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Wavelet analysis of correlation among Canary Islands octopus captures per unit effort, sea-surface temperatures and the North Atlantic Oscillation

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ABSTRACT

Short-term fluctuations in the octopus catches off the Canary Islands have been attributed to changes in the sea surface temperature (SST) and the North Atlantic Oscillation (NAO) pattern. These results have been found using stationarity assumptions. However, the behavior of environmental systems is not always linear, and environmental time series do not always satisfy the statistical property of stationarity. Wavelet spectral analysis is a methodology which can deal with non-linear, non-stationary and noisy time series. Cross wavelet analysis (wavelet coherence) is applied to investigate the environmental effects (SST, NAO) on octopus abundance fluctuations measured as capture per unit of effort (CPUE) from 1989 to 2007 in the waters of the Canary Islands. A slightly positive correlation exists between NAO and CPUE at lags and leads of a few months. Additionally, a good relationship between SST and CPUE exists on the same seasonal scale, but there is a relatively weak relationship between SST anomalies and the NAO. When the analysis is extended to the interannual scale, the wavelet coherence identifies a statistically significant relationship between CPUE and NAO, but this does not happen when the wavelet coherence between CPUE and SST is computed. These results suggest that fluctuations in octopus catches could be the result of SST fluctuations but in synergy with other unknown environmental variables which are also affected by the NAO pattern.

1. Introduction

A simple approach to study environmental processes is to consider them as linear and stationary, although, non-linear, non-stationary, and multi-scale processes are the rule rather than the exception (Hsieh et al., 2005; Rouyer et al., 2008). The main requirement of many statistical tools for time series analysis (e.g., Fourier analysis) is stationarity (Priestley, 1981). However, environmental time series do not always satisfy this requirement, and growing evidence supports the need to consider the importance of transient dynamics in environmental process (Stenseth et al., 1998; Hsieh et al., 2005; Cazelles et al., 2008; Rouyer et al., 2008).

The dynamics of transients can play an important role in the structure of natural systems (Hastings, 2001; Benton et al., 2006). Recent studies have shown that dynamics of populations can switch between different states at multidecadal scales, triggered by small environmental changes (Cazelles et al., 2008). However, environmental perturbations are not the only mechanisms able to trigger complex transients. The mix of non-linear dynamics and unstable dynamical processes can also generate complex and non-stationary dynamics (Cushing et al., 1998; Cazelles, 2001; Cazelles et al., 2008).

Wavelet spectral analysis is a powerful mathematical tool that overcomes the problems of non-stationarity in noisy time series by performing a localized spectral decomposition of the signal, determining the dominant modes of variability and how those modes vary in time and scale (Grossman and Morlet, 1984; Torrence and Compo, 1998). Wavelet spectral analysis includes the estimation of the wavelet spectrum (uni-variate analysis), the wavelet cross-spectrum, wavelet coherence, and phase coherence (bi-variate analysis). It has been applied in many fields, including climatology, meteorology, geophysics, ecology (Lau and Weng, 1995; Torrence and Compo, 1998; Grinsted et al., 2004; Keitt and Fisher, 2006; Cazelles et al., 2008).

Recent evidence using wavelet analysis and other statistical tools indicates that climatic oscillations, such as the North Atlantic Oscillation (NAO), the Indian Oscillation (IOI), or the El Niño-Southern Oscillation (ENSO) have important effects on marine fish populations (Mantua et al., 1997; Mènard et al., 2007; Rouyer et al., 2008; Hsieh et al., 2009). Particular focus has been placed on the large-scale fluctuations of salmon, sardine, and anchovy populations because these fisheries have great economical value and

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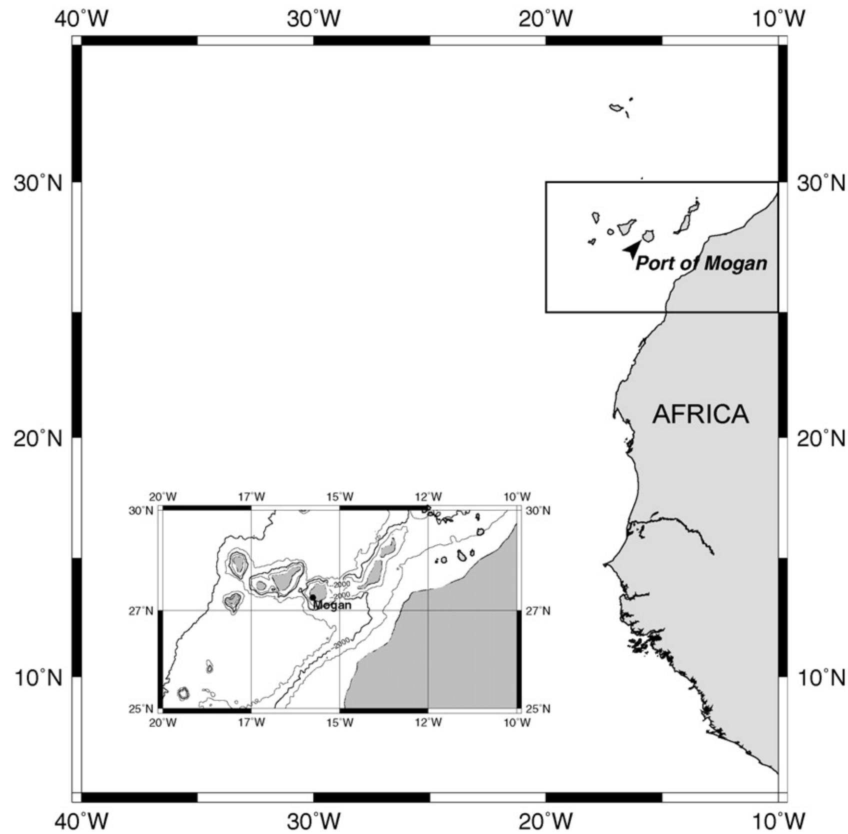

Fig. 1. Map showing the study area. The small square shows the catch location (SW Gran Canaria).

far-reaching societal impacts (Jacobson et al., 2001; Hsieh et al., 2009). However, there are relatively few studies using cephalopod species, such as octopus, especially at the geographical locations around the Saharan bank (close to the Canary Islands and Northwestern African shelf) (Pierce et al., 2008).

Octopus vulgaris is one of the most important target species for the industrial fisheries which operate in the Northwestern African upwelling system (Balguerias et al., 2000; Faure et al., 2000), and the adjacent small-scale fishery off the Canary Islands (Hernández-García et al., 1998, 2002). Previous studies have shown that cephalopods are highly sensitive to environmental conditions and changes at a wide range of spatial and temporal scales (Faure et al., 2000; Balguerias et al., 2000; Pierce et al., 2008; Caballero-Alfonso et al., 2010). Solari (2008) suggests that the oscillations in catches of *O. vulgaris* during the last 50 years in the Northwestern African upwelling system are closely related to variation in NAO index. Consequently, Caballero-Alfonso et al. (2010) emphasized the importance of sea surface temperature (SST) and the NAO on common octopus catches in a small-scale trap fishery off the Canary Islands during 1989–2007. This study extends previous result by Caballero-Alfonso et al. (2010), who used a linear model.

On the other hand, it is assumed that cephalopods, due to their short life cycle, around a year (Boyle and Boletzky, 1996; Hernández-López et al., 2001; Mangold, 1983; Doubleday et al., 2006; Leporati et al., 2008), are good indicators of climatic variability (Sims et al., 2001; Zuur and Pierce, 2004; Solari, 2008; Pierce et al., 2008; Caballero-Alfonso et al., 2010).

The climatic variability effect should be reflected on their biomass next year/month (Georgakarakos et al., 2006). In this way, yearly recruitment (Robin and Denis, 1999), and consequently the availability to the fishery (Agnew et al., 2002; Chen et al., 2006), is conditioned by the effects that climatic variability has on their relatively large pelagic paralarvae stages in relation with their longevity (Waluda et al., 1999). Therefore, it is likely that those climatic variables that can be measured at surface level (i.e., SST) may have direct effects on the survival rates of these pelagic stages. The influence could be explained either through growth, food availability or natural mortality due to other causes (Forsythe, 1993; Caveriviere et al., 1999; Robin and Denis, 1999; Waluda et al., 1999; Leporati et al., 2007; Pierce et al., 2008). It could therefore be more feasible to differentiate climatic effects from the influence of fishing in these species, because their response to environmental fluctuations should be faster (Hernández-García et al., 2002; Chen et al., 2006; Caballero-Alfonso et al., 2010).

Therefore, the main objective of this paper is to estimate the degree to which the environment variables (SST, NAO) and CPUE are linked at the different time scales and to examine their interannual fluctuations by means of a cross wavelet analysis (normalized wavelet coherence).

2. Material and methods

2.1. Data

Monthly catches of octopus (measured as CPUE) for 1989–2007 (228 monthly values) were obtained from the trap fishery landed in the southwest of the Gran Canaria Islands (Fig. 1) (see Caballero-Alfonso et al., 2010). Monthly NAO indices were obtained from NOAA database (NOAA) (http://www.cpc.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii; http://www.esrl.noaa.gov/psd/data/gridded/data.kaplan_sst.html) covering the same period. The monthly anomalies of the SST south of Gran Canaria (28.5°N/16.5°W) were obtained from Kaplan's extended dataset v2 (Kaplan et al., 1998). NAO indices and monthly SST anomalies corresponding to a longer period, 1950–2007 (696 monthly values) were also used.

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2.2. Methodology

The relationship between the NAO teleconnection pattern, SST and CPUE statistics was evaluated. A traditional analysis based on Pearson's correlation coefficient between CPUE, SST (Kaplan et al., 1998) and the NAO index was performed. After removing trends, whether the correlation coefficient was significantly different from zero at $\alpha = 0.05$ was tested using a Monte Carlo test (to account for the reduction in the degrees of freedom due to the autocorrelation of the series). Several realizations (500,000) of an AR(1) process with the corresponding autocorrelation for each of the tested series were created, and the correlation coefficients of segments with the same length as the tested series were used to create an histogram, which represents the distribution of correlation coefficients from AR(1) processes. Values of the correlation coefficient under (above) the 2.5% (97.5%) percentiles in the distribution of correlation coefficients were considered significant (Caballero-Alfonso et al., 2010).

Cross-correlation functions (CCF) (Venables and Ripley, 2002) were used to determine, after removing trends, the degree of temporal correspondence between CPUE and climate data as a first approximation to the possible relationship between these variables. A cross-wavelet analysis (normalized wavelet coherence) was also used because it is well suited to analyze the relationship in time and scale space between two time series, $x(t_i)$ and $y(t_i)$ (Maraun and Kurths, 2004; Grinsted et al., 2004; Cazelles et al., 2008).

The normalized wavelet coherence (WCO) is defined as the amplitude of the wavelet cross spectrum (WCS) normalized by the wavelet spectrum of each signal (Maraun and Kurths, 2004; Cazelles et al., 2008), that is:

$$\mathrm{WCO}_i(s) = \frac{\left| \left\langle \mathrm{WCS}_i(s) \right\rangle \right|}{\left[\left\langle \mathrm{WPS}_i^x(s) \right\rangle \left\langle \mathrm{WPS}_i^y(s) \right\rangle \right]^{1/2}}$$

where $\mathrm{WPS}_i^x(s)$ and $\mathrm{WPS}_i^y(s)$ are the wavelet power spectrum of the time series, $x(t_i)$ and $y(t_i)$, respectively, and the $\langle\rangle$ denotes a smoothing operator in both time and scale. The smoothing is performed by means of the convolution with a constant-length window function both in the time and scale (Cazelles et al., 2008; Maraun and Kurths, 2004; Maraun et al., 2007). The numerator and denominator must be smoothed to some extent or $\mathrm{WCO}_i(s)$ would be identically one (Maraun and Kurths, 2004). The wavelet coherence is bounded between 0 and 1. A 0 value means that there is no relationship between the time series at the scale-time value considered; similarly, a value of 1 implies that a perfect linear relationship exists (Maraun and Kurths, 2004; Grinsted et al., 2004).

The phase coherence is defined as (Cazelles et al., 2008):

$$J_i(s) = \tan^{-1} \frac{Im(\langle \mathrm{WCS}_i(s) \rangle)}{Re(\langle \mathrm{WCS}_i(s) \rangle)}$$

where Re() and Im() mean the real and imaginary parts of the $\mathrm{WCS}_i(s)$, respectively.

The phase coherence provides information about the possible delay in the relationship (e.g., the time series are either in or out of phase) (Cazelles et al., 2008). Mathematical details are given in Cazelles et al. (2008), Maraun and Kurths (2004) and references therein.

We follow the methodology to compute the WCO, WCS and WSP by Maraun and Kurths (2004) and Maraun et al. (2007), as implemented in the R package SOWAS. The choice of a particular wavelet mother function can influence the time, the scale, and the frequency resolution of the time series decomposition (Mallat, 1998; Torrence and Compo, 1998). The SOWAS package uses the Morlet wavelet. It provides a good balance between scale (frequencies) and time localizations (Grinsted et al., 2004; Mi et al., 2005). It is one of the best mother functions in terms of reproducing the frequency decomposition of the signal (Kirby, 2005). It has often been successfully used in the study of environmental variables, such as SST, NAO or ENSO (Torrence and Compo, 1998; Torrence and Webster, 1999; Maraun and Kurths, 2004) and ecological variables, such as tuna catches (Mènard et al., 2007; Rouyer et al., 2008), swordfish (Corbineau et al., 2008) or larval anchovy (Hsieh et al., 2009).

A test on the statistical significance of the results of the wavelet coherence has been applied (Maraun and Kurths, 2004; Maraun et al., 2007). The first requirement to apply a significance test is that an appropriate background spectrum has been chosen. For many environmental (ecological, hydrological, climatological, etc.) time series, a red noise (AR1) process is a reasonable noise model (Hasselmann, 1976; Torrence and Compo, 1998; Vasseur and Yodzis, 2004). However, it is important to take into account that some ecological time series display an autocorrelation structure that an AR1 process cannot consistently describe (Cuddington and Yodzis, 1999; Inchausti and Halley, 2002). For these reasons, alternative models of background noise have been developed; for example, the surrogate type I and II models or the 'beta surrogates' (Rouyer et al., 2008). However, similar conclusions are reached using different noise models when time series are very short and noisy (Cazelles et al., 2008). Therefore, considering the length of the available series, we have used the spectrum corresponding to an AR1 process as the one against which the null hypothesis "H0: the processes are not coherent" is tested. The significance ("pointwise") test (Maraun and Kurths, 2004; Maraun et al., 2007) is computed as follows: choose a confidence level $1 - a$. The coherences corresponding to several AR1 process with the same autocorrelation that the observed time series is computed, and estimates of the corresponding critical values at the $(1 - a)$th confidence levels are obtained by means of Monte Carlo simulation. Then, at every point in the wavelet time-scale domain, it is checked whether the estimated spectrum to the time series exceeds the corresponding randomly obtained critical values. See Maraun and Kurths (2004) for further details on the methodology implemented in SOWAS.

3. Results

The cross-correlation between the monthly CPUE and NAO is significantly different from 0 at several lags (Fig. 2a). We particularly focus at lag −1 (one month) and lag −2 (two months) of the NAO index, with positive values of 0.137 ($p < 0.05$) and 0.162 ($p < 0.05$) respectively. The cross-correlation is not significant at lag 0. Other lags are present, but due to difficulty of interpretation, we ignore them. The cross-correlation between the monthly CPUE and SST is negative and there is a significant strong cross-correlation until a twelve month (one year) lag (Fig. 2b), something which is a manifestation of the persistence of both the SST and CPUE series.

The cross-correlation between the NAO index and SST is significantly different from zero (−0.139, $p < 0.01$) from January 1950 to December 2007, at a 0 lag (Fig. 3a). The cross-correlation between the NAO index and the SST (from January 1989 to December 2007) at −1 lag (one month) is also significant (−0.156, $p < 0.05$) (Fig. 3b).

Wavelet coherence and phase between CPUE and NAO and between CPUE and SST from January 1989 to December 2007 are shown in Fig. 4a–d. Cross-wavelet coherence and phase analyses indicate a non-stationary (transient) relationship between the CPUE and both environmental variables. Significant coherency between CPUE and NAO (Fig. 4a) was found only from June 1991 to March 2001, with a periodicity c. 1.9–3.5 years, and they were in phase (0.35–0.92 radians or 0.67–1.76 months), indicating a positive correlation between those variables, particularly at those periods (interannual variability).

Despite the fact that the CCF shows a close relationship between CPUE and SST on a monthly time-scale, the interannual variability

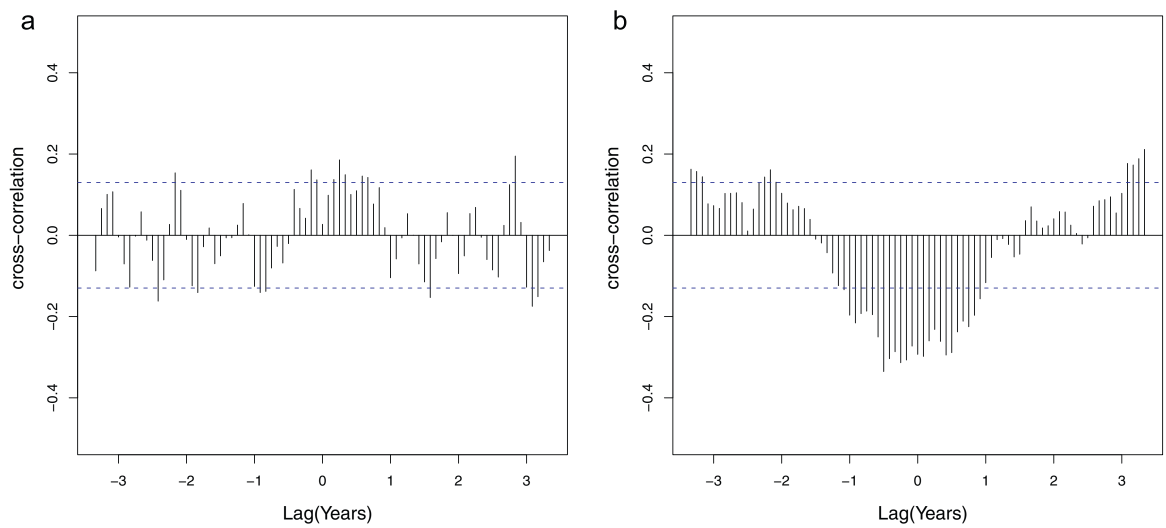

Fig. 2. Cross-correlation between (a) CPUE and NAO and (b) CPUE and SST. Both series cover the period January 1989–December 2007. The dashed lines indicate the points corresponding to a 95% confidence.

of the CPUE does not seem to be particularly affected by the SST (Fig. 4b). The only places where wavelet coherence appears over the level that could be expected by chance are inside the cone of influence and cannot be reliably interpreted.

4. Discussion

Hernández-García et al. (2002) and Caballero-Alfonso et al. (2010) have shown that there is an effect of environmental variability on *O. vulgaris* abundance off the Canary Islands due to SST. The delay between both variables can be explained alluding to the consequence of the effect of sea water temperature on octopus recruitment, which affects crucial phases in the life cycle of this cephalopod (i.e., paralarvae survival, growth rates, age of juvenile benthic settlement and timing of the reproductive peaks). Our data indicate that there is a statistically significant relationship between water temperature and CPUE on seasonal time scales. However, this does not extend to the interannual scale. On the interannual scale, the relationship between SST and CPUE is not as strong and direct as that between the NAO index and CPUE, as shown by the wavelet coherence. Therefore, the relationship between the NAO and CPUE on this time-scale is probably due to other mechanisms different to temperature.

Hernández-García et al. (2002) reported the existence of two annual cohorts in the common octopus population off the Canary Islands, the first during April and the second between October and November. This timing in the reproductive cycle of octopus has also been described in other places in the North-Eastern Atlantic (Nigmatullin and Ostapenko, 1977; Hatanaka, 1979; Nigmatullin and Barkovsky, 1990; Guerra, 1992). These reproductive peaks seem to occur when the NAO changes from lower to higher values and vice versa.

The relationship between the SST and the NAO index has been largely established by other authors (e.g., Cayan, 1992; Visbeck et al., 1998; Seager et al., 2000; Marshall et al., 2001). However, CPUE is not particularly affected by the SST on the interannual scale. Therefore the NAO is probably related to other environmental variables that affect the octopus life cycle more directly than temperature, including wave height (Lionello and Sanna, 2005; Cañellas et al., 2010; Różyński, 2010) or wind-driven ocean circulation (Penduff et al., 2004; Chhak and Moore, 2007). Even the effect of the Northwest Africa upwelling system on the Canary Islands

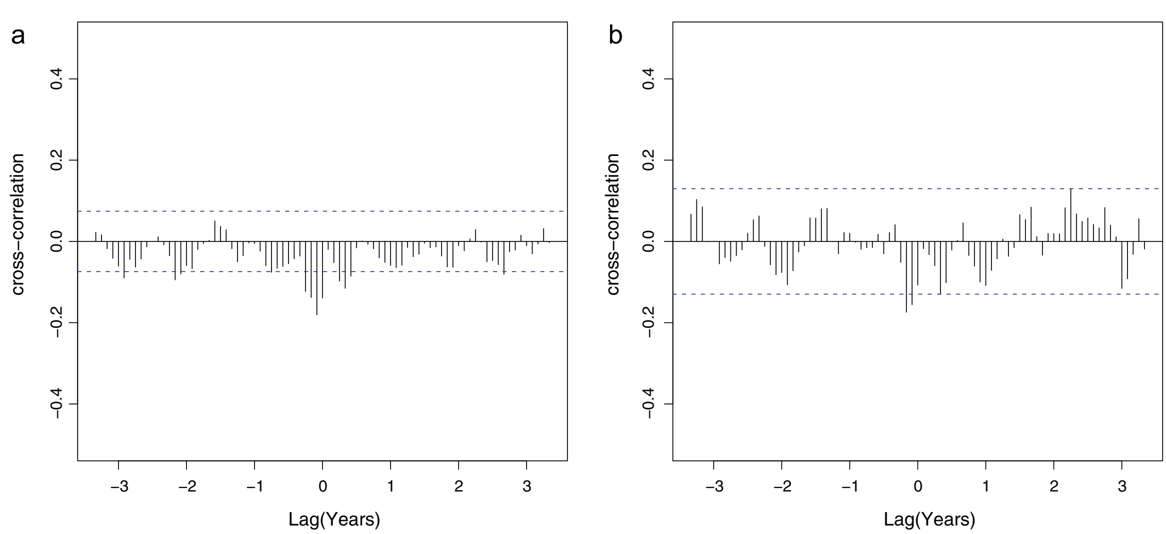

Fig. 3. Cross-correlation between SST and NAO (a) 696 data points extending from January 1950 to December 2007; (b) 228 data points extending the period from January 1989 to December 2007. The dashed lines indicate the points corresponding to a 95% confidence level.

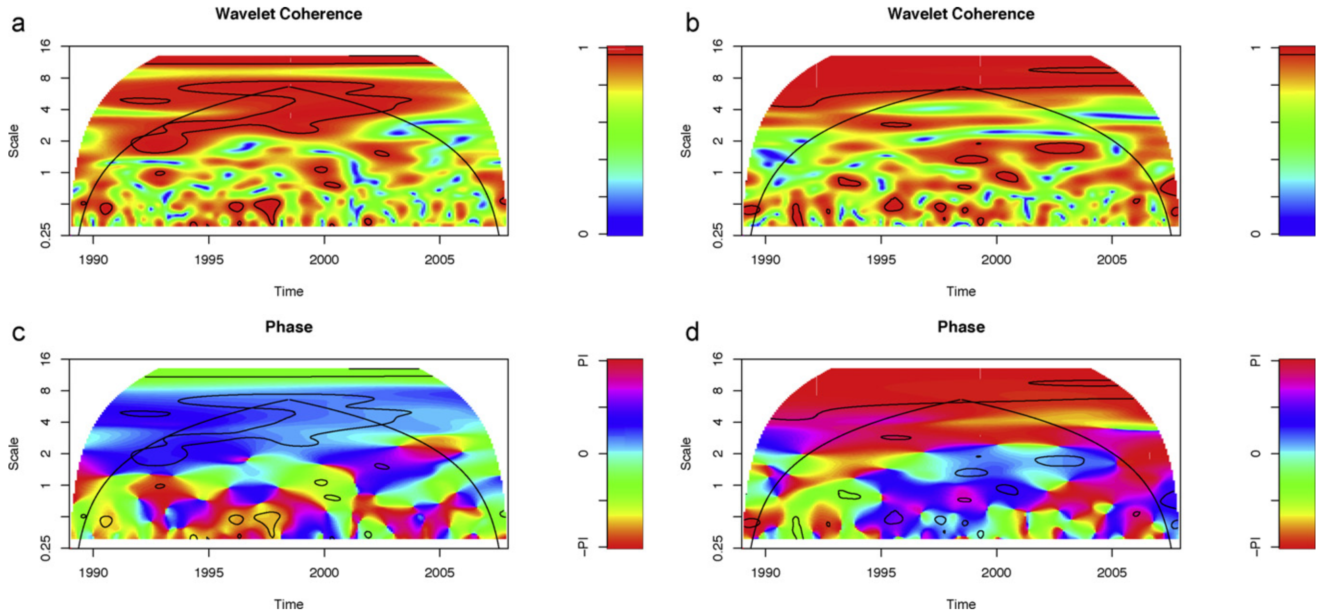

Fig. 4. Wavelet coherence (WCO) and phase (WPH), computed with data from January 1989 to December 2007. (a) WCO between the CPUE and NAO index and (b) WCO between CPUE and SST. (c) Phase (red) between the CPUE and NAO index and (d) phase (red) between the CPUE and SST. The area marked by the black lines indicates the cone of influence (COI) where edge effects become important. The solid black contour encloses regions of >95% confidence.

(Barton et al., 1998, 2004; Pelegrí et al., 2005) may vary according to the changes in the NAO pattern. Nevertheless, the relationship of the NAO with coastal upwelling off NW Africa turned out to be ambiguous due to a negative correlation between the NAO index and the meridional wind stress and a lack of correlation with the SST index (Narayan et al., 2010).

The atmospheric circulation pattern associated with the NAO can affect directly the fishery and the capture of this species. That is to say, the weather conditions when the small-scale fishery could be carried out more efficiently are coincident with a range of values in the NAO index that describe characteristic ranges of wind stress and sea waves' height. However, the NAO index recorded during both reproductive peaks are different (one-way ANOVA; $F = 9.06$; $p < 0.01$), being positive in April and negative in October, with trade-winds from the north during the first peak and winds from the south during the second one. However, it is also true that variation in CPUE of octopus from year to year are also consequence of the recruitment success (Solari, 2008), and hence paralarvae survival rates. Paralarvae of the common octopus are part of the zooplankton during the first 5–12 weeks of life (Mangold, 1983; Villanueva, 1995), changing gradually to a benthic life style (Boletzky, 1977). This process depends on temperature (Mangold, 1983), and sea water temperature depends on several factors other than the NAO, but related with it (wind stress, mixed layer depth due to sea waves, cloud cover, etc.). These processes also affect food availability for paralarvae, dispersion, intensity of the retention mechanisms of larvae around the island, etc. (Van-Heukelen, 1979; Norcross and Shaw, 1984; Boehlert et al., 1992; Villanueva, 1995; Rodríguez et al., 2001, 2004). They are more or less relevant depending on the geographical scale and local features (Mangold, 1983; Hernández-García et al., 1998). Anyway, the effect of the NAO does not seem to be similar during the whole studied period, and it was stronger between 1989 and 1994, when it coincided with high values in landed captures. During this period, the wavelet coherence shows a lag that oscillates between 1.9 and 3.5 years, which could be related with the overlapping of several cohorts in the fishery as pointed out by Hernández-García et al. (2002).

All these interactions are complex, in common with the ways climatic parameters affect biological species (i.e., time of embryonic development, paralarvae/plankton match-mismatch, growth rate, age at settlement, age at maturity, spawning season, etc.). Nonetheless, the direct and indirect influences of the NAO on the octopus fishery could take different forms, and obviously SST is one of the most important ones due to its effects on the biological system at different levels of organization (species, communities and ecosystems). It can also condition the interaction between the octopus and fishermen (i.e., making easy or complicating the handling and recovery of traps). SST is a consequence of coupling between the atmosphere (and consequently, of NAO as an atmospheric phenomenon) and the ocean, though the wind stress, sea-waves, clouds, etc., and its effects on octopus vary depending of the phase of the life cycle of the species. Therefore, its effect should be reflected in the part of the biomass available to the fishery, the CPUE.

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