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DISTRIBUTION PATTERNS OF SIZES AND SEX-RATIOS OF BLUE SHARK IN THE INDIAN OCEAN

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SUMMARY

The blue shark is the most captured shark in pelagic longline fisheries targeting tunas and swordfish. As part of an ongoing cooperative research between several institutes and national scientists, information on blue shark catch-at-size was collected, compiled and analyzed for the Indian Ocean. This included information from fishery observers, logbooks, scientific projects and scientific surveys from several fishing nations, specifically EU.Portugal, EU.France, Japan, Taiwan, South Africa and the USSR (data from historical surveys). Datasets included information on catch location and date, and specimen size and sex. A total of 77,396 blue shark records collected between 1966 and 2014 were compiled, with the sizes ranging from 41 to 369 cm FL (fork length). Considerable variability was observed in the size distribution by region and season, with larger sizes tending to occur in equatorial and tropical regions and smaller sizes in southern latitudes in more temperate waters. Some fleets/surveys showed bimodal size distributions, which may be related with the fact that those fleets/surveys operate in several locations throughout the Indian Ocean. Differences in the sex ratios, both spatially and seasonally, were also detected. The distributional patterns presented in this study provide a better understanding of different aspects of the blue shark distribution patterns in the Indian Ocean that can help to promote more informed management and conservation measures.

KEYWORDS: Blue shark, catch-at-size, Indian Ocean, sex ratios, size composition, size distribution, spatial distribution, spatial models.

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1. Introduction

The blue shark, *Prionace glauca*, is one of the widest ranging of all sharks, found throughout tropical and temperate seas from latitudes of about 60°N to 50°S (Last and Stevens, 2009). It is a pelagic species mainly distributed from the sea surface to depths of about 350m, even though deeper dives of up to 1000m have been recorded (Campana, et al., 2011). The blue shark is an oceanic species capable of large scale migrations (Queiroz et al., 2005; Silva et al., 2010; Campana et al., 2011), but can also occasionally occur closer to inshore waters, especially in areas where the continental shelf is narrow (Last and Stevens, 2009).

Blue sharks can be captured by a variety of fishing gears, but most catches take place as bycatch in pelagic longlines targeting tunas and swordfish. In the Indian Ocean, the average reported blue shark catch in the last 5 years (2009-2013) was 27,407t, of the average total 87,935t of sharks and 1,671,915t of all species combined that have been reported to the IOTC (*Indian Ocean Tuna Commission*) (IOTC, 2015). Blue shark is the most prevalent shark captured in pelagic longline fisheries from all Oceans (Mejuto, 1985; Castro et al., 2000; Matsunaga, 2007; Mejuto et al., 2009; Huang and Liu, 2010; Coelho et al., 2014), and in some cases blue shark catches can account for more than 80% of the total elasmobranch catch (Matsunaga, 2007; Coelho et al., 2011, 2012).

The main objective of this paper is to provide detailed information on the distribution patterns of the blue shark in the Indian Ocean. The specific objectives are to 1) analyze the distribution and seasonal patterns of the blue shark catch-at-size, 2) provide time series trends by region and fleet, 3) analyze the distribution of the sex ratios and 4) model the expected catch-at-size across the Indian Ocean.

2. Material and methods

2.1. Data collection

Blue shark records were taken by scientific observers onboard commercial vessels, logbooks, and during scientific cruises / surveys and scientific projects. Data were compiled for the periods 1967-2014 for Japan, 2004-2013 for Taiwan, 2011-2014 for EU.Portugal, 2012-2014 for South Africa, 2003-2014 for EU.France and 1966-1989 for the USSR (scientific surveys). Data were collected across a wide geographical range of the Indian Ocean.

For analysis purposes, the Indian Ocean region was separated into 4 areas, specifically SW = southwest, SE = southeast, NW = northwest and NE = northeast. This separation was based both on the characteristics of the sample in terms of sizes and also taking into consideration other available regional areas such as the FAO statistical regions. Specifically, and for the purposes of this analysis, the east-west separation was made at 80ºE based on the

FAO separation between areas 51 and 57, while the north-south separation was established at 25ºS and based mainly on the characteristics of the distributions of sizes of BSH in the sample.

For captured specimens, data on specimen size, sex, capture location and date was recorded. The size measurement were taken in either fork length (FL), pre-caudal or standard length (PCL) or total length (TL) as specific national programs, scientific cruises and projects can record sizes in different formats. As such, all sizes were converted to FL using the following equations created specifically for the Indian Ocean (Romanov, *pers. comm.*):

- FL = 0.9095 + 1.0934 * PCL (N=2845, R^2= 0.995)
- FL = 3.6291 + 0.8215 * TL (N=2369, R^2= 0.972)

where FL = fork length (cm), PCL = pre-caudal length (cm) and TL = total length (cm).

2.2. Data analysis

Size data were tested for normality with Kolmogorov-Smirnov normality tests with the Lilliefors correction (Lilliefors, 1967), and for homogeneity of variances with Levene tests (Levene, 1960). Specimen sizes were compared between regions, sexes and quarters of the year using non-parametric *k*-sample permutation tests (Manly, 2007). The annual trends of the mean catch-at-size were plotted and analyzed by fleet and by region.

Sex ratios were calculated and compared between regions with contingency tables and Pearson's chi-squared tests. Sex ratios were also compared between the seasons of the year and size classes (categorized by the 20% percentiles of the data) taking into account the various regions, using Cochran-Mantel-Haenszel (CMH) chi-squared tests. This test allows detecting seasonality of size-related effects in the sex ratios conditional to each of the regions analyzed.

A Generalized Additive Model (GAM) with a gaussian error structure and identity link function was specified to predict the expected blue shark catch-at-size as a function of location (latitude and longitude) and quarter. The linear predictor in this model was given by the smooth functions of latitude and longitude plus the parametric component for the factor quarter. The smooth terms for the location covariates was estimated by thin plate regression splines (Wood, 2003). The significance of the model parameters was tested with likelihood ratio tests (LRT) comparing nested models as the number of variables was added. A residuals analysis was carried out to validate the models, and the goodness-of-fit was assessed with the Akaike Information Criteria (AIC; Akaike, 1973) and with the final deviance explained. The expected mean catch-at-sizes were predicted and mapped along the study area for each quarter.

The analysis for this paper was carried out using the R language for statistical computing version 3.2.0. (R Core Team, 2015). Additional libraries that were used included packages “boot” (Davison and Hinkley, 1997; Canty and Ripley, 2013), “car” (Fox and Weisberg, 2011), “classInt” (Bivand, 2013), “ggplot2” (Wickham, 2009), “gmodels” (Warnes et al., 2013), “maps” (Becker et al., 2013), “mapplots” (Gerritsen, 2013), “maptools” (Bivand and Lewin-Koh, 2013), “mgcv” (Wood, 2006, 2011), “nortest” (Gross and Ligges, 2012), “perm” (Fay and Shaw, 2010), “plyr” (Wickham, 2011), “RColorBrewer” (Neuwirth, 2011), “rgdal” (Bivand, et al., 2013), “scales” (Wickham, 2012) and “shapefiles” (Stabler, 2013).

3. Results

3.1. Spatial distribution in the catch-at-size

A total of 77,396 blue sharks were recorded and considered within the scope of this study, specifically 44,141 from Japan, 15,276 from EU.Portugal, 10,275 from Taiwan, 4,371 from South Africa, 2,975 from the USSR and 358 from EU.France. The specimens ranged in size from 41 to 350 cm FL for females and from 45 to 369 for males, covering most of the known size range of the species (**Figure** 1).

Data from the initial years (1966-1991) came exclusively from scientific research and surveys, data between 1992 and 2002 was available both from scientific research and fisheries (observers + logbooks), and the data for the more recent years (2003-2014) came exclusively from fisheries (observers + logbooks). The sample covered a wide geographical area of the Indian Ocean, with more catches taking place along the SW and SE regions (**Figure 2**).

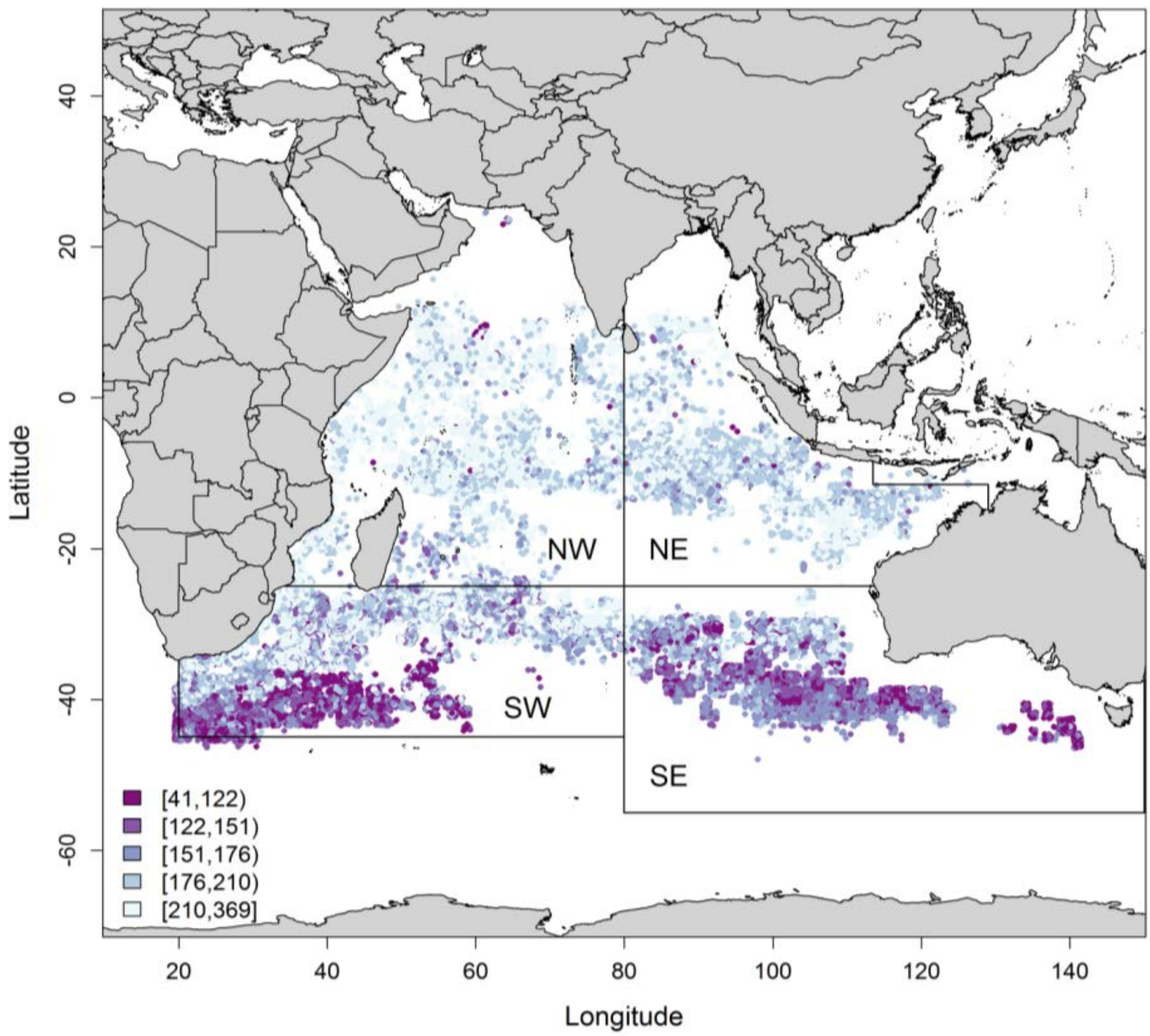

Figure 1. Location and catch-at-size (FL, cm) of the blue shark (*Prionace glauca*) recorded for this study in the Indian Ocean. The color scale of the dots represents specimen sizes, with darker colors representing smaller specimens and lighter colors larger specimens. The categorization of size classes for the map was carried out using the 0.2 quantiles of the data, and the values in parentheses in the legend represent the lower and upper limit of each 0.2 quantile. Note that the data points are jittered by 1*1 degrees, so the positions are only approximate within each 1*1 square.

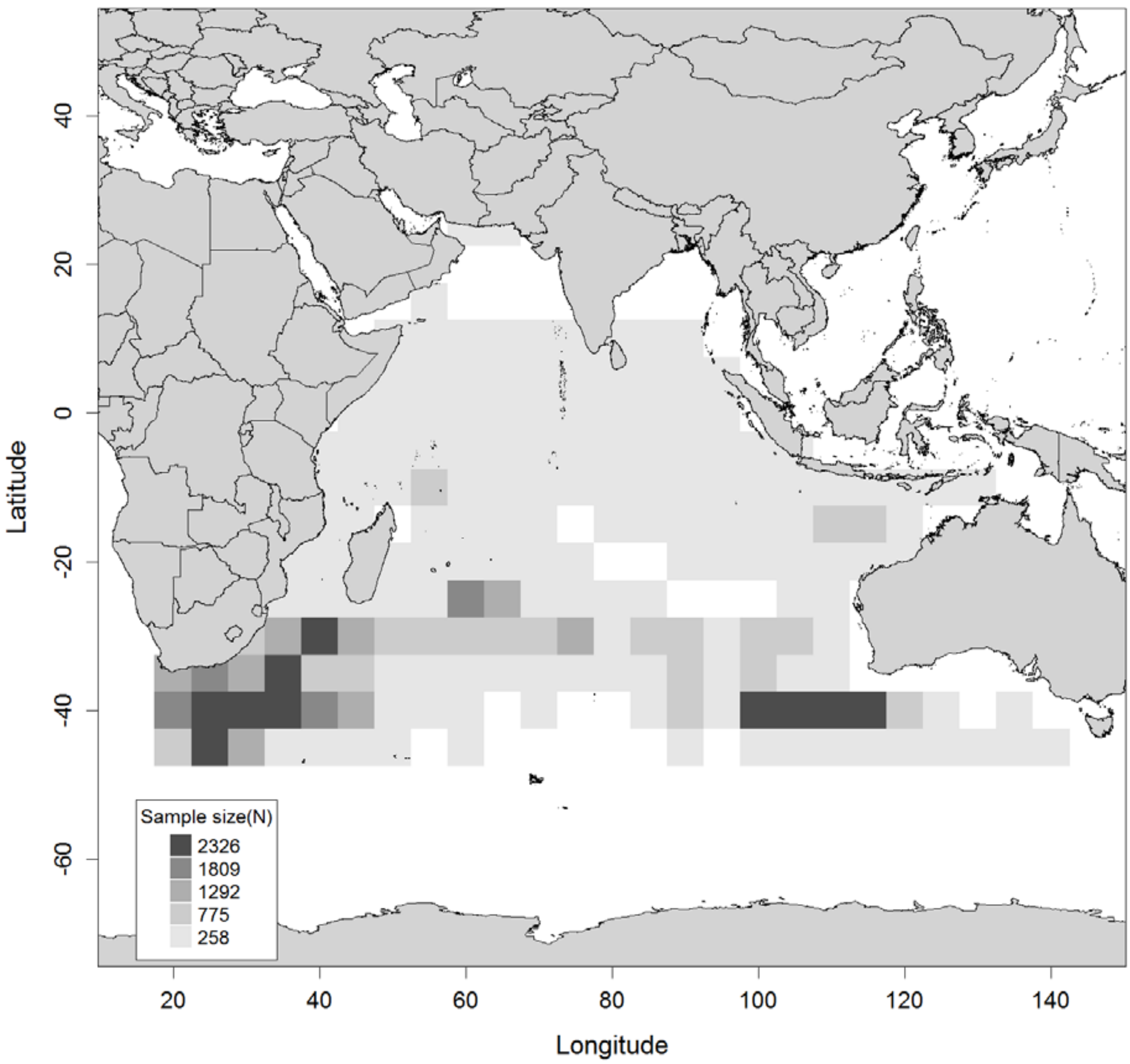

Figure 2. Sample size (N) distribution in 5*5 degrees of blue shark (*Prionace glauca*) recorded for this study in the Indian Ocean. The values in the legend refer to the upper limits in sample size class.

Size data were not normally distributed (Lilliefors test: D = 0.0215, p-value < 0.001) and the variances were heterogeneous between regions (Levene test: F = 2607.9, df = 3, p-value < 0.001), sexes (Levene test: F = 999.7, df = 1, p-value < 0.001) and quarters of the year (Levene test: F = 303.2, df = 3, p-value < 0.001). Using univariate non-parametric statistical tests revealed that sizes were significantly different between regions (Permutation test: chi-squared = 12925, df = 3, p-value < 0.001), sexes (Permutation test: chi-squared = 1942.3, df = 1, p-value < 0.001) and quarters of the year (Permutation test: chi-squared = 10366, df = 3, p-value < 0.001).

It is possible to see considerable variability in the sizes in each of the fleets/surveys analyzed. Some fleets showed unimodal distributions (e.g., South Africa, EU.France), while others showed some tendency for more bimodal distributions (e.g., Taiwan, USSR surveys)

(**Figure 3**). This is likely related with the fleets/surveys that operate both in temperate and tropical latitudes, where both smaller and larger specimens tend to be captured.

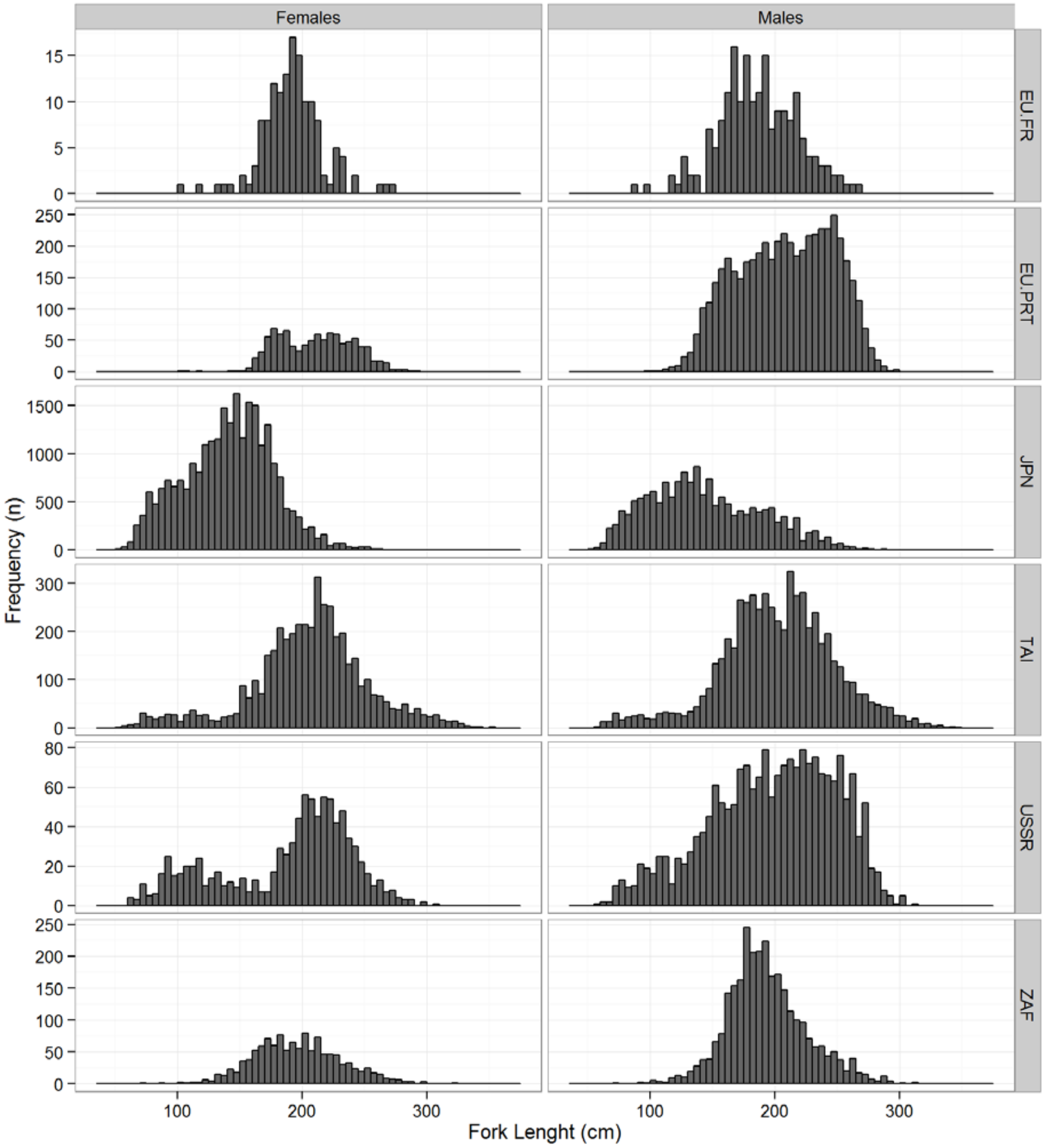

Figure 3. Size-frequency distributions of male and female blue shark (*Prionace glauca*) caught by the different fleets/surveys in the Indian Ocean. Sizes are binned in 5 cm FL classes.

When grouping the data into regions the distributions became much more unimodal, with some differences observed between the regions. The smaller sized specimens were recorded mainly in the SW and SE with the distribution mostly unimodal in the SE and slightly bimodal in the SW (**Figure 4**). Larger specimens were recorded in the NE and the

NW, also with unimodal distributions (**Figure 4**). In terms of comparison between sexes, females tended to be larger than males in the SE, while the males tended to be larger than the females on the other regions, again with a general tendency for smaller specimens in the SE and SW and larger in the NE and NW (**Figure 5**)

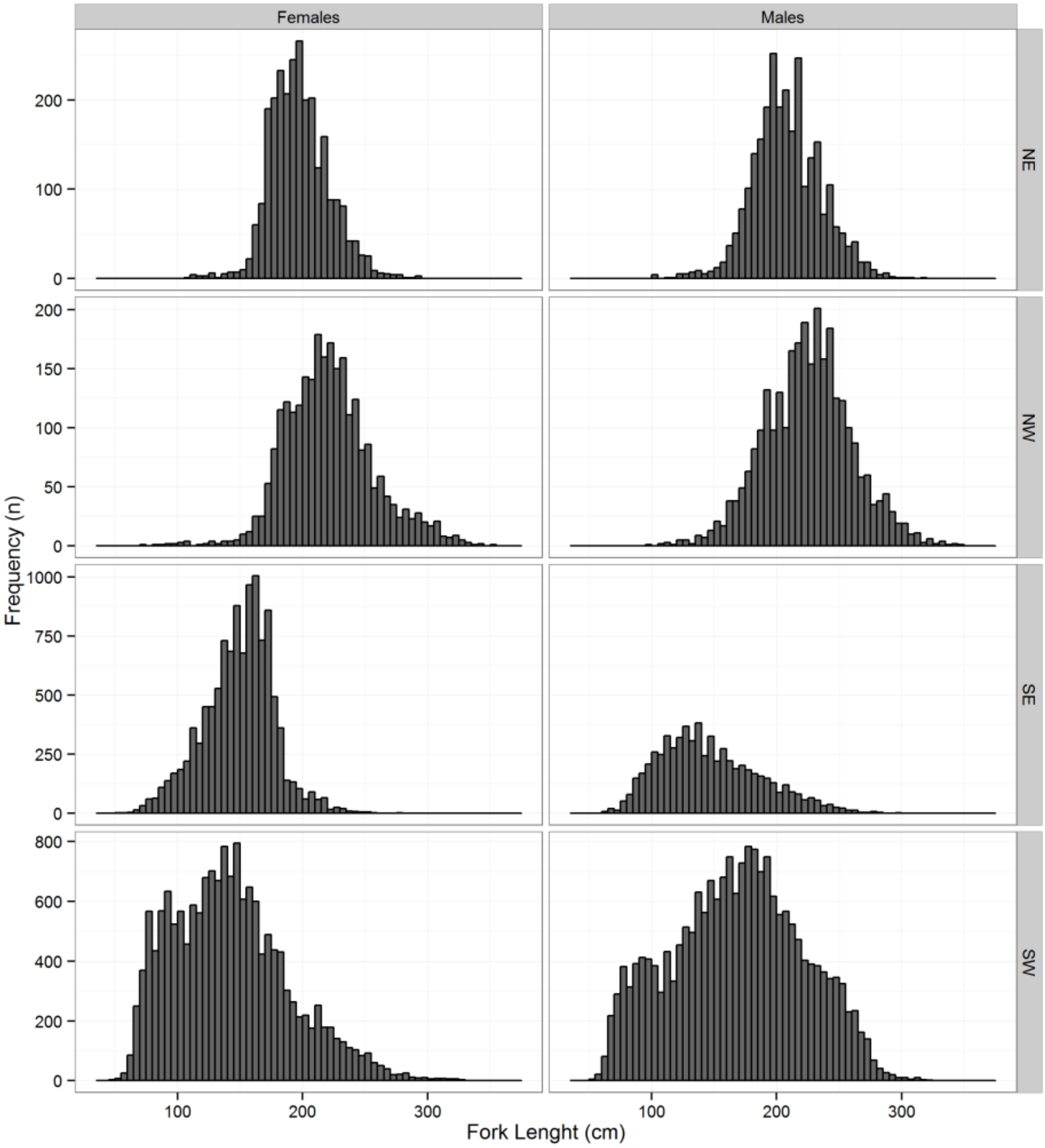

Figure 4. Size-frequency distributions of male and female blue shark (*Prionace glauca*) caught in the four IOTC areas considered for the Indian Ocean. Sizes are binned in 5 cm FL classes.

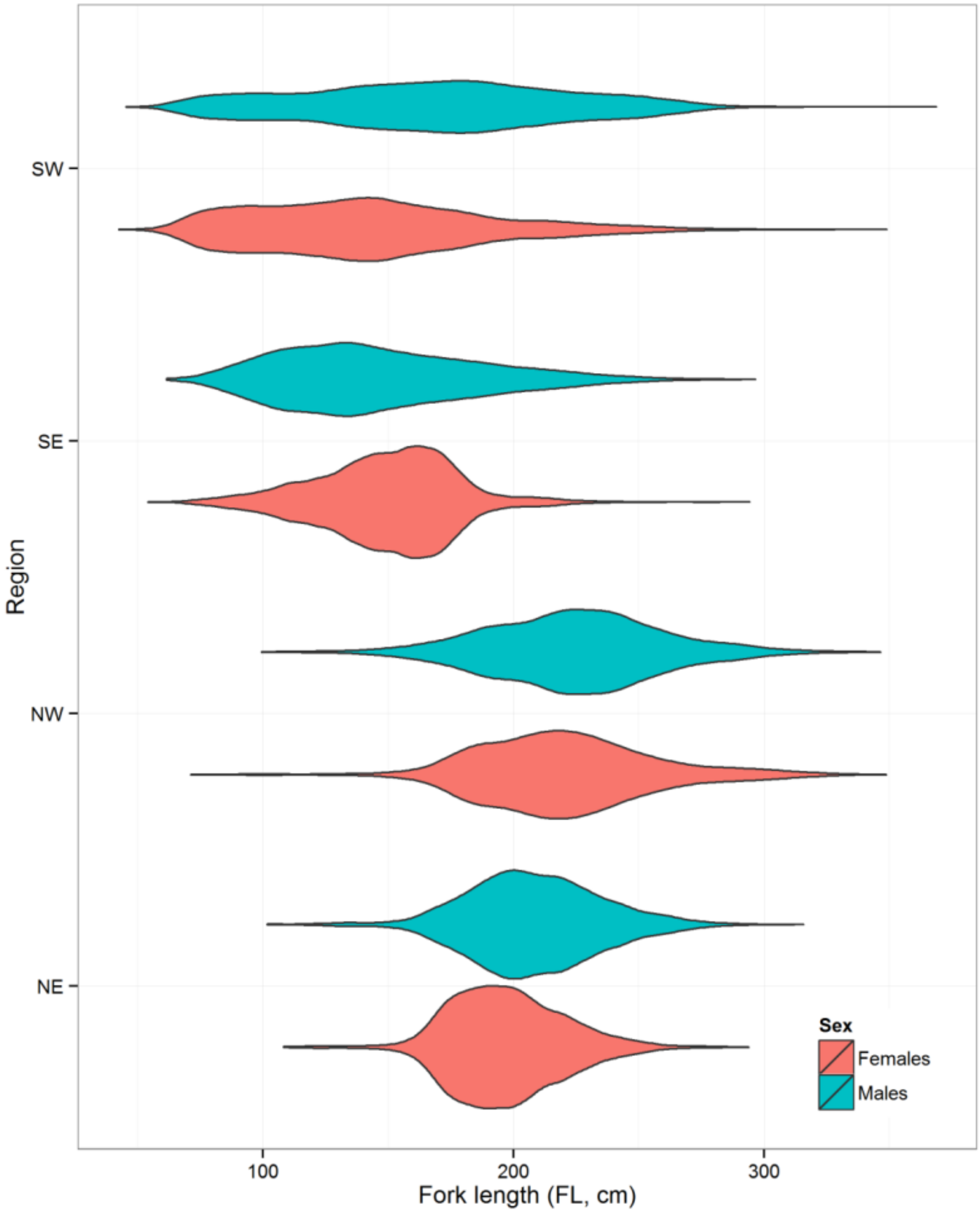

Figure 5. Overall size distribution (violin plots) of male and female blue shark (*Prionace glauca*) caught in the four IOTC areas considered for the Indian Ocean.

3.2. Seasonal variability in the catch-at-size

Seasonality and sex seems to influence the size of captured blue sharks. In the northern regions, both NE and NW, the sizes tended to increase along the year and there were little differences between males and females (**Figure 6**). By the contrary, for the SWE and SW the sizes tended to decrease along the year and there were some differences between the sexes (**Figure 6**).

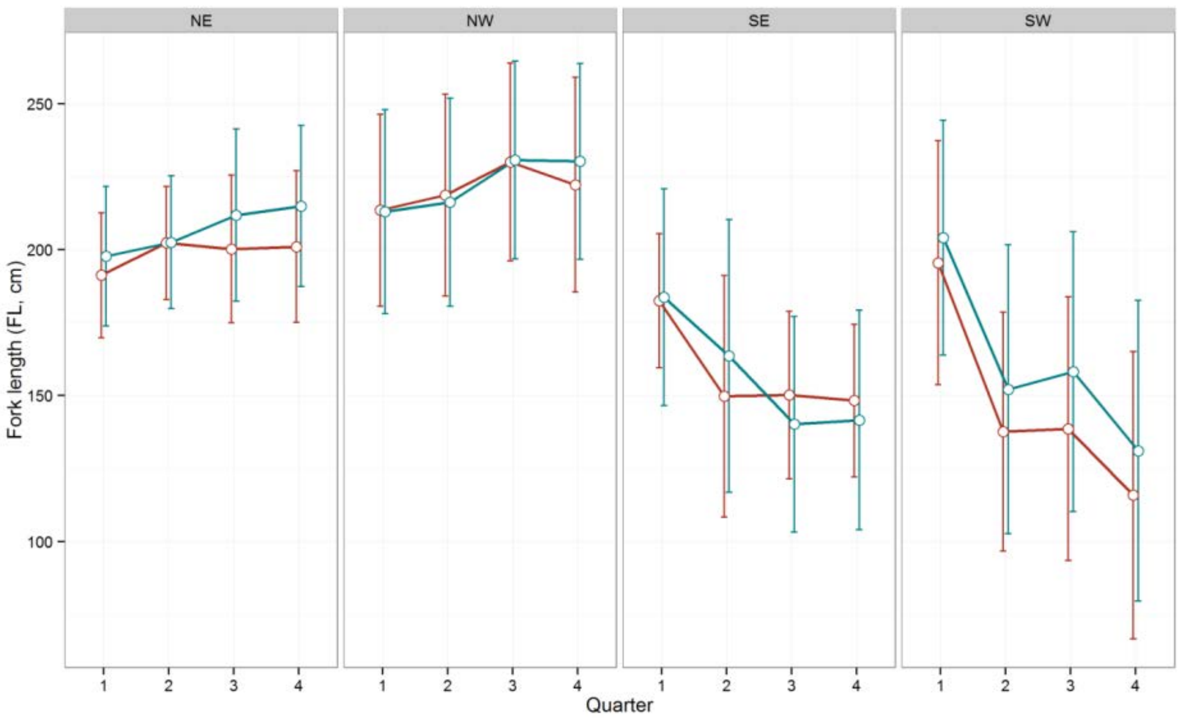

Figure 6. Mean size of male and female blue shark (*Prionace glauca*) caught in the four IOTC regions of the Indian Ocean by quarter of the year. The error bars are ± 1 standard deviation.

3.3. Annual trends in the catch-at-size

There were some variability in the time series of the sizes among regions, with some regions showing relatively more stable trends than others. The NE and SE regions seemed relatively stable along the time series, with some variability but no major trends (**Figure 7**). In the NW most of the time series showed little variability, but there was a decrease in the sizes in more recent years (**Figure 7**). The region with the larger variances was the SW with relatively larger sizes in the 1970s (research cruise data), followed by a period with smaller sizes between 1992 and 2006 and then another period with larger sizes again in the more recent years (**Figure 7**).

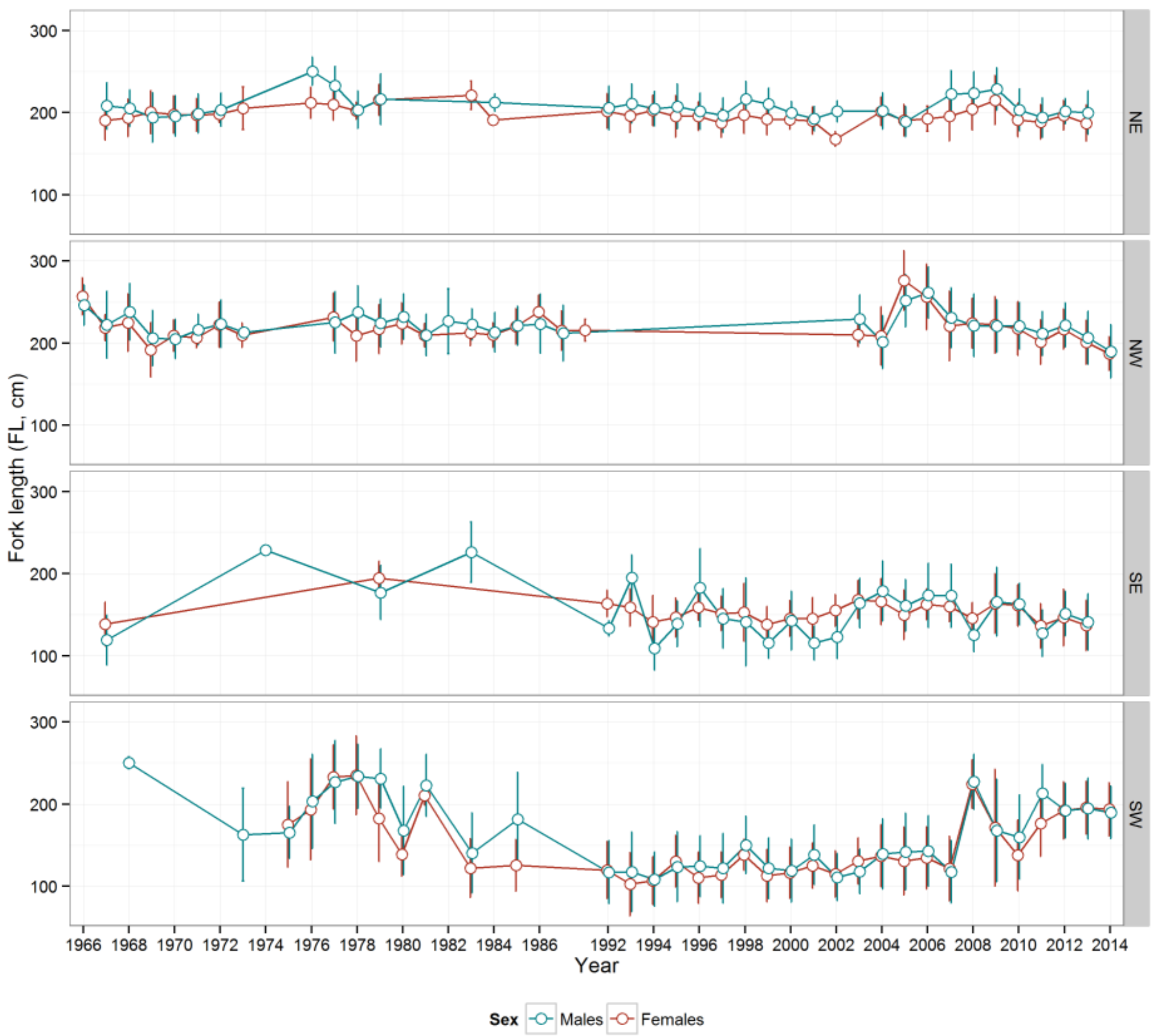

Figure 7. Mean size of blue shark (*Prionace glauca*) by sex caught in the four different IOTC regions of the Indian Ocean, during the period 1966-2014. The error bars are ± 1 standard deviation.

3.4. Sex ratios

Of the overall blue sharks with sex recorded was 64,755 specimens, of which 50.7% were females and 49.3% were males. There was some evidence of spatial variability in the sex ratios with more females recorded in southern latitudes both in the SE and SW Indian Ocean (**Figure 8**). In contrast, there was a tendency for the presence of more males immediately northern of this parallel in waters around 30ºS also both in the east and western Indian Ocean (**Figure 8**).

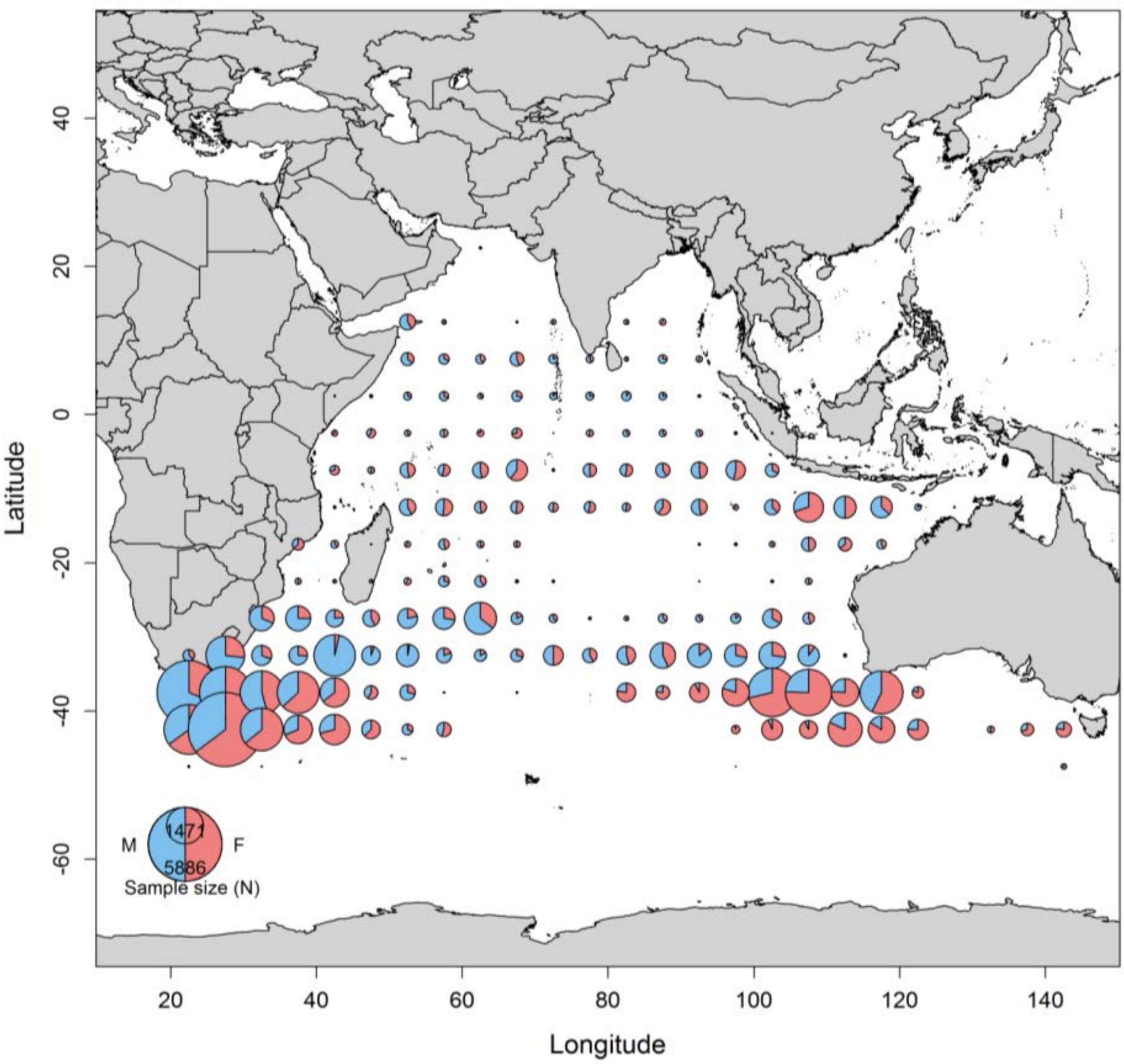

Figure 8. Blue shark (*Prionace glauca*) sex ratios recorded in 5ºx5º squares during this study in the Indian Ocean. The circle sizes are proportional to the sample size (N) in each square.

In some areas of the Indian Ocean there were noticeable changes in the sex ratios along the quarters of the year, even thought this could also be related with the seasonal effort in the fisheries and the sampling. In the SW region there seemed to be more females in quarter 2 but more males during the rest of the year (**Figure 9**). In the SE region there seemed to be more males in quarters 1 and 2 and more females in quarters 3 and 4 (**Figure 9**). Along the equatorial and more tropical regions most of the records are from quarter 4 when there was the presence of more males, while in the tropical eastern there were more females in quarter 1 (**Figure 9**).

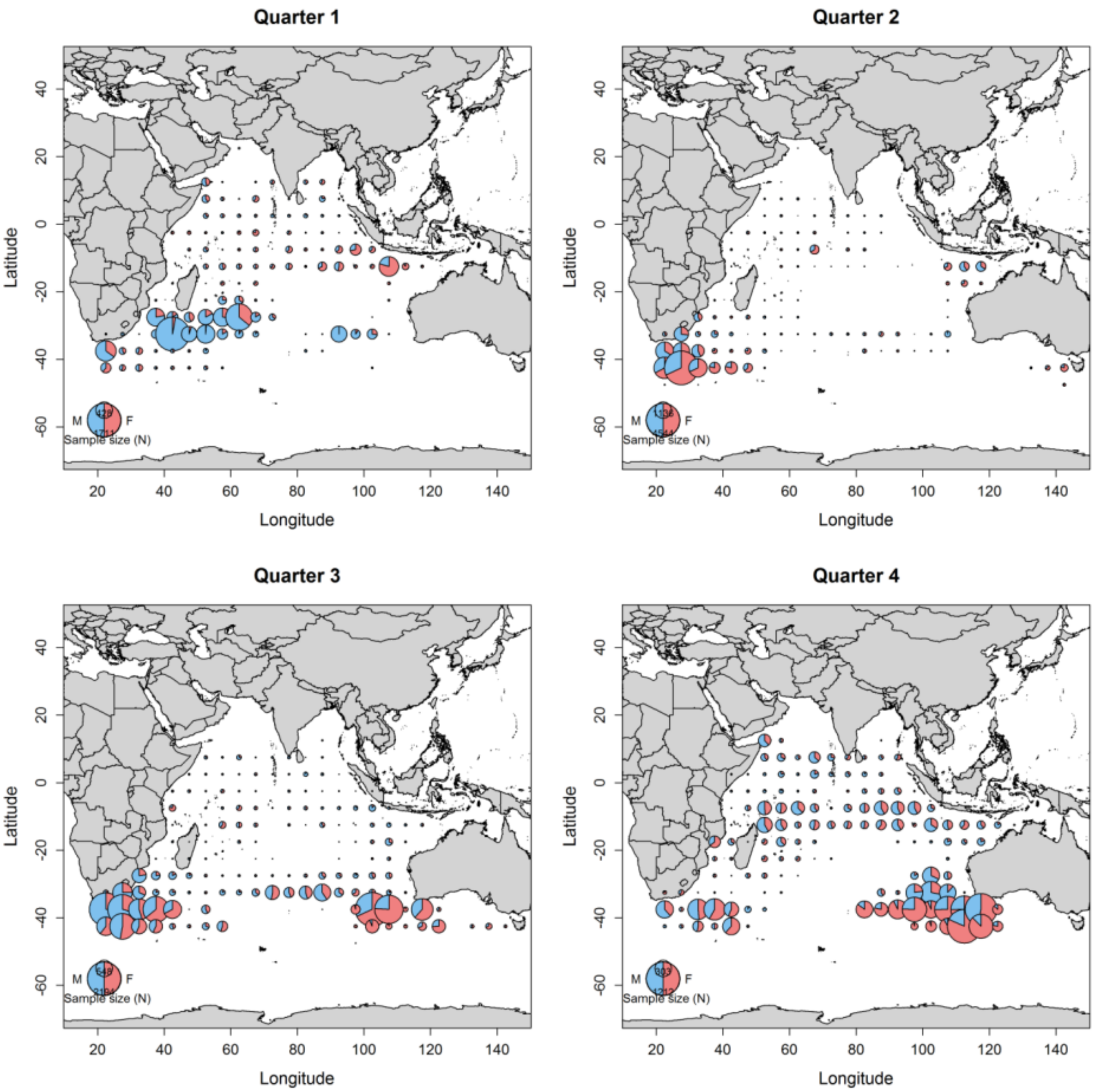

Figure 9. Blue shark (*Prionace glauca*) sex ratios recorded in 5ºx5º squares during this study in the Indian Ocean in each quarter of the year. The circle sizes are proportional to the sample size (N) in each 5ºx5 square and in each quarter.

There were significant differences in the overall sex ratios among the four IOTC regions (prop. test: chi-squared: 1711.1, df = 3, p-value < 0.001). Overall, the proportion of females was considerably higher in the SE, while in the other regions the sex-ratios were more similar (**Figure 10**).

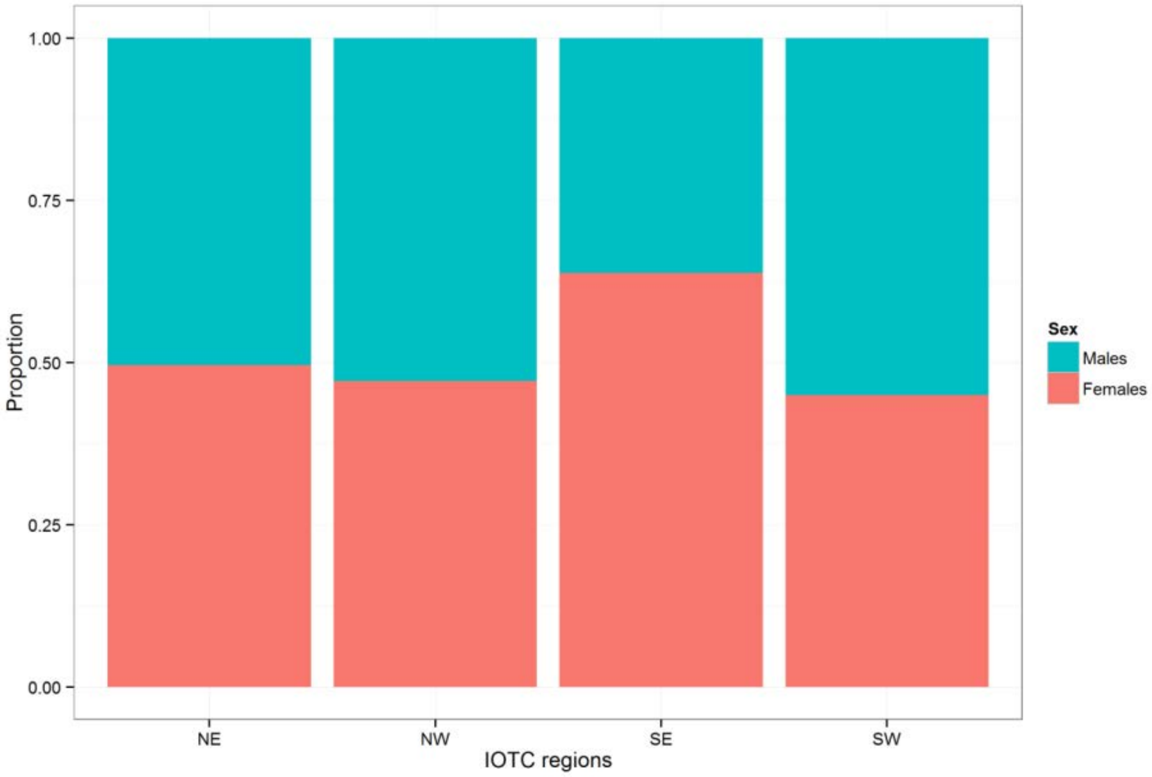

Figure 10. Sex ratios of blue shark (*Prionace glauca*, all sizes and seasons combined) in the four IOTC regions.

There were also significant differences in sex ratios among seasons, even when compared conditionally within each of the different regions (CMH test: chi-squared = 2176.5, df = 3, p-value < 0.001). In the SW and SE there were much more males than females in quarter 1, while the sex ratios were more homogeneous during the rest of the year (**Figure 11**). By the contrary, in the NE there were much more females in quarter 1 and more males during the rest of the year, while in the NW the sex ratios were more homogeneous along the entire year (**Figure 11**).

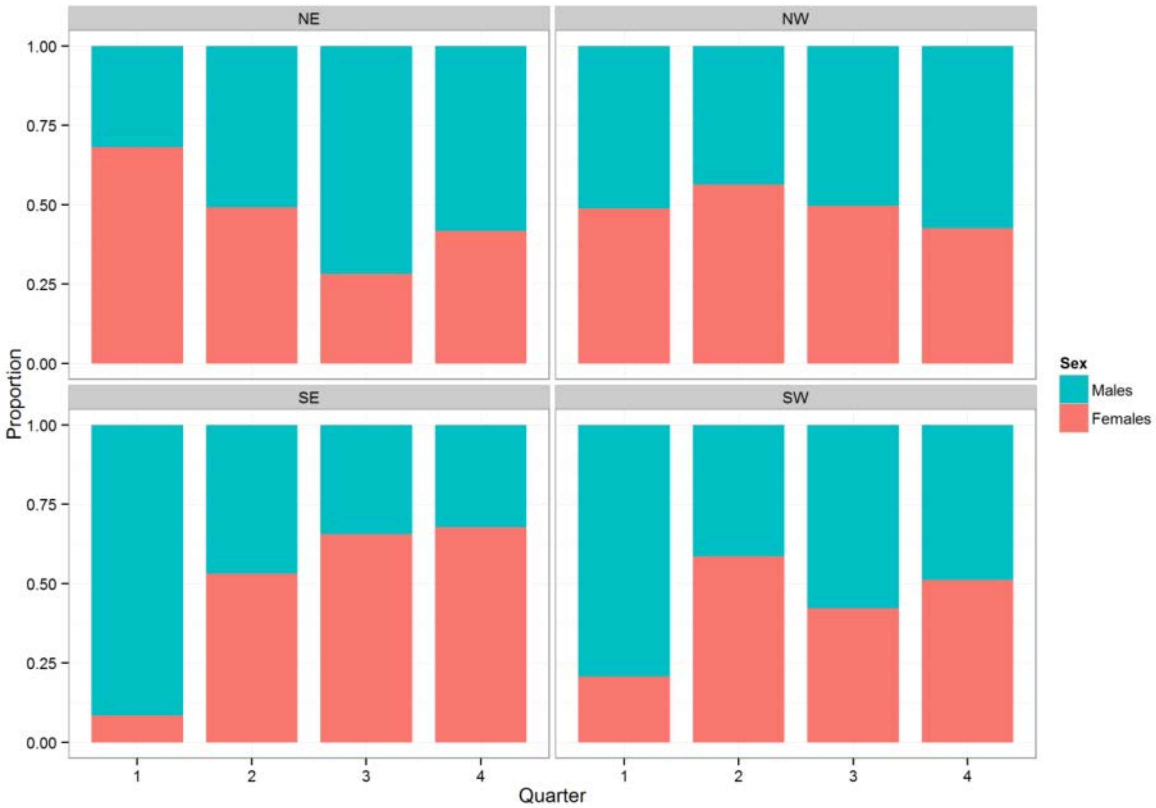

Figure 11. Sex ratios of blue shark (*Prionace glauca*, all sizes combined) per quarter of the year in the four regions.

Significant differences were also detected in the sex ratios among sizes tested conditionally within the different regions (CMH test: chi-squared = 2711.3, df = 4, p-value < 0.001). In the SW there was a clear tendency for the larger specimens to be males, while in the SE both the larger and the smaller were males and the females were predominant in the middle size classes (**Figure 12**). In the NE and NW there were some variability but without any obvious trends (**Figure 12**). This means that the differences previously observed in the overall sex ratios among regions could be caused by the size segregation of individuals in those regions along the quarters of the year.

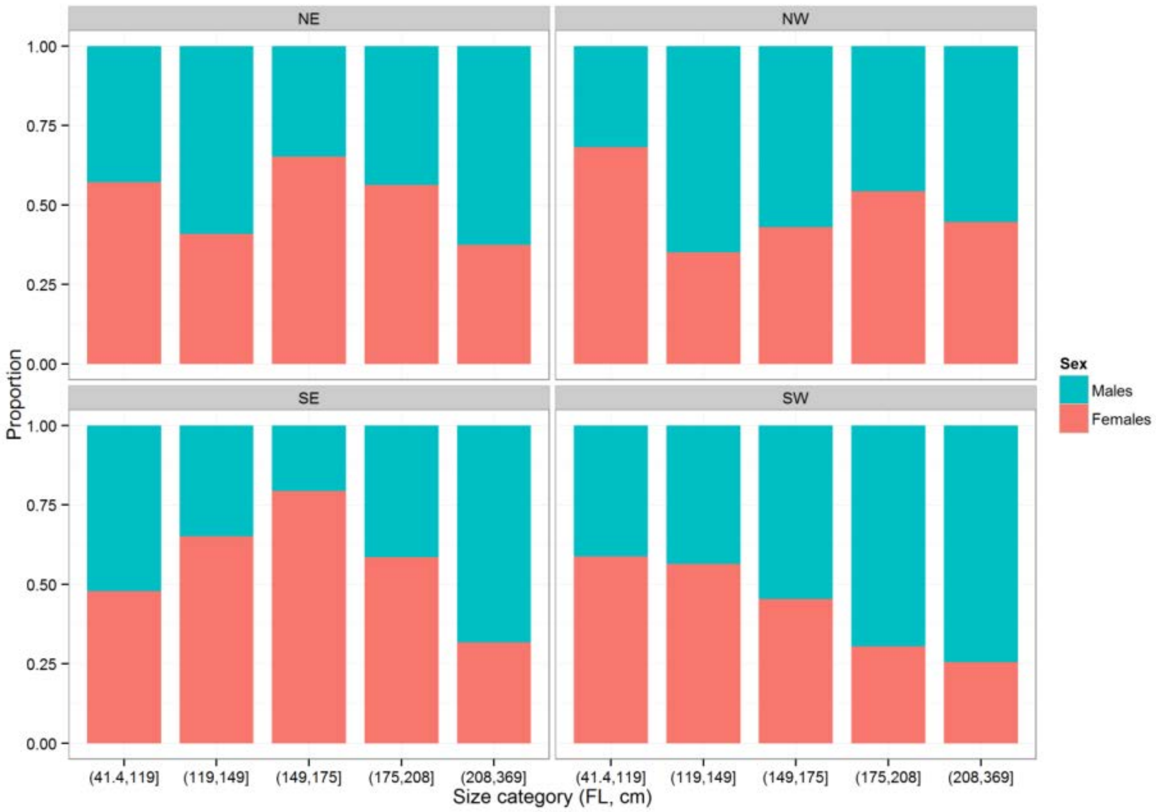

Figure 12. Sex ratios of blue shark (*Prionace glauca*, all seasons combined) per size class, in the four IOTC regions of the Indian Ocean. The categorization of the size classes was carried out using the 20% percentiles of the size data.

3.5. Modeling the catch at size

There was considerable variability in the expected catch-at-size in the Indian Ocean when taking into consideration the catch locations, and to a less extent the quarters of the year. The larger mean blue shark sizes were predicted to occur mainly along the equatorial and tropical regions, while the smaller specimens were predicted to occur mainly in higher latitudes of the southern Indian Ocean (**Figure 13**). There was also some variability within the longitudes, with the larger specimens predicted to occur mainly in the NW and the medium sizes in the NE (**Figure 13**). The final estimated GAM model considered the non-parametric smooth terms for location (latitude and longitude) and the parametric terms for quarter used as a fixed factor (F= 350.3; df=3; p-value < 0.001). The total deviance explained by this model was 46.5%, and in terms of goodness of fit the AIC decreased from 774273to 773237 when adding the quarter to the smooth location parameters, meaning that the model was better fitted when using all the variables considered.

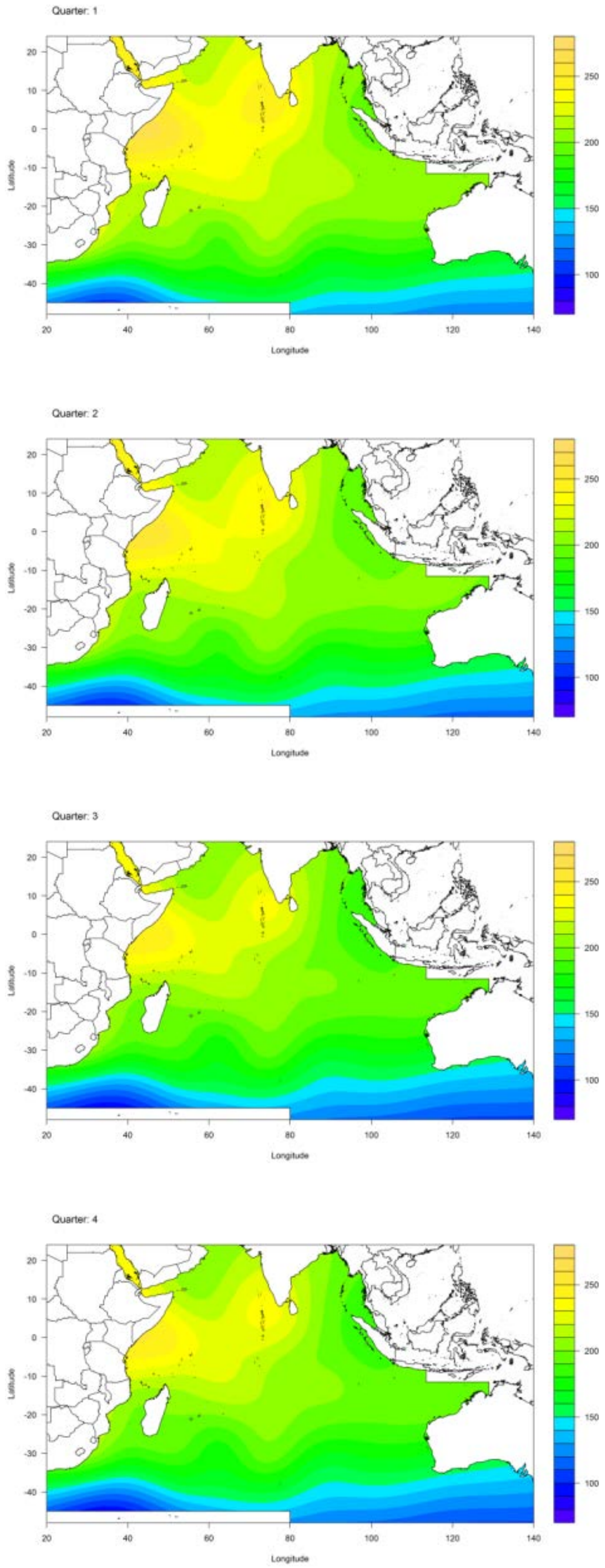

Figure 13. Prediction of the catch at size of blue sharks (*Prionace glauca*) caught in the Indian Ocean during by quarter of the year. The predicted values are the result of a Generalized Additive Model (GAM) taking into consideration the smooth terms of catch location estimated with thin plate regression splines, and the fixed parametric factor for quarter. The size range considered was 41 to 369 cm FL and the sexes were modeled together.

4. Discussion

This work provides the most comprehensive study on blue shark catch at size distribution from the Indian Ocean, compiling information from different sources including fishery observers onboard commercial longline vessels, logbooks, data from scientific projects and from scientific survey cruises. The results presented provide an important contribution to the study of the spatial and seasonal dynamics of this species in the Indian Ocean, with significant differences found in the length-frequency distributions and sex ratios in the several regions of the Indian Ocean.

There seems to be a clear latitudinal distribution of the blue shark sizes in the Indian Ocean with the larger specimens tending to occur along the equatorial and tropical areas, and the smaller sizes occurring mainly towards higher latitudes of the Southern Indian Ocean, both in the SW and SE. The reasons for these differences might be related with migratory and habitat segregation patterns by growth stages between regions and seasons of the year, with the larger specimens preferring equatorial and tropical waters and the smaller specimens preferring colder water. This is the same pattern that was also observed for blue shark in the Atlantic, where the smaller specimens also occurred mainly in colder waters (in this case both in the southern and northern hemispheres) and the larger specimens also tended to occur in tropical and equatorial regions (Coelho et al., 2015). However, for some other pelagic shark species an opposite pattern has been found, such as for example for the bigeye thresher in the Atlantic where the smaller and younger sharks tended to concentrate predominantly in the tropical regions while the larger adults seemed to prefer temperate areas of the northern and southern hemispheres (Fernandez-Carvalho et al., 2015).

It is important to note that the data used in this study comes from several different fleets, and also includes data from scientific projects and scientific surveys, that have used different fishing *métiers* and that target different species. As such, the size ranges, abundance and distribution reported by each fleet / survey for each region are also affected by area availability and fleet selectivity. With regards to the spatial distribution of the data, and while the observations reported reflect in part the species spatial dynamics, there is also some influence from the sampling effort of each fleet, and therefore the reported data may not be entirely representative of the prevalence of the species at each location. Additionally, some of the variability observed in the fleet / survey time series analysis may be explained by lower sample sizes in some years.

This study provides a general overview of the size distribution at a wide Indian Ocean scale, but one possible limitation is the fact that the analysis and the models created are focusing mainly on the major spatial effects over the entire Ocean. There are probably finer scale effects and local variability patterns taking place that are not likely to be captured in such large scale models and analyses. Therefore, this study is important as a general overview and provides the general trends in the Indian Ocean, but it is also important to continue more detailed and local analysis for specific regions.

In terms of contribution to the Indian Ocean blue shark stock assessment, it seems that splitting the catch-at-size of blue sharks in at least into two major regions (higher and lower latitudes) is recommended as there are important differences in the sizes in terms of latitudes. Additionally, further splitting the catches along the longitudes (NW, SW, SE and SE, as was done in this work) might also be appropriate as there are also some important size differences along the east-west gradient, especially in the more tropical and equatorial areas. This would result in more homogenous areas in terms of the blue shark catch at size that should provide better fits to the stock assessment models.

5. Acknowledgments

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6. References

Akaike, H. 1973 Information theory and an extension of the maximum likelihood principle. In: Petrov NB, Csáki F (eds) 2nd International Symposium on Information Theory, Akádemia Kiadó, Budapest, pp 267-281.

Becker, R.A., Wilks, A.R., Brownrigg, R., Minka, T.P. 2013. 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.

Bivand, R., Keitt, T., Rowlingson, B. 2013. rgdal: bindings for the geospatial data abstraction library. R package version 0.8-14. http://CRAN.R-project.org/package=rgdal.

Campana, S.E., Dorey, A., Fowler, M., Joyce, W., Wang, Z., Wright, D., Yashayaev, I. 2011. Migration pathways, behavioural thermoregulation and overwintering grounds of blue sharks in the northwest Atlantic. PLoS ONE, 6: e16854.

Canty, A., Ripley, B. 2013. boot: bootstrap R (S-Plus) functions. R package version 1.3-9.

Castro, J., Serna, J.M., Mácias, D., Mejuto, J. 2000. Estimaciones científicas de los desembarcos de especies asociadas realizados por la flota española de palangre de superficie en 1997 y 1998. Col Vol Sci Pap ICCAT, 51: 1882-1893.

Coelho, R., Lino, P.G., Santos, M.N. 2011. At-haulback mortality of elasmobranchs caught on the Portuguese longline swordfish fishery in the Indian Ocean. IOTC–2011–WPEB07–31.

Coelho, R., Fernandez-Carvalho, J., Lino, P.G., Santos, M.N. 2012. An overview of the hooking mortality of elasmobranchs caught in a swordfish pelagic longline fishery in the Atlantic Ocean. Aquat Living Resour, 25: 311–319.

Coelho, R., Santos, M.N., Lino, P.G. 2014. Blue shark catches by the Portuguese pelagic longline fleet between 1998-2013 in the Indian Ocean: Catch, effort and standardized CPUE. IOTC–2014–WPEB10–24.

Coelho R., Mejuto J., Domingo A., Liu K-M, Cortés E., Yokawa K., Hazin F., Arocha F., da Silva C., García-Cortés B., Ramos-Cartelle A.M., Lino P.G., Forselledo R., Mas F., Ohshimo S., Carvalho F., Santos M.N. 2015. Distribution patterns of the blue shark, *Prionace glauca*, in the Atlantic Ocean from observer data of the major fishing fleets. ICCAT SCRS/2015/039. 24pp.

Davison, A.C., Hinkley, D.V. 1997 Bootstrap methods and their applications. Cambridge University Press, Cambridge.

Fay, M.P., Shaw, P.A. 2010. Exact and asymptotic weighted logrank tests for interval censored data: the interval R package. J. Stat. Softw., 36 (2): 1-34.

Fernandez-Carvalho, J., Coelho, R., Mejuto, J., Cortés, E., Domingo, A., Yokawa, K., Liu, K.M., García-Cortés, B., Forselledo, R., Ohshimo, S., Ramos-Cartelle, A.M., Tsai, W.P., Santos, M.N. 2015. Pan-Atlantic distribution patterns and reproductive biology of the bigeye thresher, *Alopias superciliosus*. *Reviews in Fish Biology and Fisheries*, 25: 551–568.

Fox, J., Weisberg, S. 2011. An R Companion to Applied Regression, 2nd Edition. Sage, Thousand Oaks CA.

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

Gross, J., Ligges, U. 2012. nortest: tests for normality. R package version 1.0-2. http://CRAN.R-project.org/package=nortest.

Huang, H-W., Liu, K-M. 2010. Bycatch and discards by Taiwanese large-scale tuna longline fleets in the Indian Ocean. Fisheries Research, 106 (3): 261–270.

IOTC, 2015. Nominal catch by species and gear, by vessel flag reporting country. Database IOTC-2015-DATASETS-NCDB. Available at:

http://www.iotc.org/documents/nominal-catch-species-and-gear-vessel-flag-reporting-country.

Last, P.R., Stevens, J.D. 2009. Sharks and Rays of Australia, 2nd Ed. CSIRO, Melbourne, Australia. 656p.

Levene, H. 1960. Robust tests for equality of variances. In: Olkin I, Ghurye SG, Hoeffding W, Madow WG, Mann HB (eds) Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling. Stanford University Press, pp 278-292.

Lilliefors, H.W. 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. J Am Statist Assoc, 62: 399-402.

Manly, B. 2007. Randomization Bootstrap and Monte Carlo Methods in Biology, 3rd ed. Chapman & Hall/CRC, New York.

Matsunaga, H. 2007. Standardized CPUE for blue sharks caught by the Japanese tuna longline fishery in the Indian Ocean, 1971-2005. IOTC-2007-WPEB-17. 5pp.

Mejuto, J. 1985. Associated catches of sharks, *Prionace glauca*, *Isurus oxyrinchus*, and *Lamna nasus*, with NW and N Spanish swordfish fishery, in 1984. International Council for the Exploration of the Sea. C.M. 1985/H: 42, 16pp.

Mejuto, J., García-Cortés, B., Ramos-Cartelle, A., Serna, J.M. 2009. Scientific estimations of by-catch landed by the Spanish surface longline fleet targeting swordfish (*Xiphias gladius*) in the Atlantic Ocean with special reference to the years 2005 and 2006. Collect Vol Sci Pap ICCAT, 64: 2455-2468.

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

Queiroz, N, Lima, F.P., Maia, A., Ribeiro, P.A., Correia, J.P., Santos, A.M. 2005. Movement of blue shark, Prionace glauca, in the north-east Atlantic based on mark–recapture data. J. Mar. Biol. Assoc. U. K., 85: 1107-1112.

R Core Team. 2015. R: A language and environment for statistical computing. Version 3.2.0. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Silva, C., Kerwath, S.E., Wilke, C.G., Meÿer, M., Lamberth, S.J. 2010. First documented southern transatlantic migration of a blue shark Prionace glauca tagged off South Africa. Afr. J. Marine Sci., 32: 639-642.

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

Warnes GR, Bolker B, Lumley T, Johnson RC (2013) gmodels: various R programming tools for model fitting. R package version 2.15.4.1. http://CRAN.R-project.org/package=gmodels.

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

Wickham, H. 2011. The split-apply-combine strategy for data analysis. J. Stat. Softw., 40(1), 1-29.

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

Wood, S.N. 2003. Thin plate regression splines. J. R. Statist. Soc. B, 65 (1): 95-114.

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. J. R. Statist. Soc. B, 73 (1): 3-36.