Exploratory analysis of relationships between swordfish captures and environmental features in the southwest Indian Ocean

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Keywords

Abstract

Oceanic circulation plays a major in the distribution of nutrients and oceanic structures such as fronts and eddies may become hotspots of biological activity through concentration and enrichment processes. Oceanic structures generally attract forage fish and cephalopods and may therefore be targeted by marine top-predators. The link between swordfish (*Xiphias gladius*) captures and environmental structures is poorly documented in the southwest Indian Ocean despite the growing need of the local fishery from Reunion Island for such information. In this study we used a set of temporal (date, moon phase), geographic (longitude, latitude, distance to coast, bathymetry) and environmental covariates (sea surface temperature, chlorophyll-a concentration, sea level anomalies, index of convergence) to explain variations in swordfish catch per unit of effort (CPUE) throughout 2012. Univariate analyses show strong seasonal and latitudinal patterns in swordfish occurence. We also found that higher swordfish CPUE are associated with shelf-break areas and sea mounts, as well as dynamic environmental structures, even though these relationships explain only a small fraction of swordfish CPUE variations. Chlorophyll-a fronts and dynamic convergent structures as identified by finite-size Lyapunov exponents might attract swordfish.

Introduction

Oceanic circulation coupled with vertical flux plays a major role in the distribution of nutrients in the Global Ocean. Hydrodynamic features – from larger scales (several hundreds of kms) down to smaller scales (e.g. mesoscale, from 1–2 km to 100–200 km) – are known to drive the distribution and foraging patterns of top-predators because the probability of prey encounters is higher in and around these structures (Weimerskirch, 2007). It has been well documented that large convergence zones (e.g. polar front) correspond to foraging areas of marine birds and mammals (review by Bost et al., 2009). At smaller scales, dynamic mesoscale structures such as eddies, vertically-structured fronts and filaments are essential to the enrichment, concentration and retention of nutrients and planktonic organisms in surface waters (cf. Bakun's triad; Bakun, 1996) which attract and shape the aggregation patterns of plankton-eaters such as small pelagic fish (Bakun, 2006; Bertrand et al., 2008; Sabarros et al., 2009). Mesoscale structures are considered as major attracting features for large predatory fish (Young et al., 2001; Seki et al., 2002), marine mammals (Campagna et al., 2006; Cotté et al., 2007; Chaigne et al., 2012) and seabirds (Nel et al., 2001; Weimerskirch et al., 2004, 2005; Ainley et al., 2005, 2009; Hyrenbach et al., 2006).

The link between swordfish *Xiphias gladius* catch distribution and environmental features was occasionally documented in the Pacific (e.g. Seki et al., 2002; Espindola et al., 2011), Atlantic (Chang et al., 2013) and there was only one preliminary study for the south western Indian Ocean where the longline fishing fleet of Reunion Island targets swordfish (Guyomard, 2005). It is essential to better understand the ecology and distribution patterns of swordfish in relation to oceanography considering fleet efficiency and reduction of operational costs, as well as ecosystem-based management of the fishery and resource conservation.

The purpose of this study is to understand variations in catch per unit of effort (CPUE) of the main target species of pelagic longliners based in Reunion Island: swordfish, and to address the underlying question: can swordfish distribution and hence CPUE be predicted? We tested a range a potential geographic, temporal and environmental descriptors to explain swordfish CPUE using captures data from the self-reporting data collection program (Bach et al., 2013, Sabarros et al., 2013).

Material and methods

Self-reported data

Data from the self-reporting data collection program (SRP) are collected since 2011 by cooperative fishermen. This program was developed by IRD and CAP RUN in the framework of

EU Data Collection Framework (DCF) dedicated to monitoring of captures, bycatch and depredation in the local pelagic longline fishery (Bach et al., 2009). For SPR, fishermen collect data using forms based on the observer program (Bach et al., 2009) related to the boat location, fishing gear and setup used, captures, depredation, bycatch and physical environment using temperature-depth recorders (Bach et al., 2013). The exact position of setting and hauling are collected so that fishing polygons that include longline drift can be defined as well as their center of gravity (Appendix 1). In this study we used data available in 2012 where a total of 398 fishing operations (=sets) was monitored by SRP (Sabarros et al., 2013).

Catch data

We used catch per unit of effort (CPUE) from SRP of the main target species of pelagic longliners operating from Reunion Island: swordfish (*Xiphias gladius*). CPUE is defined as the number of individuals caught per 1000 hooks. In this study we intended to describe variations in swordfish CPUE (*cpue*) using a set of covariates described below.

Covariates

We used set of temporal, geographic and environmental covariates to explain swordfish CPUE variations (*cpue*). Temporal covariates were the julian day of the year (*jday*), moon phase (*moon.phase*) and semi moon phase (*moon.phase2*). Geographic covariates consisted in latitude (*lat*), longitude (*lon*), bathymetry from the ETOPO1 dataset provided by NOAA with 1 min resolution (*bat*), and the distance to the nearest coast calculated for each set (*coast.dist*). Environmental parameters describing the marine habitat were: weekly sea surface temperature (*sst*) and chlorophyll-a distribution (*chl*) monitored by MODIS Aqua satellite mission with 4 km resolution, daily sea level anomalies (*sla*) with 1/3 degree spatial resolution provided by AVISO as well as a convergence index we calculated from AVISO geostrophic currents (finite-size Lyapunov exponent: *fsle*; Appendix 2). Table 2 summarizes the covariates that were tested against swordfish CPUE.

Spatially-explicit data (i.e. *bat*, *sst*, *chl*, *fsle*, *sla*) were extracted within each fishing polygon (Appendix 1). The distribution of values extracted within each fishing polygon was characterized by its *mean*, median (*med*), *min*, *max*, and standard deviation (*sd*). The concerned descriptors (*bat*, *sst*, *chl*, *fsle* and *sla*) were therefore provided with a suffix corresponding to distribution characteristic as mentioned above. For example, *sst.med* is the median SST value of extracted values within the fishing polygon.

Correlations between covariates were considered and some variables were decomposed prior

to the main analyses. SST showed strong seasonality and latitudinal components. We used generalized additive models (GAM) to decompose SST in 3 components: the SST seasonal trend (*sst.trend*) using *jday*, SST latitudinal trend (*sst.nsgrad*) using *lat*, and the SST residuals (*sst.res*) that correspond to the remaining local variation of SST. Similarly, CHL seasonal trend (*chl.trend*) was extracted using *jday* as well as its residuals (*chl.res*).

Univariate analyses

We tested the effect of each covariate on swordfish CPUE (*cpue*), as well as between them, using non-parametric GAMs. Univariate GAM analyses allow to explore non-linear relationships between variables with non-linear LOESS smooth terms. Estimated degrees of freedom of smooth terms represent the complexity of the relationship. A summary of these results, namely the significance of the estimated smooth term of the univariate GAM is presented as a matrix in Figure 1. Correlations between covariates were also explored using Spearman's correlation coefficient. The Spearman's correlation coefficient is non-parametric measure of statistical dependence between two variables that ranges between -1 for a perfect negative correlation and 1 for a perfect positive correlation. The correlation matrix is given for information in Appendix 3.

Results

Nearly half the tested covariates (15 out of 35) have a significant effect on swordfish CPUE (bottom line in Fig. 1). Corresponding univariate models are described in Table 2 and illustrated in Figure 2. Julian day of year (*jday*) has a non-linear effect on swordfish CPUE describing a rise in CPUE between day 250 and 300 preceded and followed by lower CPUE values (model U1). The overall deviance explained by U1 is 19.8%. Latitude (*lat*; southern latitudes are negative) negatively affects CPUE (model U2) and explains 12.7% of the variance. Bathymetry standard deviation (*bat.sd*) is positively correlated to swordfish CPUE (model U4) but this model only explains 1% of the variance. Sea surface temperature (*sst.mean*; non-detrended) is negatively correlated to CPUE (model U5 with 11.4% of deviance explained. Chlorophyll-a standard deviation is an indicator of variation in chlorophyll-a concentration at the scale of a fishing operation, hence this index may indicate chlorophyll-a gradients/fronts. Finite-size Lyapunov exponent computation using geographic currents allows to detect attracting Lagrangian coherent structures that correspond to dynamical convergent structures. Chlorophyll-a standard deviation and finite-size Lyapunov exponents positively affects swordfish CPUE (models U11 and 14: Fig. 3). The total variance explained by these models is respectively 2.50 and 3.01%.

Discussion

Preliminarily results from this study suggest that swordfish CPUE variations can be linked to several covariates describing seasonality, latitudinal patterns and patterns of the dynamic environment.

*S*easonality and latitude are strong signals in CPUE variations. Swordfish availability fluctuates throughout the year with a peak around September-October. This seasonal patterns is well known by local fishermen. Also, we found that swordfish CPUE increases as fishermen go south but this might only be a consequence of the positive effect of lower temperatures on swordfish presence. Relationships between swordfish CPUE and descriptors of their habitat can sometimes be complex. Non-detrended SST is negatively correlated to swordfish CPUE and explains 11.4% of its variance while SST seasonal and latitudinal components alone explain respectively 20.4% and 12.9%. The combined effects of the seasonal, latitudinal and residual (corresponding to local variations of SST) components extracted from the raw SST signal explain together 22% of the deviance (not shown) which suggests that is necessary to consider and extract potential seasonal and geographic components in covariates.

Univariate analyses also suggest that swordfish occurrence is associated with greater bathymetry variations hence shelf-break areas and sea mounts, as well as dynamic oceanic structures such as chlorophyll-a gradient/fronts and convergence/accumulation zones even though these models do not explain much of swordfish CPUE variations. Shelf-breaks and sea mounts are geographic structures where physical processes lead to local enrichment that are therefore used worldwide by fishermen (e.g. Young et al., 2001). Fronts, whether they are defined on chlorophyll-a or temperature maps, are structured known as biological hotspots that are susceptible to attract swordfish prey (e.g. Seki et al., 2002). As a matter of fact, fishermen strategy is to target fronts and strong gradients when they have access to satellite sea surface temperature and chlorophyll-a image products (e.g. CATSAT). Convergent structures identified by finite-size Lyapunov exponent method, namely attracting Lagrangian structures, are acute structures that include additional notions of convergence and persistence of water masses compared to fronts identified with gradient methods. In a few occasions, it was demonstrated that marine top-predators use attracting Lagrangian structures while foraging (e.g. frigatebirds; Tew Kai et al. 2009) which might be here the case for swordfish.

The best univariate model can explain a fifth of variations in swordfish CPUE, which indicate that 80% of these variations cannot not be explained or predicted by a single covariate of our set of data. Further analyses would require to use multivariate models and a model selection procedure with the goal of maximizing prediction accuracy (deviance explained). Also, this would

imply to explore relationships and possible correlations between covariates that may be used to explain variations in swordfish CPUE (e.g. Figure 1, Appendix 3) because redundant information from correlated covariates needs to be considered and avoided carefully.

Table 1. Covariates tested against swordfish CPUE (*cpue*). For starred covariates, we actually used the distribution mean, median, min, max and standard deviation of extracted values within each fishing operation (cf. fishing polygons in Appendix 1)

| Type	Covariate	Source	Resolution	Description
Temporal	*jday*	-	-	Julian day of the year
	moon.phase	-	-	Moon phase
	moon.phase2			Semi moon phase
Geographic	*lat*	SRP	-	Latitude of the fishing set centre of gravity
	lon	SRP	-	Longitude of the fishing set centre of gravity
	coast.dist	SRP	-	Distance to the coast
	bathy	NOAA ETOPO1	1 arc-min	Bathymetry
Environment	*sst*	MODIS Aqua and Terra	9 km, weekly	Sea Surface Temperature
	chl	MODIS Aqua and Terra	9 km, weekly	Surface Chlorophyll-a concentration
	sla	AVISO	1/3 deg, daily	Sea Level Anomalies
	fsle	-	1/12 deg, weekly	Finite-Size Lyapunov Exponents
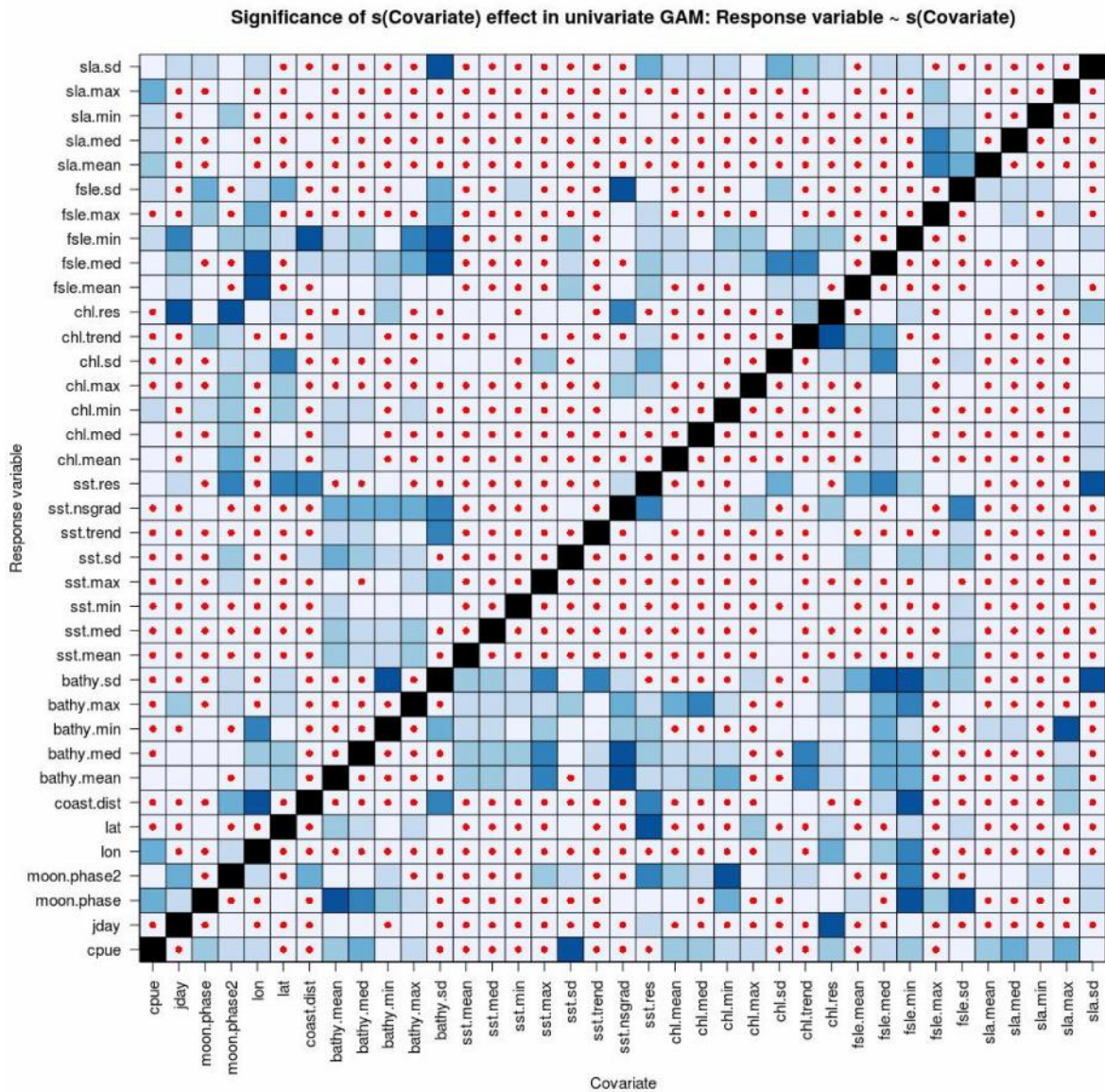
Figure 1. Significance of smooth term s(Covariate) in univariate GAM formulated as Response variable ~ s(Covariate). White-blue colorscale illustrates p-values. Bluer boxes are p-values closer to 1 while white is for p-values close to 0. Red dots indicate significant p-values < 0.05.

Table 1. Univariate generalized additive models (U1-15) where covariates have a significant effect on swordfish CPUE. Number of observations is each model is 395. For each model we present the estimated degrees of freedom for the smooth terms with their p-value. ***, ** and * respectively indicate that p-value is <0.0001, <0.001 and <0.01 (in all cases significant).We also provide the deviance explained (% dev. expl.) by the models.

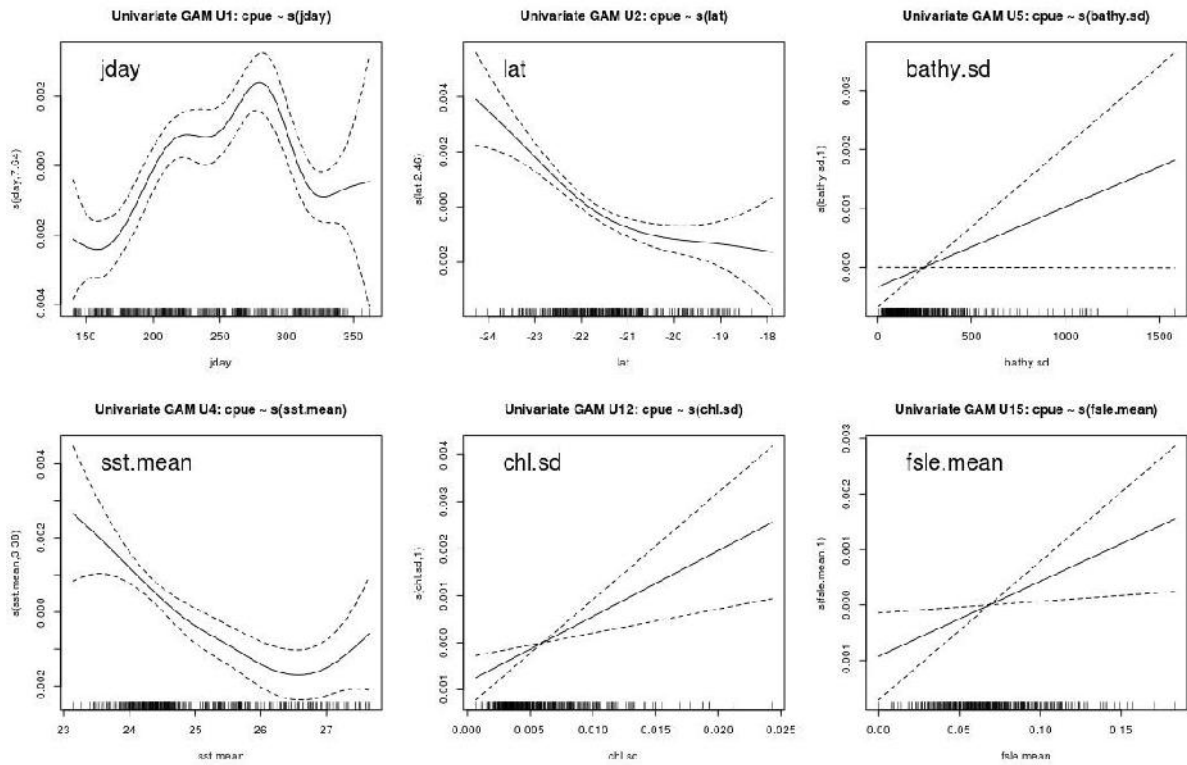| Model	Covariate	Edf	P-value	% dev. expl.
U1	*jday*	7,635	***	19,8
U2	*lat*	2,461	***	12,7
U3	*coast.dist*	3,15	*	2,95
U4	*bathy.sd*	1	*	0,99
U5	*sst.mean*	3,385	***	11,4
U6	*sst.med*	2,496	***	10,4
U7	*sst.min*	3,598	***	11,4
U8	*sst.max*	3,263	***	12,8
U9	*sst.trend*	8,047	***	20,4
U10	*sst.nsgrad*	4,151	***	12,9
U11	*sst.res*	1,497	*	1,49
U12	*chl.sd*	1	**	2,5
U13	*chl.trend*	8,004	***	9,6
U14	*fsle.mean*	1	*	3,01
U15	*fsle.max*	2,221	*	1,81

Figure 2. Examples of significant effects of the julian day (*jday*), latitude (*lat*), bathymetry standard deviation (*bathy.sd*), sea surface temperature (*sst.mean*), chlorophyll-a concentration standard deviation (*chl.sd*) and convergence index (*fsle.mean*) in univariate generalized additive models where swordfish CPUE (*cpue*) is the response variable (respectively U1, U2, U4, U5, U12 and U15)

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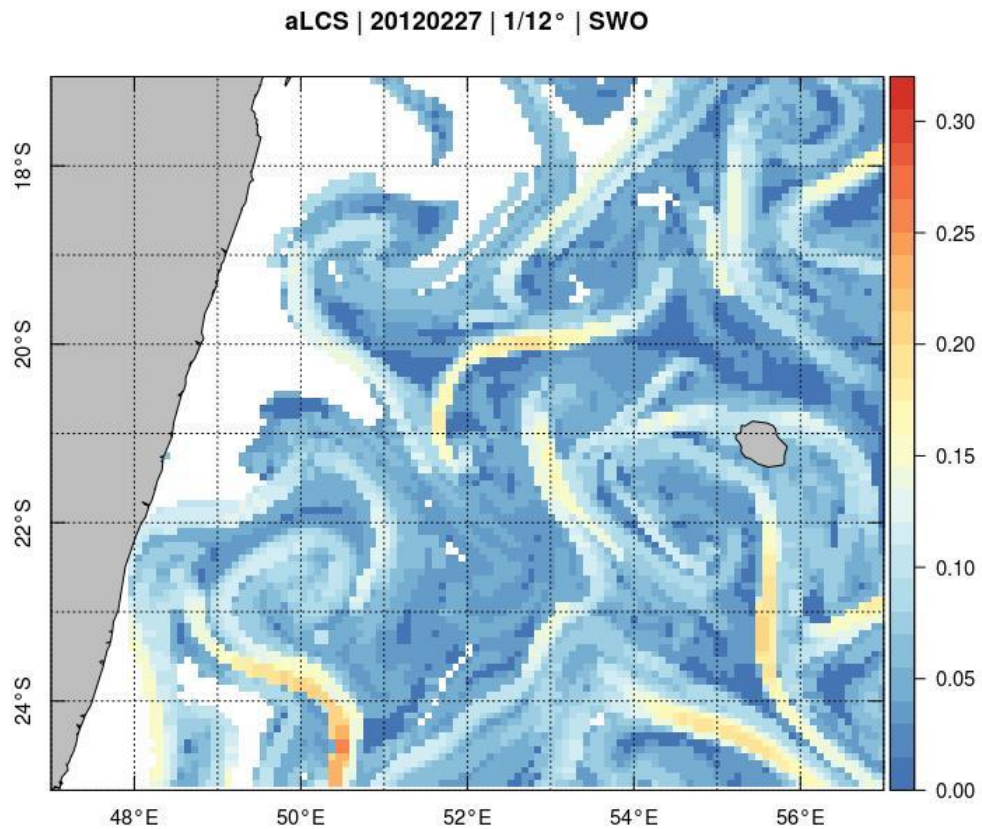
Appendix 1

Fishing polygons (=sets) in 2012

Fishing polygons

398 sets
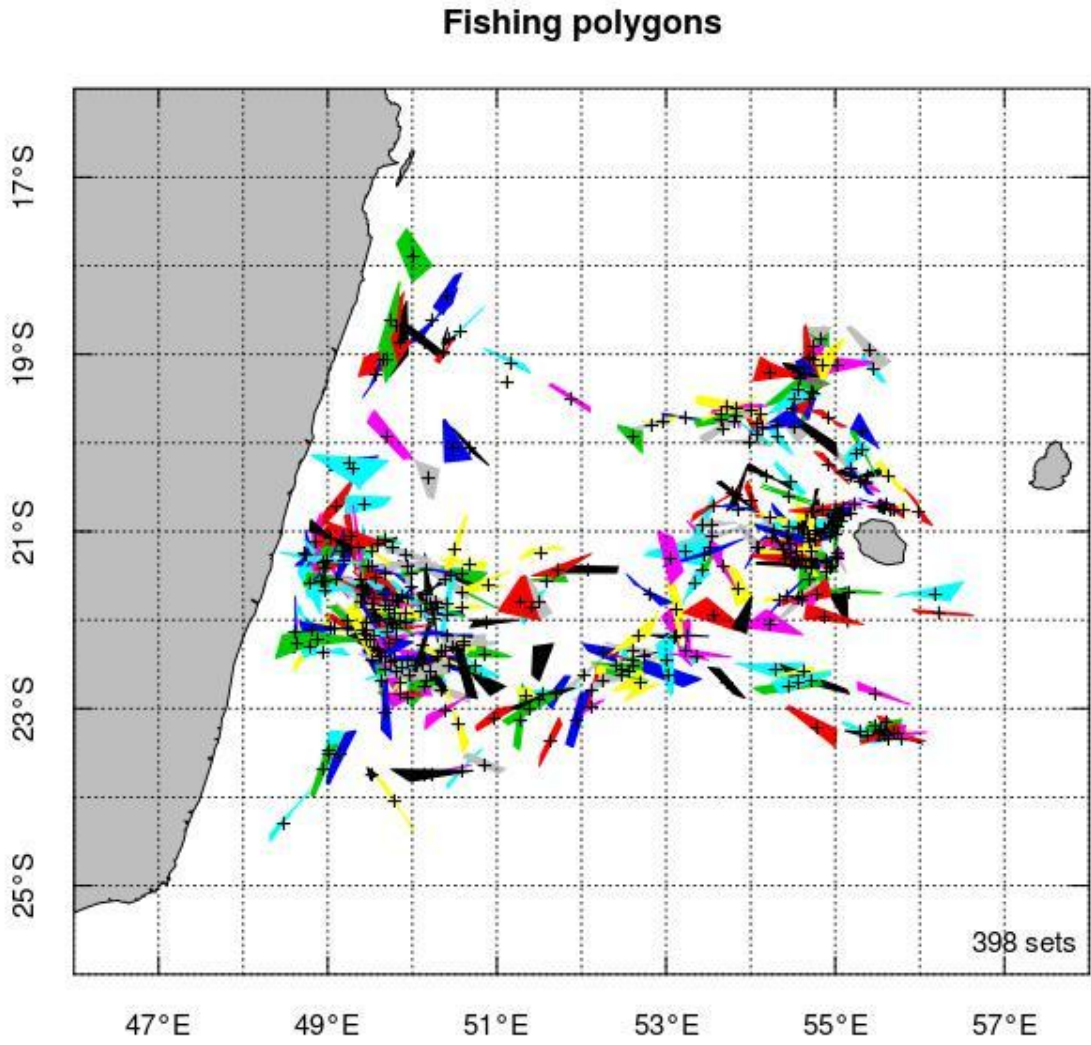
Appendix 2

Finite-size Lyapunov exponents (FSLE)

Backwards FSLE (bFSLE) quantify the convergence and aggregation patterns of water masses based on historical analysis of geostrophic surface currents (d'Ovidio et al., 2009). The principle of FSLE is to calculate backwards particle trajectories and to determine the time two particles take to reach a defined distance – hence "finite-size" (Aurell et al., 1997). For a given location, greater is FSLE, shorter was the time for two particles to converge, and stronger is the convergence. Structures can thereby be identified on bFSLE maps; they are called attracting Lagrangian structures (see map below). It is typically the case for frontal zones between eddies where strong eddies at the edge of eddies inject surface waters into the frontal zone (e.g. Tew Kai et al., 2009).

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Appendix 3

Spearman's correlation matrix of covariates. Blue-red colorscale indicates the sign and strength of the correlation. Blue for negative and red for positive correlations

Spearman's correlation matrix