Progress in Oceanography 82 (2009) 227–238

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Relationship between environment and the occurrence of the deep-water rose shrimp *Aristeus antennatus* (Risso, 1816) in the Blanes submarine canyon (NW Mediterranean)

F. Sardà[a,*], J.B. Company[a], N. Bahamón[b], G. Rotllant[a], M.M. Flexas[c], J.D. Sánchez[a], D. Zúñiga[d], J. Coenjaerts[b], D. Orellana[a], G. Jordà[c], J. Puigdefábregas[e], A. Sánchez-Vidal[d], A. Calafat[d], D. Martín[b], M. Espino[e]

[a] Institut de Ciències del Mar (ICM-CSIC), Passeig Marítim de la Barceloneta 37-49, 08003 Barcelona, Spain
[b] Centre d'Estudis Avansats de Blanes (CEAB-CSIC), Carrer d'accés a la Cala Sant Francesc 14, 17300 Blanes, Girona, Spain
[c] Institut Mediterrani d'Estudis Avançats, IMEDEA (UIB-CSIC), Miquel Marquès 21, 07190 Esporles, Mallorca, Spain
[d] Universitat de Barcelona, Facultat de Geologia, GRC Geociències Marines, Dept. Estratigrafia, P. i Geociències Marines, Martí i Franqués s/n, 08028 Barcelona, Spain
[e] Laboratori d'Enginyeria Marítima (LIM/UPC), Universitat Politècnica de Catalunya, Jordi Girona 1-3, 08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 11 February 2009
Received in revised form 8 July 2009
Accepted 8 July 2009
Available online 12 July 2009

ABSTRACT

We performed a multidisciplinary study characterizing the relationships between hydrodynamic conditions (currents and water masses) and the presence and abundance of the deep-water rose shrimp *Aristeus antennatus* in a submarine canyon (Blanes canyon in the NW Mediterranean Sea). This species is heavily commercially exploited and is the main target species of a bottom trawl fishery. Seasonal fluctuations in landings are attributed to spatio-temporal movements by this species associated with submarine canyons in the study area. Despite the economic importance of this species and the decreases in catches in the area in recent years, few studies have provided significant insight into the environmental conditions driving shrimp distribution. We therefore measured daily *A. antennatus* catches over the course of an entire year and analyzed this time series in terms of daily average temperature, salinity, mean kinetic energy (MKE), and eddy kinetic energy (EKE) values using generalized additive models and decision trees. *A. antennatus* was captured between 600 and 900 m in the Blanes canyon, depths that include Levantine Intermediate Water (LIW) and the underlying Western Mediterranean Deep Water (WMDW). The greatest catches were associated with relatively salty waters (38.5–38.6), low MKE values (6 and 9 $cm^2 s^{-2}$) and moderate EKE values (10 and 20 $cm^2 s^{-2}$). Deep-water rose shrimp occurrence appears to be driven in a non-linear manner by environmental conditions including local temperature. *A. antennatus* appears to prefer relatively salty (LIW) waters and low currents (MKE) with moderate variability (EKE).

Published by Elsevier Ltd.

1. Introduction

The relationship between the environment and the distribution and abundance of certain marine species is a fundamental issue in fisheries science, particularly for small pelagic (Cury and Roy, 1989; Lluch-Belda et al. 1989; Beverton, 1990). These fisheries are associated with changes in surface currents and weather (Bakun and Agostini, 2001; Agostini and Bakun, 2002; Chávez et al., 2003; Hare and Able, 2007). However, very few studies have examined deep-water species dwelling in demersal habitats. Most studies consider only the morphological or physiological adaptations of species to the deep-sea environment (Gage and Tyler, 1990; Childress, 1995; Herring, 2002) or to long-term variations (Billett et al., 2001; Danovaro et al., 2001; Bailey et al., 2006). Recently, Carbonell et al. (1999), Massutí et al. (2008), and Maynou (2008a,b) hypothesized that the North Atlantic Oscillation (NAO index) influences the fluctuations observed in demersal resources, particularly for red shrimp. There is very little evidence linking the presence of commercial species to specific deep-water hydrographic conditions (deeper than 600 m), and there are very few studies that consider deep-sea oceanographic processes that may influence deep-sea fisheries, such as currents, cascading (water down a slope), re-suspension, or particle flows (Puig et al., 2001; Moore and Gordon, 2003; Company et al., 2008).

Submarine canyons support high biodiversity and prodigious biological productivity and many biological processes are altered or intensified in the proximity of canyons (Hickey, 1995; Gili et al., 1999). Submarine canyons are a defining feature of the continental shelf along the continental margins in the northwestern

---

[*] Corresponding author. Tel.: +34 932309549; fax: +34 932309555.
E-mail address: siscu@icm.csis.es (F. Sardà).

0079-6611/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.pocean.2009.07.001

Mediterranean Sea (Canals et al., 1982, 1996). The canyons act as primary channels for sediment transport and particle fluxes (Monaco et al., 1990; Heussner et al., 1996); are major topographical features that alter water circulation patterns and dynamics (Durrieu de Madron et al., 1996); and serve as biodiversity refuges (Gili et al., 1998), and as key areas for the recruitment and maintenance of living resources (Cartes, 1994; Sardà et al., 1994; Stefanescu et al., 1994; Sardà and Cartes, 1997).

Circulation in the northwestern Mediterranean Sea is generally cyclonic along the continental slope and is known as the Northern Current, forced by the introduction of Atlantic Water through the Strait of Gibraltar (Hopkins, 1985; Millot, 1999; Pinot et al., 2002; Bas, 2005). Levantine Intermediate Water (LIW), originating in the Eastern Mediterranean basin, and Western Mediterranean Deep Water (WMDW), originating in the Ligurian Sea under severe winter conditions, both flow in the same direction. The surface signature of the current is intensified by a shelf-slope density front that separates cooler, fresher waters from the continental shelf from warmer, saltier waters from the open sea. A typical vertical current profile yields maximum surface speeds of about 30–50 cm s^{-1}, decreasing linearly with depth down to minimum velocities of 3–5 cm s^{-1} approximately 500 m from the bottom. The mesoscale variability of the Northern Current ranges from 3 to 10 days and is usually associated with baroclinic instability (Millot, 1999). The upper layer of the Northern Current interacts with local submarine canyons, which alter the route of the current in the region around the shelf break without altering the offshore flow (Zúñiga et al., 2009). Shelf-slope exchanges at the shelf edge have been observed near the Gulf of Lions submarine canyons, caused by intense cross-slope fluctuations in the Northern Current attributed to 2-to-5 day Northern Current meanders (Durrieu de Madron, 1996). Thus, the mean bottom flow rates in a submarine canyon may range between 2.4 and 3.7 cm s^{-1}, occasionally reaching 10 cm s^{-1} (Puig et al., 2000).

Heussner et al. (1996) observed that (i) bottom flow rates in the direction of the canyon axis within the canyons decrease substantially down-canyon, (ii) vertical flow rates increase towards the bottoms of the canyons, and (iii) mean flow rates in the direction of the canyon axis measured inside the canyons are on average twice as high as the values measured on the adjacent open slope. These observations suggest that canyons act as sumps and as primary channels for transferring particulate and organic matter towards the distal margin.

The deep-water rose shrimp *Aristeus antennatus* (Risso, 1816) is a target species of Mediterranean fisheries, particularly off the Catalunya region, and are both abundant and economically valuable. This resource is regularly exploited by a specialized fleet of relatively large boats (between 800 and 2200 HP) adapted to catch in deep-sea fishing grounds at depths between 600 and 900 m throughout the year. *A. atennatus* is the dominant crustacean in the deep-sea benthic ecosystem and plays an important role in the biological ecosystem (Abelló et al., 1988; Cartes and Sardà, 1992, 1993; Bianchini and Ragonese, 1994). A number of studies have focused on the biology and ecology of this species in the Catalan Sea (Sardà and Demestre, 1987; Cartes and Sardá, 1989; Demestre and Fortuño, 1993; Sardà and Cartes, 1993; Cartes, 1994; Demestre, 1995; Sardà et al., 1998) and also on its importance to fisheries (Demestre and Lleonart, 1993; Sardà, 1993; Carbonell et al., 1999;). *A. antennatus* is characterized by spatio-temporal movements related to the geographic structure of submarine canyons (Tobar and Sardá, 1987; Demestre and Martín, 1993). Rose shrimp fisheries are based in areas on the open slope outside the canyon, areas known locally as "*baranas*". Fishing occurs in these areas from late winter to early summer, and fishing along the canyon walls from the mid-canyon to the canyon head, known locally as the *Sot-Través* fishing ground, occurs mainly from late summer to mid-winter (Sardà and Cartes, 1994; Sardà and Cartes, 1997; Tudela et al., 2003).

Ghidalia and Bourgois (1961) proposed an association between the presence of certain shrimp populations and the temperatures of specific water masses. According to this group, temperatures between 14 and 15 °C and salinities of around 38, typical for the continental shelf and the upper slope, are associated with the presence of a shallower dwelling shrimp, *Parapenaeus longirostris*. A slightly lower temperature (ca. 13.5 °C) and slightly higher salinity (ca. 38.5) are associated with the presence of *Aristaeomorpha foliacea*. These temperatures and salinity values are characteristic of the LIW. Finally, they suggested that the species considered here, *A. antennatus*, prefers a temperature of 12.8 °C and a salinity level of 38.4, values typically observed in the WMDW underlying the LIW.

Previous studies have focused on both the geology and hydrographic processes of the studied region (Puig and Palanques, 1998a,b). Furthermore, Ghidalia and Bourgois (1961) primarily considered temperature and salinity, which are correlated with the presence of *A. antennatus* and *A. foliacea*, as discussed later in other works (Cartes et al., 2002; Sardà et al., 2004; Maynou, 2008a,b; Company et al., 2008;). Other environmental aspects related to population movements and the influence of biotic and abiotic factors, including food availability, have also been considered (Cartes and Maynou, 1998; Cartes and Carrasón, 2004; Cartes et al., 2008). Finally, the relationship between deep-sea resources and nepheliod layers as a source of nutrients on western Mediterranean middle-slopes has been described by Puig and Palanques (1998b); and Puig et al. (2001).

The objective of this study was to lay a foundation for understanding a major fishery resource in the western Mediterranean Sea, the deep-water rose shrimp (*A. antennatus*, Risso, 1816), in the framework of the environmental factors arising from the structure of a submarine canyon and the related deep-water dynamics.

2. Material and methods

2.1. Sampling

The study area was the Blanes submarine canyon and the adjacent areas along the continental slope in the northwestern Mediterranean Sea (Fig. 1). The head of the canyon is embedded in the continental shelf 60 m deep at less than 4 km offshore (Díaz and Maldonado, 1990). It then broadens while increasing in depth, with the lower course reaching down to 2000 m with a breadth of 20 km (Canals et al., 1982). Hydrological conditions and fisheries yields from the fishing grounds around this submarine canyon were monitored concurrently over the course of one full yearly cycle (March 2003–May 2004). Three instrument lines carrying current meters and Technicap PPS3 automatic sediment traps were moored throughout the region (Table 1, Fig. 1). The moored instruments made it possible to study current, physical characteristics of the water masses, and biogeochemical particle fluxes simultaneously at various depths at each station over an entire annual cycle (see further methodological details in Zúñiga et al. (2009). Shrimp catch data sources consisted of: (i) statistics compiled by the official fishermen's association of total daily sales of the Blanes harbour and (ii) the logbooks of fishing vessels targeting the shrimp fisheries, maintained by the skippers. These logbooks correspond to 8 boats of the total 13 boats that caught 80% of the total shrimp annual catch between January 2002 and July 2004. The catch statistics consisted of records of daily deep-water rose shrimp landings based on bills of sale on wharf at Blanes harbour, and included all the fishing grounds around the canyon. The logbooks specified daily landings by vessel (kg), fishing ground, depth

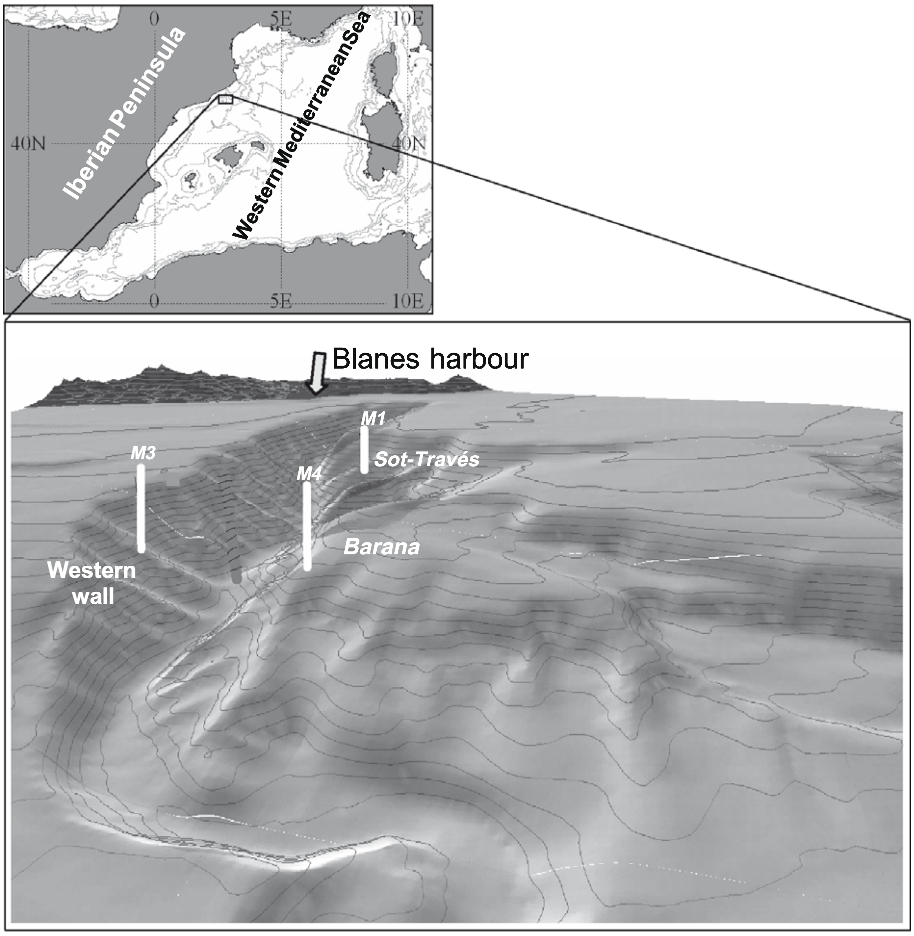

Fig. 1. Overview of the sampling sites identifying the fishing grounds. Moorings are indicated by vertical white lines.

Table 1
Geographical locations of the mooring sites with respect to the fishing grounds.

Station	Latitude	Longitude	Depth (m)	Fishing ground
1	41°50556N	02°90750E	600	*Sot-Través*
3	41°36250N	02°80530E	900	*Westernside canyon*
4	41°32806N	02°95472E	900	*Barana (easternside)*

and trawling time. Based on these data, we calculated the seasonal catch per unit of effort (kg h^{-1}) for each fishing ground. Once transferred to a database, all data were analyzed using a GIS specially implemented for that purpose. Table 2 summarizes the basic catch data recorded.

Shrimp abundance was related to the environmental parameters using the mooring closest to the fishing ground and towing depth. Accordingly, mooring 1 was associated with the *Sot-Través* grounds, mooring 4 was associated with the *Barana* grounds, and mooring 3 was associated with the *Westernside canyon* grounds (Fig. 1). Similarly, the data from each mooring was associated with the total catches based on the fishermen's association catch data, though the Generalized Additive Model (GAM) selected mooring 1 as the most representative (explaining most variability) for the total catches (see Section 3). Two other instruments, moorings 2 and 5, were deployed in the framework of the RECS project (see Zúñiga et al., 2009; for further methodological details). However, these two lines were not used in our study due to their distance from the *A. antennatus* fishing grounds.

2.2. Data processing

2.2.1. Environmental data

Daily averages were calculated to compare the temperature and salinity time series with shrimp occurrence. The daily average was used to provide a representative *T* and *S* value for each day. Current kinetic energy may also explain the sensitivity of the shrimps to environmental conditions (i.e., current intensity).

Table 2
Basic statistics (mean, standard deviation (SD), and number (*n*) of observations) for seasonal catches of deep-water rose shrimp in the whole canyon and by fishing ground.

Catch location	Spring 2003			Summer 2003			Autumn 2003			Winter 2004			Spring 2004			Total no.
	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	
Whole canyon (kg d^{-1})	183	76	86	228	88	94	89	44	90	140	54	89	126	52	50	409
Sot-Través (kg h^{-1})	9	3	34	10	4	94	8	2	90	9	2	80	2	0	8	306
Barana (kg h^{-1})	13	5	86	8	3	77	6	3	49	9	2	71	12	5	50	333
Westernside canyon (kg h^{-1})				5	2	19	10	3	9							28

However, instantaneous response of the rose shrimps to the currents measured at the time of the present study is unlikely. Thus, it was deemed preferable to use a variable in the form of an integral describing the energy conditions over a given time period. We used the mean kinetic energy (MKE), defined as the mean kinetic energy in the 30-day period preceding the shrimp catches. The complementary variable that naturally arises is the eddy kinetic energy, or EKE ($cm^2\,s^{-2}$). The EKE was defined as the mean of the variations in Kinetic Energy with respect to the MKE. Where the MKE describes the typical energy conditions during a given period, the EKE is the energy variability in that period. A 30-day window was the most appropriate timeframe for capturing seasonal intensifications in the Northern Current within the MKE and for identifying the individual contribution of mesoscale processes (Millot, 1999).

2.2.2. Biological data

Daily shrimp catches in the canyon as a whole and hourly catches in the main fishing grounds (*Sot-Través, Barana*, and *Westernside canyon*) were used in the statistical model. Three-day moving average filtering was used to reduce noise. A Gaussian distribution of catches in the canyon as a whole and in the *Sot-Través* and *Barana* grounds and a binomial distribution (presence–absence) within the *Westernside canyon* were assumed. Square-root transformation was applied to the catches for the canyon as a whole and the catches from the *Barana* in order to normalize the data.

2.3. Fitting generalized additive models (GAMs)

GAMs (Hastie and Tibshirani, 1990) were used to assess the nature of the relationships between the environmental and biological time series variables (Tobías et al., 2003), as they provide better data fits and less autocorrelation than other commonly used statistical models such as generalized linear models (Daskalov, 1999). Unlike linear models, which have a single coefficient for each model variable, additive models use an unspecified (non-parametric) function estimated for each predictor to achieve the best predictions of the dependent variable. The GAMs used employ the form $g(\mu_i) = f_1(y_{1i}) + f_2(y_{2i})$, where g is a smoothing link function, i.e., the combination of values for the predictor of the response variable $\mu_i \equiv E(y_i)$; f_1 and f_2 are smooth functions, and y_{1i} and y_2, are predictor variables.

The *Multiple Smoothing Parameter Estimation by Generalized Cross Validation* (*mgcv*) package (Wood, 2000) implemented in R software (R Development Core Team, 2007) was used to fit the GAM models. Penalized regression splines, i.e., functions designed to be optimal given the number of basis functions in the model, were used to represent the smooth functions. The smooth terms are functions of any number of covariates, e.g., s(salinity) + s(potential temperature) + s(MKE) + s(EKE). The problem of smoothing parameter estimation is solved by the package using the Generalized Cross Validation (GCV) criterion or Unbiased Risk Estimator (UBRE), which are approximations to the Akaike Information Criteria (AIC), $n \cdot d/(n - df)^2$, where n is the number of data points, d is the deviance, and df is the degree of freedom. Smoothing parameters were chosen to minimize the GCV score for the model. To suppress overfitting without overly degrading GCV or UBRE performance, an inflation factor (gamma = 1.4) was used for the model's degrees of freedom in the model's GCV and UBRE scores, thereby increasing the penalty for each degree of freedom in the model (Kim and Gu, 2004).

Because the number of combinations of predictors was too great to test individually, a custom stepwise selection procedure for obtaining the final models was used based on the following criteria: (a) parameter significance ($p \leqslant 0.05$); (b) regression deviance (the higher the better); (c) gradients at convergence (the smaller the better); (d) Hessian, which, if not positive definite, meant that some of the covariates could be highly co-linear or be subject to very high variance, and (e) residual plots (approaching normal distributions).

Model significance and deviance explained by individual predictors (e.g., potential temperature; Table 3) were compared to the significance and deviance of models with combined predictors

Table 3
Generalized additive model fits explaining shrimp catches for the entire canyon and for each fishing ground. Potential temperature, salinity, MKE, and EKE are individual covariates. The intercept probability p-values [Pr (>|t|)] and the smooth terms are highly significant ($p < 2.0E{-}03$). 1–8: mooring 1, 9–12: mooring 4, and 13–16: mooring 3.

Model no.	Response variable	Intercept	Individual smooth terms		Deviance explained (%)	N	Score
			Term	*edf*			
1	Whole canyon	12.31	s(ptem)	5.16	9.34	318	GCV = 7.1
2	Whole canyon	12.31	s(sal)	8.20	26.9	318	GCV = 5.9
3	Whole canyon	12.44	s(MKE)	7.27	26.6	259	GCV = 5.3
4	Whole canyon	12.44	s(EKE)	6.91	42.2	259	GCV = 4.2
5	*Sot-Través*	9.12	s(ptem)	3.79	9.84	210	GCV = 6.6
6	*Sot-Través*	6.12	s(sal)	3.34	35.7	210	GCV = 4.7
7	*Sot-Través*	8.98	s(MKE)	1.00	3.24	178	GCV = 6.6
8	*Sot-Través*	8.98	s(EKE)	2.61	19.9	178	GCV = 5.6
9	*Barana*	3.29	s(ptem)	2.34	34.4	149	GCV = 0.29
10	*Barana*	3.29	s(sal)	2.77	36.7	149	GCV = 0.28
11	*Barana*	3.10	s(MKE)	6.76	31.2	265	GCV = 0.28
12	*Barana*	3.10	s(EKE)	3.67	8.59	265	GCV = 0.36
13	*Westernside canyon*	−3.61	s(ptem)	2.62	19.1	407	UBRE = −0.57
14	*Westernside canyon*	−4.13	s(sal)	2.57	19.0	407	UBRE = −0.57
15	*Westernside canyon*	−3.71	s(MKE)*	1.00	11.7	260	UBRE = −0.63
16	*Westernside canyon*	−116.28	s(EKE)*	3.82	41.0	260	UBRE = −0.71

Models 1–12 assumed the response variable to be a Gaussian variable and used an identity link function.
Models 13–16 assumed the response variable to be a binomial variable and used a logit link function.
edf: Array of estimated degrees of freedom for each parameter.
GCV: Generalized Cross Validation score at the *edf* for the final set of relative smoothing parameters.
UBRE: Unbiased Risk Estimator used at the *edf* for the final set of relative smoothing parameters.
* Non-significant smooth terms ($p > 0.05$).

(e.g., potential temperature, salinity, MKE, EKE). The best combination represented the greatest amount of deviance while maintaining all terms in the equation below a significant level ($p \leqslant 0.05$) of deviance reduction.

The GAM results were compared with the results obtained using two types of decision trees: regression trees and classification trees. The former handled classification with a continuous output variable, while the latter dealt with presence–absence and discrete numbers. Regression trees were applied to the shrimp catches (catches from the all canyon, *Sot-Través* and *Barana* fishing grounds) and classification trees were applied to the presence–absence data (catches from the *Westernside canyon* fishing grounds). Decision trees (Ripley, 1996) were used to detect high-order interaction effects in complex ecological data sets (De'ath and Fabricius, 2000). A tree is constructed by binary recursive partitioning using the response in the specified GAM formula and choosing splits from predictors. The variables are divided into $X < a$ and $X > a$. The split that maximizes the reduction in the deviance is chose, the data set split, and the process repeated. Splitting continues until the terminal nodes are too small or too few to be split (Ripley, 1996). The relevance of a predictor is determined by the deviance criterion (as in GAMs). After abstraction into binary partition, the predictor with the smallest deviance is considered the most relevant. The regression and classification trees were pruned in order to simplify the structure and to avoid the over fitting to which complicated models are prone. The trees thus obtained have the advantages of higher accuracy and simplified structure. In this study, the decision trees were fitted using the regression partitioning and regression tree *mvpart* package implemented for R software (Ripley, 1996).

3. Results

3.1. Relationships between individual environmental predictors and shrimp catches

Salinity explained the greatest variability (up to 37%) for the shrimp catches (see Table 3). Temperature, salinity, MKE, and

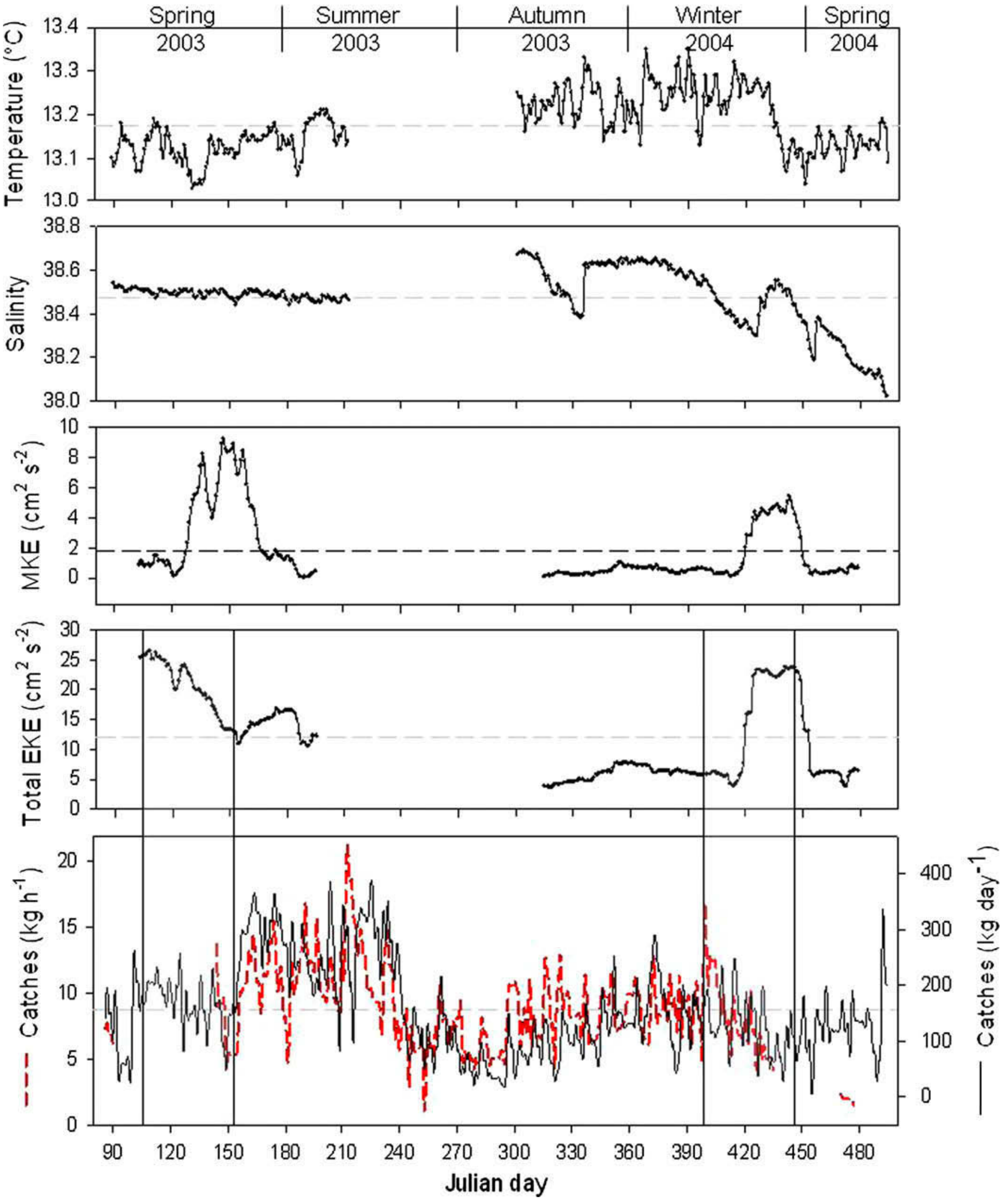

Fig. 2. Time series of hydrographic data from mooring M1 used to assess the catches from *Sot-Través* (dashed line) and from total landings (continuous line). Dashed horizontal lines represent mean catches. Note the correspondence between high EKE and low shrimp catches (shaded areas) found by the GAMs (see Fig. 3).

EKE were significant in most of the single environmental predictor models (Table 3). The models fit to the catches from the *Western-side canyon* grounds were significant in both temperature and salinity and showed relatively low model deviance values (19%) (Table 3).

3.2. Relationships between combined environmental predictors and shrimp catches

In the first approach, all environmental variables (from the three mooring sites) were used for the total catches in a single

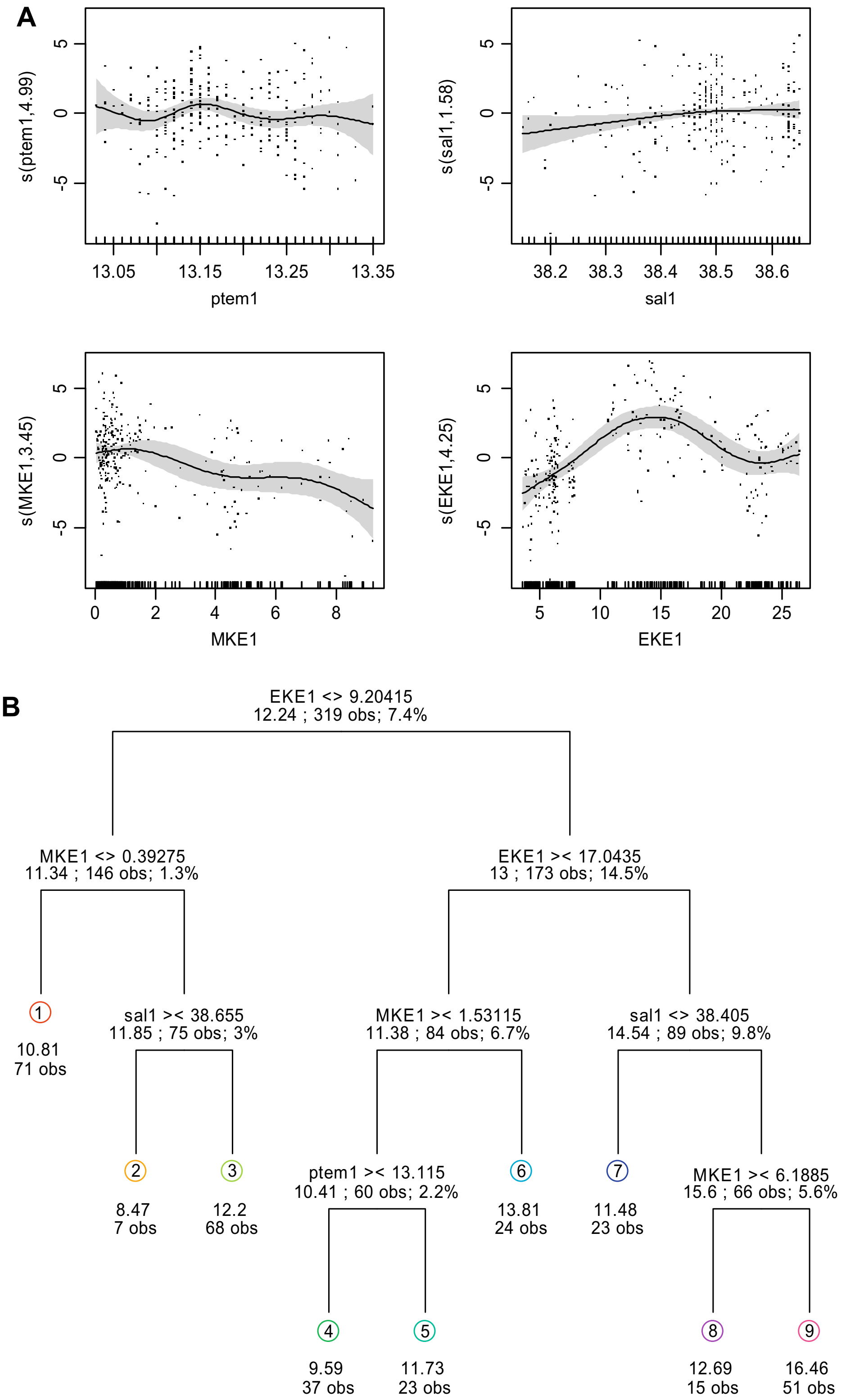

Fig. 3. Relationships between total shrimp harbour landings (*Whole canyon* landings, kg d^{-1}) and potential temperature (ptem1, °C), salinity (sal1), mean kinetic energy (MKE1, cm^2 s^{-2}), and eddy kinetic energy (EKE1, cm^2 s^{-2}) at mooring 1. (A) Fitted GAM explaining 55% of the total variability. (B) Regression tree explaining 51% of the total variability.

GAM. Environmental data from mooring 1 best explain the total catches for the whole canyon. It should be noted that *Sot-Través* and total catches displayed similar patterns and relatively high correlation (Fig. 2; $r = 0.58$, $p < 0.01$).

Significant non-linear relationships were found between the shrimp catches and temperature, salinity, MKE, and EKE (Figs. 3A, 4A, 5A, 6A) in the GAMs using environmental data from each mooring and its nearest fishing ground. Combining these variables

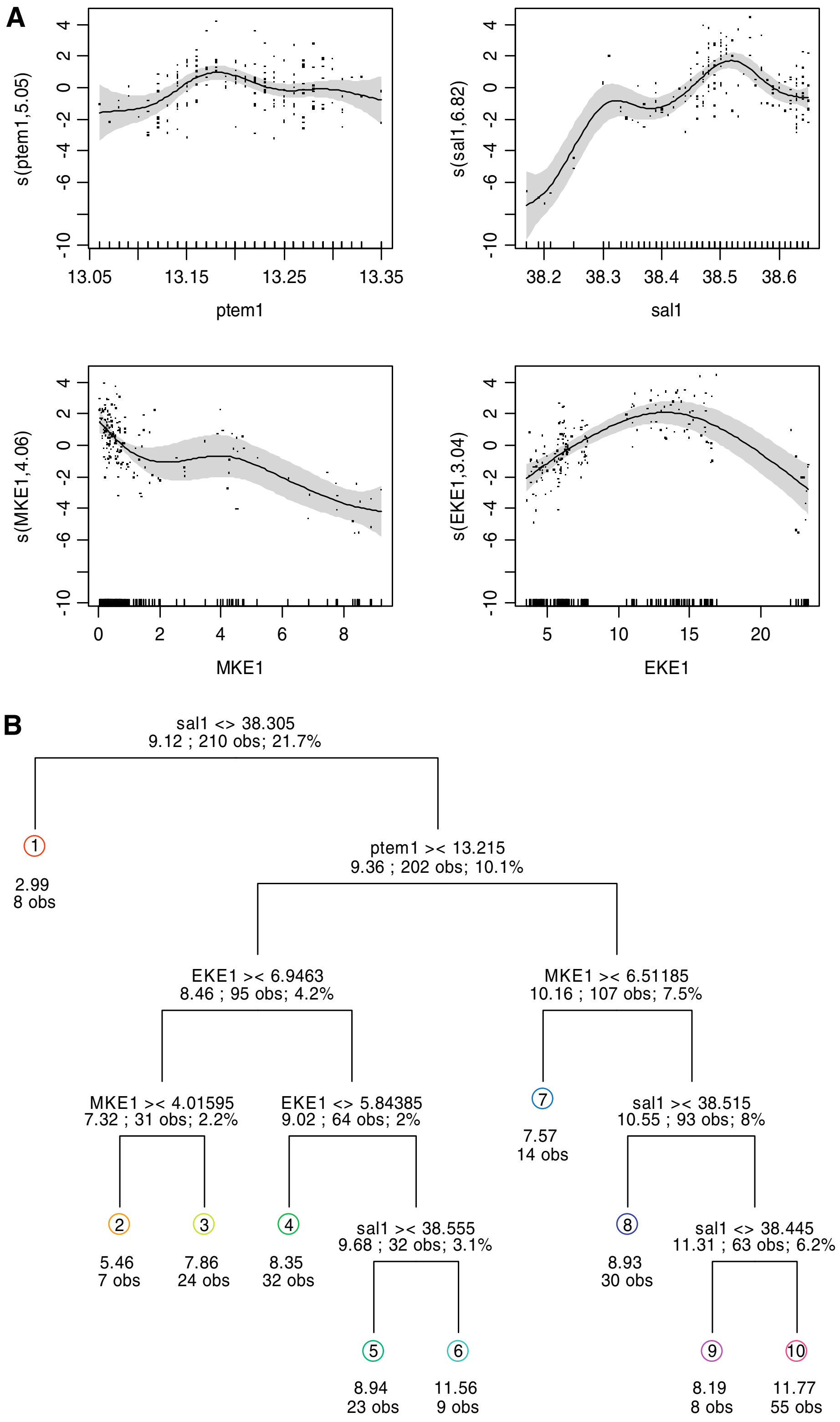

Fig. 4. Relationship between the catches (kg h^{-1}) at the *Sot-Través* fishing ground and the potential temperature (ptem1, °C), salinity (sal1), mean kinetic energy (MKE1, cm^2 s^{-2}), and eddy kinetic energy (EKE1, cm^2 s^{-2}) at mooring M1. (A) Fitted GAM explaining 75% of the total variability. (B) Regression tree explaining 65% of the total variability.

increased the explained model variability to 55%, 75%, and 88% for catches in the canyon as a whole and in the *Sot-Través* and *Barana* fishing grounds, respectively (Table 4), compared to the deviance explained by the single predictor models (Table 3). Maximum shrimp catches were associated with specific ranges of temperature, salinity, MKE, and EKE (Table 5). Temperatures between 13.13 and 13.21 °C in the *Sot-Través* and *Westernside canyon* fishing grounds occurred in conjunction with the highest catches in the canyon (Figs. 3A, 5A, 6A). Salinities between 38.15 and 38.65 were significantly correlated with the highest shrimp catches in the

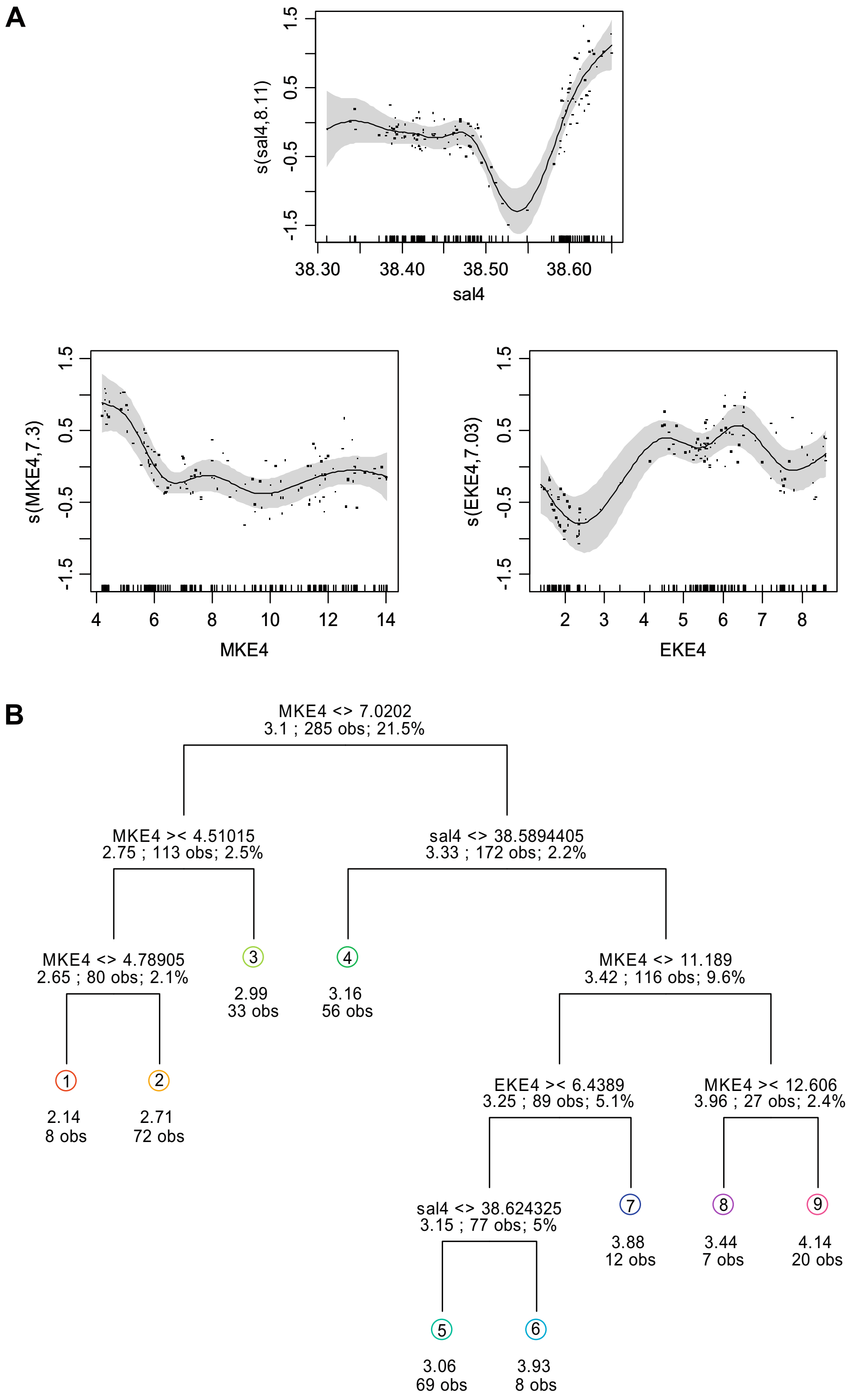

Fig. 5. Relationship between the catches (kg h^{-1}) at the *Barana* fishing ground and the potential temperature (ptem4, °C), salinity (sal4), mean kinetic energy (MKE4, cm^2 s^{-2}), and eddy kinetic energy (EKE4, cm^2 s^{-2}) at mooring M4. (A) Fitted GAM explaining 87% of the total variability. (B) Regression tree explaining 50% of the total variability.

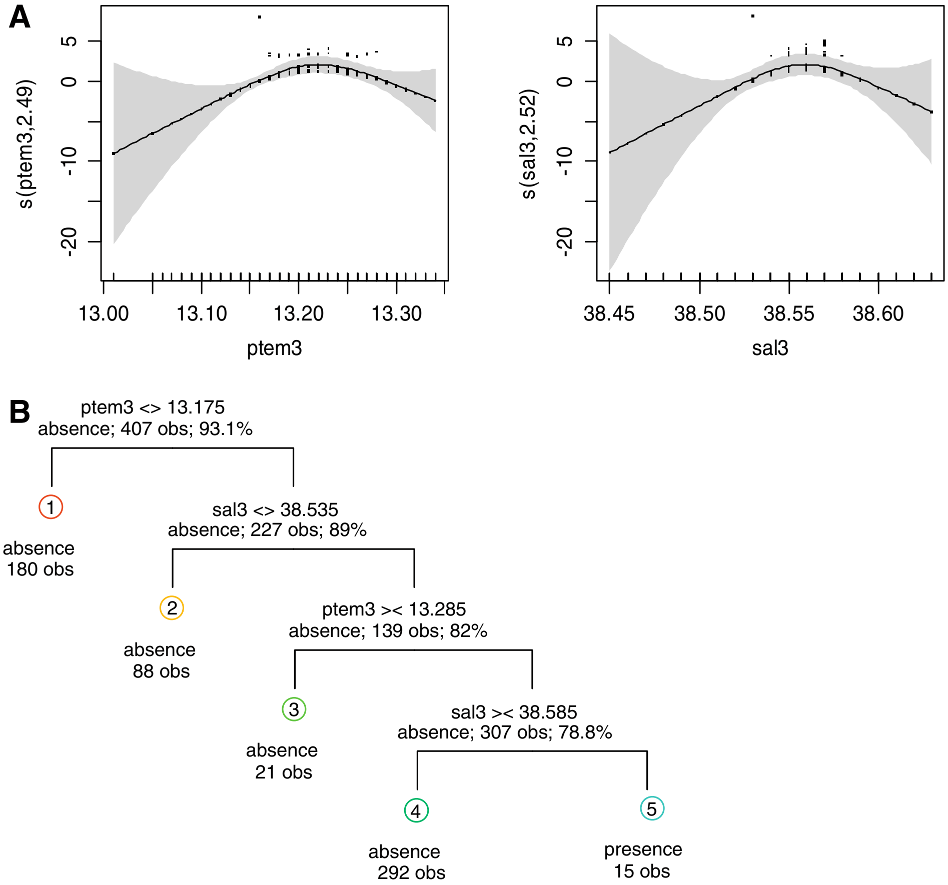

Fig. 6. Relationship between *Westernside canyon* catches (kg h^{-1}) and potential temperature (ptem3, °C) and salinity (sal3), at mooring M3. (A) Fitted GAM explaining 34% of the total variability. (B) Classification tree correctly classifying 94% based on presence.

canyon (Fig. 3A). Maximum shrimp catches in the *Sot-Través*, *Barana*, and *Westernside canyon* grounds took place at salinities of approximately 38.52, greater than 38.60, and approximately 38.56, respectively (Figs. 4A and 5A).

In the canyon and in the *Sot-Través*, catches decreased with increasing current intensity for MKEs between 0.1 and 9 $\mathrm{cm}^2\ \mathrm{s}^{-2}$ (Figs. 3A, 4A). In the *Barana* catches also decreased with increasing MKE up to about 6 $\mathrm{cm}^2\ \mathrm{s}^{-2}$, but remained stable afterward for MKEs between 6 and 14 $\mathrm{cm}^2\ \mathrm{s}^{-2}$ (Table 5). Whole canyon and *Sot-Través* catches were made at EKEs between 10 and 17 $\mathrm{cm}^2\ \mathrm{s}^{-2}$ (Figs. 3A, 4A). In the *Barana* grounds, which was associated with mooring 4, the EKE values recorded were within a smaller range

Table 4

Final Generalized Additive Models chosen to explain shrimp catches in the canyon as a whole and in the fishing grounds within the canyon. Potential temperature, salinity, MKE, and EKE were combined (additive) covariates. The intercept probability *p*-values [Pr (>|t|)] and the smooth terms were highly significant ($p < 2.0\mathrm{E}{-}03$).

Model no.	Response variable	Intercept	Combined smooth terms		Deviance explained (%)	*N*	Score
			Term	*edf*			
1	Shrimp catches in the whole canyon	12.44	s(ptem1)	5.37	54.5	259	GCV = 3.7
			s(sal1)	3.94			
			s(MKE1)	3.84			
			s(EKE1)	4.19			
2	*Sot-Través*	8.98	s(ptem1)	5.05	74.8	178	GCV = 2.3
			s(sal1)	6.82			
			s(MKE1)	4.06			
			s(EKE1)	3.08			
3	*Barana*	3.33	s(sal4)	7.79	86.9	129	GCV = 0.098
			s(MKE4)	7.46			
			s(EKE4)	7.46			
4	*Westernside canyon*	−4.55	s(ptem3)	2.49	33.5	407	UBRE = −0.625
			s(sal3)	2.52			

Models 1–3 assumed the response variable to be a Gaussian variable and used an identity link function.
Model 4 assumed the response variable to be a binomial variable and used a logit link function.
edf: array of estimated degrees of freedom for each parameter.
GCV: generalized cross validation score at the *edf* for the final set of relative smoothing parameters.
UBRE: Unbiased Risk Estimator used at the *edf* for the final set of relative smoothing parameters.

Table 5
Optimal environmental values for the highest mean catches of deep-water rose shrimp according to the GAMs and the decision tree models.

Fishing ground	Model	Temperature	Salinity	MKE	EKE	No. obs.
Whole canyon	GAM	13.13–13.18	>38.60	<2.0	10–20	–
	Regression tree	NA	>38.40	<6.2	9–17	51
	Min–max values	13.03–13.35	38.15–38.65	0.1–9.0	4–26	
Sot-Través	GAM	13.14–13.21	38.45–38.60	<1.0	15–18	–
	Regression tree	<13.2	38.40–38.50	<6.5	NA	55
		>13.2	38.30–38.60	NA	>5.8	9
	Min–max values	13.03–13.35	38.15–38.65	0.1–9.0	4–26	
Barana	GAM	NS	>38.6	4–6	4–7.5	–
	Regression tree	NS	>38.6	7–11	>6.4	89
		NS	>38.6	>11	NA	27
	Min–max values	13.05–13.20	38.30–38.65	4–14	1–9	
Westernside canyon	GAM	13.19–13.21	38.54–38.57	NS	NS	–
	Classification tree	13.20–13.23	38.54–38.56	NS	NS	15
	Min–max values	13.05–13.34	38.45–38.63	NS	NS	

NA = relatively high catch values not linked to specific values of this variable.
Significance level: 0.01.
[1] Values of the environmental variables linked to the highest catch values.

(.1–9 cm^2 s^{-2}) than at mooring 1, which was associated with the *Sot-Través* grounds, and there was a broader range of MKE values (0.1–14 cm^2 s^{-2}; Table 5, Fig. 6A). Maximum *Barana* catches were associated with EKEs between 4 and 7 cm^2 s^{-2}.

3.3. Decision trees for the shrimp catches using the combined predictors

Analyzing the GAMs, the tree revealed associations between specific environmental variables and maximum catch (Figs. 3B, 4B, 5B, 6B). The trees indicated that the total catches in the canyon were mainly driven by current variability (EKE) and intensity (MKE; Fig. 3B). The highest mean (root squared) catches of 12.7 and 16.5 kg d^{-1} were associated with EKE values between 9 and 17 cm^2 s^{-2} at salinities higher than 38.4 and MKEs lower than 6.2 cm^2 s^{-2}. Relatively high *Sot-Través* catches (11.8 kg h^{-1}) were linked to temperatures below 13.2 °C at salinities between 38.4 and 38.5 and MKEs higher than 6.5 cm^2 s^{-2} (Fig. 4B). Another set of relatively high mean catches (11.6 kg h^{-1}) was linked to temperatures higher than 13.2 °C, salinities between 38.3 and 38.5 and EKEs between 5.8 and 6.9 cm^2 s^{-2}.

MKE was the most relevant environmental variable in the *Barana* grounds in the lower canyon (Fig. 5B). The mean (root squared) catch of 3.4 kg h^{-1} was associated with salinities greater than 38.6 and MKEs greater than 7 cm^2 s^{-2}. Another set of relatively high catch values (3.0 kg h^{-1}) was linked to MKEs lower than 4.5 cm^2 s^{-2} independent of salinity. Temperature was not included in this analysis, as it was found to not be significant in the GAM model. On the *Westernside canyon* grounds where very few daily catches were sampled, the decision tree analysis indicated that catches were associated with temperatures of approximately 13.2 °C and salinities of approximately 38.6 (Fig. 6B).

4. Discussion

Aristeus antennatus populations have been associated with temperatures of 12.8 °C in the so-called northern upperlying and underlying waters at a depth of approximately 600 m with various salinity conditions (Ghidalia and Bourgois, 1961). While the above-mentioned temperature is considered optimal, researchers have reported this species to be present at temperatures of up to 13.5 °C, though at lower frequencies of occurrence. Previous studies have shown that other aspects of the behavior of this species could be related to feeding habits. Consequently, different behavioral patterns according to sex, age, physical condition during the course of the spawning cycle, and the photoperiod have been postulated. Behavioral factors of this type relating to age and the reproductive cycle have recently been identified (Sardà et al., 1994; Sardà and Cartes, 1997; Sardà et al., 2003, 2004).

In the Ionian Sea, rose shrimp have been reported at different depths, but the highest abundances are found at 600–800 m depths both in the Western basin (at 13.3 and 13.7 °C) and in the Eastern basin (at up 13.9 °C) (Politou et al., 2004). However, the hypothetical distribution range of this species could extend to a depth of 2800 m (Sardà et al., 2004). In the Catalan Sea and the Balearic Islands rose shrimp are abundant between 12.8 and 13.9 °C. Nevertheless, peak densities occur at around 12.8 °C at depths between 600 and 800 m, as previously reported by Ghidalia and Bourgois (1961). Thus, the distribution of *A. antennatus* may reasonably encompass broader temperature/salinity ranges, with narrower ranges associated with optimal conditions, where the rose shrimp density and occurrence are higher. Nevertheless, there is no obvious, direct association between high densities of rose shrimp and deep-water masses (LIW/WMDW), since this species can be found from 80-to-600 m off Algeria and Tunisia at temperatures ranging from 12.8 to 14 °C (Yahiaoui, 1994). Populations are also found at shallow depths between 100 and 150 m in the Ionian Sea canyons of southern Italy (Relini and Relini-Orsi, 1987; Matarrese et al., 1995; D'Onghia et al., 1996). This species also occurs in the Atlantic Ocean off Portugal at lower temperatures between 11 and 12 °C and relatively high salinities between 36 and 36.9 (Ribeiro-Cascalho, 1988). Additionally, the distribution of the species reaches the Indian Ocean coast of Africa at depths between 200 and 1400 m (Freitas, 1985), suggesting that its association with a given water mass, as postulated by Ghidalia and Bourgois (1961), is not based on temperature alone.

In the Eastern Mediterranean, decreasing salinity has been observed at depths between 500 and 1400 m in the last decade as a consequence of changes in the thermohaline circulation (Klein et al., 1999; Manca et al., 2002). Alteration of the thermohaline circulation in the Blanes canyon as a result of persistent winter overheating of surface waters could initiate changes in the currents in the intermediate water layer located between the LIW and the WMDW, where the deep-water rose shrimp is dominant. A recent hypothesis links the shrimp or demersal fish fluctuation with the NAO index (Massutí et al., 2008; Maynou, 2008b). However, Company et al. (2008) and our current results indicate that the local hydrography, linked to physical processes and geomorphology of the fishing grounds around the canyons, are directly responsible for these fluctuations.

Our results indicate a significant relationship between deep-water rose shrimp, salinity, and the energy conditions of the water. Indeed, the best hydrodynamic conditions generating a deep-water habitat conducive to deep-water rose shrimp abundance appear to be a combination of relatively cold temperatures (13.1–13.2 °C) and high salinity (>38.5). Concurrently, these conditions appear to be important as higher shrimp density areas are associated with moderate EKE values. The relatively high mean shrimp catch under specific environmental conditions suggests that optimal environmental conditions for *A. antennatus* in the Blanes canyon are relatively saltier (LIW) waters, low flow intensities (MKE) and moderate variability (EKE). Under these conditions the existing turbulence and sediment re-suspension contribute to the dispersal of particulate matter above the sediment (Gardner et al., 2000; Accornero et al., 2003). This increases the availability of organic matter, allowing shrimp to forage more effectively (Zúñiga et al., 2009). In spatio-temporal terms, these conditions occur most often in the northern part of the canyon (the *Barana* grounds) during the spring months, coinciding with the largest spawning aggregations of shrimp. These oceanographic conditions explain 88% of the variability between catches. These optimum conditions occur in the fishing grounds yielding the highest catches: *Sot-Través* grounds (northern margin of the canyon) in winter and *Barana* in spring. Finally, the current energy seems to be a more limiting factor than the *T–S* relationship, as evidenced by the percentage variability explained by the different variables considered in the GAMs.

The low or non-existent catches observed in the *Westernside canyon* grounds (southern margin of the Blanes canyon) result from the current flow features and the low deep-sea productivity in this area. Current speed and direction in the Blanes canyon are linked to those of the incoming current (Northern Current) and the geomorphology of the canyon itself: the Northern Current flows over the eastern side and encounters the western side, giving rise to persistent, unidirectional flow against the southern side (Flexas et al., 2008). As described by Zúñiga et al. (2009) the sandier bottoms in this area result in impoverishment of the substratum, with less POM (Particulate Organic Matter) and hence less abundant meiobenthos. The decrease in food availability in the form of POM on the bottom is associated with relatively more energetic waters with a high level of advective variability resulting in increased turbulence (Gardner et al., 2000; Accornero et al., 2003). In turn, less energetic waters give rise to more stable areas, less dynamic in terms of current flow and thus supporting more available organic matter, giving rise to a more suitable habitat for the shrimp.

Furthermore, the physiological conditions of berried adult females that result in high densities of the rose shrimp in the *Barana* fishing grounds could be linked to readily available food on the substrate. Cartes (1994), Cartes and Maynou (1998) and Cartes et al. (2008) showed that mature adult females of *A. antennatus* require food of suprabenthic prey of higher energy content during late winter and spring. For this reason we propose that further research should examine the protein, lipid, and carbohydrate content of deep-water rose shrimp for the different fishing grounds at different times of year.

We were unable to establish a conclusive relationship between variable environmental fluctuations and catch size. The data-mining techniques (GAMs and decision trees) allowed us to conclude that catches are non-linearly driven by environmental conditions. At the constant prevailing temperatures, the significant optimal environmental conditions for the highest mean catch for *A. antennatus* are relatively salty waters (LIW) with low current flow rates (MKE) and moderate variability (EKE).

Acknowledgements

We thank the officers and crew of the R/V García del Cid and UTM technicians for generous help during the RECS cruises. This study was supported by a national research project founded by the Spanish CICYT agency (RECS II project, reference number REN2002-04556-C02-01/MAR).

References

Abelló, P., Valladares, F., Castellón, A., 1988. Analysis of the structure of decapod crustaceans assemblages off the Catalan coast (North-West Mediterranean). Marine Biology 98, 39–49.

Accornero, A., Manno, C., Arrigo, K.R., Martini, A., Tucci, S., 2003. The vertical flux of particulate matter in the polynya of Terra Nova Bay. Part I. Chemical constituents. Antarctic Science 15, 119–132.

Agostini, V.N., Bakun, .A., 2002. "Ocean triads" in the Mediterranean Sea: physical mechanisms potentially structuring reproductive habitat stability (with example application to European anchovy, *Engraulis encrasicolus*). Fisheries and Oceanography 11, 129–142.

Bas, C., 2005. The Mediterranean Sea: Living resources and exploitation. Zaragoza CIHEAM-IAMZ/COPEMED Project, p. 1–509.

Bakun, A., Agostini, V.N., 2001. Seasonal patterns of wind-induced upwelling/downwelling in the Mediterranean Sea. Scientia Marina 65, 243–257.

Beverton, R.J.H., 1990. Small marine pelagic fish and threat of fishing; are they endangered? Journal of Fish Biology 37 (Suppl. A), 5–16.

Bianchini, M., Ragonese, S., 1994. Life cycles and fisheries of the deep-water shrimps *Aristaemorpha foliacea* and *Aristeus antennatus*. In: Proceedings of the International Workshop Held in the Istitute di Tecnologia, della Pesca e del Pescato (ITPP-CNR), Mazara del Vallo. Italy, p. 1–87 (special publication 3).

Billett, D.S.M., Bett, B.J., Rice, A.L., Thurston, M.H., Galéron, J., Sibuet, M., Wolff, G.A., 2001. Long-term change in the megabenthos of the Porcupine Abyssal Plain (NE Atlantic). Progress in Oceanography 50, 325–348.

Bailey, D.M., Ruhl, H.A., Smith, K.L., 2006. Long-term change in benthopelagic fish abundance in the abyssal northeast Pacific Ocean. Ecology 87, 549–555.

Canals, M., Serra, J., Riba, O., 1982. Toponimia de la Mar Catalano-Balear. Bulletti de la Societat d'Història Nataural de Balears 26, 169–194.

Canals, M., Casamor, J.L., Cacho, I., Calafat, A., Monaco, A., 1996. EUROMARGE-NB, Final Report, MAST II Progr., EC; Comp. RG Mar. Geosciències, Univiversitat de Barcelona.

Carbonell, A., Carbonell, M., Demestre, M., Grau, A., Montserrat, S., 1999. The red shrimp *Aristeus antennatus* (Risso, 1816) fishery and biology in the Balearic Islands, Western Mediterranean. Fishery Research 44, 1–13.

Cartes, J.E., 1994. Influence of depth and seasonality on the diet of the deep-water aristeid *Aristeus antennatus* along the continental slope (400 to 2300 m) in the Catalan Sea (Western Mediterranean). Marine Biology 120, 639–648.

Cartes, J.E., Carrasón, M., 2004. The influence of trophic variables in the depth-range distribution and zonation rates of deep-sea megafauna: the case of the Western Mediterranean assemblages. Deep Sea Research II 51, 263–279.

Cartes, J.E., Maynou, F., 1998. Food consumption by bathyal decapod crustacean assemblages in the western Mediterranean: an approach to predatory impact by megafauna and to a food consumption-food supply balance in a deep-water food web. Marine Ecology Progress Series 171, 233–246.

Cartes, J.E., Sardá, F., 1989. Feeding ecology of the deeper-water penaeid crustacean *Aristeus antennatus* (Risso, 1816) in the Mediterranean Sea. Marine Ecology Progress series 54, 229–238.

Cartes, J.E., Sardà, F., 1992. Abundance and diversity of decapod crustaceans in the deep-catalan sea (Western Mediterranean). Journal of Natural History 26, 1305–1323.

Cartes, J.E., Sardà, F., 1993. Zonation of the deep-sea decapod fauna in the Catalan Sea (Western Mediterranean). Marine Ecology Progress Series 94, 27–34.

Cartes, J.E., Papiol, V., Guijarro, B., 2008. The feeding and diet of the deep-sea shrimp *Aristeus antennatus* off the Balearic Islands (Western Mediterranean): influence of environmental factors and relationship with the biological cycle. Progress in Oceanography 79, 37–54.

Cartes, J., Grémare, A., Maynou, F., Villora-Moreno, S., Dinet, A., 2002. Bathymetric changes in the distribution of particulate organic matter and associated fauna along a deep-sea transect down the Catalan sea slope (Northwestern Mediterranean). Progress in Oceanography 53, 29–56.

Company, J.B., Puig, P., Sardà, F., Palanques, A., Latasa, M., Scharek, R., 2008. Climate control on deep-sea fisheries. PloS ONE, 2008. <http://www.plosone.org/doi/pone.0001431>.

Cury, P., Roy, C., 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Canadian Journal Fish and Aquatic Sciences 46, 670–680.

Chávez, F.P., Ryan, J., Lluch-Cota, S.E., Ñiquen, M., 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299, 217–221.

Childress, J.J., 1995. Are there physiological and biochemical adaptations of metabolism in deep-sea animals? Trends in Ecology and Evolution 10, 30–36.

Danovaro, R., Dell'Anno, A., Fabiano, M., Pusceddu, A., Tselepides, A., 2001. Deep-sea ecosystem response to climate changes: the Eastern Mediterranean case study. Trends in Ecology and Evolution 16, 505–510.

Daskalov, G., 1999. Relating fish recruitment to stock biomass and physical environment in the Black Sea using generalized additive models. Fishery Research 41, 1–23.

De'ath, G., Fabricius, K.E., 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81, 3178–3192.

Demestre, M., 1995. Moult activity-related spawning success in the Mediterranean deep shrimp *Aristeus antennatus* (Decapoda: Dendrobranchiata). Marine Ecology Progress Series 127, 57–64.

Demestre, M., Fortuño, J.M., 1993. Reproduction of the deep-water shrimp *Aristeus antennatus* (Decapoda: Dendrobranchiata). Marine Ecology Progress Series 84, 41–51.

Demestre, M., Lleonart, J., 1993. Population dynamics of *Aristeus antennatus* (Decapoda: Dendrobranchiata) in the Northwestern Mediterranean. Scientia Marina 57, 183–189.

Demestre, M., Martín, P., 1993. Optimum exploitation of a demersal resource in the Western Mediterranean: the fishery of the deep-water shrimp *Aristeus antennatus* (Risso, 1816). Scientia Marina 57, 175–182.

Díaz, J.I., Maldonado, A., 1990. Transgressive sand bodies on the Maresme continental shelf, Western Mediterranean sea. Marine Geology 91, 53–72.

D'Onghia, G., Tursi, A., Basanisi, M., 1996. Reproduction of macrurids in the upper slope of the North-western Ionian Sea. Journal of Marine Biology 49 (Suppl. A), 311–317.

Durrieu de Madron, X., Nyffeler, F., Monaco, A., Casamor, J.L., 1996. Circulation and dynamics of suspended particulate matter. In: Canals, M., Casamor, J.L., Cacho. I., Calafat, A.M., Monaco, A. (Eds.), EUROMARGE-NB Final Report, MAST II Programme, EC, pp. 13–39.

Flexas, M.M., Boyer, D.L., Espino, M., Puigdefàbregas, J., Rubio, A., Company, J.B., 2008. Circulation over a submarine canyon in the NW Mediterranean. Journal of Geophysics Research 113, C12002.

Freitas, A.J., 1985. The penaeoidea of Southeast Africa. II – the families Aristeidae and Solecenoridae. Oceanographic Research Institute, Durban. Investigational Report, vol. 57, p. 69.

Klein, B., Roether, W., Manca, B.B., Bregant, D., Beitzel, V., Kovacevic, V., Luchetta, A., 1999. The large deep water transient in the Eastern Mediterranean. Deep Sea Research I 371, 371–414.

Gage, J.D., Tyler, A., 1990. Deep Sea Biology: A Natural History of Organisms at the Deep-Sea Floor. Cambridge University Press. p. 504.

Gardner, W.D., Richardson, M.J., Smith Jr., W.O., 2000. Seasonal patterns of water column particulate organic carbon and fluxes in the Ross Sea, Antarctica. Deep-Sea Research II 47, 3423–3449.

Ghidalia, W., Bourgois, F., 1961. Influence de la temperature et de l'eclairement sur canyon la distribution des crevettes des moyennes et grandes profondeurs; CGPM. Etudes et Revues 16, 1–53.

Gili, J.M., Bouillon, J., Pagès, F., Palanques, A., Puig, P., Heussner, S., 1998. Origin and biogeography of the deep-water Mediterranean Hydromedusae including the description of two new species collected in submarine canyons of Northwestern Mediterranean. Scientia Marina 6, 113–134.

Gili, J.M., Bouillon, J., Pagès, F., Palanques, A., Puig, P., 1999. Submarine canyons as habitats of prolific plankton populations: three new deep-sea Hydrodomedusae in the Western Mediterranean. Zoological Journal of the Linnean Society 125, 313–329.

Hare, J.A., Able, K.V., 2007. Mechanistic links between climate and fisheries along the east coast of the United States: explaining population outbursts of Atlantic croaker (*Micropogonias undulates*). Fisheries and Oceanography 16, 31–45.

Hastie, T.J., Tibshirani, R.J., 1990. Generalized Additive Models. Chapman Hall, New York. p. 356.

Herring, P., 2002. The Biology of the Deep Ocean. Oxford University Press. p. 314.

Heussner, S., Calafat, A., Palanques, A., 1996. Quantitative and qualitative features of particle fluxes in the North-Balearic Basin; In: Canals, M., Casamor, J.L., Cacho, I., Calafat, A.M., Monaco, A. (Eds.), EUROMARGE-NB Final Report, MAST II Programme, EC, p. 41–66.

Hickey, B.M., 1995. Coastal submarine canyons. In: Müller, P., Henderson, D. (Eds.), Topographic Effects in the Ocean, Proceedings of the Aha Huliko'a Hawaiian Winter Workshop, University of Hawaii, Manoa, SOEST, pp. 95–110 (special publication 1).

Hopkins, T.S., 1985. Physics of the sea. In: Margalef, R. (Ed.), Western Mediterranean. Pergamon Press, pp. 100–125.

Kim, Y.-J., Gu, C., 2004. Smoothing spline Gaussian regression: more scalable computation via efficient approximation. Journal of the Royal Statistical Society Series B 66 (Part 2), 337–356.

Lluch-Belda, D., Crawford, R.J.M., Kawasaki, T., MacCall, A.D., Parrish, R.H., Schwartzlose, R.A., Smith, P.E., 1989. World-wide fluctuations of sardine and anchovy stocks: the regime problem. South Africa Journal Marine Science 8, 195–205.

Manca, B.B., Ursella, L., Scorazzato, P., 2002. New development of eastern Mediterranean circulation based on hydrological observations and current measurements. Marine Ecology Progress Series 23, 237–257.

Massutí, E., Montserrat, S., Oliver, P., Moranta, J., López-Jurado, J.L., Marcos, M., Hidalgo, M., Guijarro, B., Carbonell, A., Pereda, P., 2008. The influence of oceanographic scenarios on the population dynamics of demersal resources in the western Mediterranean: Hipótesis for hake and red shrimp off Balearic Islands. Journal of Marine Systems 71, 421–438.

Maynou, F., 2008a. Environmental causes of the fluctuations of red shrimp (*Aristeus antennatus*) landings in the Catalan Sea. Journal of Marine Systems 71, 294–302.

Maynou, F., 2008b. Influence of the North Atlantic oscillation on Mediterranean deep-sea shrimp landings. Climate Research 36, 253–257.

Matarrese, A., D'Onghia, G., De Florio, M., Panza, M., Constantino, G., 1995. Resentí adquisición sulla distribuzione batimetrica di *Aristaeomorpha foliacea* and *Aristeus antennatus* (Crustacea, Decapada) nel Mar Jonio. Biologia Marina Mediterranea 2, 299–300.

Millot, C., 1999. Circulation in the Western Mediterranean. Journal of Marine Systems 20, 423–442.

Monaco, A., Biscaye, P., Soyer, J., Pocklington, R., Heussner, S., 1990. Particle fluxes and ecosystem response on a continental margin: the 1985–1988 Mediterranean EUROMARGE experiment. Continental Shelf Research 10, 809–839.

Moore, J.A., Gordon, J.D.M., 2003. Symposium on deep-sea fisheries. Journal of Northwest Atlantic Fishery Science, vol. 31. NAFO/ICES/CSIRO Symposium, 466p.

Pinot, J.M., López-Jurado, J.L., Riera, M., 2002. The CANALES project (1996–1999): interannual, seasonal, and mesoscale variability of the circulation in the Baleric Channels. Progress in Oceanography 55, 335–370.

Politou, Ch.-Y., Kapiris, K., Maiorano, P., Capezzuto, F., Dokos, J., 2004. Deep-sea Mediterranean biology: the case of *Aristaeomorpha foliacea* (Risso, 1827) (Crustacea: Decapoda: Aristeidae). Scientia Marina 68 (Suppl. 3), 129–139.

Puig, P., Palanques, A., 1998a. Temporal variability and composition of settling particle fluxes on the Barcelona continental margin (Northwestern Mediterranean). Journal Marine Research 56, 639–654.

Puig, P., Palanques, A., 1998b. Nepheloid structure and hydrographic control on the Barcelona continental margin, Northwestern Mediterranean. Marine Geology 149, 39–54.

Puig, P., Company, J.B., Sardà, F., Palanques, A., 2001. Responses of deep-water shrimp populations to the presence of intermediate nepheloid layers on continental margins. Deep-Sea Research II 48, 2195–2207.

Puig, P., Palanques, A., Guillén, J., García-Ladona, E., 2000. Deep slope currents and suspended sediment fluxes in and around the Foix submarine canyon (NW Mediterranean). Deep-Sea Research I 47, 343–366.

R Development Core Team, 2007. A language and environment for statistical computing. Royal Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. <http://www.R-project.org>.

Relini, G., Relini-Orsi, L., 1987. The decline or red shrimp stocks in the Gulf of Genoa. Investigación Pesquera 51 (Suppl. 1), 245–260.

Ribeiro-Cascalho, A.F., 1988. Biologia, ecologia e pesca dos peneidos de profundidade *Parapenaeus longirostris* (Lucas) e *Aristeus antennatus* (Risso) da costa portuguesa. Instituto National de Investigaçao das Pescas. 171pp.

Ripley, B.D., 1996. Pattern Recognition and Neural Networks. Cambridge University Press, Cambridge, UK. 422pp.

Sardà, F., 1993. Bio-ecologicalationship between sizel aspects of the decapod crustacean fisheries in the Western Mediterranean. Aquatic Living Resources 6, 299–305.

Sardà, F., Demestre, M., 1987. Estudio bioecológico de la gamba, *Aristeus antennatus*, Risso 1816, en el mar Catalán. Investigaciones Pesqueras 51 (Suppl.1), 213–232.

Sardà, F., Cartes, J.E., 1993. Re and depth in decapod crustacean populations on the deep slope in the Western Mediterranean. Deep-Sea Research I 40, 2389–2400.

Sardà, F., Cartes, J.E., 1997. Morphological features and ecological aspects of early juvenile specimens of the aristeid shrimp *Aristeus antennatus* (Risso, 1816). Marine and Freshwater Research 48, 73–77.

Sardà, F., Cartes, J.E., Norbis, W., 1994. Spatio-temporal structure of the deep-water shrimp *Aristeus antennatus* Risso, 1816 (Decapoda: Aristeidae) population in the Western Mediterranean. Fishery Bulletin NOAA 92, 599–607.

Sardà, F., Company, J.B., Castellón, A., 2003. Intraspecific aggregation structure of a shoal of a western Mediterranean (Catalan coast) deep-sea shrimp, *Aristeus antennatus* (Risso, 1816), during the reproductive period. Journal Shellfish Research 22, 569–579.

Sardà, F., Maynou, F., Talló, Ll., 1998. Seasonal and spatial mobility patterns of rose shrimp (*Aristeus antennatus* Risso, 1816) in the western Mediterranean: results of a long-term study. Marine Ecology Progress Series 159, 133–141.

Sardà, F., D'Onghia, G., Politou, C.-Y., Tselepides, A., (Eds.), 2004. Mediterranean Deep-sea Biology. Monographs of Scientia Marina, vol. 68, p. 204.

Stefanescu, C., Morales-Nin, B., Massutí, E., 1994. Fish assemblages on the slope in the Catalan sea (Western Mediterranean): influence of a submarine canyon. Journal of the Marine Biology, 499–512 (Association UK74).

Tobías, A., Sáez, M., Galán, I., Campbell, M.J., 2003. Sensitivity analysis of common statistical models used to study the short-term effects of air pollution on health. International Journal of Biometeorology 47, 227–229.

Tobar, R., Sardá, F., 1987. Análisis de las capturas de gamba en los últimos decenios en Cataluña. Informes Técnicos del Instituto de ciencias del Mart de Barcelona (CSIC) 142, 1–20.

Tudela, S., Sardà, F., Maynou, F., Demestre, M., 2003. Influence of submarine canyons on the distribution of the deep-water shrimp (*Aristeus antennatus*, Risso 1816) in the Northwestern Mediterranean. Crustaceana 76, 217–225.

Wood, S.M., 2000. Modelling and smoothing parameter estimation with multiple quadratic penalties. Journal of the Royal Statistics Society Series B 62, 413–428.

Yahiaoui, M., 1994 Distribution and reproductive cycle of *Aristeus antennatus* and *Aristaeomorpha foliace* in Algeria. NRT-ITPP. In: Bianchini, M., Ragonese, S., (Eds.), Life Cycles and Fisheries of the Deep-water Shrimps *Aristaeomorpha foliacea* and *Aristeus antennatus*, pp. 51–529 [Proceedings of the International Workshop held in the Istituto di Tecnologia della Pesca e del Pescato (ITPP-CNR), Mazara del Vallo, Italy, pp. 1–88 (special publication 3)].

Zúñiga, D., Fleixas, M.M., Sánchez-Vidal, A., Coenjearts, J., Calafat, A., Puigdefàbregas, J., Jordà, G., García-Orellana, J., Canals, M., Espino, M., Sardà, F., Company, J.B., 2009. Paticle fluxes dynamics in Blanes submarine canyon (Northwestern Mediterranean). Progress in Oceanography (in this volume), doi:10.1016/j.pocean.2009.07.02.