Environmental causes of the fluctuations of red shrimp (*Aristeus antennatus*) landings in the Catalan Sea

Francesc Maynou

Institut de Ciències del Mar, CSIC
Psg. Marítim de la Barceloneta 37-49
08003-Barcelona
Spain

tel.: +34 932309500
fax: +34 932309555
e-mail: maynouf@icm.csic.es

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Abstract

The fluctuations of catches of the deep-sea shrimp *Aristeus antennatus* (Risso, 1816) were analysed in the 6 ports of Catalonia where production is concentrated, based on monthly landings from 1988 to 2004. The 6 selected ports produced 300 t of red shrimp in 2004, or 80% of the total production in Catalonia. The series for each port showed clear interannual variability, with peaks of production in the early 1990's and more recently from 2001 to 2003. The time periods of the monthly data series, estimated by frequency analysis based on Fourier transform, varied around 7-8 y in the four central ports and 12-13 y in the two northern ports. Additionally, the different curves were not in phase: even in nearby ports, the maximum production is observed in different years. Since the North Atlantic Oscillation (NAO) index is an excellent proxy for long-term series of environmental variables, we aimed to explore relationships between the fluctuation of the NAO index and *A. antennatus* landings in the Catalan Sea. The correlation between the mean annual NAO index and the annual catches in each port was positive and significant with some time lags (from 1 to 3 years). The existence of clear patterns linking the NAO with marine ecological processes has been demonstrated in many studies, but the underlying ecological mechanisms are far from being well understood. The variations in environmental parameters linked to the NAO may act on biological organisms at different levels (individual, population) through physiology (metabolic and reproductive processes) or through trophic relationships, including ecological cascade effects. We propose that NAO-induced environmental variability may enhance food supply to *A. antennatus* and hence strengthen the reproductive potential of particular year classes, that result in increased catches 1 to 3 years later, although other possible effects of environmental variability on the population dynamics of this species are worth investigating.

Keywords: *Aristeus antennatus*, fisheries, NW Mediterranean, North Atlantic Oscillation.

1 Introduction

The red shrimp *Aristeus antennatus* (Risso, 1816) is the most important deep-water commercial species in the western Mediterranean. In the Catalan sea, it is fished by bottom trawling along the continental slope between 600 and 800 m depth and in the vicinity of submarine canyons (especially in autumn and winter) between 400 and 600 m depth, where catches are mainly composed of juvenile females and males. It is a highly dimorphic species, with females reaching larger sizes than males and living longer (~7 y vs ~4 y). In the Catalan Sea, studies on the reproductive biology (Demestre and Fortuño, 1992; Demestre, 1995), trophic biology (Cartes, 1994; Cartes, 1998), spatial ecology (Sardà et al., 1994; Maynou et al., 1996; Sardà et al., 1997) and fisheries (Demestre and Martín, 1993; Demestre and Lleonart, 1993; Maynou et al., 2006) are abundant. It is an eurybathic species, and has been recently reported from 3300 m in the eastern Mediterranean (Sardà et al., 2004).

The distribution of *Aristeus antennatus* along the Mediterranean continental margin of the Iberian peninsula is related to submarine canyons. It presents important spatio-temporal segregation of age classes and sexes. Juvenile individuals and males are preferentially associated with submarine canyons, where they are caught by the trawl fleet in autumn and winter, while mature and spawning females are mainly found on the slope from late winter to late summer (Sardà et al., 1994; Sardà et al., 1997). Mature females are found in spring and summer (March-September), with a peak occurrence between June and August; while mature males do not show a clear peak and can be found year-round (Demestre, 1995). Females of *A. antennatus* constitute between 70 and 80% of the commercial catch, both because they are larger and because the sex-ratio in the catches is biased towards females (Demestre and Lleonart, 1993).

Knowledge on larval and postlarval stages is very scarce, most of the biological and ecological information on this species is based on individuals recruited to the fishery. Sardà and Cartes (1997) found the smallest individuals (6.4 mm CL) at 1300 m depth in March, suggesting that settlement to the sea-floor habitat takes place during winter.

Aristeus antennatus is an opportunistic predator with a wide trophic spectrum (Cartes, 1994; 1998). It feeds mainly on endobenthic prey (polychaetes, burrowing decapod crustaceans such as *Calocaris macandreae*, bivalves), but epibenthic prey (such as ophiuroids, peracarids) can be important seasonally or at specific spatial locations (upper middle slope, Cartes, 1994). In late summer and autumn the importance of suprabenthos and mesopelagic prey increases in the upper middle slope. Within submarine canyons *A. antennatus* feeds mainly on endobenthic prey, while in the lower slope (> 1300 m depth) it feeds mainly on calcified prey items with lower energetic content. Hence, its diet changes along a depth gradient, reflecting the abundance of different prey groups in the environment. *A. antennatus* has a low dietary overlap with other decapod crustaceans co-occurring in the same depths, even with other red shrimps such as *Aristaeomorpha foliacea* (Cartes, 1998).

The North Atlantic Oscillation (NAO) refers to the most prominent atmospheric phenomenon over the middle and high latitudes of the Northern Hemisphere (Hurrell et al., 2003). The NAO has profound implications on the weather over the North Atlantic and Europe, but also on the terrestrial and marine environments, affecting human

economic activities, such as agricultural harvests and fisheries yields (Hurrell et al., 2003). Several indices have been defined for the NAO (reviewed in Hurrell et al., 2003), but the most useful for our purposes is the difference between sea level pressures in Gibraltar and Iceland, as computed and maintained by the Climatic Research Unit of the University of East Anglia (Norwich, UK). The climatic and oceanographic implications of the NAO have been the focus of numerous studies. Briefly, the main influence of the NAO on European weather consists in increased precipitation in Atlantic Europe and decreased precipitation in the Mediterranean during winters when the NAO index is high and the opposite precipitation pattern during winters when the NAO index is low. This variation in rainfall, together with associated changes in air temperature, winds and river runoff determine the dynamics of the upper layers of the North Atlantic Ocean at seasonal scales (Cayan, 1992a,b in Hurrell et al., 2003) and also the characteristics of Mediterranean waters (Mariotti et al., 2002). Fluctuations in temperature and salinity, vertical mixing, circulation patterns and ice formation of the North Atlantic Ocean induced by the NAO (Visbeck et al., 2003) have a demonstrated influence (both direct and indirect) on the biology of marine organisms, including fish stocks (Drinkwater et al., 2003).

Fromentin and Planque (1996) showed that the NAO impacts the pelagic ecosystem of the east Atlantic and the North Sea by determining, among other things, fluctuations in the abundance of two copepod species, *Calanus finnmarchicus* and *C. helgolandicus*, resulting mainly from the combination of two atmospheric factors driven by the NAO. These species form a major food source for fish in the North Atlantic; hence the NAO may have important ecological consequences in the marine food web through cascading effects. Tunberg and Nelson (1998) showed that variability of soft-bottom macrofauna in the Swedish Skagerrak was in phase with the NAO from 10 to 100 m depth, but out of phase with that at 300 m. Furthermore, these authors showed that cod landings were positively related with macrofaunal abundance, while landings of crustacean species were negatively correlated with macrofaunal abundance. Hence, the NAO can have positive or negative effects on commercial fish landings through trophic cascade effects. Borges et al. (2003) showed a relationship between long-term trends in the NAO index and catches of sardine (*Sardina pilchardus*) off Portugal, mediated by trends in wind conditions: High NAO indices are associated with winter northerly winds, enhancing upwelling, which is detrimental for sardine recruitment. Ottersen and Stenseth (2001) showed that the NAO and sea surface temperature (SST) explain 55% of the variability in cod (*Gadus morhua*) recruitment in the Barents Sea, and suggested the existence of a complex relationship between large-scale atmospheric variability, oceanography and marine living resources. In addition to recruitment, the influence of the NAO on cod growth has also been shown for the Northern cod stock off Newfoundland (Drinkwater, 2002). Other examples of NAO influence on marine organisms, including commercial fish species, can be found in the comprehensive review by Drinkwater et al. (2003).

The objectives of this paper are to present the evolution of catches of *Aristeus antennatus* in representative ports of the Catalan Sea, seeking a relationship between catch fluctuations and environmental variability using the NAO index as a proxy, and putting forward ecological hypotheses to explain the patterns observed.

2 Material and Methods

2.1 Data sources

The main fishing ports in Catalonia where red shrimp *Aristeus antennatus* are landed are Roses, Palamós, Blanes, Arenys de Mar, Barcelona and Vilanova i la Geltrú (Fig. 1). The 6 selected ports produced 300 t of red shrimp in 2004, or 80% of the total production in Catalonia (378 t, valued at 15.5 M€, with an average price at first sale of 41 €/kg). The data series analysed were monthly data furnished by the Fishers' Associations from 1988 to 2004 (17 years) for each port, reporting the catch by species and price. The monthly value of the NAO index was obtained from the Climatic Research Unit of the University of East Anglia (Norwich, UK) <http://www.met.rdg.ac.uk/cag/NAO/slpdata.html>. From 1999 to 2004 the updates provided by Tim Osborn were also included (http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm). In addition to the mean annual value of the NAO index, a winter NAO index was calculated by averaging the NAO index from December to March (Hurrell et al., 2003).

2.2 Statistical methods

The periodicity of the monthly catch data of red shrimp for the 6 selected ports was analysed by least squares fitting of the Fourier transform, following Bloomfield (1976):

$$y = \bar{x} + A \cos(\omega t) + B \sin(\omega t),$$

where ω is $2\pi f$ (f frequency in months⁻¹), $\bar{x}$ is the mean catch in the data x_t ($t=1 \dots n$) and the coefficients A and B are given by:

$$A = \frac{2}{n} \sum_{t=1}^n (x_t - \bar{x}) \cos(\omega t),$$
$$B = \frac{2}{n} \sum_{t=1}^n (x_t - \bar{x}) \sin(\omega t).$$

In one instance (Blanes monthly series) it was necessary to remove a long-term decreasing trend to render the catch series stationary. Spectral analysis and time series analysis could not be successfully applied due to the limited span of the data series (17 years).

We computed the cross-correlation function using Pearson's correlation coefficient between the NAO indices (annual and winter) and the annual catches for each port and tested the significance of the correlation coefficients considering time lags from 0 to 4 years.

3 Results

The series for each port showed clear interannual variability, with peaks of production in the early 1990's (1991-1992, in the ports from Blanes to Vilanova i la Geltrú, 1993-1995 in Roses) and more recently from 1999 to 2002. Depending on the port, years of low catches were observed from 1996 to 1999 (Fig. 2).

The catch data series for each port with the Fourier transform fitted by least squares are shown in Fig. 3, including the estimated time periods. The time periods calculated varied around 6.7 – 8.9 years in the 4 central ports (Blanes, Arenys de Mar, Barcelona and Vilanova i la Geltrú) and 11.8 - 12.7 years in the 2 northern ports (Roses and Palamós). Additionally, the different curves were not in phase, even in ports that are close to one another the maximum production is observed in different years (Fig. 3).

The correlation between the mean annual NAO index and the catches in each port was positive and significant for some lags, as shown in Table 1. In Roses, the catches were positively correlated with the NAO index of 3 and 4 years before, while in Palamós there was no significant correlation for any lags. In Blanes the catches were significantly correlated with the NAO index of 1, 2 and 3 years before. In Arenys de Mar the catches were correlated with the NAO index of 2 years before. In Barcelona the catches were correlated with the annual NAO index of 1 and 2 years before. In Vilanova i la Geltrú the catches were correlated with the NAO index of the previous year. For all ports, the significant correlations were always positive and relatively high ($r = 0.493$ to 0.721 , Table 1). Note also that the winter NAO index did not produce significant correlation with the catches.

4. Discussion

The catches of *Aristeus antennatus* in the 6 ports analysed showed clear fluctuations for the period 1988-2004, but were not in phase between nearby ports, with differences of 1 or 2 years in the year of peak catches. The catches for the ports of Palamós to Vilanova i la Geltrú were highest in the early 1990s (1991-1992), with a second maximum between 1999 and 2003. In the northernmost port, Roses, the catches were highest from 1993 to 1995 and again in 2002. On the other hand, for the 4 central ports (Blanes, Arenys de Mar, Barcelona and Vilanova i la Geltrú) the fluctuations in catches showed periodicities from 7-8 years, while the two northernmost ports (Roses and Palamós) showed periods of 12-13 years.

The catches of 5 of the 6 ports analysed were positively and significantly correlated with the mean annual NAO index at different time lags for the different ports, from 1-2 years in the central ports to 3-4 years in the northernmost port, Roses. Although no significant periods have been demonstrated for the NAO index (Hurrell et al., 2003) the power spectrum of the winter NAO index shows a non-significant peak in the 8-10 year band, especially enhanced in the second half of the 20th century (Hurrell and van Loon, 1997 in Hurrell et al., 2003). The possible link between the (non-significant) 8-10 year period of the NAO index and the 8 year period shown for *A. antennatus* was already pointed out by Carbonell et al. (1999) for the Balearic islands. Our results show that the influence of the NAO periodicity on catches of the deep-water shrimp *A. antennatus*, if any, is lagged from 1 to 4 years, depending on the port, with the northernmost ports showing longer periods and larger time lags. Assuming that the catches reported are a valid index of population abundance, our results suggest that the *A. antennatus* stock in central Catalonia follow a different time dynamics from the northernmost stock, perhaps indicating a different response to environmental forcing or different demographic structure.

Our results show that environmental processes in the atmosphere and surface waters have an impact on the temporal dynamics of deep-sea living resources (at least down to 800 m depth, the lower limit of the red shrimp fishery at present). Tunberg and Nelson (1998) also found a 7-8 year periodicity of abundance and biomass of soft-bottom macrofauna, coinciding with the non-significant periodicity of the NAO index. In their study the NAO signal was positively correlated with Skagerrak deep-waters down to 600 m. They proposed that NAO association with the benthos occurs by bottom-up control of the population through influences on primary production.

In the Mediterranean region, Mariotti et al. (2002) reported that the interannual variation in freshwater fluxes was mostly driven by the influence of the NAO. Changes in the freshwater flux produced significant variations in the characteristics of Mediterranean waters, due to the fact that decreasing rainfall during NAO positive years reduces the freshwater flux and results in relatively saltier, and denser, upper layers in coastal waters. We can speculate that these hydrological situations would lead to increased vertical mixing of the water masses, ultimately enriching the deep water with organic matter of superficial origin. Lloret et al. (2001) reported that catches of continental shelf species in north Catalonia were positively correlated with run-off of local rivers and the wind mixing index during the spawning season. In turn, river run-off of the major rivers in the NW Mediterranean (the Rhone and the Ebro rivers) was negatively correlated with high NAO episodes. Hence, for continental shelf species a link with the NAO was shown, albeit of different sign to the one reported here for *A. antennatus*. Recently, Orsi-Relini et al. (2006) have also established a relationship between recruitment of the horned octopus (*Eledone cirrhosa*) and the NAO index in the Ligurian sea. In their study, positive NAO winters enhanced spring recruitment of the horned octopus, without year lags.

The existence of clear patterns linking the NAO with marine ecological processes has been shown in several studies (Fromentin and Planque, 1996; Ottersen and Stenseth, 2001; among others), but the underlying ecological mechanisms are far from being well understood (Stenseth et al., 2002). The variations in environmental parameters linked to the NAO may act on biological organisms at different levels (individual, population) through physiology (metabolic and reproductive processes) or through trophic relationships, including ecological cascade effects (Stenseth et al., 2002). In the case of fish populations comprising several cohorts, the effects of environmental variation become more difficult to analyse, but the time lags observed in our results may suggest that the relationship between the catches and the NAO are influenced by the dominant cohort in the fishery. In central Catalonia (Demestre and Lleonart, 1993; Maynou et al., 2006) the catches are dominated by 2-year old females, although the age-groups 1 and 3 of males and females are also important. The effects of NAO-associated events on cod have been shown to be sustained for several years (Ottersen and Stenseth, 2001) to the cumulative effect of stronger year classes on spawning in later years.

Although recruitment in fish populations is known to be a key process strongly influenced by environmental variability, very little is known about the population dynamics of red shrimp pre-recruits, larval and egg stages. Individuals of *A. antennatus* smaller than 20 mm CL have been caught by experimental trawl surveys deeper than 800 m and they are more abundant below 1300 m depth (Sardà and Cartes, 1997; Sardà et al., 2004), with the smallest individuals (5-10 mm CL) being caught in winter (December to March) at 1300 m (Sardà and Cartes, 1997).

On the other hand, for fish and other high-trophic level organisms, the links of abundance levels to the NAO are often considered to occur through the association between the NAO and zooplankton production (Drinkwater et al., 2003). In the case of *A. antennatus*, studies on diet composition (Cartes, 1994; Cartes, 1998) showed that during spring and summer, coinciding with the maturity of adult females, ovigerous females switch their opportunistic, endobenthic diet to suprabenthos and meso-zooplankton, of higher energy content. Thus, a possible explanation for the relationship between positive NAO years and increased catches of *A. antennatus* 1-3 years later would be the following: Years of higher food availability (indirectly related to positive NAO years through secondary production) would lead to enhanced spawning by shrimp females, contributing to stronger year-classes that would appear in the catches 1 to 3 years later.

5. Conclusions:

According to Drinkwater et al. (2003) the NAO is an excellent proxy for long-term series on environmental variables, since the NAO captures more the overall physical variability than any individual local climate index, as it integrates the local climate changes.

Despite the explanation proposed above, that NAO-induced environmental variability may enhance food supply to *A. antennatus* and hence strengthen particular year classes that appear in the catches 1 to 3 years later, many questions remain open. Among these questions, it would be worth investigating the dynamics of *A. antennatus* pre-recruits. It is also necessary to consider the effect of negative NAO years on condition and natural mortality. The observation that the catches between nearby ports (< 50 km) are not exactly in phase is also interesting, as it suggests that the effects of the NAO may present some spatial variability, even at small scale (Drinkwater et al., 2003). Additionally, it may be suggested that the different ports operate on shrimp stocks organised as metapopulations, more or less interconnected, but responding individually to local environmental forcing.

Further research is needed to have a clearer conceptual model and to quantify the relationships between environmental variability and the population dynamics of red shrimp, moving beyond computing correlations and establishing the precise mechanisms through which environmental forcing, such as NAO, acts (Drinkwater et al., 2003). In any case, the possible response of a deep-water organism to environmental changes originated in the atmosphere is remarkable and should be incorporated in population dynamics models (Stenseth et al., 2002)

6 References

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Figure captions

Fig. 1. Map of the study area showing the location of the 6 ports studied. Depth contours from 200 to 2000 m at 200 m intervals are shown.

Fig. 2. Annual catches (kg) of *Aristeus antennatus* for the 6 ports studied and NAO index (bottom panel) for 1988-2004.

Fig. 3. Monthly catches (kg) of *Aristeus antennatus* for the 6 ports studied with fitted Fourier transform for 1988-2004, showing the time periods (years).

Table 1. Cross-correlation between the mean annual NAO index (1983-2004) and the catch of *Aristeus antennatus* in the main fishing ports of Catalonia (1988-2004), considering lags from 0 to 4 years. Bold face indicates significant correlation at the 95% level.

lag	-4	-3	-2	-1	0	1	2	3	4
Roses	0.721	0.610	0.205	0.144	-0.16	-0.268	-0.396	-0.173	-0.121
Palamós	-0.274	0.034	0.262	0.239	0.223	0.156	0.214	0.175	0.076
Blanes	0.202	0.527	0.607	0.501	0.298	0.144	-0.067	-0.189	-0.398
Arenys de Mar	-0.188	0.380	0.521	0.412	0.234	-0.184	-0.123	-0.353	-0.303
Barcelona	-0.183	0.189	0.541	0.493	0.452	0.052	-0.048	-0.430	-0.293
Vilanova	-0.203	-0.138	0.303	0.500	0.192	0.110	-0.088	-0.277	-0.435
Total	0.100	0.400	0.481 ^a	0.462	0.216	-0.027	-0.139	-0.246	-0.299

^a significant at the 90% level

{figure 1}

{figure 2}

{figure 3}