ICES CM 2005/U:15

A geostatistical method for assessing biomass of tuna aggregations around moored Fish Aggregating Devices with star acoustic surveys

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ABSTRACT

In this work we aim at computing geostatistical estimates and estimation variance of the biomass of the single large tuna aggregation observed near moored Fish Aggregating Devices (FADs) in Martinique during star echosounding surveys. After pre-processing of acoustic data, the inertia of the tuna density distribution is analyzed in relation to environmental descriptors to identify eventual strata and correct trends in the spatial distribution caused by the influence of environmental gradients. We therefore apply to the mean tuna density distribution a Generalized Diffusion Equation which models animal grouping to precise the relative influence of advection and diffusion in the tuna aggregation process. An appropriate variogram model is selected based on the results of the diffusion/advection patterns analysis and applied to the mean tuna density distribution. The variance of the biomass estimates of tuna aggregations obtained with star acoustic surveys around moored FADs is then computed based on the mean tuna density and on the variogram model. Actually, the spatial structure of the mean residuals is studied.

Day and night strata were significant effects in the analysis of the variance of inertia. Diffusion/advection patterns were quite similar for both strata with a predominance of diffusion processes within the tuna aggregation. A Gaussian variogram with a nugget effect was then used to compute variance estimates, which were low for both strata (estimation CV of 3 and 7% for day and night strata). Low residual spatial correlation was found in the residuals. We then concluded that, on average, star acoustic surveys were well suited for estimating the biomass of the single large tuna aggregation located near moored FADs in Martinique.

Key words: tuna fisheries, aggregative behavior, FAD, echosounder, geostatistics, diffusion

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Introduction

Large pelagic fishes such as tunas, dolphinfishes or billfishes naturally aggregates around moored fish aggregating devices (FADs) (Fréon & Dagorn 2000). Significant and fast development of moored FAD small scale fisheries with high rates of juvenile tuna catches had been pointed out in Martinique and Guadeloupe islands (French West Indies) (Doray *et al.* 2002). Three French research institutes (French Research Institute for the Exploitation of the Sea, "Institut de recherche pour le développement" (IRD) and of the National Superior School of Agronomy of Rennes) initiated the 'DAUPHIN' research project designed to provide new scientific knowledge on the pelagic ecosystem in the vicinity of moored FADs for achieving a sustainable management of the local moored FAD fishery and to improve general knowledge on the aggregative behaviour of large pelagic fish,.

Echosounding surveys were conducted around moored FADs in combination with fishing, underwater video and environment monitoring for i) classifying the large pelagic fish aggregations ii) characterizing their temporal and spatial dynamics in relation with environment and fishing. A star survey pattern (fig. 1) previously used around moored FAD in French Polynesia (Josse *et al.* 1999) was adapted to conduct 516 acoustic surveys around 2 moored FADs on the leeward coast of Martinique.

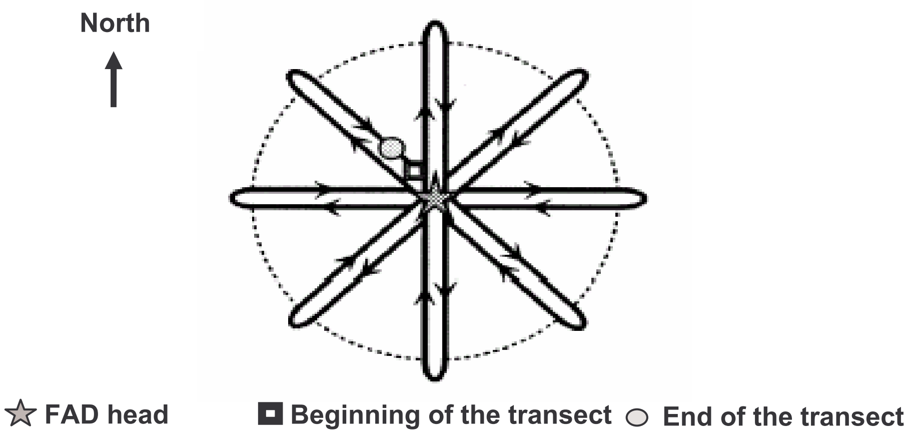


Figure 1: Star acoustic transect redrawn from Josse *et al.* (1999)

These surveys revealed the presence of a large aggregation distributed within a radius of 400 m around every group of terminal buoys of the moored FAD. This aggregation accounted for the vast majority of the fish biomass aggregated around the moored FAD (Doray in press-b). Single acoustic echo analysis combined with underwater video and fishing allowed classifying this aggregation as a 50cm FL tuna aggregation (Doray in press-a).

The assessment of the biomass alongside with an estimation variance of this tuna aggregation was one of the major outputs of the project in terms of sustainable fishery management. This paper presents the geostatistical method that was used to produce such an estimation variance of the biomass estimate of the large tuna aggregation.

Material and methods

Acoustic data pre-processing

The acoustic data were collected with a Simrad EK60 scientific echosounder (version 1.4.6.72) connected to 2 hull-mounted, spherical split-beam transducers (ES38-B and ES120-7G), emitting with an equivalent beam angle of 7°, at frequencies of 38 and 120 kHz. The echosounder was linked to a Garmin 12 XL Global Positioning System equipped with an extern antenna. 88 star acoustic surveys conducted each month around 2 moored FADs in Martinique from May, 03 to August, 03 were analysed. 59 surveys were conducted within a radius of 0.2 nautical miles around the moored FADs (small surveys) and 29 within a higher radius of 0.8 nautical miles (large surveys) to assess that the biomass of the biomass was always located within a 0.2 nautical miles radius around the moored FAD. 22 surveys were conducted on average each month during this time period. 61 surveys were conducted around the coastal FAD (7 nautical miles from the coast leeward coast) and 27 around the offshore one (25 nautical miles). To account for the diel variability of the distribution of tropical fishes (Freon *et al.* 1993), 4 temporal strata were defined following the Freon *et al.* (1993) recommendations: day (sunrise+30 minutes to sunset less 30 minutes), night (sunset+30 minutes to sunrise less 30 minutes) and dawn and dusk for transition periods of 1 hour around sunrise and sunset. 55 surveys were conducted at daytime, 23 at night-time, 7 at dawn and 3 at dusk.

Only 120 kHz data were processed because tuna shoals were far easier to isolate from commonly dense surrounding micronecton layers in 120 kHz than in 38 kHz. Tuna shoals were extracted using the echo-integration by shoal module of the Movies + software (© 1997-2002 Ifremer). As the spatial scale of the survey was very narrow the mean elementary sampling unit (ESU) for the echo-integration was set very small (5 pings; about 15 m) to get a good spatial definition for geostatistical analysis. Echo integration by shoal parameters were defined respectively for day and night surveys and allowed satisfying extraction of tuna shoal. The efficiency of the classification was assessed visually for all of the surveys. 4 depth strata of 50 m were defined from 0 to 200 m. An area backscattering coefficient s_a (MacLennan *et al.* 2002) was computed for each ESU in each depth stratum as the sum of the aggregate backscattering cross-sections, σ_{ag} of each tuna shoal detected in the ESU divided by the length of the ESU in meters (Diner *et al.* 2004). Longitudes of ESUs expressed in degrees were converted in distances while multiplying by the correcting factor $\cos(mean(latitudes))$ (Rivoirard *et al.* 2000) and all coordinates were referenced to the position of the moored FAD. As the length of the anchoring rope of the moored FAD was higher than the mooring depth for a better resistance to current (Guillou *et al.* 2000), the moored FAD could sometimes drift over hundreds of meters during a single acoustic survey. All the ESU coordinates being referenced according to the FAD position, ESU coordinates had to be corrected for the FAD drift to maintain the geometry of the sample pattern. As the position of the moored FAD was recorded each time the vessel passed near the terminal buoys and the survey pattern allowed the vessel to pass often near the FAD, the position of the FAD during the survey were modelled as a function of time, based on the headings and drifting speeds of the FAD computed between each recorded positions. The ESU coordinates were therefore corrected for the FAD drift and s_a values computed for each ESU were attributed to the geographical center of the ESUs.

Large acoustic surveys were completed within 2 hours and small acoustic surveys within 30 minutes at 6-7 knots. The small survey scale was defined as the elementary temporal observation scale i.e. we assumed that the tuna density distribution was stationary at the scale of a small survey (400 m radius, 30 minutes). However, due to the geometry of the survey pattern and to the uncertainty of the vessel trajectories, samples could be recorded at very close geographical locations but with a time gap of several minutes, whereas the local tuna density at scale of ten meters could have dramatically changed in a few minutes. Moreover, we estimated the systematic positioning error of the GPS at about 7 meters, based on the analysis of some trajectories of the vessel and on available literature. We then applied a 15 m squared grid to the ESU positions and averaged the s_a of the ESUs belonging to the same cell to smooth the positioning errors and the variations of tuna density that occurred at scales smaller than our elementary observation scale. Resulting s_a values were attributed to the center of the cells.

Analysis of the effect of environmental factors on the variance of the tuna distribution

Tuna abundance around moored FADs proved to undergo dramatic diel and day-to day variations ((Cillauren 1994; Doray in press-a; Josse *et al.* 2000) which indicate a rather high variability of the aggregation process. We assumed that the tuna density distribution was stationary at the scale of a small acoustic survey, however this assumption should be validated while analysing the effect of available environmental factors on the variance of the spatial distribution. Moreover, as we plan to use geostatistics for analysing the spatial correlation in the tuna biomass distribution, we should previously check for the existence of any trend or strata in the variance of the density distribution for the hypothesis of stationarity of the increments of the intrinsic geostatistical method to be honoured.

Basic summary statistics showed that the vertical distribution of tuna appeared to be quite homogeneous over the surveyed range of 200 m depth , 94% of the total mean s_a being distributed within 10 to 100 m. We then chose to integrate the s_a over depth and to focus on the variability of the horizontal 2D tuna distribution.

The spatial distribution of population can be easily summarized by tools such as center of gravity (CG) and inertia (I) (Bez *et al.* 1997). These 2 descriptors were computed for each of the surveys with the R package RgeoS (Woillez *et al.* 2005). The center of gravity is the mean location of an individual taken at random in the field and the inertia is the mean square distance between such an individual and the center of gravity (Woillez *et al.* 2005). Inertia was taken as the descriptor of the spatial dispersion of the tuna distribution and modeled according to i) environment descriptors describing processes whose scale is close to the elementary scale of observation: these processes can directly influence the tuna distribution at the scale of observation. They are high frequency (or fine scale) descriptors, averaged over the duration of the acoustic survey: mean surface PAR intensity, current intensity, current heading ii) environment descriptors of larger scale, accounting for low frequency processes which could affect globally the tuna distribution: diel stratum , 2 hours classes, FAD, number of the cruise (month effect). A linear model was fitted on the log transformed of the inertia to assess the influence of these descriptors and identify any trends or strata that should be taken into account before studying the spatial correlation within data by geostatistics. Similar model and descriptors were applied respectively on the distance and on the angle between the gravity center and the moored FAD to assess eventual effects of the environmental descriptors on the position of the gravity center.

Geostatistical biomass estimation

Application of a Generalized Diffusion Equation to tuna aggregation

Geostatistics is a set of methods designed to study one or more variables which are distributed in space. The method implies the use of a model of the spatial correlation between punctual samples, the variogram, to produce maps and biomass estimates (Rivoirard *et al.* 2000). Considering the high number of surveys in the database, manual fitting of variogram for each of the surveys was too time consuming and was not retained to study the spatial correlation in the tuna density distribution. Instead of applying a more or less automatic variogram fitting procedure on each of the surveys, we took advantage of the high number of observations that were recorded over time in a reduced spatial window around the moored FAD to study the mean tuna density distribution for all of the surveys. In fact, distinct variogram models have been developed according to distinct assumptions concerning the regularity of the underlying natural process (Petitgas 2001). We first studied the regularity of the mean distribution to get insights on the type of variogram model to be used to characterize the spatial correlation of the mean tuna aggregation process. To do so, we applied to tuna aggregation around moored FADs a methodology proposed by Okubo and Chiang (1974) to study the relation between spatial density distribution and grouping behaviour within an advection/diffusion framework. This method is based on a Generalized Diffusion Equation for animal grouping that what first applied to study swarms of midges (Okubo & Chiang 1974). The equation assumes that the spatial distribution of animals in a group cannot be based on a simple random walk, i.e. on a passive diffusion model. Okubo & Chiang (1974) assumed instead that animal grouping include a mechanism that opposed the action of diffusion i.e. the flux of organisms through a plane perpendicular to the x-axis must consist of at least two components, one random and the other non-random (Okubo & Levin 2001). For stationary grouping, the non random flux must be exactly balanced by the random flux and we have:

$$uS = D\frac{\delta S}{\delta x}$$

Where: uS is the non random, advection component, where u is the mean drift of individual organisms passing through the plane and S the mean spatial individual density

$D\frac{\delta S}{\delta x}$ is the random or diffusive component, where D denotes diffusivity and $\frac{\delta S}{\delta x}$ is the gradient of the mean spatial density of organisms. The parameter $\frac{D}{|u|}$ characterizing the ratio between diffusion and advection processes within the group can thus be evaluated from the spatial density distribution (Okubo & Chiang 1974).

As the objective was here to compare relative spatial distributions, acoustic density and coordinates were standardized in order to filter out spatial trends caused by factors other than grouping behaviour (e.g. environment factors, abundance fluctuations…). Computations were restricted to the circular area of radius 400 m around the moored FAD where the vast majority of tuna density was observed (Doray in press-a). The tuna density distribution was first stratified and detrended according to the results of the effect of the environmental descriptors. We then expressed the proportion of the acoustic density of tuna $S_p(x)$ in each cell x for each survey p relatively to the mean acoustic density of the survey as follow:

$$S_p(x) = s_a(x,p) / \sum_p \frac{s_a(x,p)}{n_p}$$

With: $s_a(x,p)$: s_a value in the cell x during survey p, n_p: number of cells sampled during survey p. This transformation was used to allow comparison of spatial density distributions coming from surveys with very different mean abundance. The tuna density distributions of each survey were therefore centred around their center of gravity and the standard deviations of cells with positive tuna density were adjusted so as to equal one another, in order to get spatial distributions in terms of a normalized coordinate system (Okubo & Chiang 1974). Mean tuna densities per cell and strata were therefore computed and averaged along x and y axis. Smooth regression curves were fitted on the mean density distribution expressed as a function of the absolute values of x and y to evaluate the mean spatial densities along the x and y axis. The fitted values of density were therefore used to compute the ratio $\frac{D}{|u|}$. As noted by Okubo and Chiang (1974), D and u can not both be constant to have a distinct group boundary and both quantities may depend upon the local density of individuals. Plots of $\frac{D}{|u|}$ against S were drawn for each directions in each strata and regression curves were fitted on the regular parts of the curves to characterize the regularity of the density distribution. Diffusion in fact originates from random walk processes (Okubo & Levin 2001) and generates very smooth density distributions (Gaussian in the case of pure passive diffusion), whereas advection causes far more irregular density distributions.

Biomass estimation based on the mean tuna density distribution

The biomass estimate for a given survey will be obtained while multiplying the mean areal tuna density recorded during the survey by the area of the zone where the aggregation was distributed. The estimation variance depends on (i) the covariance or variogram model and the shape of zone *V*; (ii) the position of the sample locations in relation to each other; and (iii) the location of the samples in relation to the limits of the zone (Petitgas 2001).

The zone S used for computing biomass estimates and estimation variances was the zone occupied by the mean tuna density distribution in each strata. The variogram model was chosen in each strata based on the values of the $\frac{D}{|u|}$ ratio, used as a proxy of the regularity of the mean density distribution. The variogram model was therefore fitted to the map of the mean tuna density distribution expressed in non standardized coordinates. The EVA 2 software (Petitgas & Lafont 1997) was used to compute the variance of the estimate of the mean tuna biomass obtained from acoustic data collected with a star survey pattern in the zone S. The coefficient of variation (CV) of the biomass estimate was computed as a relative estimation error.

Residuals

In each strata, the mean tuna density map was subtracted from the tuna density maps of each of the surveys to compute the residuals of the mean aggregation model of. The absolute value of the minimum of the residuals of each survey map was subtracted from the residuals in order to ensure their positivity and allow further geostatistical analysis. A mean map of the residuals was computed per stratum. An experimental variogram was computed from this map and fitted with a variogram model to check for eventual residual spatial correlation.

All statistics except variogram fitting and estimation variance computation were implemented using the R language (R Development Core Team 2005).

Results

Analysis of the effect of environmental factors on the variance of the tuna distribution

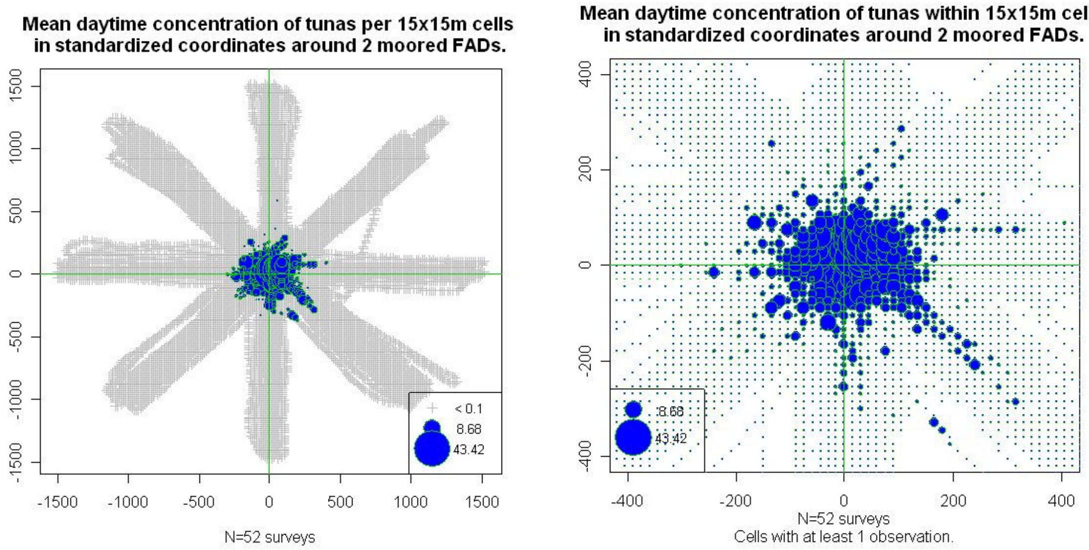
The only significant effect in the linear model describing inertia were the “day” and “night” factors. The R squared value was low: 0.18 and the residuals globally normally distributed. Inertia at daytime was not significantly higher or equal to inertia at night-time with a 5% confidence interval using a Kosmogorov-Smirnov goodness of fit test. No significant effects were found in the models describing the distance and angle from FAD to GC. Further analysis of the tuna density distribution were conducted while distinguishing 2 diel strata: night and day.

Geostatistical biomass estimation

Application of a Generalized Diffusion Equation to tuna aggregation

Figures 2a and 2b present the 2D mean tuna density distributions around the 2 moored FADs at day and night. These plots were drawn with the R package RgeoS (Woillez *et al.* 2005).

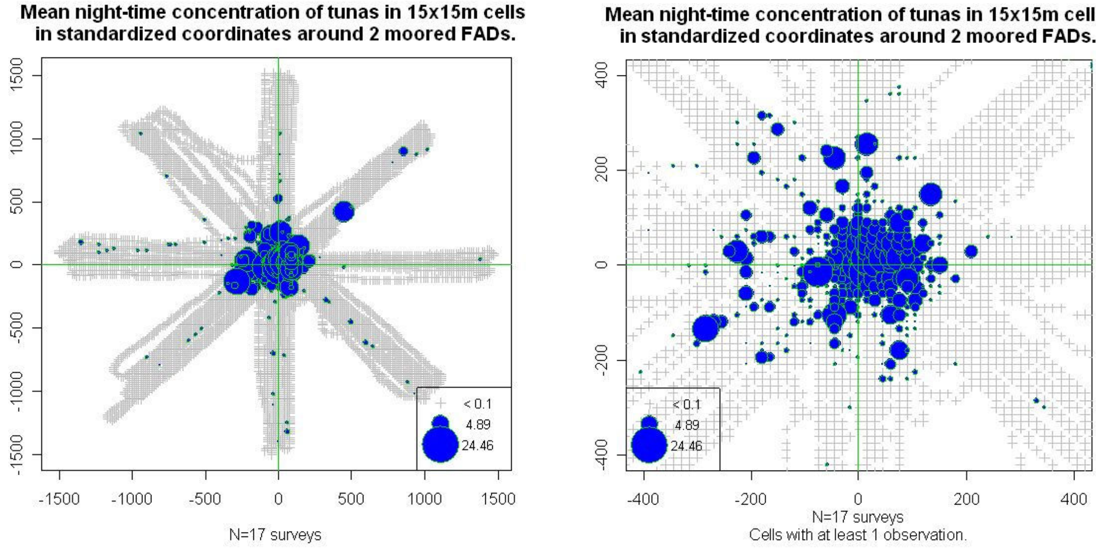
a)



Mean daytime concentration of tunas per 15x15m cells in standardized coordinates around 2 moored FADs.

Mean daytime concentration of tunas within 15x15m cells in standardized coordinates around 2 moored FADs.

b)



Mean night-time concentration of tunas in 15x15m cells in standardized coordinates around 2 moored FADs.

Mean night-time concentration of tunas in 15x15m cells in standardized coordinates around 2 moored FADs.

Figure 2b

Figure 2: Mean acoustic density distribution of tuna around 2 moored FADs in Martinique at daytime (a) and night-time (b)

Figure 3a and 3b present the tuna density distribution along x and y axis at daytime and night-time.

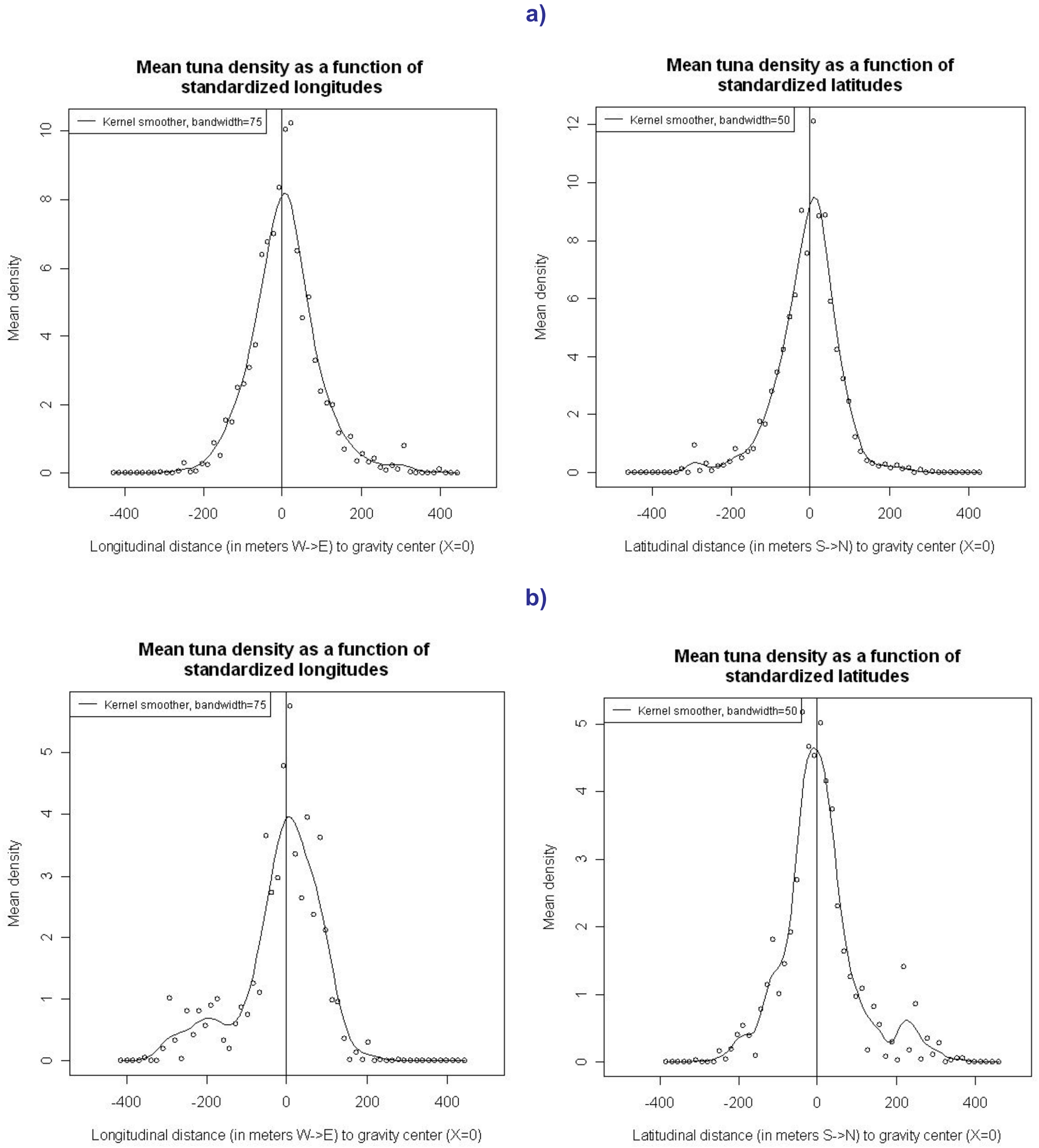


Figure 3: Mean acoustic density distribution of tuna along x and y axis around 2 moored FADs in Martinique at daytime (a) and night-time (b)

The density distributions appeared to be roughly normal at daytime in x and y directions. At night-time, the distribution is less regular. Figures 4a and 4b present the tuna density distribution as a function of absolute values of x and y at daytime and night-time. The smooth spline curve fitted on the density distribution is drawn on the figures alongside with the $-\frac{D}{|u|}$ ratio.

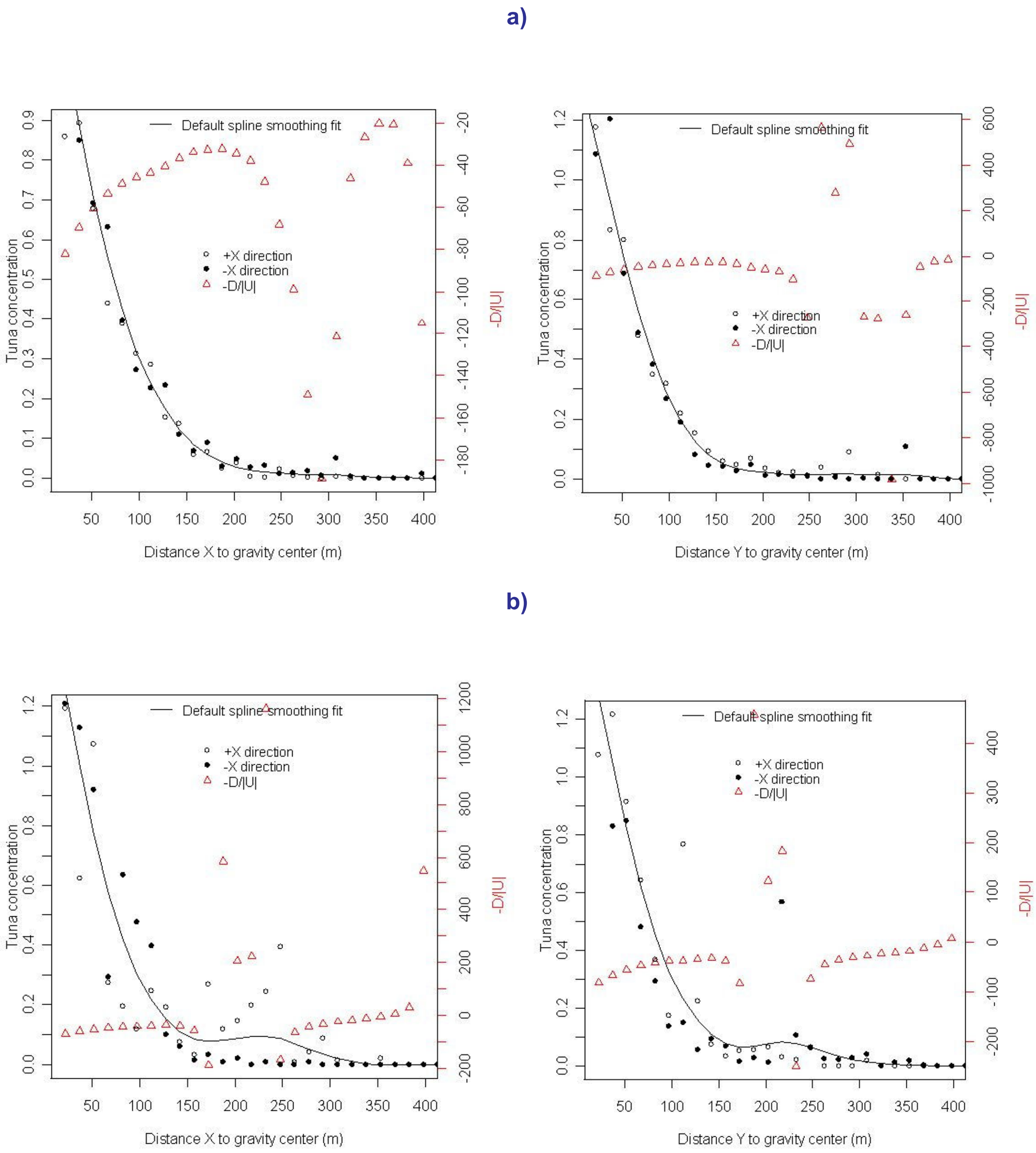


Figure 4: Mean acoustic density distribution of tuna along x and y axis and $-\frac{D}{|u|}$ ratio around 2 moored FADs in Martinique at daytime (a) and night-time (b)

The shape of the curve of the diffusion/advection ratio (DAr) $-\frac{D}{|u|}$ against distance to gravity center is similar both in x and y direction and at daytime and night-time: the DAr curve is quite continuous and stable from the GC to 250 m at daytime and 200 m at night-time, therefore it undergoes dramatic variation before stabilizing again at about 350 m at daytime and 250 m at night time. The distances beyond which the DAr becomes unstable correspond to the boundaries of the aggregation at daytime and night-time. The curves of Dar against tuna density at daytime and night-time are presented in figures 5a and 5b.

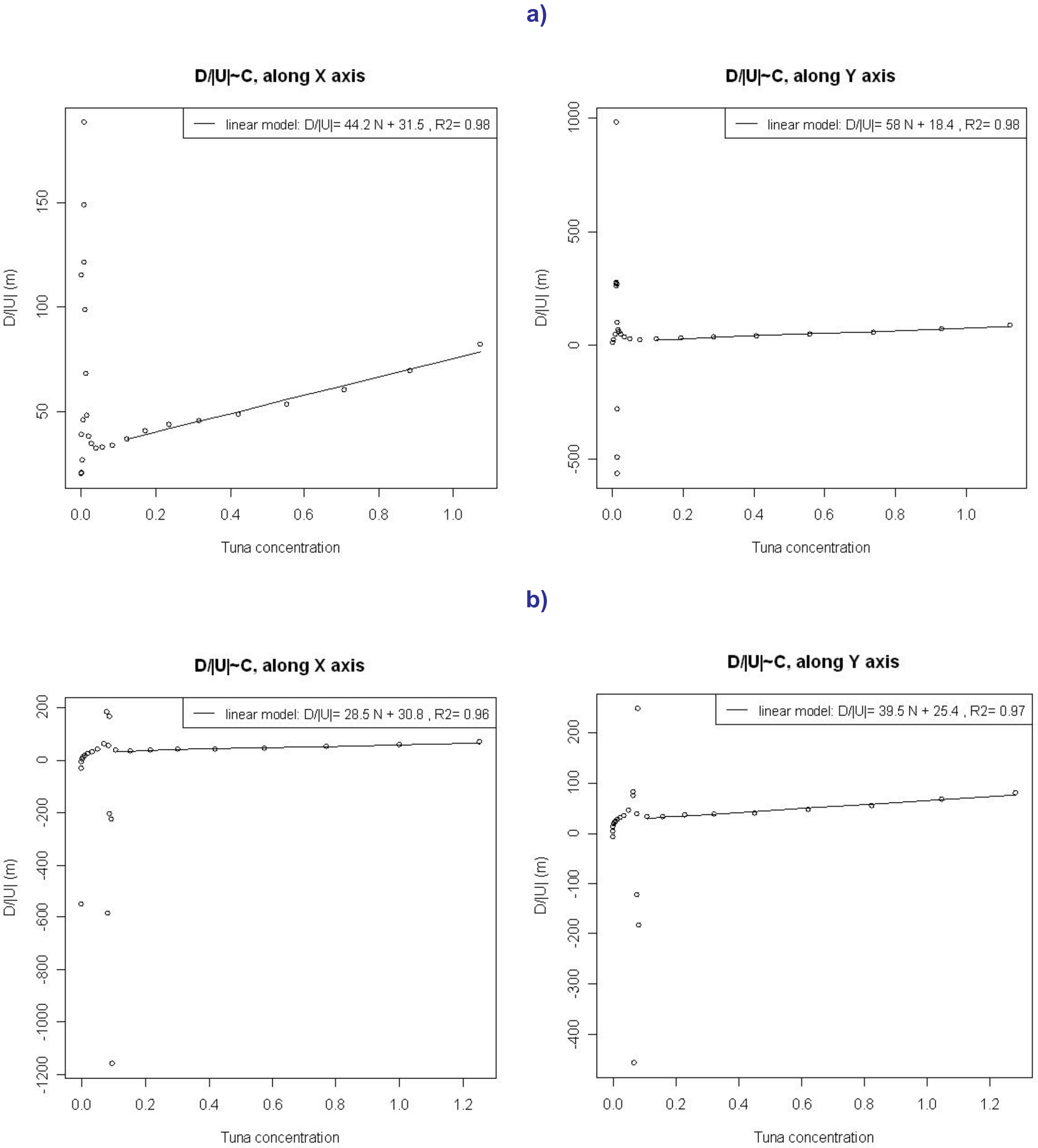


Figure 5: Diffusion/advection ratio $\frac{D}{|u|}$ against mean tuna density and linear fit along x and y axis around 2 moored FADs in Martinique at daytime (a) and night-time (b)

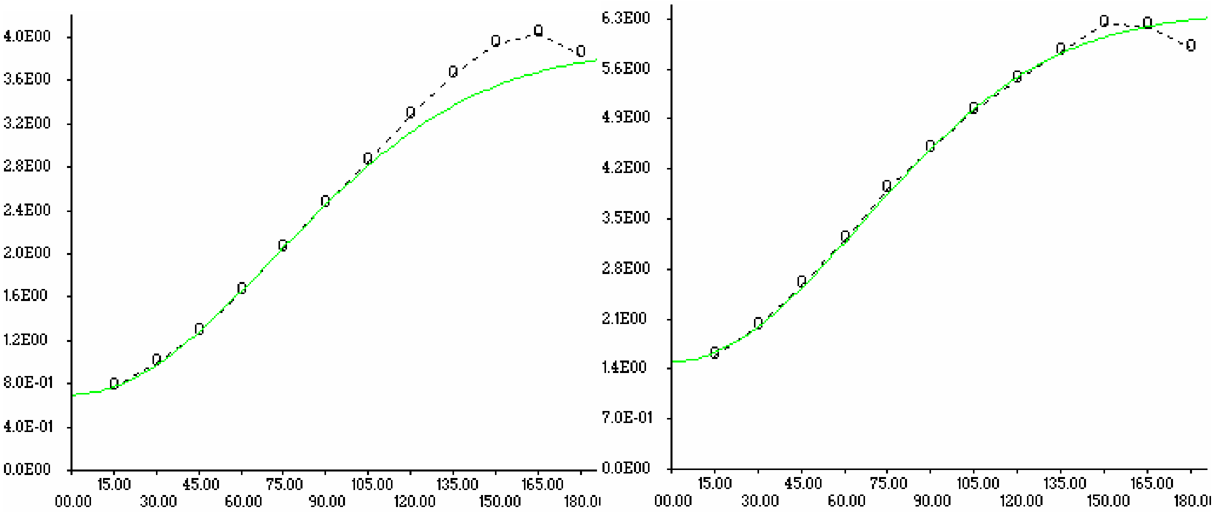
The general shapes of the curves were similar in both directions and diel strata, with a linear part for tuna density values higher than 0.1, dramatic increase and decrease of the DAr over a very short density span and a large decrease of the ratio for density values near zero. This final decrease was less abrupt at night than during daytime, which might suggest a more diffuse distribution of the tuna density beyond the boundaries of the aggregation at night-time. This hypothesis is supported by the higher inertia value observed at night and the presence of numerous isolated patches (fig. 2b). A linear model was adjusted on the right part of the curves which proved to be quite linear, with a mean R2 of 0.97 and significant slopes and intercepts.

The evolution of the DAr could be interpreted in this way: on the linear part, the DAr was always positive denoting a predominance of diffusion over advection for the tuna density values found inside the aggregation. The DAr rapidly decreased to zero or less for lower density values, when advection overruns diffusion beyond the aggregation boundaries.

Biomass estimation based on the mean tuna density distribution

The zone S where to compute geostatistical estimates was define as a circular zone of radius 200 m around the moored FAD, based on the mean tuna density distributions (fig. 2a and 2b).

As the DAr values allowed concluding that diffusive processes were dominant within the tuna aggregation, a Gaussian variogram, which characterizes very smooth density distributions (Petitgas 2001), was used to model the spatial correlation of samples at daytime and night-time. Figures 6a and 6b present omni-directional Gaussian models fitted on experimental variograms computed for day and night mean tuna density distributions.



a) **b)**

Figure 6: Experimental and fitted Gaussian variogram of the mean tuna density distributions around 2 moored FADs in Martinique, at daytime (a) and night-time (b)

Results of the variogram fitting are presented in table 1.

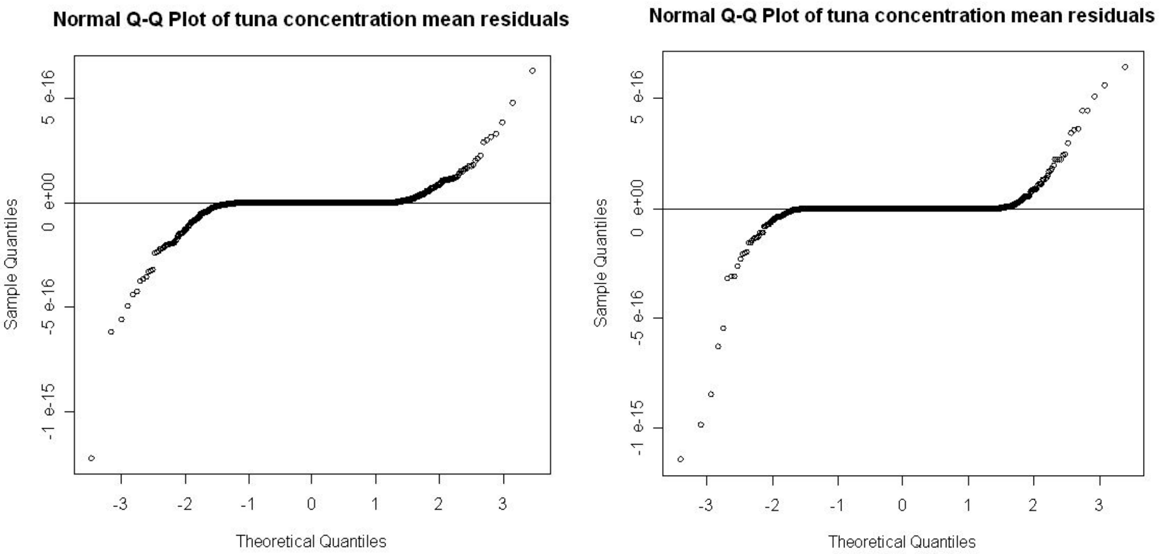
Table 1: results of the variogram fitting on mean tuna density distribution

Variable statistics		**Day**	**Night**
	Number of observations :	566	554
	Minimum :	0	0
	Maximum :	9.02	13.12
	Average :	0.87	0.74
	Variance (s²) :	2.25	3.52
	Coefficient of variation (s/m) :	1.72	2.54
Model parameters			
	Nugget :	0.7	1.5
	Model 1:	Gaussian	Gaussian
	Sill:	3.2	4.9
	Practical range:	175	161
Estimation variance (Scheme E)			
	Est. Var.:	9.03E-04	2.99E-03
	Est. CV:	3%	7%
	Gvv:	3.32	5.63
	Gab:	3.32	5.62
	Area:	128712.80	128712.80

The estimation CV was very low at daytime (3%) and a little higher at night-time (7%). The mean tuna density distribution around the 2 moored FADs was hence properly sampled with star acoustic surveys.

Residuals

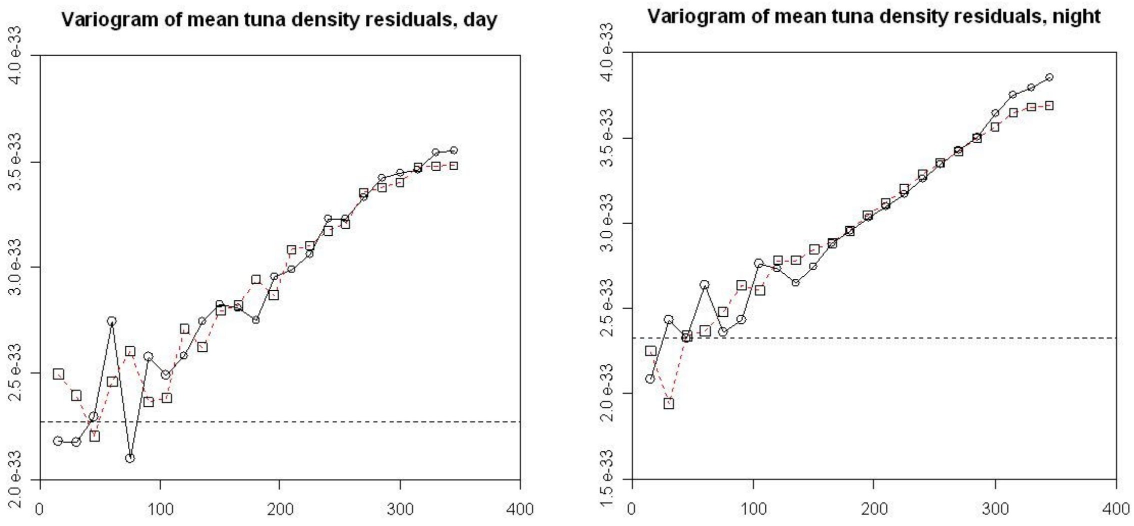
Residuals were very low with strong outliers visible on quantile-quantile plots of the mean daytime and night-time residuals presented in figure 7a and 7b.



a) **b)**

Figure 7: Normal quantile-quantile plots of the residuals of the mean tuna density distributions around 2 moored FADs in Martinique, at daytime (a) and night-time (b)

Their spatial structure appeared to be quite linear according to the 2 dimensional experimental variograms presented in figures 8a and 8b. Due to their very low value, they were neglected.



a) **b)**

Figure 7: Experimental variogram of the mean residuals of the mean tuna density distributions around 2 moored FADs in Martinique, at daytime (a) and night-time (b)

Discussion

Sampling

The vertical dimension was not included in the characterization of the variance of the tuna density distribution. In fact, the vertical dimension was better far sampled than the horizontal ones by the vertical echosounder which gathered high resolution data (10cm height with a pulse length of 0.5 ms) at high frequency (1 sample per second) over long distances (200m in 120 kHz). The horizontal dimension was sampled through the geometry of the survey pattern, assuming the biomass distribution was roughly stationary during an elementary acoustic survey. Estimation variance of the biomass estimate hence came mainly from the efficiency of the survey pattern at providing a good horizontal 2D spatial coverage of the biomass distribution. This estimation variance was assessed by geostatistics and proved to be low. However, bias in the vertical sampling could have been caused by the geometry of the acoustic beam that did not cover the same surface at different depths. In our case, as the tuna density was only distributed over half of the maximum range in the form of a unique large aggregation, this bias could be assumed to be low. In fact, the acoustic beam radius was 6 m at 100 m that is less 8.5% of the minimum mean dimension of the tuna aggregation.

Analysis of the effect of environmental factors on the variance of the tuna distribution

The diel cycle proved once more in this paper to be very important in pelagic fish aggregation. However, even if the current effect did not appear to be significant it might be because of a lack of precision in the estimation of this parameter. No direct measurements of current at different depths and at a proper frequency were available in this study. The speed and heading of current were derived from the drift of the FAD head, mainly caused by a global current integrated over the whole water column by the FAD structure. More work should be conducted on the surveys for which precise information on different current conditions are available to assess the influence of this prominent factor on tuna distribution around moored FAD.

Geostatistical biomass estimation

Application of a Generalized Diffusion Equation to tuna aggregation

Okubo & Chiang (1974) designed a Generalized Diffusion Equation for modelling animal grouping while studying swarms of midges of several meters with a video camera. The framework they provided for studying animal density distribution applied well to tuna density distribution around moored FADs. The density distribution of midges on the x axis was, as in this paper, close to a normal distribution, however, the plots of DAr against density of midges were rather different from the ones obtained in this study. In the case of midges, the DAr against density curves did not presented abrupt variations, as on the boundary of tuna aggregations and were fitted with a power 0.5 model. According to Okubo & Chiang (1974) it will not be surprising if in general the Gaussian distribution does not hold the density distribution of the midges in space because interaction between individuals tends to maintain boundaries of the group, which is not compatible with the characteristically long tails toward plus and minus infinites in space of a Gaussian.

Variogram fitting and residuals

The low estimation variances obtained with the Gaussian variogram model and the mean tuna density distribution attest that the estimation of the biomass of a single, large aggregation of tuna located near a moored FAD with a star survey pattern is, on average, accurate. Nonetheless, a more detailed analysis of residuals should be conducted to assess the eventual residual spatial correlation. Variograms could be automatically fitted on each of the maps of survey residuals and the variance of the types of models and parameters could be analysed to detect eventual common spatial patterns in the residuals. This additional spatial correlation should be modelled before considering further analysis of the variance of the tuna density distribution (by applying mixed models including other environmental descriptors for example).

Conclusion

The study of tuna aggregations around moored FADs was conducted here in an Eulerian viewpoint, that is while observing the flow of tunas through a restricted spatial window. The repetition of systematic surveys within this very narrow spatial window combined to the fact that a unique tuna aggregation was always present very close to the FAD, allowed gathering a large amount of punctual observations of the tuna aggregation stochastic process. However, as outlined by Okubo and Levin (2001), “nearly all biological processes are stochastic (…) however, a greater portion of the individuals involved in a process may be said to follow a single deterministic path *on the average*”. The study of the mean density of tuna, within strata where the density was proven to be relatively stationary, allowed exhibiting general spatial patterns that provided insights on both aggregative behaviour of tunas and on the precision of biomass estimates. In other words, the acoustic study, in the temporal dimension, of the variations of the tuna density distribution in 2 spatial dimensions allowed characterizing quantitatively at multiple scales the structure and dynamics of a hotspot of biomass in the pelagic environment.

The pioneering work of Okubo & Chiang (1974) provided an interesting framework and a set of methods that can be applied at different scales for studying the animal grouping. In this paper, we successfully applied to tuna aggregations around moored FADs a method designed for studying the global density of individuals in a swarm. The results obtained confirmed that the structure and dynamics of the tuna aggregations observed around moored FADs in Martinique were closer to these of a midge swarm than to the structure and dynamics of a school of small pelagic fishes, where advective processes seem to be stronger. The diffusion theory of animal grouping of Okubo & Chiang (1974) can also be applied for studying individual velocities and trajectories within a group. Echosounding surveys conducted in Martinique allowed collecting tuna tracks that could be used to precise the preliminary model of tuna aggregation around moored FAD presented in this paper.

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