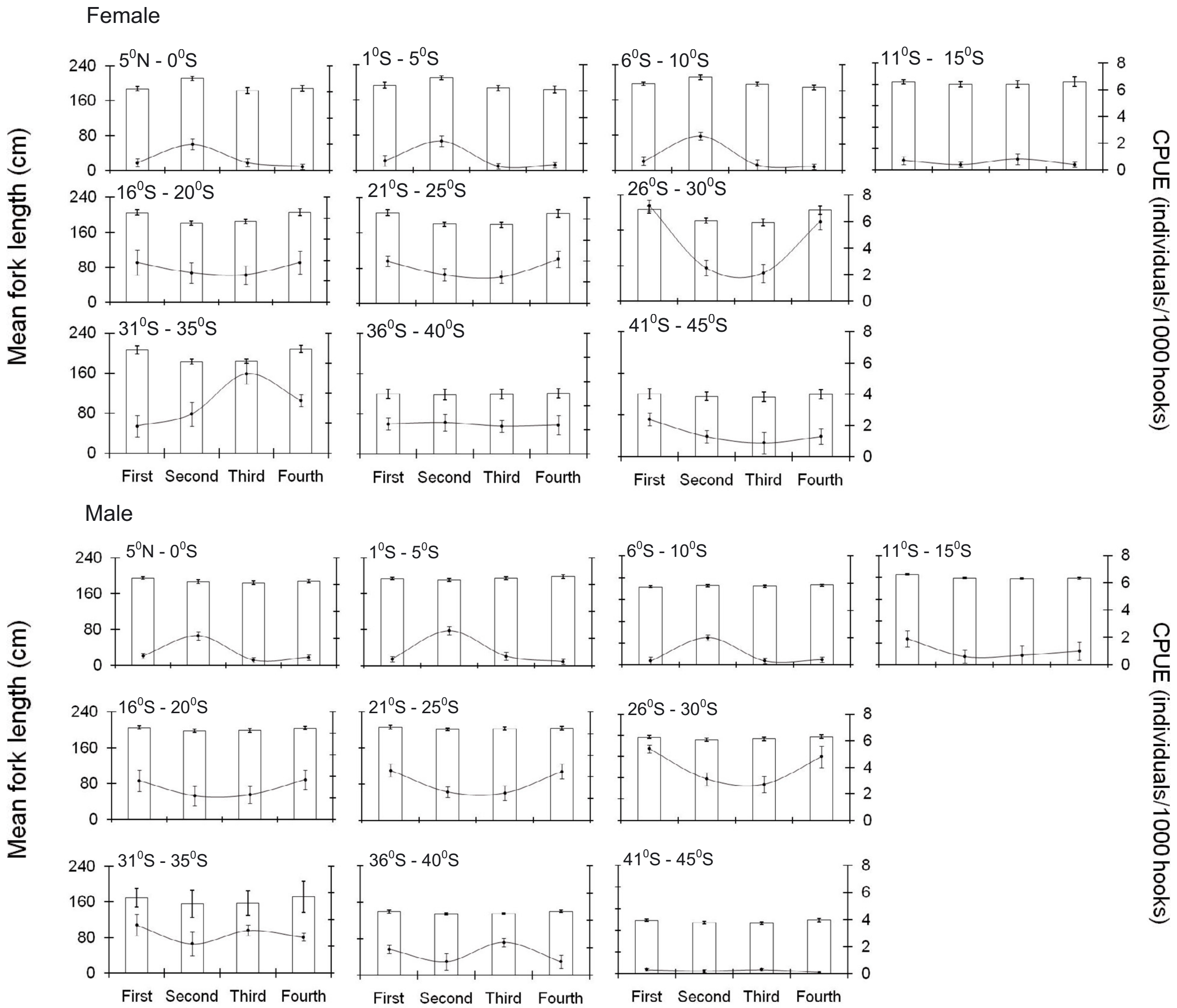

Fig. 9. Quarterly mean *FL* (± *SE*) (histograms) and CPUE (± *SE*) (lines) of female (6774) and male (5158) blue sharks by subareas and blocks of 5^o latitude, obtained from the Brazilian Observer Program, aboard Brazilian pelagic tuna longline vessels, between 2006 and 2008. Sub-area I (5^{0}N–15^{0}S), Sub-area II (16^{0}S–30^{0}S), Sub-area III (31^{0}S–45^{0}S).

blocks between 16°S – 20°S (p = 0.022), 21°S – 25°S (p = 0.003), and 26°S – 30°S (p = 0.010) (Fig. 9). In the first block of latitude of Sub-area III, between 31°S – 35°S, the distribution of the mean FL indicated a larger mean FL during the first and fourth quarters, compared to the second and third quarters (p = 0.011). The second (36°S – 40°S) and third (41°S – 45°S) blocks of latitude showed a predominance of juvenile females, with no significant difference in FL among quarters of the year (Fig. 9).

Comparison of CPUE mean values among quarter of the year showed significant differences for the first three blocks of latitude in Sub-area I, with the mean peak of CPUE during the second quarter of the year for 5°N – 0° (p = 0.004), 1°S – 5°S (p = 0.004), and 6°S – 10°S (p = 0.001). In Sub-area II, mean CPUE was significantly higher in the first and fourth quarters of the year for latitudes between 21°S – 25°S (p = 0.002) and 26°S – 30°S (p = 0.001), with the highest mean CPUE values from the entire fishing area occurring in the last latitudinal block of this Sub-area (Fig. 9). Mean CPUE was significantly higher in the third quarter of the year for the first latitudinal block of Sub-area III ($p < 0.001$). However, in the most southern latitudinal block of this Sub-area, 41°S – 45°S, the highest mean CPUE occurred in the first quarter of the year ($p < 0.001$) (Fig. 9). Comparison of mean FL among Sub-areas indicated significantly smaller female individuals occurring in the sub-area III (p = 0.014) (Fig. 10)

Males

For Sub-area I, there was a predominance of adult males during the second quarter of the year in the first three latitudinal blocks, however, there was no significant difference in mean FL between 5°N – 0S°(p = 0.073), 1°S – 5°S (p = 0.058), and 6°S – 10°S (p = 0.071) (Fig. 9). However, significantly larger adult males were found during the first quarter of the year between latitudes 11°S – 15°S (p = 0.002). The same

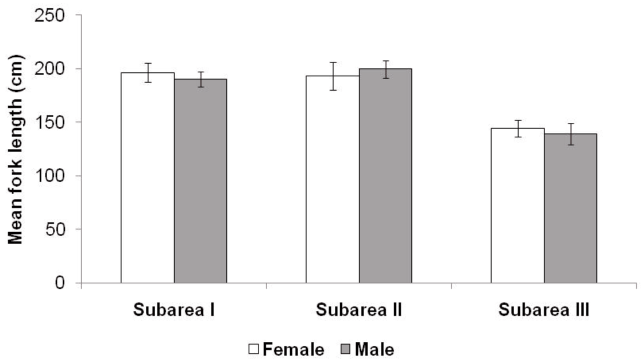

Fig. 10. Mean FL (± SE) of female (6774) and male (5158) blue sharks by subareas obtained from the Brazilian Observer Program, aboard Brazilian pelagic tuna longline vessels, between 2006 and 2008. Sub-area I (5^0N–15^0S), Sub-area II (16^0S–30^0S), Sub-area III (31^0S–45^0S).

analysis for Sub-area II showed slightly larger individuals during the first and fourth quarters of the year, although there was no significant difference in mean FL for 16°S – 20°S, 21°S – 25°S, and 26°S – 30°S (Fig. 9). As in females, juvenile males occurred in the second (36°S – 40°S) and third (41°S – 45°S) latitudinal blocks of Sub-area III, with no significant difference in shark size among quarters between 36°S – 40°S and 41°S – 45°S (Fig. 9).

Significantly higher mean CPUE occurred during the second quarter of the year for latitudinal blocks between 5°N – 0° (p = 0.003), 1°S – 5°S (p= 0.008), 6°S – 10°S (p = 0.001), and during the first quarter between 11°S – 15°S (p = 0.002), in Sub-area I, and during the first and fourth quarter between 16°S – 20°S(p = 0.007), 21°S – 25°S (p= 0.009), and 26°S – 30°S (p= 0.001) in sub-area II. For Sub-area III, significant higher CPUE was found during the third quarter of the year between latitudes 41°S – 45°S (p = 0.004). However, the lowest mean CPUE values for males from the entire fishing area were observed in the last block of this Sub-area (Fig. 9). Sub-area III showed also individuals with mean smaller FL compared with the other two sub-areas (p = 0.040) (Fig. 10).

4 Discussion

4.1 Fishing strategy

Cluster analysis has been proven to be an effective quantitative method to identify different fishing strategies in studies of other fisheries (Rogers and Pikitch 1992; Lewy and Vinther 1994). This method is useful, especially in analyses of multi-species fisheries, because commercial fisheries data often do not provide enough information on fishing behavior and operations (e.g., changing target species within a trip). A variety of different fishing strategies have been employed since the pelagic longline fishery began in the South Atlantic Ocean (Hazin 1993; Arfelli 1996; Menezes de Lima et al. 2000). In Brazil, pelagic longline fishing originated in 1956 with chartered Japanese vessels based in the northeast region of Brazil (Aragão and Menezes de Lima 1985). Later, fishing activity was interrupted because of economic and political issues, resulting in the migration of the Japanese fleet to other regions of the Atlantic Ocean. In 1966, results obtained from experimental fishing using pelagic longlines lead national vessels to begin commercial fishing activities in the southeast region of Brazil, targeting tunas (Aragão and Menezes de Lima 1985). Ten years later, Korean and Japanese boats were again chartered to operate off northeast and southeast Brazil, respectively (Aragão and Menezes de Lima (1985).

In response to market changes in the early 1980's, multi-filament longline (Japanese type) fishing that targeted swordfish was initiated in the southeastern region, with hooks set at dusk using squid as bait. At the same time, another portion of the Japanese fleet began to target bigeye tuna by making deeper longline sets, and yellowfin tuna (Travassos 1999), which might explain the high frequency of these three clusters combined in the 1980s (yearly average of 70%).

In the early 1990s an increasing number of Brazilian fishing companies began chartering longline boats from other countries, including Barbados, Spain and Honduras. By 1998 chartering activity was intensified by the creation of the Department of Fisheries and Aquaculture (currently Brazilian Ministry of Fisheries and Aquaculture), which had a goal of developing a genuinely national fleet through the acquisition of new technologies from chartered foreign vessels (Travassos 1999; Hazin et al. 2000b; Zagaglia 2004).

The consolidation of a longline fishery targeting swordfish occurred in the 1990's in the southeast region, primarily involving Honduras-flagged vessels based in the Port of Santos. These vessels used a new fishing gear technology, known as the "American type" which included a monofilament longline and chemically luminescent light-sticks (Arfelli 1996). Due to the effectiveness of this fishing technique the entire Port of Santos longline fleet replaced the traditional multifilament longline with monofilament longline in 1995. Concurrently, Spanish and American vessels using monofilament longlines were chartered by Brazilian companies based in the northeast region of Brazil (Hazin et al. 2000b), supplementing several Brazilian vessels. However, even with a large proportion of the Brazilian fleet using monofilament longline, the annual frequency of the swordfish cluster (Cluster 4) decreased from an average of 33.7% in the 1980s to 14.1%, in the 1990s.

The increase in the yearly frequency of the swordfish cluster (Cluster 4) after 2001 was likely a function of the progressive and gradual assimilation of the swordfish fishing technology by the national vessels from the chartered fleet targeting swordfish during the late 1990s. After 2000, a large part of the chartered fleet targeted tunas, which drove the national vessels to target swordfish. Furthermore, good market conditions for swordfish were an extra stimulus for the national fleet, which was reflected in the number of vessels increasing 15% from 2002 to 2003 and 19% from 2004 to 2005 (Hazin 2006).

The blue shark was the second most common species caught in the swordfish cluster, while swordfish was the second most common species caught in the blue shark cluster. This indicates that both species are commonly caught together in the longline fishery, probably due to similarities of habitat use and feeding habits (Azevedo 2003). The yearly frequency distribution of the six clusters, from 1978 to 2007, showed that the relative contribution of Clusters 4 (swordfish) and 5 (blue shark) pooled together equaled 9.4% in 1996, almost doubling to 18.4% in 2001, and then jumped to almost 50% in 2003, and to 73% in 2007. This showed that after the introduction of the American-type fishing gear in 1995-96, the change in targeting strategy was gradual, with a significant increase in 2000 and later. In addition, the steady supply of blue shark meat gradually helped to build a market for the species in Brazil, thereby driving landing values upward. The value of fins, which were largely exported to Asian markets in the early 2000's, followed a similar trend in increasing price during this time period.

4.2 Catch trends

Although CPUE is usually assumed to be proportional to the actual stock abundance, there are several limitations to this approach. Such constraints are even more serious in the case of non-target species, such as sharks, where data sets often have many zero-valued observations as well as some very large values due to local aggregations (e.g., Bigelow et al. 1999; Ward and Myers 2005). Modeling these data, however, is essential to the estimation of trends in catch rates and for understanding processes that might lead to increases or decreases in the levels of catch. Indeed the large number of zero-valued observations has led scientists to develop models that relate covariates to the occurrence of excess zeros (e.g., Welsh et al. 1996; Barry and Welsh 2002; O'Neill and Faddy 2003; Minami et al. 2007).

In the present study, the delta-lognormal, negative binomial, and the Tweedie models showed comparatively similar results and all were seemingly satisfactory to standardize the CPUE-series. The Tweedie distribution, however, appeared to be the best option to standardize blue shark CPUE from the Brazilian longline fleet. Similarly, Shono (2008) standardizing catch and effort data for silky shark (*Carcharhimus falciformis*) in the North Pacific Ocean concluded that the Tweedie model performed better than negative binomial or delta-lognormal models based on Pearson's correlation coefficient and residuals.

Blue shark CPUE standardized by the Tweedie GLM in the present study indicated a stable trend until 1995, when values began to increase, peaking in 2008. The catch rates observed between 1978–1995 in the present study were similar to those observed by Carvalho et al. (2008) studying blue shark catches in the early 1960's, which was at the very beginning of the longline fisheries in the South Atlantic Ocean. One of the possible reasons for this rise might have been the introduction of monofilament gear in 1995–1996 to target swordfish, followed by a gradual increase in the market value of blue shark with time. The discrepancy between the nominal and standardized CPUE values from the year 2000 and later indicates the importance of inclusion of the "target" factor in the standardization. The observed influence of the targeting strategy on CPUE variability indicated a need for further studies on developing more accurate ways to incorporate such influences in the CPUE standardization process. In this context, given the increasingly frequent changes of species target/ gear configuration within individual fishing trips, it must be duly recognized that there is a growing difficulty in defining the target species of a particular longline fishing set (Anon. 2009).

4.3 Length-frequency composition and seasonal variation of CPUE

The overall spatial distribution of blue sharks by size showed a general tendency of large-adults to concentrate in lower latitudes, with the juveniles being more common in higher latitudes. This pattern is similar to those of blue shark size distributions observed in the North Pacific (Strasburg 1958; Nakano 1994), South Pacific (Stevens 1992), and North Atlantic (Vas 1990; Buencuerpo et al. 1998; Henderson et al.2001; Senba and Nakano 2004; Campana et al. 2006). The seasonal and sex variation in the mean FL for Sub-area I was similar to that observed by Hazin et al. (1990), with large-adult females occurring in the second quarter of the year between latitudes 5°N – 10°S and adult males present throughout the entire year. This female seasonality may be a consequence of both horizontal and vertical migrations triggered by a reproductive stimulus, as suggested by Pratt (1979). According to Hazin et al. (1990), in the equatorial Atlantic region the warmest sea surface temperatures occur during the months of March and April (Hazin et al. 1994a), which might suggest that these sharks are taking advantage of these warmer waters to hasten the ovulation and fertilization process (Hazin et al. 2000a). Gubanov and Grigor'yev (1975) showed that in the equatorial Indian Ocean the pregnant females are concentrated from the east coast of Africa to 55°E, and between 2°N and 6° S. They added that most of the females in that region were in the early stages of pregnancy.

Amorin (1992) observed fresh mating scars on female blue sharks captured off southeastearn Brazil (latitudes 20°S–33°S) during the months of November to March of 1988-1992. Mating scars were observed to occur the most in December to February, and in January, which is the peak of the mating season, 80% of the females had fresh scars compared to 14% in March. This indicated that the area was a major mating ground, especially during the first quarter of the year (Amorin 1992). This mating season pattern parallels the distribution of blue sharks noted in the present study, specifically the observations that adult females were most abundant in Sub-area II and that larger females were present during the first and fourth quarters.

It is interesting to highlight that this study found peaks in mean CPUE for males and females in Sub-areas I and II exactly during the periods when individuals with larger mean FL were observed. Finding the highest abundance and largest females off southeast Brazil during the fourth and first quarter of the year (mating season), in combination with highest catches of these large females off northeast Brazil during the second quarter of the year (season of peak ovulation), might indicate a seasonal movement from south to north. Hazin et al. (1990), summarizing the blue shark life cycle in the North Atlantic, proposed that female blue sharks mate with males between latitudes of 30°N and 40°N, moving after this into the northwestern equatorial Atlantic to ovulate and fertilize their eggs. Nakano and Stevens (2008) mentioned also that adult females and males mate around 32°N and 35°N in the Atlantic. In the Pacific Ocean, mating takes place at 20°N to 30°N, and large adults occur mainly in equatorial waters (Nakano 1994). In the Gulf of Guinea, females in early pregnancy are found mainly during the third quarter of the year (Castro and Mejuto 1995). Mejuto and García-Cortéz (2004) mentioned that this might be due to the benefits of highly productive surface layers of temperate water linked to the coastal upwelling areas in the Gulf of Guinea. It is interesting to observe that these females in the Gulf of Guinea were found one quarter of the year ahead of the peak of mean female CPUE off the coast of Brazil, but at the same latitudes. The parturition area is not possible to guess from the present information, but based on the data available from other oceans (Nakano 1994), it would probably be located from the south coast of Africa, where upwelling occurs, to the subtropical convergence (Hazin et al. 2000a). It is important to emphasize that the blue shark migratory routes in the South Atlantic are hypothetical at this point. Currently, a tagging study using Pop-up Satellite Archival Tags (PSATs) on blue sharks in the Southwest Atlantic is being carried out to investigate large-scale movements and vertical distribution of this species. Preliminary results indicate trans-oceanic migration of female blue sharks, with one individual having moved from its tagging site off the northeast coast of Brazil to the Gulf of Guinea area off the west coast of Africa (F. Carvalho *unpublished data*).

In the North Pacific, Nakano (1994) reported high abundances of juvenile blue sharks at high latitudes, between 35°N–45°N. This was similar to the spatial distribution pattern of juvenile blue sharks in the southwest Atlantic observed in the present study. The results observed for juvenile males off Brazil at latitudes >35°S in the present study indicated the highest abundances during the first and third quarters of the year for the latitudinal blocks of 36°S–40°S and 41°S–45°S, respectively. Montealegre-Quijano and Vooren (2010), studying in the same area, found that small juvenile males (FL ≤ 129 cm) were more abundant between the latitudes 33°S in winter (third quarter of the year in the present study) and 46°S in summer (first quarter of the year in the present study). Regarding the spatial distribution of juvenile female blue sharks in the Southwest Atlantic, Montealegre-Quijano and Vooren (2010) mentioned that these individuals move to areas south of the subtropical convergence, however due the lack of data collected in latitudes below 38°S these authors could not confirm this hypothesis. Results showed an increase in mean CPUE values for juvenile females from the latitudinal block 36°S–40°S to 41°S–45°S, which suggested that these sharks were moving to more southern areas. Mean CPUE of juvenile males into Sub-area III, on the other hand, showed a decrease towards the south.

As proposed by Mourato (unpublished data), the seasonality in blue shark distribution and abundance off the southern coast of Brazil might be explained by a variety of oceanographic characteristics of this area. The Subtropical Convergence (SC), a mixture of cold waters brought by the Malvinas Current and tropical waters of the Brazil Current, occurs in the southwestern Atlantic Ocean between 34° and 36°S. The presence of water rich in nutrients promotes higher primary and secondary productivity in the SC region (Montu et al. 1997). This in turn increases the amount of potential prey for blue sharks, such as squid, *Illex argentinus* (Vaske and Rincón 1998). In addition, the Rio Grande Rise is in this area. It is a large seismic ridge situated between the Mid-Atlantic Ridge and the Brazilian continental shelf, approximately 600 nm off the southern Brazilian coast, where depths range between 300 and 4000 m. Seamounts like the Rio Grande are well known to cause vertical water transport, resulting in local increases of primary productivity (Pitcher et al. 2007). Furthermore, according to Ciotti et al. (1995), the highest primary production in the southwestern Atlantic Ocean is under the influence of sub-Antarctic waters, which are rich in nutrients. This maximizes the availability of food for young blue sharks, which represents the most vulnerable stage of the life history of all pelagic fishes.

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