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Characterisation of blue shark (*Prionace glauca*) hotspots in the South-West Indian Ocean

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ABSTRACT. Oceanic circulation structures nutrients distribution and affects primary productivity. Hydrodynamic features drive the distribution of intermediate trophic level species which aggregations commonly attract top predators. Blue shark (*Prionace glauca*, BSH) is the main bycatch species of Réunion Island pelagic longline fishery that mainly targets swordfish in the South-West Indian Ocean. The relation between BSH abundance and the environment is poorly known and deserves to be investigated if fishing management measures to reduce blue shark bycatch would have to be considered. The goal of this study is to characterise environmental factors favouring BSH hotspots. Nominal catch per unit of effort (CPUEn) from fishermen-reported data (2011-2013; 671 sets and 2 517 blue sharks caught) was used as proxy of local abundance. We proceeded in two steps: (i) the nominal CPUE (CPUEn) was standardized using a Tweedie generalized additive model (GAM) to remove variability from distribution of fishing effort, boat and gear which were summarised in a vessel typology, (ii) the residual CPUE (CPUEres) from the standardisation model was used to test with a GAM for the effect of environmental variables. We found that (i) vessel typology explains 11.1% of CPUEn variations and that (ii) the environmental model explains 13.8 % of CPUEres. The environmental model that was used to predict BSH abundance includes the effect of chlorophyll-a surface concentration, and sea level anomalies, with anticylonic eddies driving local variations of BSH abundance.

KEYWORDS. CPUE | Blue shark | Oceanographic patterns | GAM | Tweedie distribution | Pelagic longline | South-west Indian Ocean

1. Introduction

Bycatch – catch of non-targeted species – in worldwide fisheries have become a serious concern for scientists and managers as it represents a non-negligible source of mortality for a range of species (among them, endangered and vulnerable species), and as it reduces fishing profitability (Dunn et al., 2011). The impact of fishing practise on the marine system is now considered in the ecosystemic approach to fisheries. We observe an increase in the number of studies addressing bycatch mortality estimation in various fisheries worldwide (e.g. Lewison et al., 2004; Gilman et al., 2005).

The Réunion Island pelagic longline fishery operating in the south-west Indian Ocean mainly targets swordfish (*Xiphias gladius*) even though, at certain periods, tuna are also targeted (Sabarros et al., 2013). The most important bycatch in Reunion Island longline fishery is the blue shark (*Prionace glauca*, BSH) that represents about 1000 tons per year (Sabarros, pers. com.).

BSH is currently a non-valuable catch for the Reunion Island fishery due to the absence of shark meal market and because finning has been banned with IOTC resolution 05/05. The Portuguese and Spanish fleets however target in certain seasons BSH because of the emergence of a shark meal market similarly to the Atlantic pelagic longline fishery (e.g. Aires-da-Silva et al., 2008; Vandeperre et al., 2014). BSH bycatch levels may affect the population with high mortality level after release (13.3-35%; Campana et al.,2009; Coelho et al., 2013a), and its impact on the pelagic system is uncertain. It is essential today to anticipate the impact of bycatch on the ecosystem and to consider measures to reduce bycatch in the Indian Ocean Tuna Commission (IOTC) governance area. Mitigating measures could be for example the temporary spatio-temporal closure of a fishing area (e.g Little et al., 2014). To define a such measure, predictions of spatio-temporal abundance of the main target species and bycatch are necessary, notably in relation to the local environment.

The link between BSH catch distribution (nominal CPUE[1]) and environmental features was documented in the Pacific and Atlantic (e.g. Biegelow et al., 1999; Carvalho et al., 2011; Vandeperre et al., 2014; Mitchell et al., 2014) but rarely in the south-west Indian Ocean (Filmater et al., 2012). These studies have demonstrated habitat preferences for BSH characterized by specific ranges of sea surface temperature (SST), chlorophyll-a concentration (CHLa) and sea level anomaly (SLA). SST from 16°C to 19°C, CHLa over 2 $mg.m^{-3}$ and convergent structures like eddies (core and periphery) are favourable to BSH aggregations

Our study provides an analysis of BSH local abundance variability in the south-west Indian Ocean

1 Gross CPUE, non-standardized.

and aims at demonstrating the influence of local environmental conditions. We first used a standardisation model, called operational standardisation, to remove the CPUE variability that was associated to operational fishing factors. The residual CPUE from that first model (CPUEres) was assumed to be an index of local blue shark abundance. We then used CPUEres to test for the effects of environmental variables in the environmental model. The environmental model was finally used to predict BSH abundance and distribution.

2. Material and methods

2.1. Data

2.1.1. Catch data

The Reunion Island's fishing vessels operating in the IOTC area consist of pelagic longliners ranging from 11 to 24 m. A number of 23 active vessels were monitored by the 'Self-Reporting program' (SR). This program consists in an improvement of the regular declarative data (log-books) as it provides detailed information on fishing operations including bycatch (Bach et al., 2013). SR covers about 12% of the total fishing effort (Sabarros et al., 2013). In this study we used data available between 2011 to 2013 corresponding to 923 fishing operations (1 149 195 hooks) monitored by SR. CPUE was defined as the number of individuals caught per 1000 hooks.

2.1.2. Explanatory variables

2.1.2.1. Fishing practice

A vessel 'typology' was realised to group vessels according to their fishing practise (e.g. gear deployment, vessel characteristics). The typology is based on a principal component analysis (PCA, Appendix II) combined with a hierarchical clustering method (HCPC; Appendix III; Husson et al., 2010). In HCPC, intra group inertia gain criterion defines the optimal number of vessel clusters. All operational covariates were tested for collinearity in a Pearson's correlation matrix (Appendix I). Various operational variables were used to describe gear and vessel to determine vessel typology (Tab. 1, Appendix IV). Vessel characteristics are summarized by the length of the vessel ('vessel_length'). Gear characteristics correspond to the percentage of squid used as bait ('bait_type'), the percentage of circle hooks ('hook_type') for each set compared to J and tuna hooks. Circle hooks are expected to decrease mortality, and increase tuna selectivity (Carruthers et al., 2009). The number of chemical lightsticks per basket ('sticks_basket') may attract large pelagic. The leader length ('leader_length' in m, line which connect the hooks to the mainline) can play a role in catches with reducing mainline visibility. Setting hour is also integrated in the typology ('start_setting' in hour). And the estimated fishing depth ('fishing_depth') indicates the vertical fishing strategy for a set.

Table 1. Description of operational covariates used in the vessel typology for blue shark CPUE standardisation.

Covariate	Description
'vessel_length'	Length (m)
'start_setting'	Time setting (h)
'start_hauling'	Time hauling (h)
'baits_type'	% of squid bait
'hooks_type'	% of circle hook
'sticks_basket'	Number of chemical light stick per basket
'leader_length'	Leader length (m)
'fishing_depth'	Maximal mean fishing depth (m)

2.1.2.2. Environmental data

Environmental covariates are described in Table 2. Sea surface temperature (*'sst'* in °C) provided by OSTIA with the GHRSST project with a daily, 5km resolution. Chlorophyll-a surface concentration ('*chla'* in mg.m$^{-3)}$ monitored by MODIS Aqua satellite mission (NASA, http://modis.gsfc.nasa.gov) with a weekly, 4 km resolution. Bathymetry from the ETOPO1 dataset provided by NOAA with 1 min resolution ('*bat'* in m). Sea level anomalies ('*sla'* in cm) with a daily, 1/3 degree spatial resolution provided by salto/Duacs and distributed by AVISO with support from CNES (http://aviso.altimetry.fr). Also, we calculated descriptors of hydrographic features from AVISO altimetry-derived geostrophic currents such as Lagrangian and Eulerian turbulence descriptors. Finite-Size Lyapunov Exponents ('fsle', day^{-1}) are a Lagrangian convergence index with a daily, 1/12° resolution. FSLE describe the convergence of water masses and to some extent concentrating fronts (e.g., d'Ovidio et al., 2013, Sabarros et al., 2013). Eddy Kinetic Energy ('eke' in cm^2.s^{-2}) is an

Eulerian index of kinetic energy in turbulence structure with a daily, 1/12° resolution. EKE characterizes local zones of strong current activity like meso-scale fronts for instance (e.g. Zainuddin et al., 2008). Okubo-Weiss factor ('ow' en day^{-2}) is an Eulerian index based on eddies strain and vorticity. OW characterises the limit of eddies cores where recirculation is higher than stretching (e.g. Fontanet et al., 2008; D'Ovidio et al., 2009). Spatially-explicit data were extracted within fishing polygons and extracted values were summarised as a mean value. The mean value is then associated to the barycentre position of the fishing operation (see Sabarros et al., 2013).

Table 2. Description of covariates used for blue shark CPUE anomaly model.

Covariate	**Description**	**Source**	**Resolution**
sst	Sea Surface Temperature (°C)	OSTIA Level 4 composite	5km composite, daily
chl	Chlorophyll-a concentration in the surface layer (mg.m-3)	MODIS Aqua Level 3	4 km composite, daily
sla	Sea Level Anomalies : topography of the ocean, highlights meso-scale eddies (cm)	AVISO NRT-MSLAH	1/3°, daily
ow	Okubo Weiss Factor : highlights eddies cores (day^{-2})	Calculated using AVISO altimetry-derived geostrophic currents product NRT-MSLA-UV	1/3°, daily
fsle	Finite-Size Lyapunov Exponents : mesoscale index of convergence of water masses (day^{-1})	Calculated using AVISO altimetry-derived geostrophic currents product NRT-MSLA-UV	1/12°, daily
eke	Eddy Kinetic Energy : highlights frontal zones with strong currents (cm^2.s^{-2})	Calculated using AVISO altimetry-derived geostrophic currents product NRT-MSLA-UV	1/3°, daily
bat	Bathymetry: topography of the ocean floor (m)	ETOPO1	1’

2.2. Modelling blue shark local abundance

Data collected/extracted for each set were assumed to be independent from a set to another. We used a two-steps modelling approach that consists in using a first operational standardisation model on CPUEn to remove the variability that can be explained by operational aspects of fishing operations (see Sabarros et al., 2014). The residual CPUE (CPUEres = residuals of the standardisation model = anomaly of CPUE) was used as a proxy of BSH local abundance in the second model to investigate the effects of temporal variation and environmental conditions on BSH distribution. The two-steps modelling approach allows to predict BSH local abundance with a set of environmental variables (the ones that were selected) independently of fishing operations (e.g. vessel typology). Generalized Additive Models (GAM, with mgcv package Wood 2006) were used here to allow non-linear relationships.

2.2.1. Operational standardisation

The operational standardisation consists in removing the effects from fishing practise and gear used on blue shark CPUEn by using the vessel typology in a GAM with a Tweedie distribution to consider the relatively high proportion of zeros (e.g. Candy 2004; Coelho et al., 2013b, 2014).

2.2.2. Environmental model

The second step of the modelling approach consists in using residuals from operational standardisation model (CPUEres) to test for the effects of environmental local conditions. CPUEres is a proxy of blue shark abundance. We used a Gaussian GAM model. Model selection was performed with a step-wise forward procedure by selecting the model with the lowest cross validation criterion (GCV, Wood, 2006). All environmental covariates were tested for collinearity in a Spearman's correlation matrix (Appendix VI, Maunder et al., 2004).

2.2.3. Mapped predictions

The resulting environmental model was used to produce daily prediction maps of blue shark local abundance anomaly on the only base of environmental remote sensing data. This tool is very useful to understand the distribution of blue shark hotspots driven by environmental conditions (corrected from the effect of fishing practise). Predicted distributions were made for given dates with a spatial resolution of 1/8° and are shown for contrasted periods of the year defined by the temporal variation in the environmental model (Figs. 5, 6).

3. Results

3.1. Trends in CPUEn

Blue shark CPUEn shows two seasons, a period of high blue shark CPUEn during the austral summer and a period of lower CPUEn during the austral winter. This period coincides with a higher fishing effort close to Madasgascar EEZ where blue shark CPUEn is always lower than in Reunion EEZ (Fig. 1). This spatial shift in fishing effort corresponds to the targeting of albacore tuna (*Thunnus alalunga*) in Reunion EEZ during austral summer.

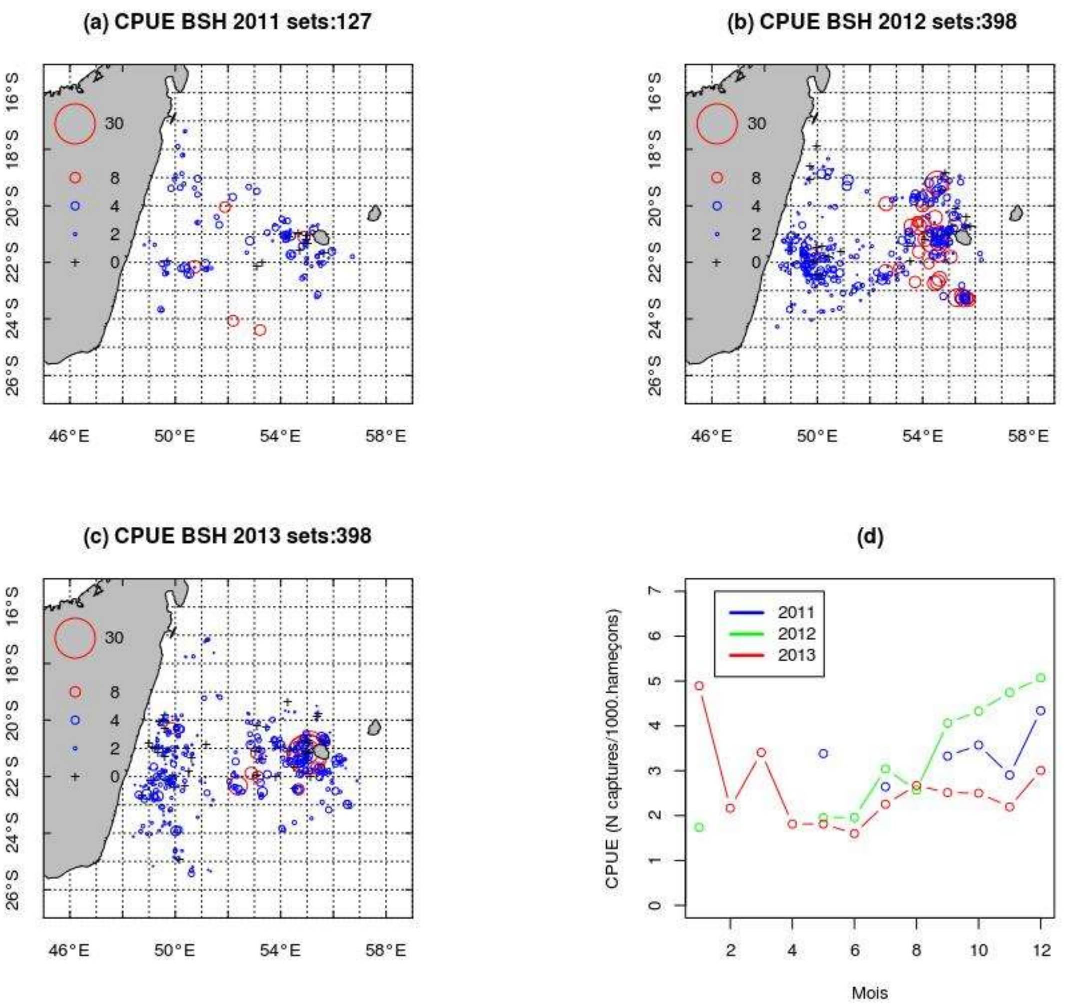

Figure 1. Distribution of BSH CPUEn (N individuals/1000 hooks) of the 923 sets available in 2011 (a), 2012 (b) and 2013 (c). (d) Temporal variation in CPUEn. Circles are proportional to the CPUEn value, in blue CPUEn lower than the 75% quantile and in red CPUEn higher than this quantile. (d) Time series of monthly mean CPUEn over the period from 2011 to 2013.

3.2. CPUEn operational standardisation

The CPUEn operational standardisation model using the typology explains 11.1 % of the total deviance (Tab. 3). Each cluster of vessel has a different level of blue shark CPUEn. Five of the 9 vessel groups have a lower impact on BSH (Fig. 3). These groups correspond to larger vessels (> 14m) that set their longline deeper than 50 m (Appendix II). Large vessels are the only ones able to fish in Madagascar EEZ (due to their storage capacity) where blue shark CPUEn is always lower than in Réunion EEZ (Fig. 2). Residuals of the Tweedie GAM are normally distributed (Appendix V).

Table 3. Operational model description.

StepGAM	DF	Pvalue	R^2	% deviance explained
CPUEn ~ typo	8.0	$< 2.10^{-16}$	0.103	11.1 %

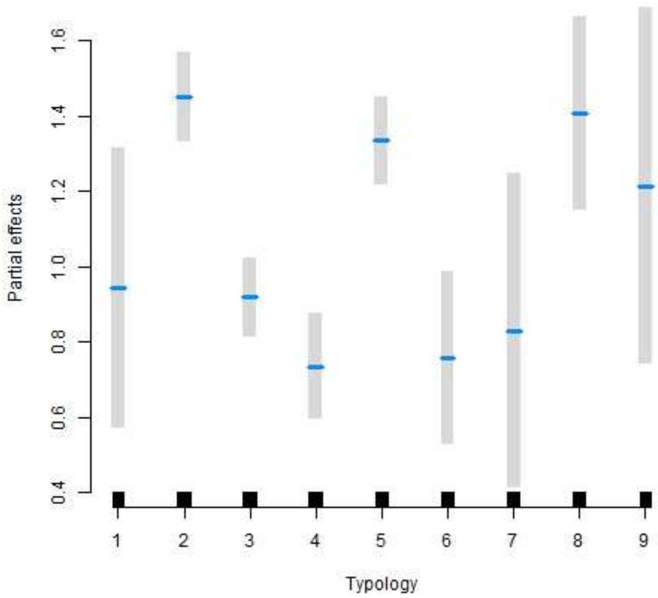

Figure 2. Partial effects of 'typology' on blue shark CPUEn in the operational model. Vessels are sorted in 9 clusters defined by vessel and gear characteristics. 95 % confidence interval in grey.

3.3. Environmental model

The environmental model explains 13.8 % of the total deviance (Tab. 4) and cumulated with the standardisation model, the amount of nCPUEn deviance explained reaches 23.4 %. The temporal part of the variability in CPUEres expresses 9.9 % of the deviance with a higher intra-annual variability (monthly variability) explaining 7.9% of the total deviance. This intra-annual variation mostly describes two periods. The austral summer (warmer period; September to March) is characterised by a greater CPUE anomaly with a temporal hot spot in March (Fig. 3). The austral winter (cooler period) from April to August shows a sharp decline until June where CPUE anomaly is the lowest (Fig. 3). The annual variability expresses 2 % of blue shark abundance variations. Blue shark CPUEres was lower in 2013. The environmental part of the variability in CPUEres expresses 3.9 % of the total deviance. Sea level anomaly ('s*la*') is a driving factor of the local CPUE anomaly. This is the most significant variable with 3 % of total deviance explained. Positive sea level anomaly (anticyclonic eddies) positively influence the local abundance of blue shark (Fig. 4). Chlorophyll-a surface concentration ('*chla*') explains 0.9 % of the total deviance. This proxy of productivity shows a positive linear relation with CPUE anomaly between 0 and 0.2 mg.m^{-3}. Residuals of the Gaussian GAM are normally distributed (Appendix VII).

Table 4. Step-wise forward variable selection process to determine abundance anomaly model based on the optimization of cross validation criterion 'GCV'. Each new variable is also validated by AIC, R^2 score, cumulated deviance percentage explained and the significance of the relation (F test).

Step	**StepGAM**	**DF**	**Pvalue**	**Cumulated R^2**	**Cumulated AIC**	**Cumulated GCV**	**Cum. deviance explained**
1	CPUE ~ year	2	$6.8.10^{-6}$	0.02	2116.6	1.4	2.0 %
2	+ month	11	$1.6.10^{-8}$	0.07	2084.6	1.3	9.9 %
3	+ s(sla)	1.0	0.0006	0.09	2076.2	1.3	12.9 %
5	+ s(chla)	1.0	0.007	0.11	2066.7	1.2	13.8 %

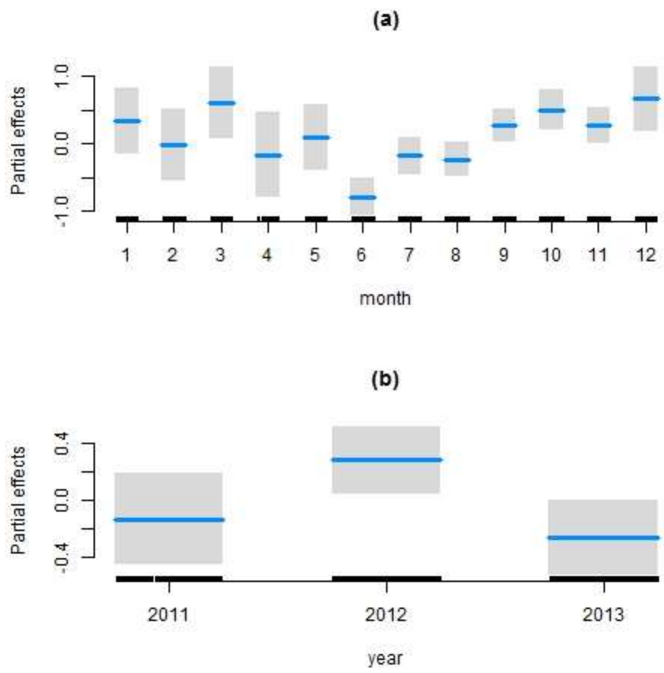

Figure 3. Partial effects of temporal variation in BSH environmental model. (a) month: intra annual local abundance variation and (b) year: inter-annual local abundance variation. 95 % confidence interval in grey.

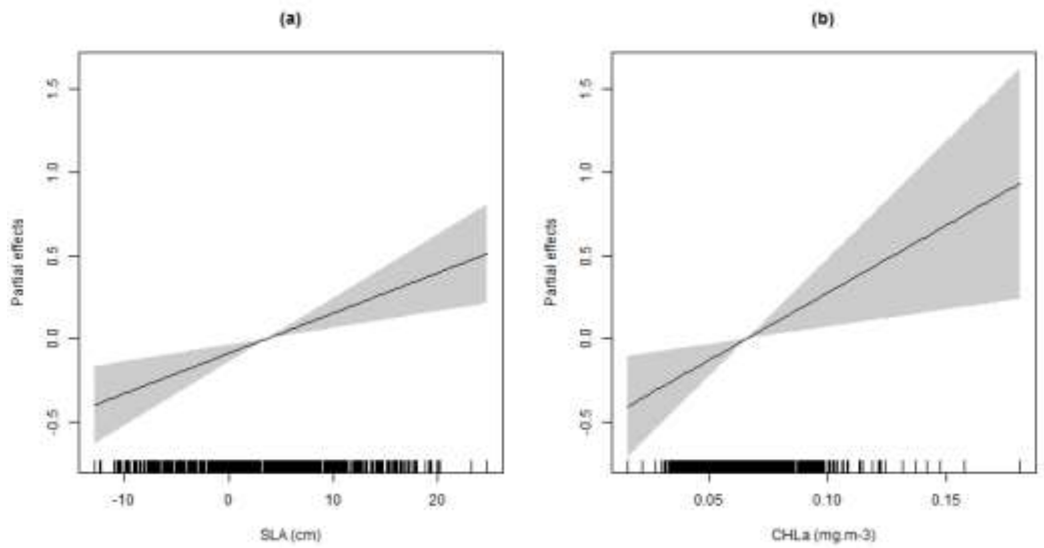

Figure 4. Partial effects of environmental features in BSH environmental model. (a) SLA: sea level anomaly (cm); (b) CHLa: chlorophyll-a surface concentration (mg.m^{-3}). 95 % confidence interval in grey.

3.4. Predicted BSH distribution

We used predictions of blue shark abundance from the environmental model to identify local hotspots (Figs. 5, 6). For interpretation, we distinguish (i) the area covered by the dataset and (ii) the extrapolation area. The dataset area extends from 19°S to 24°S and from 48°E to 56°E. The predictions within the spatial area covered by the data can be viewed with a higher level of confidence. Consistent local hotspots of BSH abundance occur close to 55°E-24°S, south-east of Reunion Island and close to 55°W-24°S, south-east of Madagascar where stable anticyclonic meso-scale activity characterised by high values of SLA, and higher chlorophyll-a concentrations are present (Figs. 5, 6). Chlorophyll-a concentration also drives higher blue shark abundance on the coast of Madagascar (mostly in the south) where phytoplankton blooms occurs (Raj et al., 2010).

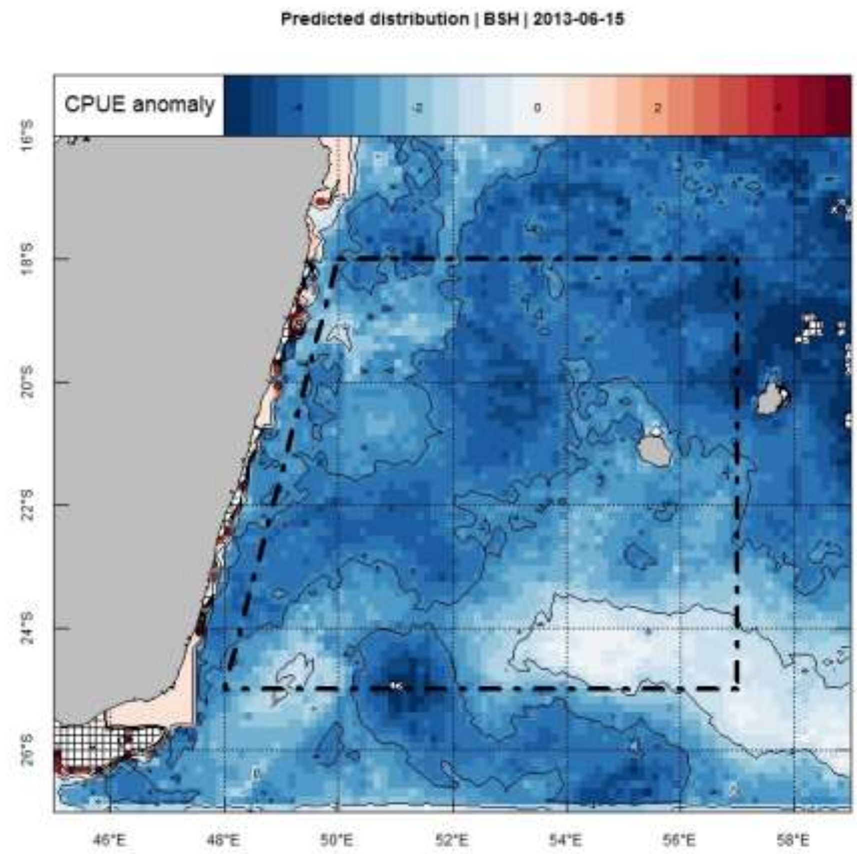

Figure 5. BSH local abundance anomaly prediction on June 6th 2013 during the low season. The region delimited by the dashed line defines the fishing zone where SR data were collected.

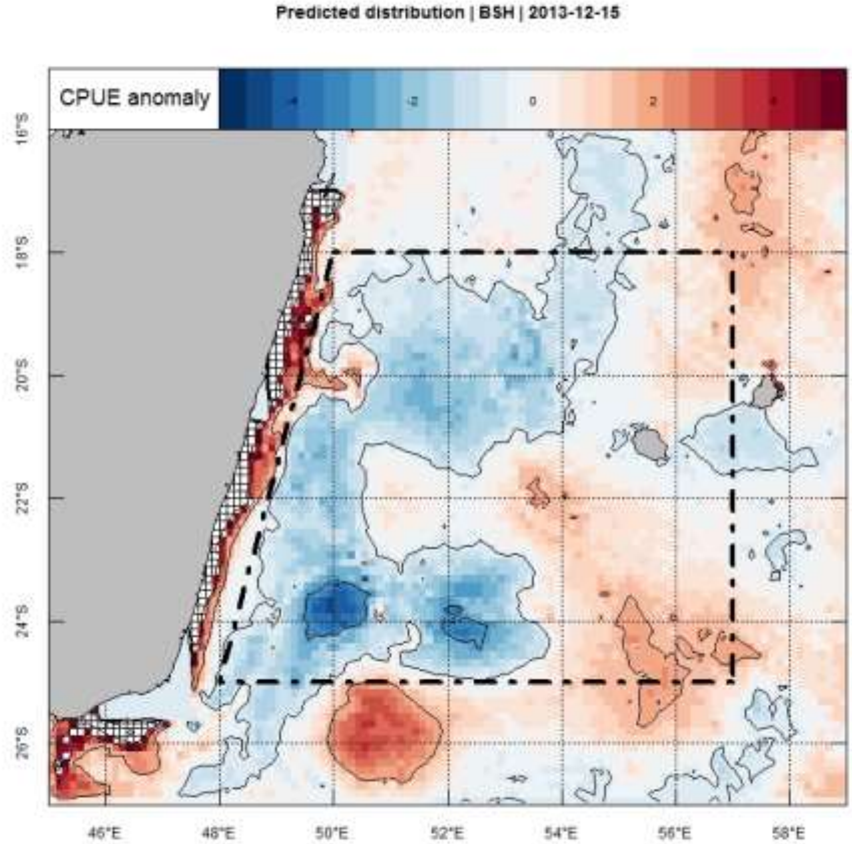

Figure 6. BSH local abundance anomaly prediction on December 15th 2013 during the high season. The region delimited by the dashed line defines the fishing zone where SR data were collected.

4. Discussion

The two-steps modelling approach is useful as this methodological framework allows to predict BSH abundance with a model fitted on CPUEres data that have been corrected from operational effects. Predictions of BSH abundance and distribution only necessitate a set of temporal and environmental variables, here the year, the month, the chlorophyll-a surface concentration and the sea level anomaly. This tool applied on the main bycatch of Reunion Island pelagic fishery (blue shark) provided useful spatio-temporal information to predict fishery performance and to possibly consider spatio-temportal management measures for the fishery.

In the operational model that was used to standardise blue shark CPUEn, the vessel typology was able to identify different fishing practice in targeting swordfish by Réunion longline fishery. Larger vessels (>14 m) exploit a larger spatial area from Reunion island to Madagascar coast compared to smaller vessels that are restricted to the Reunion EEZ.

Predictions of BSH abundance only necessitate a set of environmental variables, here the sea level anomaly and the chlorophyll-a surface concentration. We demonstrated that, a local environment variable characterising meso-scale activity, namely the SLA, drives the distribution patterns of the blue shark. This suggests that anti-cylonic eddies are hydrodynamic structures that attract blue sharks. Anti-cylonic eddies influence the vertical and horizontal distribution of intermediate components of the food-web (e.g. Polovina et al., 2004; Weimerskirch et al., 2004; Sabarros et al., 2009; Kai and Marsac, 2010; Cotté et al., 2011; d'Ovidio et al. 2013) and may therefore be foraging grounds for the blue shark.

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6. Acknowledgements

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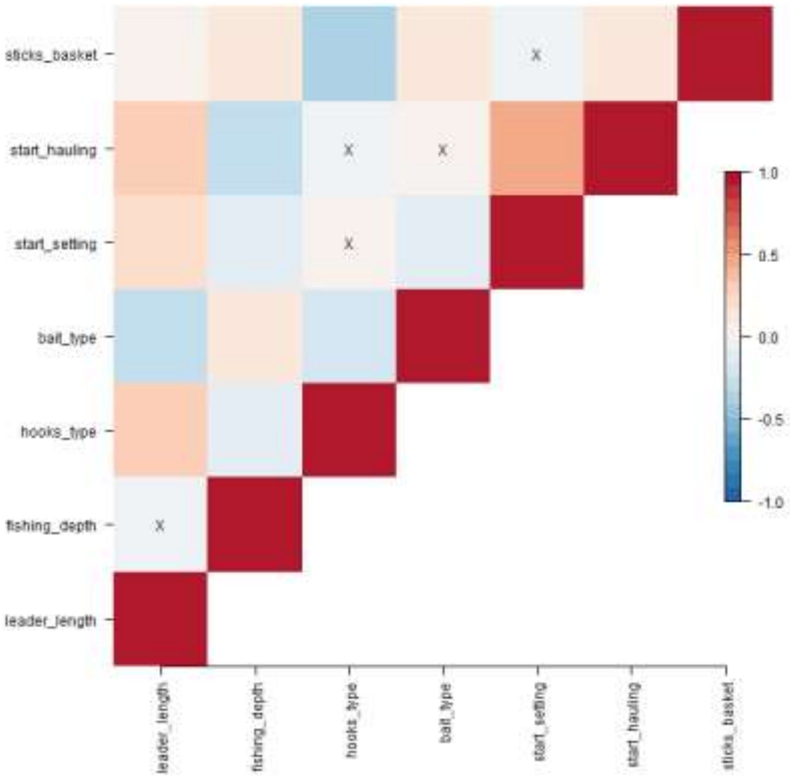
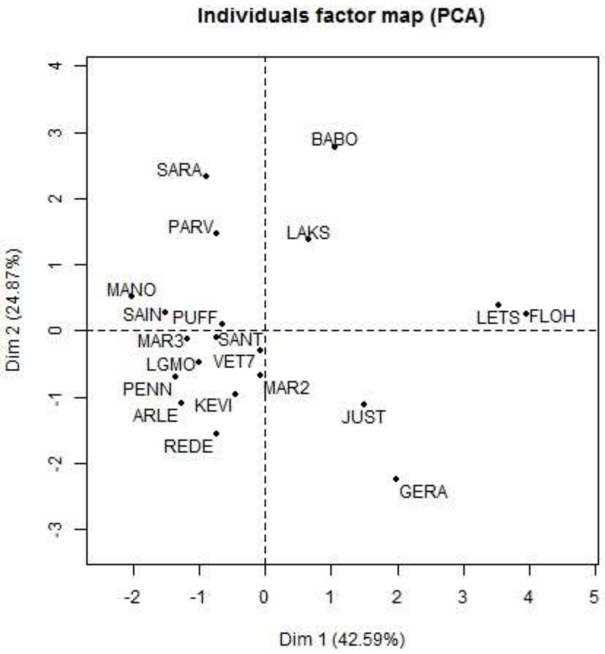
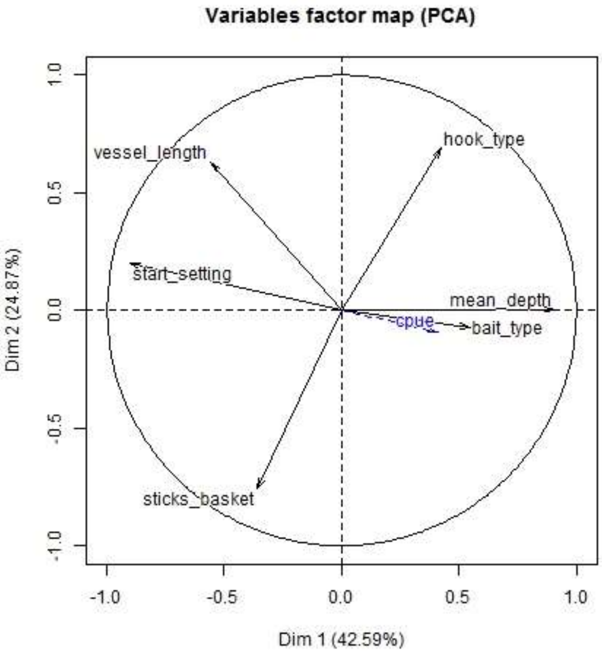
7. Appendices

Appendix I. Pearson's correlation matrix for operational variables. The colorbar indicates the level of correlation, positive correlation in red and negative in blue. Black crosses indicate independence between variables.

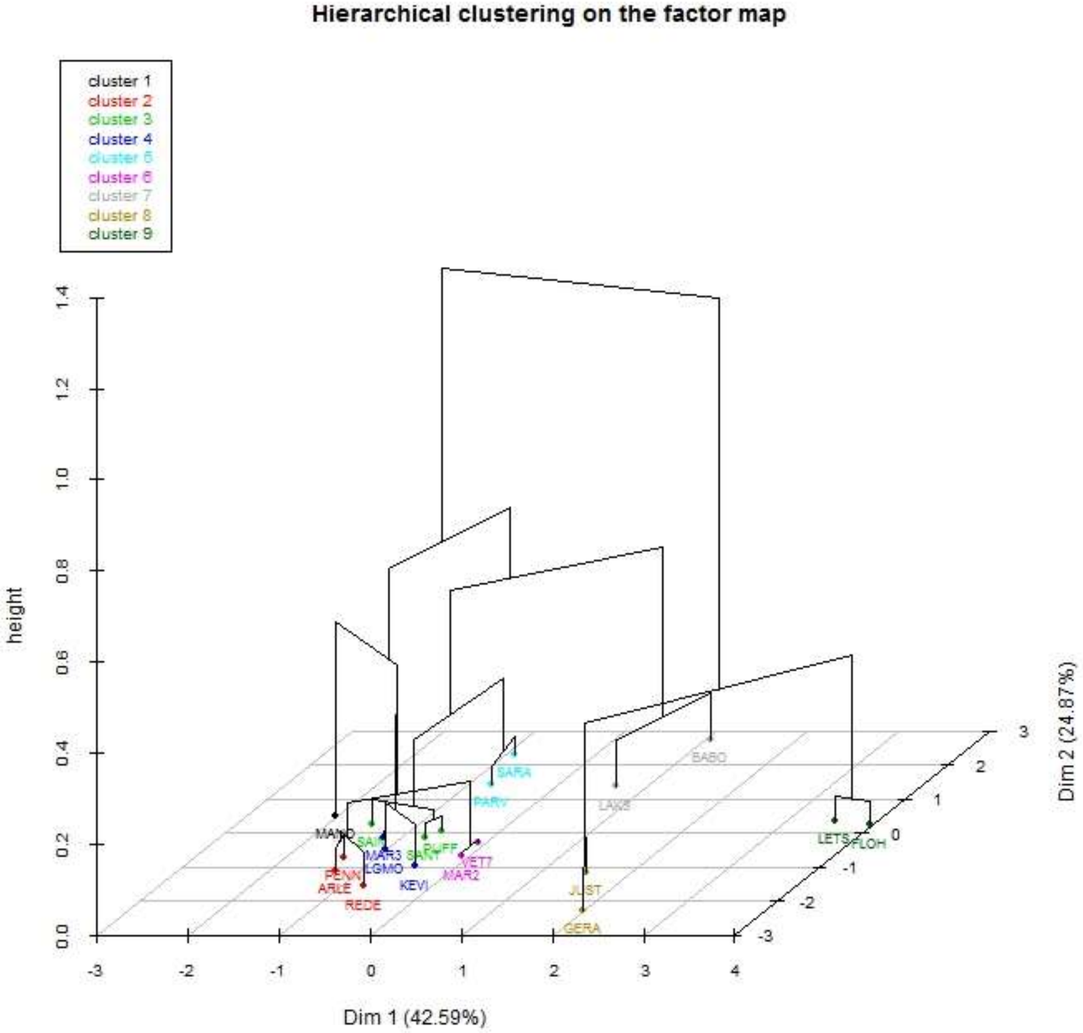


Appendix II. Principal component analysis on vessel characteristics. In blue: variables that do not interfere with PCA axes construction.





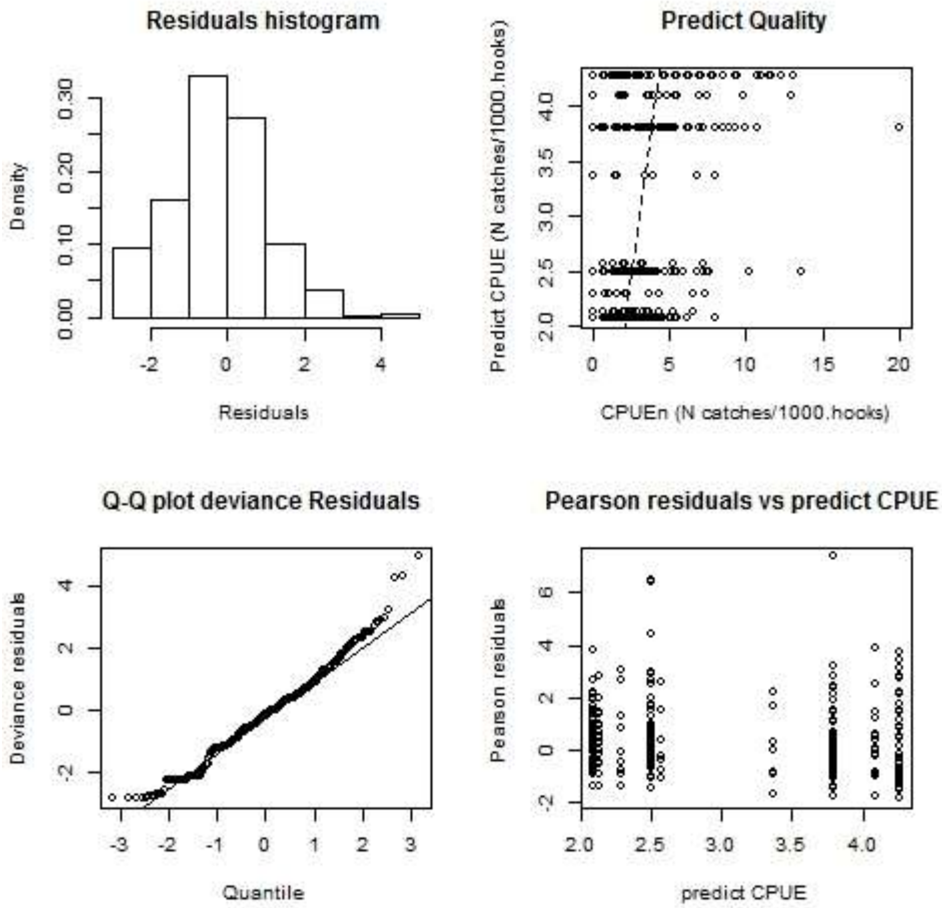
Appendix III: Hierarchical clustering on vessel characteristic PCA that defines 7 types of fishing method projected onto the PCA factorial map. Intra-group inertia gain criterion defines the optimal number of vessel clusters.



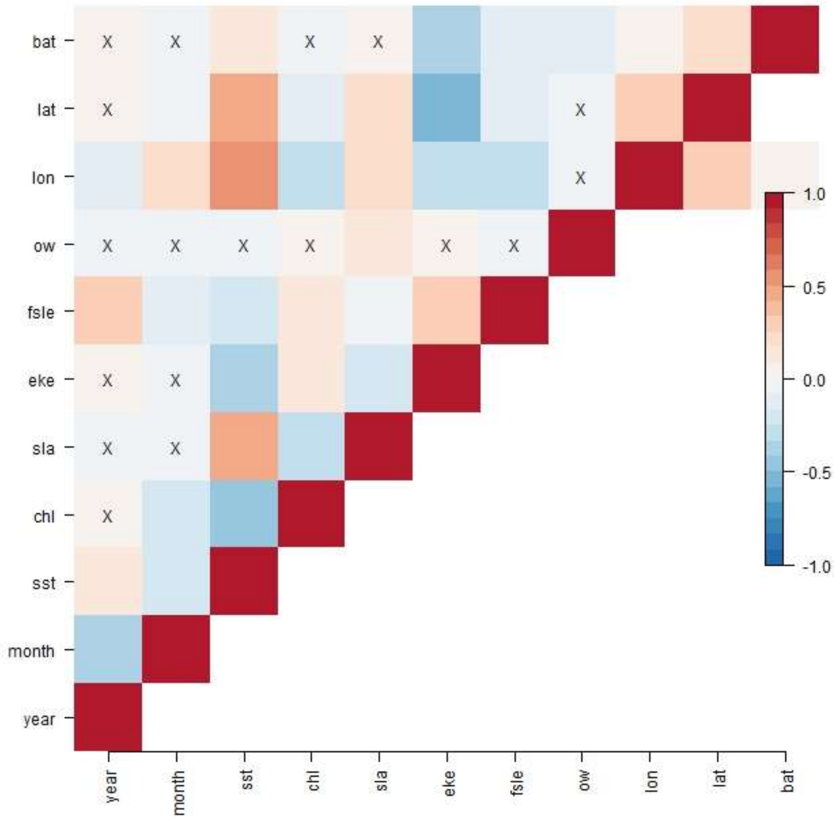
Appendix IV. Vessel typology. In red: significant variables in the Chi² test (p-value <0.05).

Variable	**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**	**Type 7**	**Type 8**	**Type 9**
vessel_length	**23.9**	**13.1**	**14.3**	**15.7**	**18.2**	**15.1**	**18.1**	**10.6**	**10.6**
sticks_basket	3	3	2.4	**3.2**	**2.1**	3.0	**2.0**	2.8	2.1
start_setting	17.2	16.9	17.0	17.2	16.9	16.9	16.9	**15.7**	**15.3**
leader_length	11.5	12.9	14.9	16.7	14.3	15.1	14.9	11.4	12.4
bait_type	100.0	87.3	**71.1**	**75.1**	70.1	98.1	100	97.5	100.0
hook_type	20.0	15.6	32.8	46.8	85.6	80.0	78.9	28.8	74.3
fishing_depth	52.7	49.9	51.7	57.7	48.4	53.4	66.7	64.6	**81.1**

Appendix V. Residuals analysis of the CPUEn operational standardisation model



Appendix VI. Spearman's correlation matrix for environmental variables. The colorscale shows the correlation, positive correlation in red and negative in blue. Black crosses indicate independence between variables.



Appendix VII: Residuals analysis of the environmental model.