Fishing activity of tuna purse seiners estimated from vessel monitoring system (VMS) data

Nicolas Bez, Emily Walker, Daniel Gaertner, Jacques Rivoirard, and Philippe Gaspar

Abstract: In the lack of fishery-independent information, catch per unit of effort (CPUE) is the conventional abundance index. In the case of the tropical tuna purse seine fisheries, a critical difficulty lies in the definition of an effective fishing effort, because fishermen use two different fishing modes (free swimming schools versus schools under fish aggregating devices) alternatively during the same trip. In this study, vessel monitoring system (VMS) data were used in an operational level to study and quantify the spatial dynamic of the tropical tuna purse seine fishing activity. A Bayesian state–space model allowed classifying VMS steps into three activities (fishing, tracking, and cruising), which were characterized by a small set of complementary spatial indicators. The dominant activity (49%) was clearly the tracking of tuna schools within areas of aggregations. A hierarchical spatial organization of the three fishing activities was also evidenced. Fishing strategies described by the triplets of proportions of time devoted to each activity and interpreted as compositional data were modelled by the sum of a vessel effect and a seasonal effect.

Résumé : En l’absence d’information indépendante des pêches commerciales, la capture par unité d’effort (CPUE) sert d’indice conventionnel d’abondance. Dans le cas des pêches tropicales de thons à la seine coulissante, une difficulté particulière est reliée à la définition d’un effort effectif de pêche, car les pêcheurs utilisent deux modes différents de pêche (sur des bancs à nage libre et sur des bancs associés à des dispositifs de concentration des poissons) en alternance durant la même sortie en mer. Dans notre étude, nous utilisons des données du système de surveillance des navires (VMS) à un niveau opérationnel pour examiner et mesurer la dynamique spatiale de l’activité de pêche tropicale aux thons à la seine coulissante. Un modèle état–espace bayésien a permis de classifier les étapes VMS en trois activités (pêche, poursuite et croisière) qui sont caractérisées par un petit ensemble d’indicateurs spatiaux complémentaires. L’activité dominante (49 %) est nettement la poursuite des bancs de thons au sein des zones de rassemblement. On a aussi pu dégager une organisation spatiale hiérarchique des trois activités de pêche. Les stratégies de pêche décrites par les triplets de proportions de temps consacrées à chaque activité et interprétées comme des données composées se modélisent par la somme d’un effet du navire et d’un effet de la saison.

[Traduit par la Rédaction]

Introduction

Traditional indirect and fisheries-dependent methods used to estimate stock sizes have either to be fed (surplus production methods) or tuned (cohort analyses) by an index of abundance. To be a reasonable surrogate for the unknown abundance, indices of abundance should behave over time like the true abundance. In the lack of fishery-independent information, such as scientific surveys, and assuming some strong working hypothesis (e.g., constant catchability), catch per unit of effort (CPUE) is the most used index of abundance in stock assessments. However, if this definition is simple in essence, its relevant evaluation may be unrealistic, as it needs the proper quantification of the amount of (effective) effort developed to catch fish. Nominal efforts are usually standardized to account for difference among vessels, areas, seasons, and years, but it was showed in many situations that final estimates remained close to nominal values (e.g., Soto et al. 2009).

For the case analyzed in the present paper, namely the French tropical tuna purse seiners operating in the Indian Ocean, the nominal fishing effort used to perform CPUEs is

Received 31 January 2011. Accepted 7 July 2011. Published at www.nrcresearchpress.com/cjfas on 31 October 2011.
J2011-0014

Paper handled by Associate Editor Carl Walters.

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expressed as the time spent searching for tuna schools (i.e., the daylight time spent in the fishing grounds after removing the setting time and the inactive time: bad weather conditions, breakdown, etc.; Pianet 1998). Nominal fishing effort is then supposedly standardized accounting for different factors, such as the characteristics of the vessel, the season, and the fishing area (Pella and Psaropulos 1975; Laurec and Fonteneau 1979; Allen and Punsly 1984).

In the case of the tuna purse seine fishery, for which the detection of free-swimming schools depends upon visual clues (birds, radars, and sonars), the individual searching path of a vessel may be used to determine which proportions of the fishing day are effective in terms of fishing effort (Polacheck 1988). However, a developing fishing tactic used by tropical purse seiners in the world's oceans is to fish tuna schools associated with floating objects, which includes natural objects (e.g., logs, flotsams, etc.) or artificial man-made fish aggregating devices (FADs), usually bamboo rafts. Thousands of drifting FADs are regularly deployed in the Indian Ocean by the tuna purse seine fisheries (Moreno et al. 2007), and half of the world catch of tuna are captured around those FADs (Fonteneau et al. 1999). In the Indian Ocean, FAD fishing operations started in the late 1980s (Hallier and Parajua 1999) and developed since, but the definition of a proper fishing effort associated to the catch realized under FADs remains an open question. It must be stressed that fishing on free schools or on FADs are two different strategies characterized by different catches in terms of species composition and size categories. In this regard we assumed that the behaviour of the fishermen, and consequently the trajectories of the vessels, were strategy-dependent. The analysis of the individual vessel trajectories might then be helpful to detect what parts of the trips correspond to routes towards aggregative devices.

Because of a European regulation, European tuna purse seiners have been equipped since 2000 with vessel monitoring systems (VMSs). Based on previous studies performed in terrestrial behavioural ecology (Morales et al. 2004; Jonsen et al. 2005), we developed a method to infer the activity of purse seiners from their VMS trajectories (Walker and Bez 2010). The advantage of this later work was that the model predictions were validated by scientific observations made on board 10% of the fleet. These estimated fishing activities formed the basis of the present work and was summed up by a small set of complementary spatial indicators characterizing the spatio-temporal fishing activity.

Materials and methods

VMS and observers' data

Since 2000, the European Commission legislated that all European fishing vessels longer than 24 m should be equipped with a VMS. Using a global positioning system (GPS), positions of the purse seiners were registered every hour and transmitted to shore by satellite (Argos or Inmarsat). Being GPS positions, the data were accurate (error smaller than few tens of metres). Speeds (in knots; 1 kn = 1.853 km·h^{-1}) and turning angles (in radians, rad) between consecutive positions were readily calculated from VMS data. Data concerned only the western Indian Ocean French purse seiners exploiting yellowfin tuna (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and, even if this species is not targeted, bigeye tuna (*Thunnus obesus*). This fleet (between 14 vessels in 2006 and 17 vessels 2008) landed around 100 000 tonnes per year (Pianet et al. 2008). Given the schooling behaviour of tropical tunas and that fishers detect visually tuna schools at the surface of the sea, fishing activity occurs at day. Consequently only the daytime part of the individual trajectory was used (Fig. 1).

The VMS database used in this study included 141 489 GPS positions recorded daily from 1 January 2006 to 31 December 2008. However, data collected in January suffered a large level of misreporting (for uncontrolled reasons) and were thus excluded from the analyses. The full data set corresponded to 131 fishing trips performed by the 18 French purse seiners operating in the Indian Ocean. Hourly speeds depicted two clear modes corresponding, respectively, to stillness and full speed (around 12 kn; Fig. 2*a*). Meanwhile, turning angles showed a mode around 0 rad (straight line trajectories; Fig. 2*b*). These distributions were considered as a mixture of three distributions corresponding to different states (namely cruising, tracking, and fishing); each of them being characterized by specific speed and angle distributions. First, we expected a purse seiner to move quickly through abundance-poor areas and (or) towards fishing grounds (either indicated by the presence of other vessels or by beacon-instrumented FADs). These "cruising" phases were associated with high speeds and turning angles predominantly around 0 rad. It is worth mentioning that visual checking of tuna schools is constant on board fishing vessels during daylight, so that cruising phases have to be considered as effectively contributing to fishing effort (effective in terms of detection of new, rich patches). On the other hand, within areas where tuna schools are abundant (e.g., clusters or patches of tuna schools), skippers intensively try to track schools. In these "tracking" phases, the trajectory of the vessel is expected to be more sinuous, and consequently, apparent hourly speeds are expected to be smaller on average, even though the instantaneous speeds remain large, and turning angles should be widely distributed over the full 360° because of the numerous detections appearing in both sides of the vessel. Finally, purse seiners can remain still (i.e., immobile) for a while to set the net, to observe the behavior of school prior to setting, or to repair engine breakdown (this latter is considered to be seldom as skipper would tend as much as possible to postpone reparation until night). We thus considered that each of these three states contributed to the total amount of fishing effort with different but unknown respective weight.

An observers' database was used to complement the definition of the model structure used for estimating activities from VMS data, as well as to validate model predictions. The scientific observers' program conducted in the Indian Ocean is part of the European Data Collection Framework and targets 10% of the trips. Observers on board recorded the position of the vessel every hour or each time a change in speed or in turning angle (course) occurred. The beginning and the ending time of each fishing operation were also reported as well as the fishing mode (i.e., nonassociated school or free-swimming school and FAD school). Eleven trips (corresponding to 301 days at sea and 265 sets) were available for the analysis.

Fig. 1. Example of vessel monitoring system (VMS) trajectory (one vessel; August–October 2007). Continuous lines represent night data; circles represent daylight data. Strata 1 to 4 of the Indian Ocean Tuna Commission (IOTC) are represented. Inset shows location in eastern Africa.

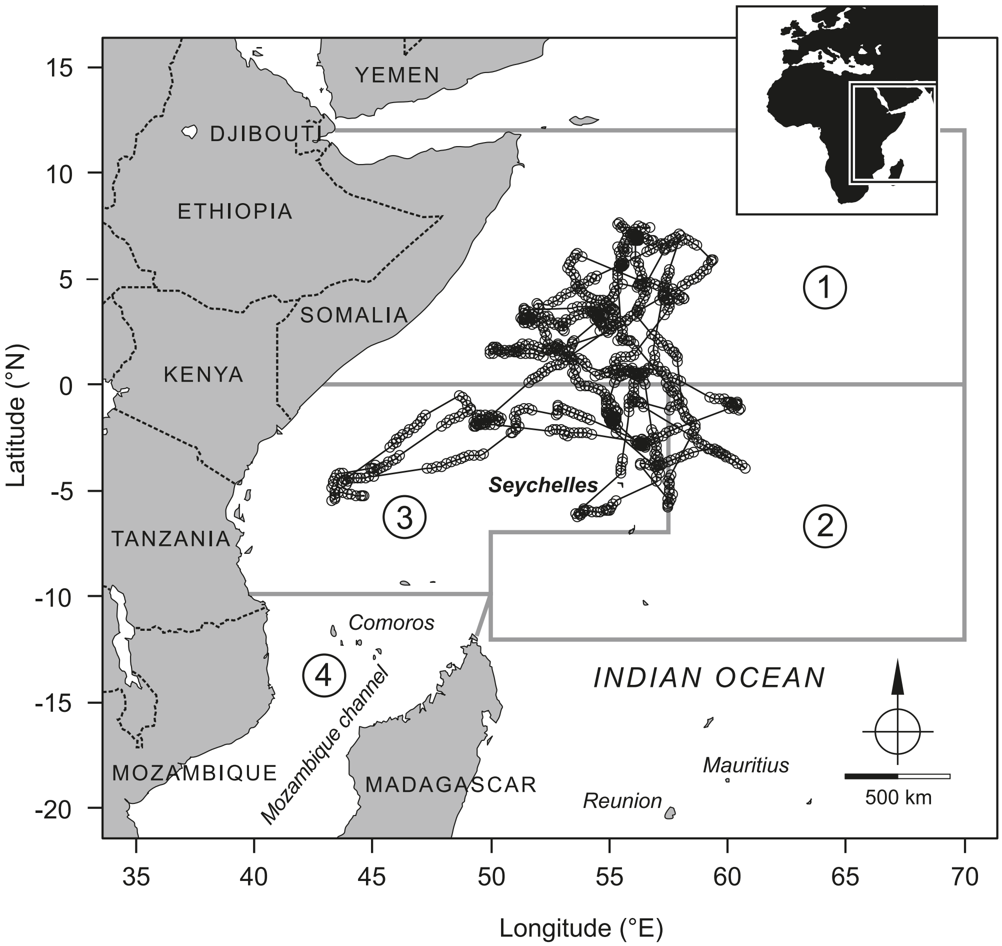
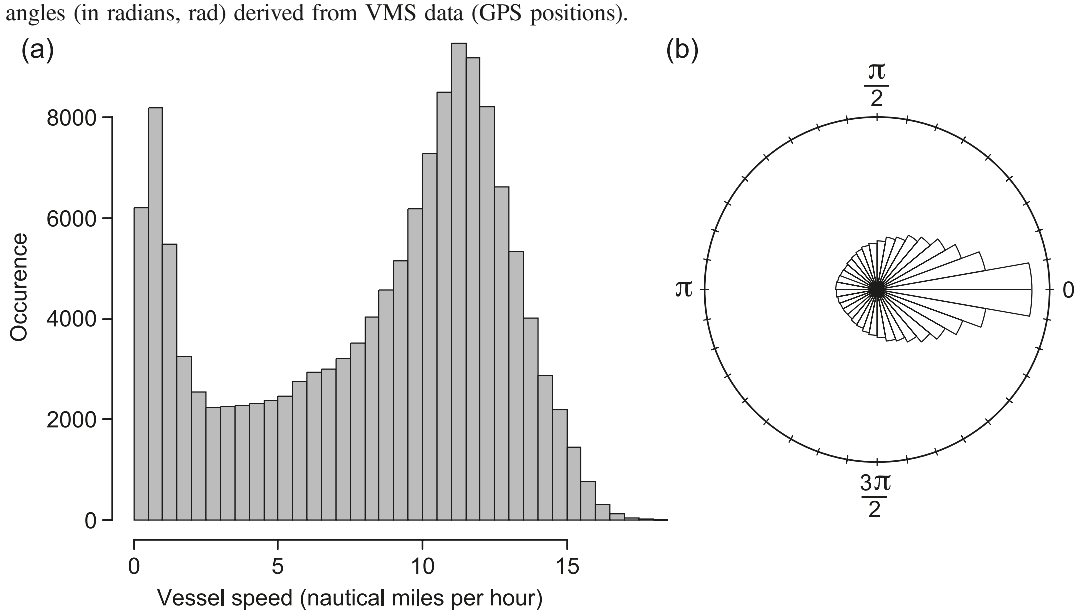


Fig. 2. 2006–2008 data of western Indian Ocean French purse seiners showing (*a*) histogram of hourly speeds (in knots; 1 kn = 1.853 km·h^{-1}) and (*b*) turning angles (in radians, rad) derived from VMS data (GPS positions).



Estimation of vessels' activities from the VMS trajectories

The model, for which a thorough description can be found in Walker and Bez (2010), consisted of a state–space model (Buckland et al. 2004; Royer et al. 2005; Patterson et al. 2008). Based on empirical evidence provided by observers' data, states were assumed to follow an order one Markovian process. States were inferred in a Bayesian framework (Gelman et al. 2004), knowing both vessel speeds and turning angles. Estimates corresponded to the state having the maximum a posteriori probability to occur.

The subset of VMS data corresponding to observers' data was extracted with the objective to tune some of the model parameters and, more importantly, to validate the model outputs before its application to the entire data set (97% of the fishing sets declared by observers were detected by the model; true-positive). Some sequences (e.g., three fishing sets of 2 h each only separated by a quarter of an hour) were viewed as one long sequence of six fishing steps.

The stops at sea (i.e., still phases that were estimated not to be fishing sets) represented 3% of the (daylight) time spent at sea by the studied fleet (Walker and Bez 2010). They were thus removed from the analysis.

Summary statistics of the components of the fishing effort at the fleet level

Model predictions were pooled at the fleet level by month and by geographical area (pixels of 0.2° × 0.2° or strata used by the Indian Ocean Tuna Commission (IOTC); see Fig. 1). Monthly time windows were chosen as a compromise to get enough data and to get relevant spatial coverages on the one hand and to have as much as possible small time windows to seek as much as possible synoptic views of the fishing effort spatial distributions on the other hand. The size of the pixels was chosen in reference to the lateral detection (~15 n.mi; 1 n.mi = 1.852 km) of tuna schools by visual inspection (binocular). Given this value, a 0.2° × 0.2° pixel was considered as exhaustively sampled as far as a vessel visited it. All results are given in hours spent in the states contributing to the total fishing effort.

Time series of the time spent by the French fleet in each type of fishing activities (fishing, tracking, and cruising) by month were produced either for the entire fishing grounds or by IOTC strata. Only the information coming from vessels operating at least 10% of the spatio-temporal window were considered.

As far as spatial characteristics are concerned, we used monthly maps of the model outputs aggregated (summed) at the fleet level and over 0.2° × 0.2° pixels for each activity (fishing, tracking, and cruising). Since it was not easy to compare simultaneously the 108 (36 × 3 = 108) raw maps, the main features of each map were summarized by using few dedicated statistics. First, the spatial extension of each activity was expressed in number of positive pixels. The homogeneity of the statistical distributions of the time spent by activity and by pixel was quantified by the Gini's index (1921) of the positive values; its variability over time was measured by the coefficient of variation (CV) of the 36 available Gini's indices. Gini's index equals 0 when all positively valued pixels have the same value, increases when there are a few patches of large values, and tends to 1 when one pixel value is much higher than all others. The analysis of each spatial distribution was complemented by the computation of an omnidirectional variogram (Rivoirard et al. 2000). The sets of the 36 standardized variograms by activity (i.e., empirical variogram divided by the sample variance) were represented by boxplots, allowing highlighting of dominant and temporally stable spatial features when they exist.

The two by two relationships between activities were summarized by Spearman's coefficients of correlation. This was complemented by the local index of collocation (Bez and Rivoirard 2000). This index, computed as a noncentered coefficient of correlation (mean product of noncentered variables divided by the root mean squares of each variable), is not impacted by zeroes. It is sensitive to the fact that large (versus low) values of each component occur in the same pixel. The local index of collocation equals 0 when one variable is null and the other is positive. It equals 1 when the two variables are identical or proportional. In addition to the correlation analysis, all omnidirectional cross-variograms were performed. They were standardized by the product of the standard deviations and represented by boxplots.

It is important to note that all the spatial statistics are dependent on the pixel size chosen for the analysis (support effect; Rivoirard et al. 2000).

Data analyses were performed with R and the package RGeoS (http://cg.ensmp.fr/rgeos).

Compositional data and fishing strategies at the vessel level

To account for temporal changes in the total time spent at sea, the time spent by each vessel and by month in each of the three activities was expressed as a percentage. Each triplet of proportions was interpreted as a fishing strategy. Mathematically speaking, each triplet is a composition (Aitchison 1982), that is, a set of values constrained by a closure relationship (the closure here was nothing but the fact that the proportions sum to one). The closure induces negative dependencies among the data that must be taken into account in the interpretation of graphical representations and analyses. Compositions are properly represented in simplex, here a triangle that is a trigone (three components) in a two-dimensional space (one degree of freedom missing because of the closure).

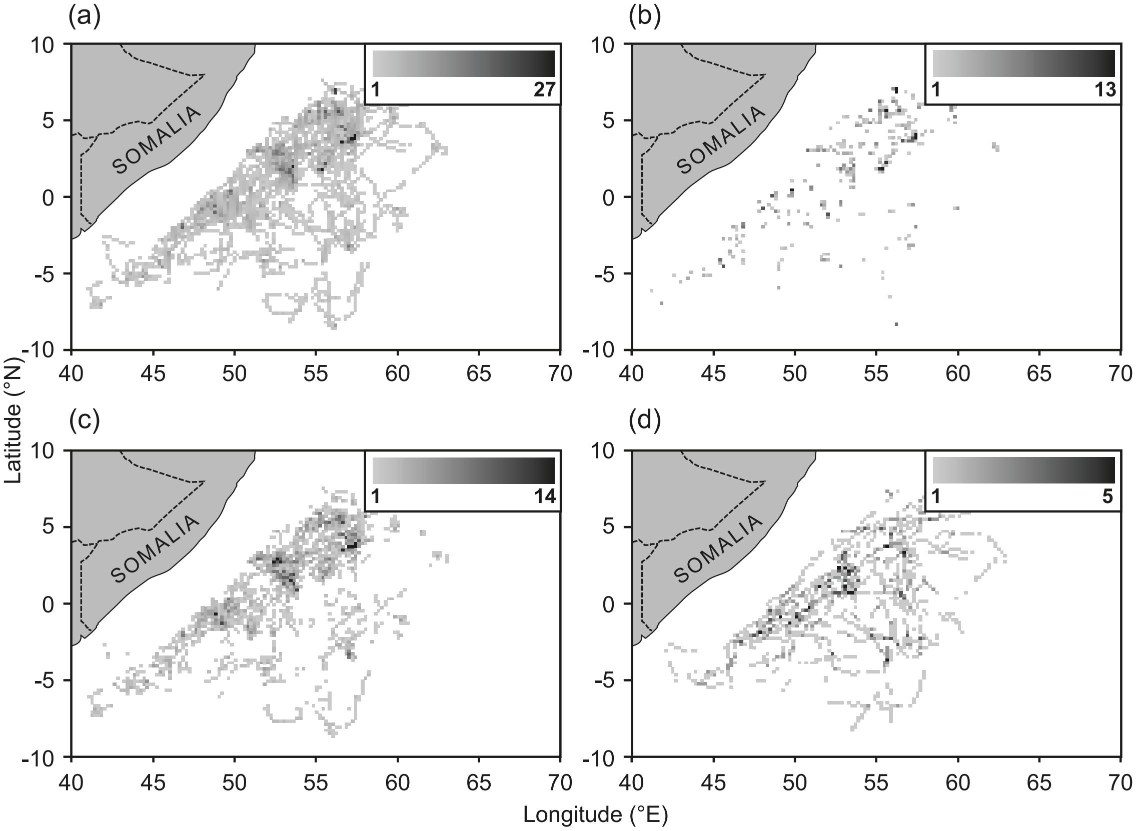
A log-ratio transformation allows projecting the data in a Euclidean space where all the usual statistical tools apply (Aitchison 1982). This transformation was used to explain the fishing strategies (i.e., the triplets of proportions) by the explanatory variables available in this analysis: month, vessel number, and strata. A linear model with all the simple effects and all the cross effects was applied. After selecting the statistically significant effects, these were back-transformed for a proper representation in the simplex. Analyses of the compositions were performed with the R package "compositions" (http://cran.r-project.org/).

Results

Fishing effort deployed by the fleet

Monthly distribution maps allowed a fine-scale analysis of the fishing effort (see Fig. 3 as an example). Over the whole period analyzed (2006–2008), the longest times ever spent by the French fleet by 0.2° × 0.2° pixel and by month were 90 h

Fig. 3. Spatial repartition of the fishing effort (hours) at the scale of 0.2° × 0.2° pixels. August 2007: (*a*) the time spent by the fleet irrespective of its activity representing the sampling effort distribution; (*b*) fishing operations (sets); (*c*) tracking phases; and (*d*) cruising phases.



(fishing), 71 h (tracking), and 10 h (cruising). The corresponding coefficients of variation were 4.2, 1.7, and 1.1, respectively.

The time spent in each type of fishing activity fluctuated around 1500 h per month for the fleet, with strong variations upon season and strata (Fig. 4). Overall, the percentage of this time spent at sea devoted to fishing, tracking, or cruising were 24%, 49%, and 27%, respectively (Fig. 4*a*). A clear spatio-temporal pattern emerged for each component of the fishing effort associated to the already known (Fonteneau 2010) seasonal displacement of the fleet connected to the tuna migrations (Figs. 4*b*–4*e*). As a matter of fact, the fleet, and thus the catch, follows tuna migrations over the western part of the Indian Ocean, shifting from strata 4, 2, 1, and 3 as time progresses over the year (Fonteneau 2010) and peaking in each of these areas in May, July, October, and December, respectively, with, however, fluctuations of dominant activities during these peaks.

The area where fishing took place was stable over time (CV = 0.23) and small (110 000 km^2 on average), while it was more variable (CVs = 0.32 for both) and large (426 000 and 405 000 km^2, respectively) for tracking and cruising (Fig. 5*a*). While the surface occupied was the same from month to month, the times spent inside these areas were not distributed similarly. Gini's index (Fig. 5*b*) showed similar levels for fishing and tracking activities with, however, a significantly smaller average value for cruising (Wilcoxon test; p value ≈ 2.10^{-5}); no clear temporal pattern emerged. Cruising activity depicted systematically smaller Gini's indices than fishing and tracking activities. A significant slight increase over time appeared, indicating that the cruising activity tended to be slightly patchier at the end than at the beginning of the studied period (2006–2008).

Monthly spatial structures of each activity (Fig. 6*a*) were strongly consistent over time (small expansion of the boxplots). This stability of the spatial structures of the vessels activities was observed despite large month-to-month geographical shifts of the fleet in the Indian Ocean (Figs. 4*b*–4*e*). The same spatial features were thus repeatedly observed for each of the three fishing activities considered whatever the location of the fleet in the western Indian Ocean. The spatial ranges happened to be about 0.6° (36 n.mi.) for the fishing activity and 1° (60 n.mi.) for the other two. The local heterogeneity of the spatial distributions was quantified by the (proportion) nugget effect of the empirical variogram. It was small for tracking (smooth maps on average) and large for fishing and cruising (rough maps on average).

At the resolution chosen for this study (i.e., monthly pixels of 0.2° × 0.2°), the coefficients of correlation were generally negative and small between cruising and fishing or tracking (Fig. 7*a*). It was significantly smaller between cruising and tracking than between cruising and fishing ($\overline{\rho}_{C,T}$ = –0.13; $\overline{\rho}_{C,F}$ = –0.04; Wilcoxon test; p value = 0.0052). Meanwhile it was positive and quite large for tracking and fishing ($\overline{\rho}_{T,F}$ = 0.55, CV = 0.23). The hierarchy between pairs was different when looking at the local co-occurrences (Fig. 7*b*). Fishing and tracking remained the most co-occurrent vessels' activities, but fishing and cruising were in strong opposition

Fig. 4. Monthly time series of the time spent by the French fleet in each type of fishing activity (fishing — open; tracking — grey; cruising — solid): (*a*) total area, (*b*) strata 4, (*c*) strata 2, (*d*) strata 1, and (*e*) strata 3. Boxplots of each set of values are represented on the right end side of each graph. The *x* axis represents months for the period 2006–2008.

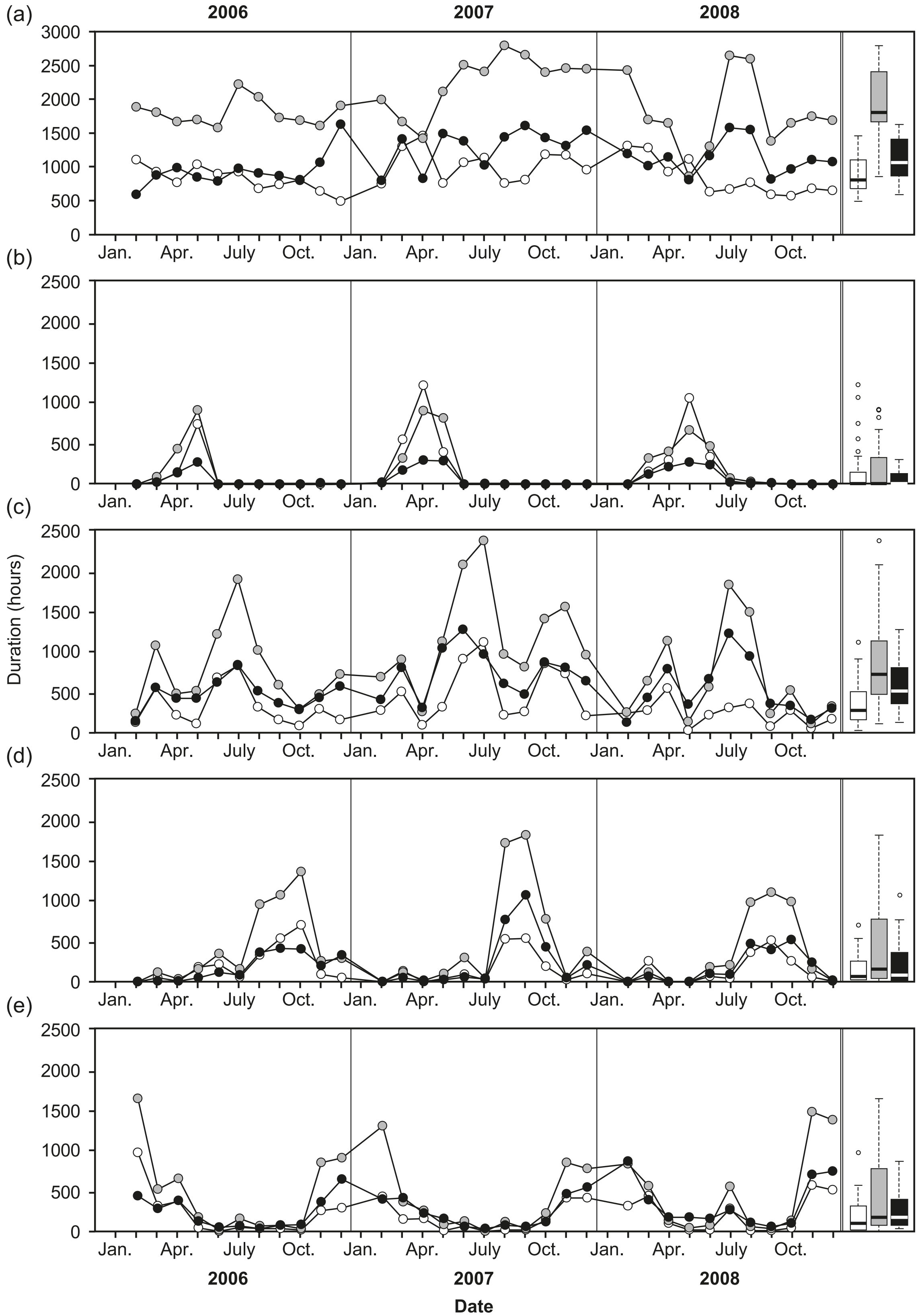
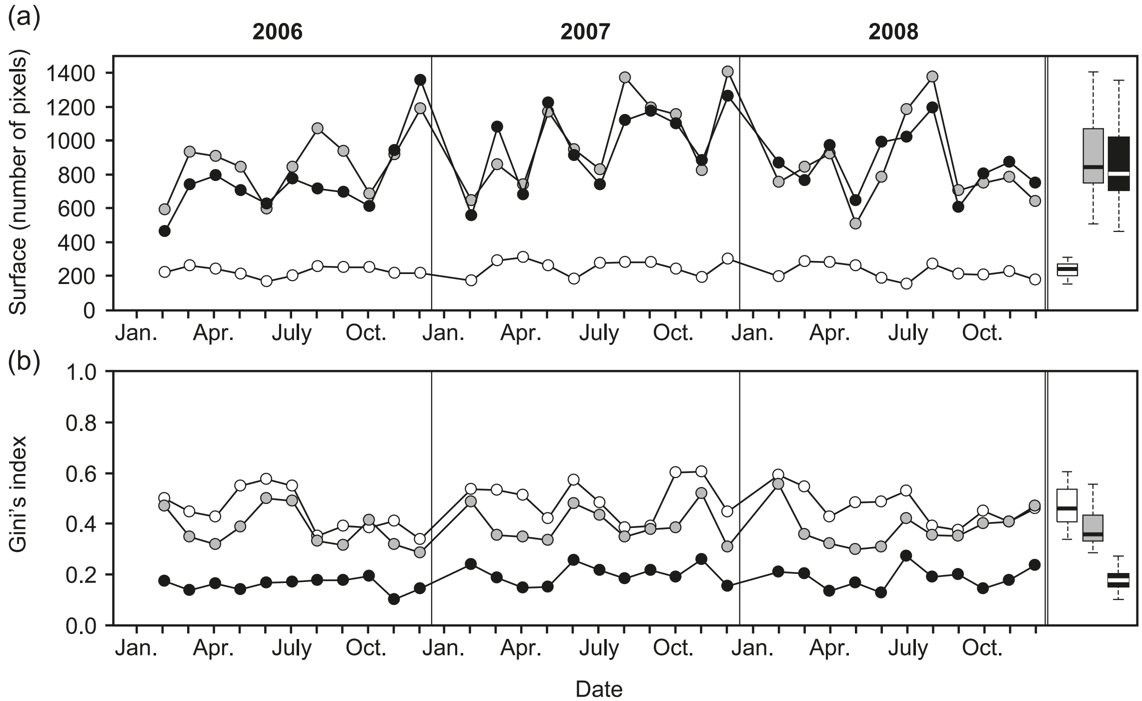


Fig. 5. Monthly monovariate summary statistics of the various fishing activities (fishing — open; tracking — grey; cruising — solid) aggregated at the fleet level: (*a*) area of presence (in number of 0.2° × 0.2° pixels); (*b*) Gini's index. Boxplots of each set of values are represented on the right end side of each graph. The *x* axis represents months for the period 2006–2008.



with small local indices of collocation (LIC); the times spent fishing and cruising were not large or small, respectively, in the same time (i.e., in the same pixel).

The (standardized) cross-variograms between activities depicted spatial structures strongly consistent over time (Fig. 6*b*). Fishing and tracking covaried positively in space, that is, a positive increase of one variable being associated, on average, to a positive increase of the other, up to 0.6°–0.8° distance (~40 n.mi.). Fishing and cruising spatial patterns were very weakly correlated. Finally, tracking and cruising cross-variograms were, on average, negative, indicating opposition in their spatial covariation (one increasing when the other decreases) with no clear spatial range. Notice that contrary to the simple variograms, none of the three average cross-variograms got nugget effect. (The average values of the various summary statistics are recapped in Table 1.)

Fishing strategies

The proportions of time spent by activity, month, pixel, and vessel were not uniformly distributed over the entire triangle but rather concentrated around the centre of gravity (24% fishing, 49% tracking, 27% cruising). Tracking represented systematically more than 20% of the time spent at sea (Fig. 8).

After selecting out the strata and the cross effects that were not significant, the best linear model explaining the compositions of fishing activities was a sum of quarter effect and a vessel ID effect without interaction. The p values were 1.7×10^{-9} and less than 2.2×10^{-16}, respectively.

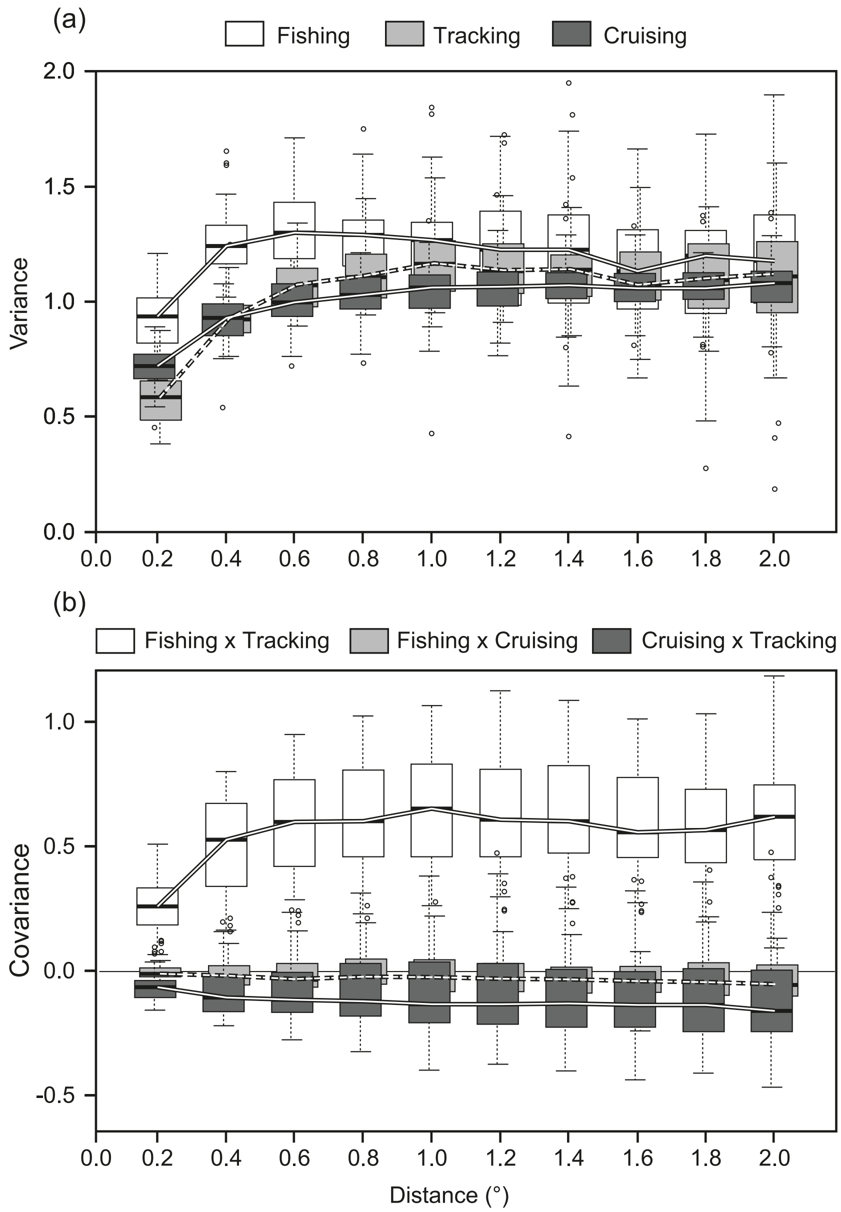
Once represented in the simplex, the quarter effect was parallel to the basis of the triangle associated with cruising. Fishing strategies changed significantly with quarter, and this change concerned essentially the allocation of time spent on fishing and tracking, the proportion of cruising activity being, on average, stable over time. Vessel ID also explained changes in fishing strategy, but orthogonally to trimester. Vessels realized, on average, the same proportion of fishing but differed significantly from the proportion of time they allocated to tracking and cruising. The two extremes were vessels whose strategies happened to allocate 40% and 65% of their time to the tracking of schools.

Discussion

VMS data for fisheries management

Defining a relevant fishing effort is a dilemma in the general case. CPUEs ought to be indices of abundance, but they are not until fishing effort measures properly the effective effort spent at sea to generate the catch. In the case of the purse seine tuna fisheries, in addition to the usual weaknesses associated to the definition of an effective fishing effort, the problem is particularly salient because purse seiners target different components of the tuna resource by using two different fishing modes (free-swimming schools versus logged schools under FADs) to which two different effective fishing efforts should be associated. Purse seiners are indeed practicing two different métiers simultaneously. In the absence of knowledge on fleet fishing strategies, crude fishing effort definitions, such as number of daylight hour minus the time spent effectively fishing, are traditionally used by the relevant tuna regional fisheries management organizations for stock assessments. The fact that this fleet is practicing two different métiers is indeed not properly addressed. One single and common definition of fishing effort is applied to all catches. In some cases, only free-school CPUEs of large yellowfins

Fig. 6. Monthly simple (*a*) and cross- (*b*) variograms of the various components of the fishing effort (fishing, tracking, cruising). Variograms were standardized by the experimental variances. Cross-variograms were standardized by the product of the standard deviations. Boxplots are based on monthly omnidirectional computations. They are slightly shifted horizontally to make them visible. The *x* axis represents the distance in degrees.



are considered relevant to follow the response of the stocks to the exploitation.

One explanation for this is that the spatio-temporal resolution of the information available in the logbook does not provide sufficient information on the vessel behavior to build any finer fishing effort. Observers' data do, at least in the context of the European Data Collection Framework, where one record must be done each hour at minimum and at any change of activity of the vessel. However, the observer program available in this fishery has a limited coverage (only 10% of the fleet), which precludes the use of these data for computing any relevant effort for the entire fleet. The present work demonstrated the interest in using VMS data at an operational level with the objective to quantify and localize three major components of the fishing effort. Fishing behaviors of tuna purse seiners and time spent in different fishing activities have already been studied from observers on board (Gaertner et al. 1999). This latter work studied in detail the chasing behavior of fishermen in the vicinity of tuna schools and in particular the phases when vessels decide to pursue schools or to set the seine. The authors also documented factors leading fishermen to change fishing zone, but this did not provide the means, at the fleet level, to move towards the definition of an effective fishing effort. The VMS data and the methodological framework developed to analyze them in a finalized manner (including combined with observers' on board data) provide, in our opinion, a unique opportunity to tackle the question of fishing effort.

Most of the VMS studies that are found in the literature have dealt with trawl fisheries (Lee et al. 2010; Rijnsdorp et

Fig. 7. Monthly bivariate summary statistics of the various fishing activities (fishing, tracking, and cruising: fishing × tracking — open; fishing × cruising — gray; cruising × tracking — solid): (*a*) coefficients of correlation; (*b*) local index of collocation (LIC); it equals 1 when large values occur in the same pixel. Boxplots of each set of values are represented on the right side of each graph. The *x* axis represents months for the period 2006–2008.

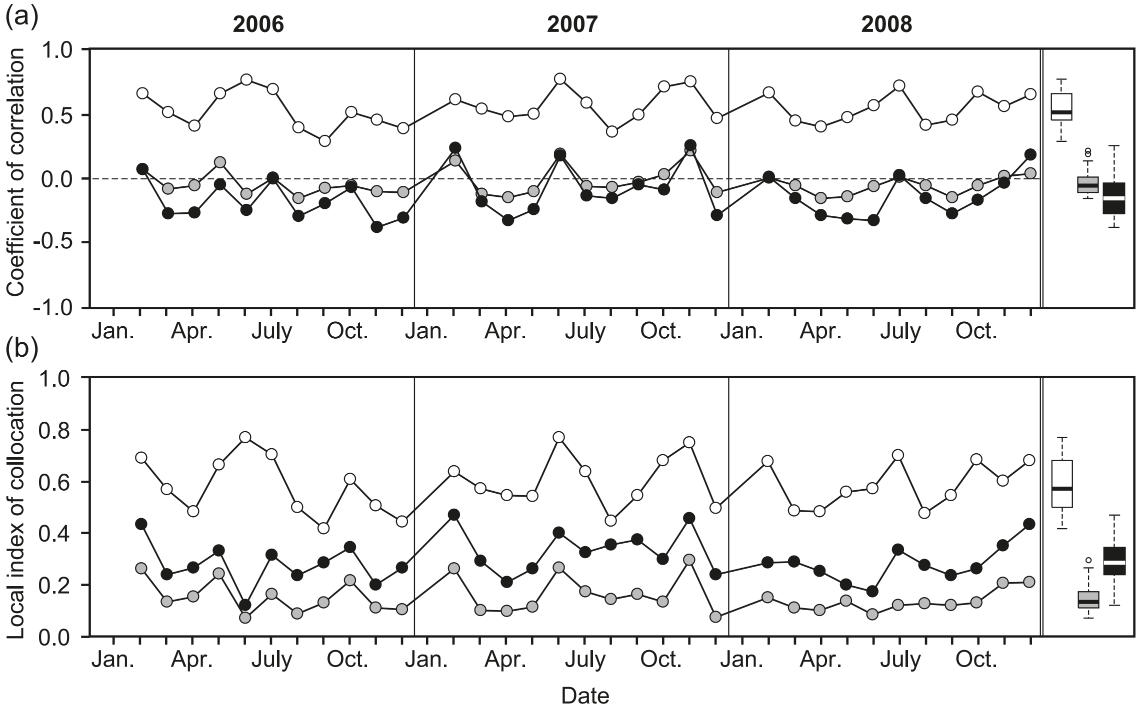


Table 1. Average values of the summary statistics for each activity.

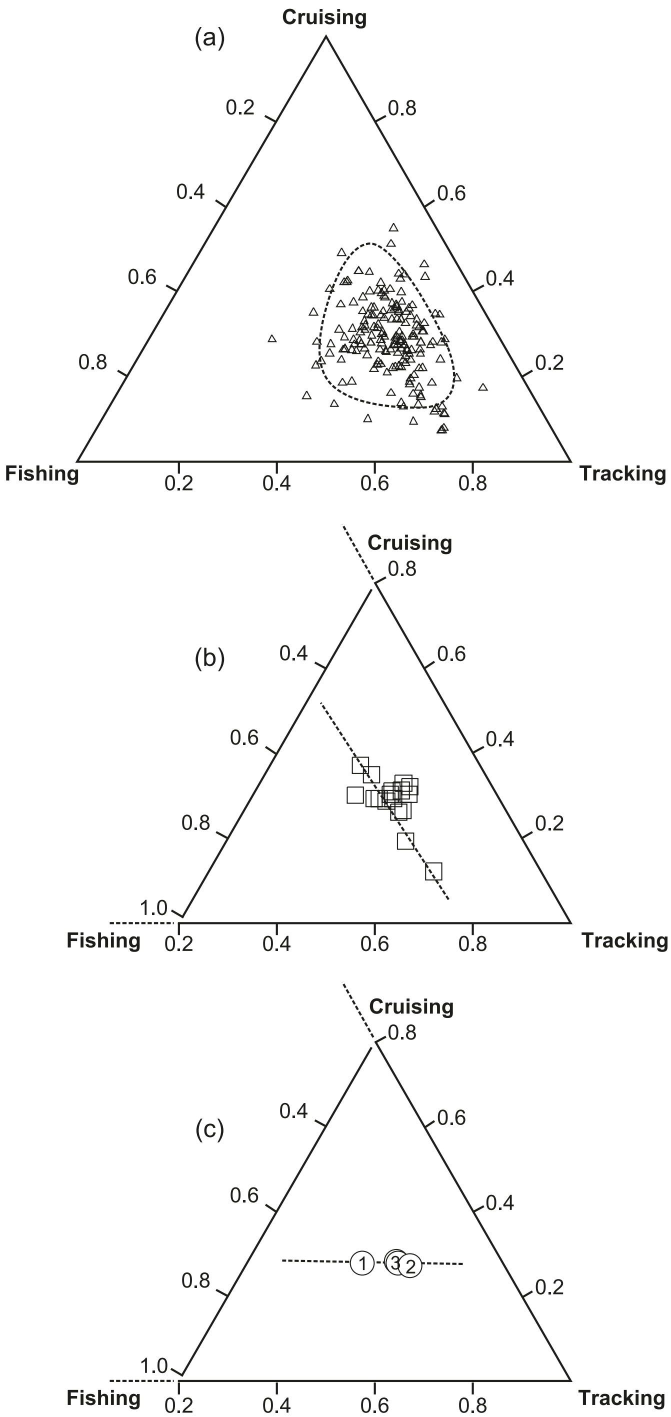
(*a*) Monovariate statistics.			
	Fishing	Tracking	Cruising
Time spent (h)	867	1861	1058
Surface of occupancy (km^2)	110 000	405 000	425 000
Gini's index	0.47	0.40	0.18
Nugget (%)	>50	25	50
Spatial range (°)	0.6	1	1

(*b*) Bivariate statistics.			
	Fishing × Tracking	Fishing × Cruising	Tracking × Cruising
Coefficient of correlation	0.55	–0.04	–0.13
LIC	0.59	0.15	0.29
Nugget (%)	0	0	0
Spatial range (°)	0.6	—	0.6

Note: Monovariate statistics: time spent (h), surface of occupancy (km^2), Gini's index (no unit), nugget (%), and spatial range (°) of the standardized variograms. Bivariate statistics: coefficient of correlation (no unit), local index of correlation (LIC, no unit), nugget (%), and ranges (°) of the standardized cross-variograms.

al. 2001; Witt and Godley 2007). This may be the reason why most of the analyses of VMS data have only targeted the identification of fishing operations strictly speaking, without considering the vessel activities in between fishing sets (Bastardie et al. 2010; Piet et al. 2007; Mills et al. 2007). A small number of studies were focussed on purse seiners but targeted also the location of the fishing sets (Bertrand et al. 2008; Joo et al. 2011). However, a VMS trajectory, specifically for pelagic fleets, contains much more potential information than the strict location of fishing operations. The searching behaviour of demersal fishing vessels is indeed reduced to a minimum and is not comparable to the larger panel of decisions to which skippers are confronted in pelagic fisheries. Contrary to trawlers, purse seiners, at least when fishing on free-swimming schools, spent the majority of their time searching for rich patch areas and, once found, for fish schools. In the present case, we estimated that the French tropical tuna purse seiners fleet spent 49% of its time searching for schools in areas with clues for tuna aggregations. We also estimated that 25% of the daylight time spent

Fig. 8. Analysis of the fishing strategies. (*a*) Proportions (small triangles) of time spent in fishing, tracking, and cruising activities by vessel and trimester are represented as compositional data (set of values with a closure relationship; Aitchison 1982). The envelope embracing 95% of the observations is represented. Significant effects of a linear model are represented: (*b*) vessel effect (17 modalities; squares) and (*c*) trimester effect (circles, four modalities; Trimester 1 = March–April–May; Trimester 2 = June–July–August; Trimester 3 = September–October–November; Trimester 4 = December–January–February. Vessel effect and trimester effect are orthogonal in the space of the compositions (i.e., parallel to different basis of the triangle); the cross effect was not statistically significant.



at sea (this would be larger if night time were considered, as they allow straight navigation towards new areas or FADs) was dedicated to cruising between rich areas, towards a beacon–FAD, or simply searching for tuna aggregations. However, within the limits of the current available information, we do not know which part of the cruising activity must be associated to change of fishing zones or to a move towards an FAD. We also do not know how to relate this cruising effort to the catches realized under the FADs it allowed to visit. In this sense, the present work is a step towards the definition of an effective fishing effort rather than a formal proposal for a new one.

The majority of the papers analyzing VMS data deal with the classification of VMS data according to the speeds deduced from them and sometimes, but not always, their turning angles. More sophisticated approaches seek for classification based on artificial neural networks (Joo et al. 2011). Recent papers (Vermard et al. 2010; Walker and Bez 2010) also suggested applying hidden Markov models following earlier applications in continental ecology (Jonsen et al. 2005; Morales et al. 2004). One of the advantages of these methods relies on the fact that they take into account sequences of VMS data.

The common weakness of most of these applications is that they were not confronted with field data. The state–space model used in the present study to estimate vessel activity all along the vessel track, step by step, has been validated on the subset of VMS data for which concomitant observers' data were available (Walker and Bez 2010). This was indeed central in our work. From an academic perspective, the fact that the model worked properly (i.e., provided results) and honoured relevant statistical criteria (e.g., mixing and convergence of MCMC chains) would have been considered sufficient. A validation step was necessary when dealing with finalized objective like fisheries management. The misdetection rate was about 10% at the step level. This rate diminished to 3% of under-detection and 15% of overdetection when dealing with fishing sets. Again, case studies where field truth allowed qualifying the model outputs are rare in the literature. Working on another fleet (Peruvian anchovy purse seiners) with another method (artificial neural networks), Joo et al. (2011) got 76% of true positives. Compared with this, the reasonably low level of misdetection we observed makes it possible to use VMS data to infer information on the vessel activity and on fishing effort in an operational perspective.

Fishing effort for the French purse seiners in the Indian Ocean

Wrapping up results

The summary statistics brought several pieces of information about the relative spatial distributions of the vessels' activities at the fleet level. The first three statistics, namely the spatial extensions, the total amounts of time allocated to each type of activity, and the Gini's index, were not spatial statistics strictly speaking, as they were not sensitive to the geolocation of the data. For each statistic, two activities got similar values, but they were different from one statistic to the other, reinforcing the fact that the three statistics formed a complementary set.

Comparing fishing and tracking, we observed that a given proportion of their total allocated times were recovered within the same proportion of area (same Gini's indices) even though the total allocated times and the total areas were strongly different. Tracking and cruising covered the same geographic area, with, overall, twice less time devoted to cruising, making mean density (i.e., the time spent by unit surface) twice smaller for cruising than tracking. Relative to this difference in overall quantities, the proportion of space required to recover a given proportion of the total was smaller for tracking than for cruising. Finally, fishing had a geographical imprint four times smaller than cruising, but both methods had the same total amount of time spent. The density was thus in the same proportion.

The spatial covariations (cross-variograms), positive between fishing and tracking and negative between the other two pairs, were strongly consistent over time. The local spatial variabilities present in each activity were not correlated (nugget effects present in each variogram, but not in the cross-variograms).

Spatial hierarchy in the fishing effort components

As expected, fishing and tracking occurred mainly in the same areas, while cruising occurred in separated areas (LIC and coefficient of correlations). The relative intermediate value of the LIC between fishing and tracking can be explained by the pixel size. At this fine spatial resolution ($0.2° \times 0.2°$ square; i.e., at a fixed time), it is difficult to imagine observing two different activities simultaneously. The time window used in this study (1 month) allowed, however, to get both activities in the same pixel. Their Gini's indices were equally large, indicating that fishing and tracking were similarly patchy. Finally, as fishing occurred in a smaller area than tracking, we can postulate that small patches of fishing activity were included in patchy areas of tracking. In the same way, the large values of surface of occupancy and the small values of Gini's index and of LIC observed for cruising proved that cruising spread in large areas outside fishing and tracking patches.

The large nugget effect and the small spatial range observed for fishing indicated that at the pixel scale, this activity could be viewed as the sum of two random processes: one being pure random and the other producing small patches of three pixels. Tracking activity was more structured (small nugget) over larger spatial aggregation. The whole set of summary statistics supported the principle of a hierarchical spatial organization of the three fishing activities with different scales: tiny to small heterogeneous patches of fishing activity included in intermediate tracking areas themselves included in foraging (cruising) area of the fleet.

Fishing strategies

The state–space model developed in this study allowed a detailed inspection of fishing strategies. Given the spatio-temporal window selected for the analysis, a fishing strategy was quantified by the proportion of daytime spent doing each of the three main activities (i.e., fishing–tracking–cruising) at a month scale. In such context, fishing strategies were likely to change from month to month and from vessel to vessel. The colinearity between strata and time of the year was strong and the two explanatory variables highly redundant. The two remaining variables happened to be orthogonal in their potential to explain the variability of the fishing strategies. Fishing strategies, described by triplets of proportions, were explained by the sum of a vessel effect ($R^2 = 66\%$) and a seasonal effect ($R^2 = 56\%$).

Vessels were not different in their proportions of time devoted to fishing. They were, however, discriminated by the way they allocated the remaining time over tracking and cruising activities. In the literature, one generally opposes obstinate predators (large percentage of tracking) to other ones capable of innovation (large proportions of cruising to survey wide and distant areas). Our analysis indicated that for the French purse seiner fleet, vessels could be discriminated by their more or less innovative versus obstinate nature. However, it is unclear how to relate this aspect with a fishing mode specialization. Considering the cost of a modern purse seiner, locating and exploiting the ephemeral patches of tuna schools with efficacy is a necessity to economically sustain the fleet (Gaertner et al. 1999). In such a context, and because the fact that (*i*) the price of large yellowfin is higher than the price of juveniles of the three major tuna species caught in the Indian Ocean and (*ii*) that large yellowfin are mainly caught in free schools while juveniles are caught under FADs, it makes sense to assume that the trajectory of a vessel targeting preferentially high-value free schools depicts predominantly tracking. However, in reality, even when targeting and tracking free schools, a skipper may decide to move to a far away potential rich area. Conversely, large amounts of drifting floating objects may be found in areas of convergence by chance without the need to locate and to travel to its own FADs. The only observed difference in behaviour between both strategies is that skippers generally prefer exploring fishing grounds alone when they decide to seed or visiting their FADs (Ariz et al. 2002).

Although the area effect was not significant to explain differences in the fishing strategies, the quarters reflected the periodicity of the fleet dynamics. This is a characteristic of the French purse seiner fleet, which follows the tuna migrations and visit, successively, strata 4, 2, 1, and 3. The largest proportion of time devoted to fishing, as opposed to tracking, was observed in May (first quarter in our analysis) when the fleet, and the tuna, seat in the Mozambique Channel, a less opened sea than north off Madagascar, where the fleet spends the rest of the year. This is also when and where tuna habitat is the most dynamic, with strong and sharp gyres moving southwards, generating clear and active fronts (Schouten et al. 2003).

Compared with the information reported in logbooks, in which only one record per day is reported, VMS data opened the possibility (*i*) to georeference multiple fishing events by day and (*ii*) to qualify and quantify the time spent at sea all along a vessel's trip. Fishing effort is thus no longer reduced to a simple number of days at sea or a raw searching time. VMS data associated with an adequate model to analyze them and data to calibrate their performance provided a way to study and quantify the spatial fleet dynamic of the exploitation.

The behavior of a vessel before a fishing operation is a clue for the fishing mode selected and consequently the fish size category targeted. Sets on free-swimming schools are likely to be performed after a tracking phase. On the contrary, sets on FADs are likely to be performed after a cruising phase. Still, the automatic discrimination of the type of set realized was not operational at the resolution used in this study, and additional information (e.g., day time of the setting (Harley et al. 2009; Fonteneau et al. 2010), proportion of artificial/natural objects by spatio-temporal strata (Fauvel et al. 2009), etc.) is required. Furthermore, some improvements are expected to be possible when increasing the frequency of VMS acquisition and (or) by the use of logbooks as the quality of the set (i.e., free versus associated schools) is a compulsory piece of information that skippers must register.

A fleet is not a simple addition of vessels. Competitive and cooperative interactions between skippers occur at various spatio-temporal scales. At one extreme, the security rules settled in 2010 to counter the development of piracy in the Indian Ocean force vessel to operate by pairs. This imposed and strong cooperation has severe consequence in terms of effective fishing effort, which should be considered carefully.

Finally, from a bio-logging perspective, it is likely that the vessel behavior could be used directly as an index of abundance without going through the rigorous definition of an effective fishing effort or a CPUE. As a matter of fact, purse seiner fisheries are such that irrespective of the fishing strategies followed by the skippers that lead them to survey space in different ways, the choices of the skipper to fish, versus not to fish, are very good clues for the presence, versus the absence, of fish. In this respect, the behavior of fishermen at sea is considered to have the same informative power about their prey as birds show for their prey (Boyd and Murray 2001; Tremblay et al. 2009). The direct use of the present work to correct the traditional CPUEs could have been an issue. However, we do not know the relative importance one should give to each component of the fishing activity when computing the effective fishing effort. How many times is searching activity more important than cruising in measuring effective fishing effort? Nobody knows. By the way these components are correlated (their sum being the nominal fishing effort), it is likely that their use in a corrected CPUE would not drastically change the results. More importantly, no field truth will ever be available to tune such analyses, which makes useless any comparison between traditional and new CPUEs, as we would then lack objective means to evaluate their difference. Fishermen, and especially seiners, have top predator-like behaviours (Bertrand et al. 2007). We thus believe that the next challenge will be to use the behaviours of the vessels to directly infer the level of the biomass of their prey (in gross terms) without having to compute any catch ratio.

Acknowledgements

Thanks to a general agreement between the French tuna owner companies (ORTHONGEL) and the French Administration of Fisheries, French tropical purse seiners' VMS data have been made available to IRD scientists.

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