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DETERMINING BLUEFIN TUNA HABITAT THROUGH FRONTAL FEATURES IN THE MEDITERRANEAN SEA

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SUMMARY

The distribution patterns of bluefin tuna schools observed during the STROMBOLI EU project (2000-2002) were analysed in relation to oceanographic conditions. High-resolution radiometers (AVHRR and SeaWiFS) were used on a daily basis to derive maps of environmental variability. An edge detection technique was especially applied to estimate the position of frontal features. Using a variety of geostatistical and point process techniques, we were able to show that the distribution of bluefin schools was partially driven by the occurrence of transient fronts in the Gulf of Lions. This is believed to be mainly a trophic association, since enhanced convergence and retention processes occur at fronts, possibly leading to higher prey densities (e.g. anchovies). The spatial density and frequency of transient fronts may therefore have an influence on the foraging activity of bluefin tuna: the distribution and evolution of the thermal fronts in the western Mediterranean Sea are further detailed for the 2001-2004 period.

RESUME

Les distributions de bancs de thon rouge observés lors du projet européen STROMBOLI (2000-2002) ont été analysées et mises en corrélation avec des données océanographiques. Des radiomètres à haute résolution (AVHRR et SeaWiFS) ont fourni des cartes quotidiennes de la variabilité de surface. Un algorithme de détection des interfaces a permis la cartographie des fronts. A l'aide d'outils géostatistiques et de processus ponctuels, on a montré que la distribution des bancs de juvéniles était partiellement conditionné par la présence et la position de fronts dans le Golfe du Lion. Cette association est vraisemblablement d'ordre trophique, car les processus de convergence et de rétention au niveau des fronts peuvent contribuer à la présence de proies (e.g. anchois) en grand nombre. La densité et la fréquence de ces fronts peuvent donc avoir un rôle important sur l'activité de foraging du thon rouge : la distribution et l'évolution des fronts thermiques en Méditerranée occidental sont ici détaillées pour la période 2001-2004.

RESUMEN

Se analizaron los patrones de distribución de los cardúmenes de atún rojo observados durante el proyecto STROMBOLI UE (2000-2002), relacionándolos con los datos oceanográficos. Los radiómetros de alta resolución (AVHRR y SeaWiFS) proporcionaron mapas diarios de variabilidad de superficie. Un algoritmo de detección de bordes permitió cartografiar los frentes. Con la ayuda de herramientas geoestadísticas y procesos puntuales, se mostró que la distribución de los cardúmenes de juveniles estaba parcialmente condicionada por la presencia y posición de los frentes marítimos en el Golfo de Lion. Esta asociación parece ser de carácter trófico, ya que el proceso de convergencia y retención en los frentes puede contribuir a una mayor presencia de presas (por ejemplo, anchoas). La densidad y frecuencia de dichos frentes podría, por tanto, desempeñar un importante papel en la actividad de forraje del atún rojo: en este documento se detalla la distribución y evolución de los frentes térmicos en el Mediterráneo occidental para el periodo 2001-2004.

KEYWORDS

Thunnus thynnus, aerial survey, Gulf of Lions, sea surface temperature, ocean colour, fronts

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1. Introduction

The Gulf of Lions is considered as an important feeding area for juvenile bluefin tuna and is also a major fishing ground for Mediterranean purse seiners (Farrugio 1981). Aerial surveys were conducted in this area during summers 2000-2002 as part of the Stromboli EU project (Fromentin 2002). This study was an attempt to derive a fishery-independent abundance index, and also provided daily distribution patterns of bluefin tuna schools in the surface layers. Our goal here was to investigate their spatial structure (e.g. clusters, trends) using spotting data, since the local rate of aggregation of the resource can have significant effects on catches or abundance indices (Petitgas *et al.* 2001). We also wanted to determine the role of oceanographic conditions in structuring the observed patterns, using satellite based high-resolution radiometers : features such as fronts are getting more and more interest from fisheries scientists, as « hot-spots » of potentially high importance for exploited resources (see e.g. Royer *et al.*, Etnoyer *et al.*, Schick, *et al.* 2004) . It is also not clearly known to which extent fishermen adjust their strategies to local peaks in abundance, thus creating highly varying fishing pressure: this effect needs to be accounted for in CPUE standardization procedures.

2. Data

2.1 Aerial survey counts

Flights were performed during August and September, involving two scientists and a professional pilot. Two flight paths (each path being completed in about 5 hours) were followed to cover the eastern and the western part of the gulf. The studied area is delimited by (3°5'E, 5°2'E) and (42°N, 43°3'N). Each school spotted during a survey day along each track were precisely located through a GPS and recorded using a GIS-equipped laptop (for more details on the aerial surveys, see Fromentin 2002). A total number of 80 juveniles BFT schools were spotted in 2000 for a number of 6 flight days, 77 in 2001 for a number of 8 flight days and 54 in 2002 for a number of 16 flight days.

2.2 Remote sensing data

High resolution maps were derived from the Sea-Viewing High Field of View Sensor and NOAA's Advanced Very High Resolution Radiometer. SeaWiFS LAC daily raw radiances were downloaded from NASA's Distributed Active Archive Center (URL: http://eosdata.gsfc.nasa.gov/data/dataset/SEAWIFS/) at a ground resolution of 1.1 km. Level-2 AVHRR SST maps were supplied by the CMS of Lannion (France), at a ground resolution of 2 km (Brisson *et al.* 2001). A total of 76 SST images (30 in 2000, 29 in 2001 and 17 in 2002) and 49 OC images (19 in 2000, 21 in 2001 and 9 in 2002) were collected to span the whole survey period. Images spoiled by clouds and nebulosity were discarded.

3. Methods

3.1 Edge detection algorithm

Two edge detection algorithms were employed: a simple yet robust enhancement technique was first applied to detect frontal boundaries on sea surface temperature and ocean colour maps. This algorithm is based on the Canny-Deriche filter (Canny 1986) and basically consists in i) image smoothing, ii) gradient computation in both (x and y) directions, iii) non-maxima suppression across the edges, and iv) hysteresis thresholding along the edges. The outputs of this filter were employed to compute the shortest distance of each detected school to the nearest thermal or ocean colour front. A second state-of-the-art algorithm was later employed for systematic analysis of daily SST maps over the 2001-2004 period. This method, based on the work of (Cayula and Cornillon 1992), allows to detect the occurrence of two neighbouring water masses with sufficiently different characteristics. The outputs were summed to derive the annual and seasonal distribution of surface fronts, as well as their temporal evolution in specific areas such as the Gulf of Lions, the Balearic Sea and the Ligurian and Tyrrhenian Seas.

3.2 Spatial statistics

A range of statistical tools were applied to the data set of school locations to assess their spatial structure. The total distribution of bluefin tuna schools was represented using kernel-density estimates with a bandwidth of 30 km **(Figure 1)**. Geostatistics, and in particular point processes were employed to study the spatial variability of the school distribution patterns. A second-order statistic in point process is given by Ripley's K-function (Ripley 1976): it is equivalent to the semi-variogram in geostatistics and measures spatial structure at different ranges, under the assumption of homogeneity and isotropy. An estimate of K is provided by:

$$\hat{K}(d) = \frac{1}{\lambda}\sum_{i=1}^{n}\sum_{j=1}^{n}(\delta_{ij}(\|x_i - x_j\| \leq d))/n$$, where δ_{ij} is 1 if $\|x_i - x_j\| \leq d$, 0 otherwise.

An edge effect correction was applied near the boundaries of the study area (Ripley 1977). Under Complete Spatial Randomness (CSR) , such as a Poisson process, the expected K(d) is equal to $\pi.d^2$. A variance-stabilized version of $\hat{K}$ is the Besag function (Besag 1977):

$$\hat{L}(d) = \sqrt{\hat{K}(d)/\pi} - d$$

L(d)=0 is equivalent to $K(d)=\pi.d^2$ and indicates Complete Spatial Randomness, L(d)>0 indicates more clustering than expected from a Poisson process (e.g. CSR), L(d)<0 indicates more repulsion than expected. Various other models than the Poisson process can be tested, such as heterogeneous Poisson process where the observed point pattern is assumed to be generated randomly by a given intensity surface $\lambda(x)$. The external variables considered in this study are: the sea surface temperature, the chlorophyll concentration, the distance to nearest thermal or ocean colour front. Compared to the homogeneous Ripley's K which assumes a Poisson random distribution, the heterogeneous version of Ripley's K (Baddeley *et al.* 2000) assumes a user defined intensity surface $\lambda(x)$=f(environment) and can be written as:

$$\hat{K}_{heterog}(d) = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{(\delta_{ij}(\|x_i - x_j\| \leq d))}{\lambda(x_i)\lambda(x_j)}$$

$K_{heterog}$ can reveal second-order aggregative properties, conditional on the environment (the Complete Spatial Randomness model is in this case an heterogeneous Poisson process of intensity $\lambda(x)$). In other words, the question we investigated is: "are the fish schools more or less aggregated than expected when modelling them using environmental descriptors?".

4. Results: Spatial structure of bluefin tuna schools

Kernel density estimates between 2000 and 2002 showed a heterogeneous distribution over the survey area: most schools were irregularly located offshore in the southern area of the survey **(Figure 1)**. Peaks in observed density coincide with the shelf-break area, and particularly with the extension of the Rhone plume (see the "comma shape" in **Figure 2**). The plume is the main feature of the Gulf of Lions area: it shows both a strong signature in chlorophyllae-a concentration **(Figure 2.b)**, and frontal density in general (i.e. it is delimited by strong thermal and ocean colour fronts densities, as seen in **Figures 2.c and 2.d**). The average sea surface temperature does not show strong spatial patterns, except for a weak north-south gradient, with colder waters (21-22°C) over the continental shelf area.

To see if any "environmental preferences" could arise from the data set, we plotted the histograms of the four environmental variables, sampled at each school location each day **(Figure 3)**, as well as the distribution of the four variables computed over the whole survey area. Temperature exhibited three peaks at 16, 21 and 24°C (corresponding to a seasonal signal sampled over the different survey periods), whereas chlorophyll concentration exhibited a single peak at 0.25 mg/l. It was not possible anymore to establish any preferendum: the distributions of these values at each school location were not significantly different from their empirical distribution in the entire survey area. This was confirmed by the acceptance of Ho in the Kolmogorov-smirnov tests ($p=0.102$ and $p=0.303$ for SST and OC respectively). On the other hand, the distances to nearest surface front were still sampled with a preference for small values (roughly less than 10 km): Ho was rejected for ocean colour fronts ($p=0.028$) and, to a lesser extent, for thermal fronts ($p=0.071$). This is interpreted as follows: when pooling the daily data, local relationships may vanish, while association with frontal features remains significant. Our conclusion is that fronts are ubiquitous features occuring at the sea surface and may be better suited in describing relationships over entire seasons, while optima in SST or OC appear more difficult to characterize since they strongly depend on local conditions (both in space and time).

We then considered the spatial structure of the observed distributions: the empirical variograms tend to indicate a spatial structure of the BFT schools at around 40 km, but they varied widely from a day to another **(Figure 4)**. The underlying processes (be them physical or biological) are thus likely to change over time. The second order characteristic of a point process (Ripley's K), as well as the spatial autocorrelation plots, revealed that the fish schools were clustered over a wider range of scales (from 10 to 80 km), indicating more aggregation than expected from a random process.

Finally, we modelled on a daily basis the observed point patterns using Poisson processes with defined intensity surfaces $\lambda(x)$. Various intensity surfaces were defined as follows: (1) a combination of the distances to the nearest ocean colour and thermal fronts, (2) the distance to nearest thermal front along with the surface temperature field, (3) the distance to nearest ocean colour front along with the phytoplankton field, and (4) all the four variables. The distance to flight path was always included to account for biases induced by transect sampling. Results were not consistent from a day to another, but clear association with neighbouring fronts could arise over a certain range of scales (figures not shown here, see Royer, et al. 2004 for more details). Satisfying fits were obtained in particular at ranges from 10 to 40 km. Still, some spatial structures still were unexplained by oceanic features, especially at very small scales (< 10km) and at larger scales (> 40km). , the migration patterns of juveniles BFT within the study area (i.e. the Gulf of Lions), which remain largely unknown, could explain such a departure at large scales. At smaller scales, over-aggregation could also be due to interactions between BFT juvenile schools, leading to larger than expected gatherings in specific zones. Another major cause for clustering on feeding grounds may be the spatial distribution of their prey, such as clupeids, that are strongly affected by oceanographic variability.

5. Thermal fronts in the western Mediterranean Sea

Considering that surface fronts can affect the spatial aggregation of bluefin tuna schools, at least at certain scales, we conducted a systematic analysis of thermal fronts density and evolution over 2001-2004 in the western basin. The main features of the Mediterranean counter-clockwise circulation are visible in **Figure 5**: well-known features such as the pseudo-steady eddies in the Alboran Sea or the Balearic fronts can be retrieved. Fishing grounds such as the Rhone plume's extension in the Gulf of Lions or the Liguro-provencal current have a clear frontal signature. Shelf-break fronts can be seen all around the basin, and very close to the shore where the continental shelf is narrow (see the west coast of Corsica, or the Algerian coast). Coastal fronts are also visible along the southern Sicilian coast. The circulation in the Tyrrhenian Sea apparently produces an important signal in the vicinity of Corsica, which an area of sport fishing for bluefin tuna.

For illustration purposes, four areas were delimited for the extraction of seasonal signals in frontal density **(Figure 6)**. The Alboran Sea, the Gulf of Lions and the central Tyrrhenian sea all display a strong increase in frontal probability during May or June, with a relatively flat plateau until December. Such signal may be linked to enhanced Eddy Kinetic Energy which display comparable seasonal fluctuations. The Gulf of Gabes in Tunisia shows a decline in frontal density during September, which may be linked to tidal phenomena. Analysis of interannual and seasonal variability of Kinetic Energy in the Mediterranean basin are currently conducted using Topex/Poseidon and Jason altimetry data.

6. Discussion-conclusion

In this study, we were able to show the effect of the environment, and especially fronts, in structuring the distribution of juvenile bluefin tuna schools observed by aerial surveys. The association was valid only over a limited range of spatial scales (10 to 40 km), indicating that other processes occur at small scales (over-aggregation due to unseen prey clusters or other behavioural processes) and larger scales (in and out movement at the border of the studied area). The relationship between tuna aggregates and frontal meanders is most probably indirect and trophic-related, which has been confirmed by observation through aerial spotting in this study. Advected material at fronts can provide favourable feeding grounds to small clupeids, which are in turn sought by bluefin tuna. Interannual and seasonal variations in frontal density in the Mediterranean Sea may not have a direct influence on the global carrying capacity of the basin. However, it may have an important impact on the local aggregation of nutrients, phytoplankton and zooplankton species, and eventually fish schools, thus leading to possible changes in density-dependent responses in marine populations. Transient surface fronts are particularly difficult to observe and assess, but automatic tools applied to high resolution satellite maps may allow to monitor such features for further studies on Mediterranean top predators. Further work may involve the analysis of fluctuations of catches in some delimited, well-known fishing grounds, in regard to variations of frontal densities.

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References

BADDELEY, A., J. Moller and R. P. Waagepetersen. 2000. Non- and semiparametric estimation of interaction in inhomogeneous point patterns. Statistica Neerlandica 54: 329-350.

BESAG, J. 1977. Efficiency of pseudo-likelihood estimation for simple Gaussian fields. - Biometrika 64: 616-618.

BRISSON, A., P. Le Borgne and A. Marsouin. 2001. North Atlantic Regional Sea Surface Temperature Product Manual Version 1.1. - Météo-France, p. 30.

CANNY, J. 1986. A computational approach to edge detection. - IEEE Transactions on Pattern Analysis and Machine Intelligence 8.

CAYULA, J. F. and P. Cornillon. 1992. Edge detection Algorithm for SST images. - J. Atmos. Oceanic Technol. 9: 67-80.

ETNOYER, P., D. Canny, B. Mate and L. Morgan. 2004. Persistent Pelagic Habitats in the Baja California to Bering Sea Ecoregion. - Oceanogr. 17: 90-101.

FARRUGIO, H. 1981. Exploitation et dynamique des populations de thon rouge, *Thunnus thynnus* (Linné 1758) Atlanto-Méditerranéennes. - Université des Sciences et Techniques du Languedoc, p. 266.

FROMENTIN, J.M. 2002. Final Report of STROMBOLI. - European Community - DG XIV, p. 109.

PETITGAS, P., D. Reid, P. Carrera, M. Iglesias, S. Georgakarakos, B. Liorzou and J. Massé. 2001. On the relation between schools, clusters of schools, and abundance in pelagic fish stocks. - ICES J. Mar. Sci. 58: 1150-1160.

RIPLEY, B. D. 1976. The second-order analysis of stationary point processes. - J. Appl. Proba. 13: 255-266.

RIPLEY, B. D. 1977. Modelling spatial patterns. - J. R. Stat. Soc. 39: 172-212.

ROYER, F., J.M. Fromentin, and P. Gaspar. 2004. Association between bluefin tuna schools and oceanic features in the western Mediterranean. - Mar. Ecol. Prog. Ser. 269: 249-263.

SCHICK, R. S., J. Goldstein and M. Lutcavage. 2004. Bluefin tuna (Thunnus thynnus) distribution in relation to sea surface temperature fronts in the Gulf of Maine (1994-96). - Fish. Oceanogr. 13: 225-239.

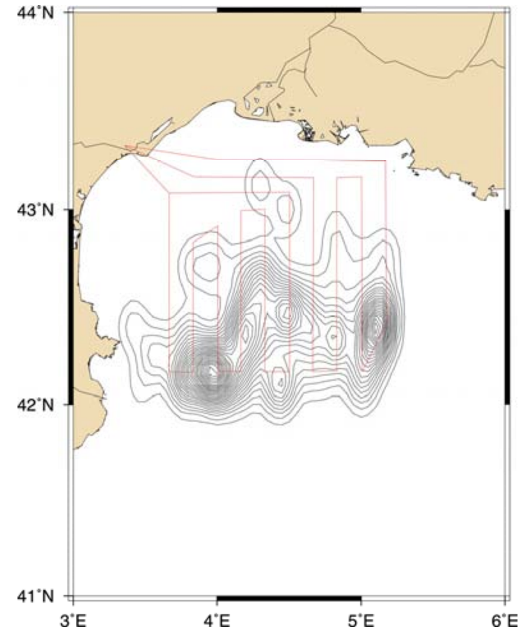

Figure 1. 2000-20002 bluefin schools density in the Gulf of Lions, estimated with a gaussian kernel filter of width 30 km.

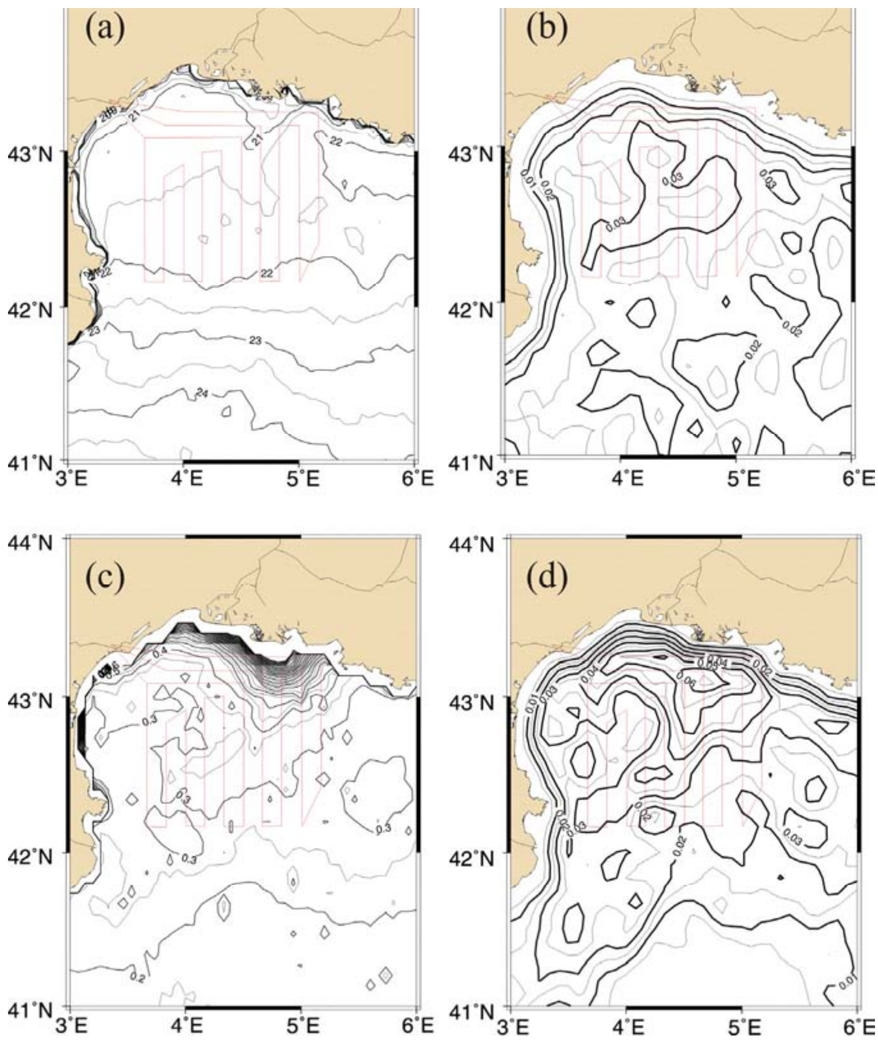

Figure 2. a) AVHRR Sea Surface Temperature, b) SeaWiFS chlorophyll concentration, c) thermal fronts density, d) ocean colour fronts density, averaged over the survey seasons (2000-2001-2002). Front density refers to a probability of occurrence.

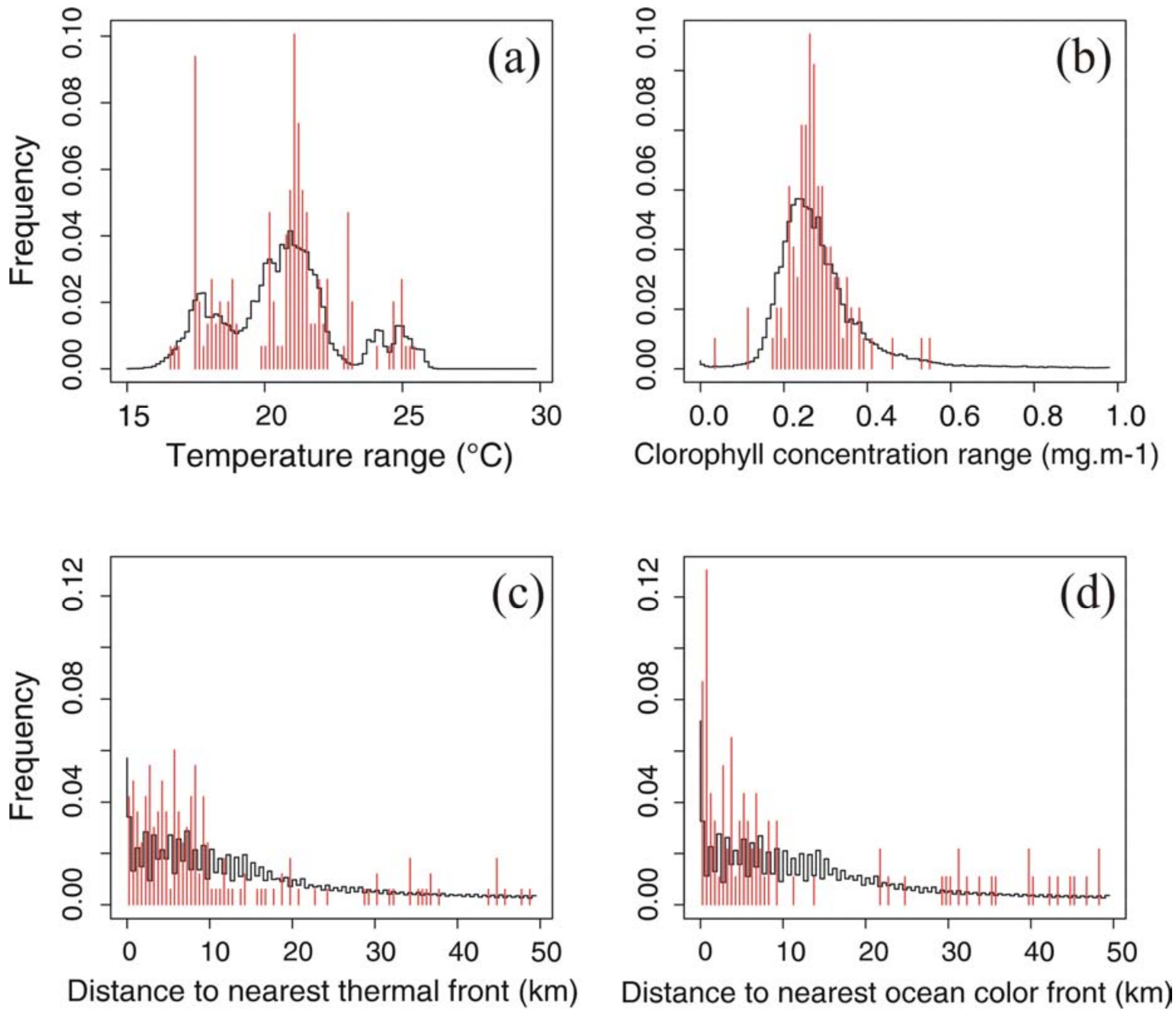

Figure 3. Prior (continuous line) and sampled at each school (vertical bars) distributions of four environmental descriptors, considering the whole survey in 2000, 2001 and 2002: sea surface temperature (a), chlorophyll concentration (b), distance to nearest thermal front (c), distance to nearest ocean colour front (d).

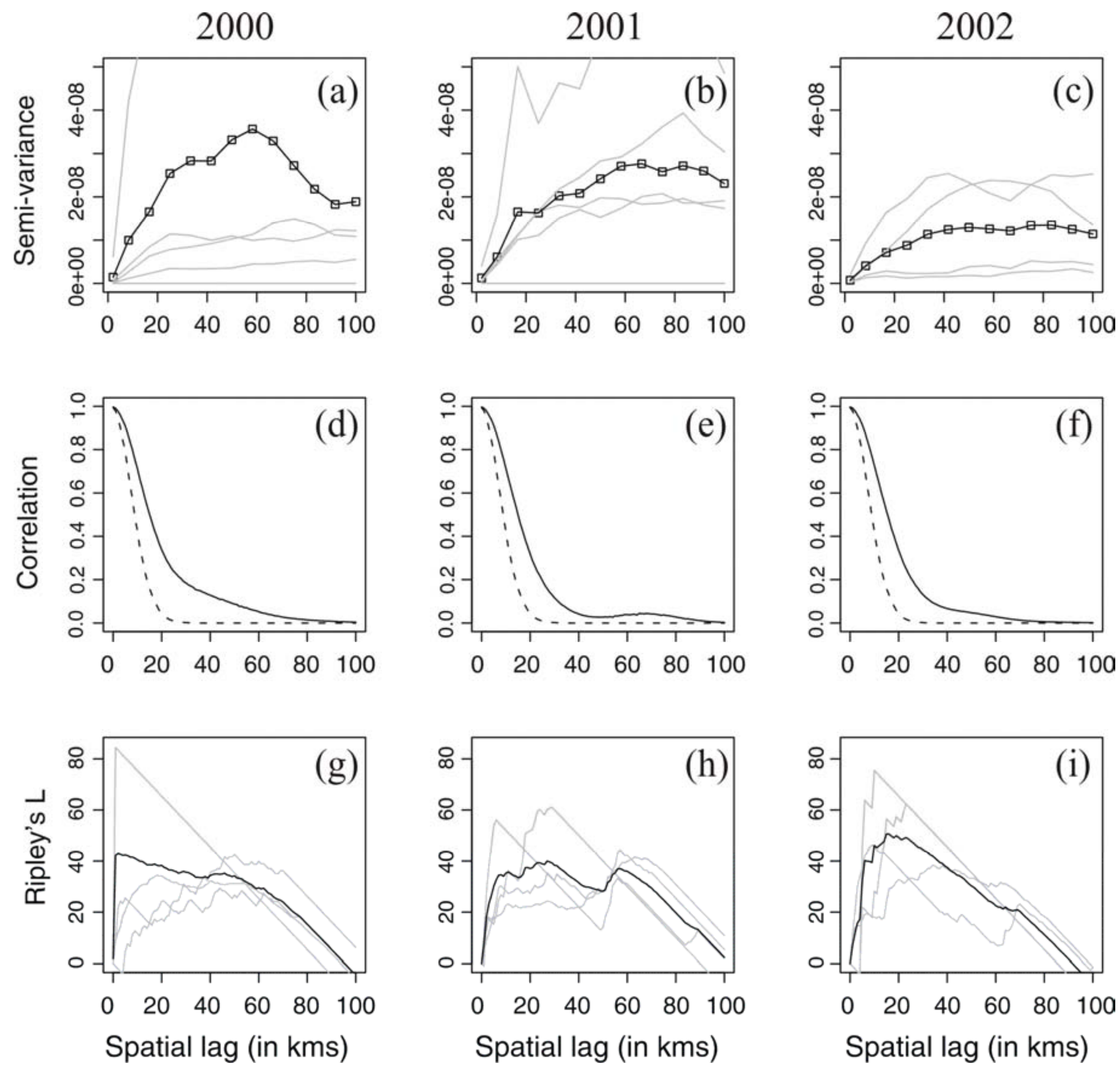

Figure 4. Spatial statistics for Bluefin schools density in 2000 (left), 2001 (center), and 2002 (right). Top panel shows daily empirical variograms (grey line) superimposed with yearly-average (black line), middle panel shows the spatial autocorrelation of the intensity surface (dark line) along with the spatial autocorrelation induced by the kernel smoothing (dotted line), bottom panel shows the corresponding Ripley's K functions.

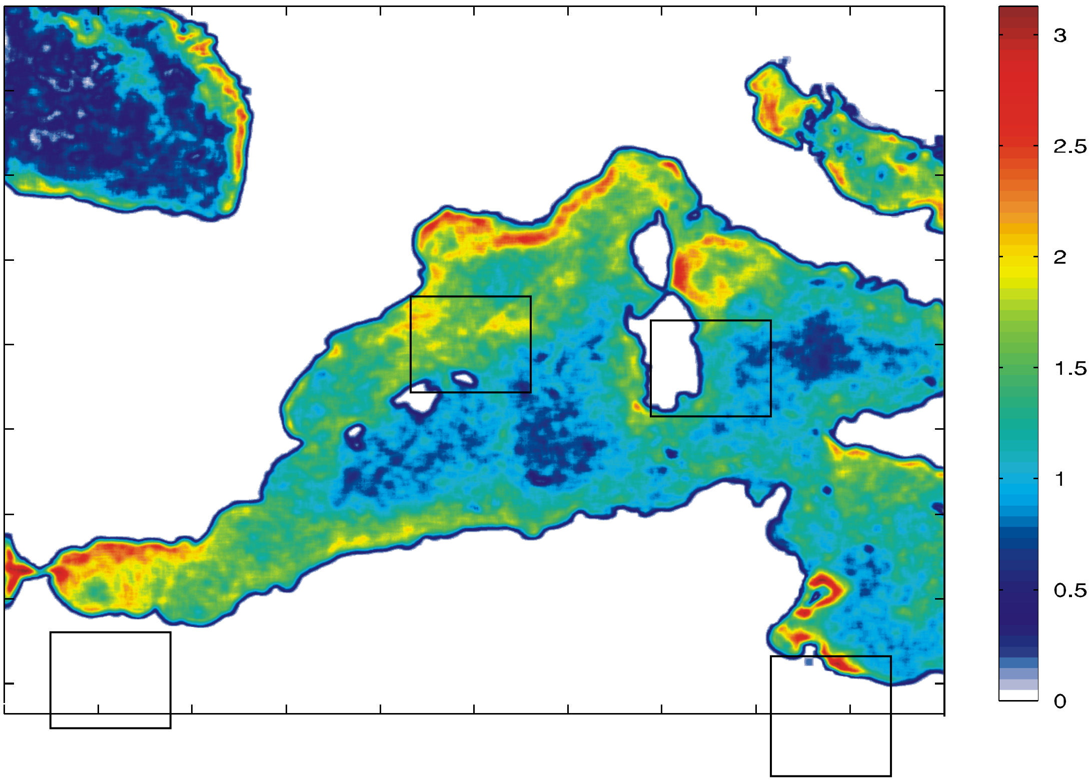

Figure 5. Density of thermal fronts in the western Mediterranean sea over 2001-2004. Coloured scale indicates the probability of occurrence in % (i.e. the ratio of the number of times a pixel was classified as a front to the number of times the pixel was clear). Monthly time series of mean frontal probability were extracted from the four areas delimited in black.

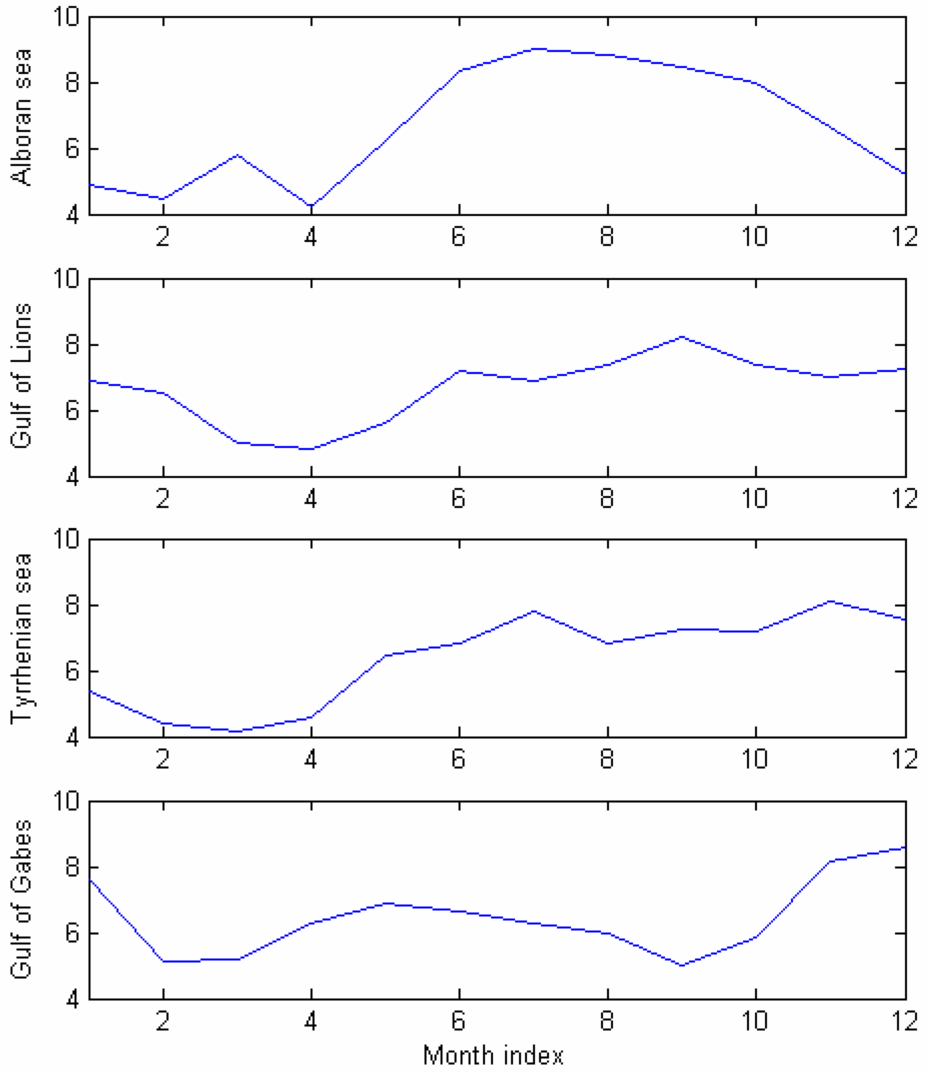

Figure 6. Monthly time series of mean probability of frontal occurrence in the Alboran Sea, the Gulf of Lions, the Tyrrhenian Sea and the Gulf of Gabes (Tunisia), as delimited in Figure 5. The four time series were averaged over the years 2001-2004.