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FISH STOCK ASSESSMENTS AND PREDICTIONS: INTEGRATING RELEVANT KNOWLEDGE.
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Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions*

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SUMMARY: Decadal changes have been observed in the annual catch of sardine (*Sardina pilchardus* W). Long-term changes have also been observed in alongshore winds off Portugal in the last decades in winter months. During sardine spawning season (winter), northerly winds that favour upwelling led to unfavourable conditions for egg and larval survival. By using time series analysis, we investigated the effect of wind conditions and North Atlantic Oscillation (NAO) on the sardine catches, in the period from 1946-1991. We also investigated the time lag between recruitment strength and its turnout in catches. We concluded that recruitment is forced to a lower level when the frequency and intensity of northerly wind exceeds a certain limit in winter. Our time series retrospective analyses led to evidence of climatic driven regime-shifts in West Portugal sardine productivity in late 1960s-early 1970s. These results are discussed in terms of their implications in fisheries management plans.

Key words: sardine, *Sardina pilchardus*, regime shifts, time series analysis, catch, recruitment, Portugal, wind, coastal upwelling, NAO.

INTRODUCTION

Sardine (*Sardina pilchardus* W.) is the main pelagic fish species off Portugal. It is of great socio-economical importance for the Portuguese fishing community and industry, as well as for other countries of the region (Morocco, Spain and France). Thus, the fluctuations in its productivity place important problems for fisheries' sustainability in the scope of fishery management and policies.

These fluctuations in small pelagic fish stocks (e.g., sardines and anchovies) are believed to be associated with environmental factors and climatic changes (e.g., Sharp and Csirke, 1983; Lluch-Belda, 1989; Kawasaki *et al*., 1991; Bakun, 1996; Durand *et al*., 1998). On the west coast of Portugal, Borges *et al*. (1997) and Santos *et al*. (2001) reported that decreasing trends in the recruitment of small pelagic populations in the 1980s and 1990s were related with the increase of upwelling events during winter. Off Portugal, sardine spawn predominantly in winter (Figueiredo and Santos, 1989; Ré *et al*., 1990), thus these upwelling events in winter have a negative impact on recruitment, limiting the success of spawning to the beneficial upwelling conditions occurring later during summer (Santos *et al*., 2001).

The location of the Portuguese west coast at the eastern boundary of the North Atlantic, determines many of its atmospheric and oceanographic characteristics. One main consequence is the occurrence of coastal upwelling during summer in response to the

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intensification and steadiness of favourable northerly winds (e.g., Wooster *et al*., 1976; Fiúza *et al*., 1982). However, the North Atlantic Oscillation (NAO, defined as the normalized pressure difference measured in meteorological stations located on the Azores and in Iceland) is responsible for generating large amplitude patterns in wind speed anomalies and modifications in the direction of the wind during winter time (Cayan, 1992). From the early 1940s until the early 1970s, the NAO exhibited a downward trend, but the dominance of NAO positive phase has occurred over the past 25 years, with unprecedented highly positive index values since 1980 (Hurrell, 1995; Hurrell and van Loon, 1997; Jones *et al*., 1997). An increase in NAO index reflects a corresponding change in the strength of the winds across the North Atlantic. Dickson *et al*. (1988) showed how the increased northerly winds during the 1970s were coupled with increasing upwelling off Portugal, a decline in zooplankton and phytoplankton in the North Atlantic, and declines in the catch of sardines off Portugal. Dias (IPIMAR, *personal communication*) noted an increase in the frequency of upwelling favourable winds during winter on the west coast of Portugal, in the 1970s and 1980s. The increasing frequency of winter wind led to changes in the upwelling seasonal patterns off Portugal, which adversely affected recruitment (Borges *et al*., 1997; Santos *et al*., 2001).

In the present study, we start from the hypothesis of the underlying regional scale processes of the unfavourable effect of the winter upwelling on the recruitment. We move on, to a larger scale, to the hypothesis that the North Atlantic Oscillation (NAO) could play an important role in the long-term variability of the winter wind patterns, and so on the recruitment variability. We start from these hypotheses and present the results of time series retrospective and comparative analysis of sardine catches, winter wind conditions and NAO. Finally, we discuss the results in the context of its potential use in population dynamics for advice in fisheries management.

MATERIAL AND METHODS

Time series data sets

Meteorological data

Information from the U. S. National Center for Atmospheric Research (NCAR) data set was extracted from one main grid composed of 5º latitude by 5º longitude daily values of the Sea Level Pressure (SLP) at 12 UTC, covering the period from 1 January 1946 to 31 December 1991. From this information, we constructed three atmospheric time series: (i) the North Atlantic Oscillation (NAO) winter (January-March) index, calculated from the normalized SLP difference from Ponta Delgada (Azores) and Reykjavik (Iceland) meteorological stations; (ii) the northern wind frequency (Freq_nw), defined as the percentage of days during winter (January-March) with northerly winds; and (iii) the mean northern wind (Mean_nw) index, defined as the monthly mean of the meridional component of the geostrophic wind during winter months (January-March). Note that in the present study a positive Mean_nw value means that the wind direction is from the north (northerly wind) and a negative value means that the wind blows from south (southerlies). The wind time series values were calculated on a grid of 5º latitude by 5º longitude extending between latitude 30ºN-50ºN and longitude 25ºW-5ºE. This area is concentrated over the Iberian Peninsula, with centre at 40ºN and 10ºW, just offshore the Portuguese west coast. At these latitudes the geostrophic wind is a good approach to the real wind. Considering that the horizontal components of the Coriolis effect and the pressure gradient are in balance, the geostrophic winds were computed using the equation of the geostrophic balance (Peixoto and Oort, 1992):

$$\mathrm{v_g} = \frac{1}{\rho f}\mathrm{k} \times \nabla p$$

where

$\mathrm{v_g}$ is the geostrophic wind
ρ is the density
f is the Coriolis parameter
$\mathrm{k} \times \nabla p$ is the position vector of the pressure gradient

The Mean_nw index was then calculated using the methodology described in Trigo and DaCamara (2000).

Sardine data

At present, Portuguese sardine catch time series are available from 1926 to 1999. The catch time series were taken from ICES' "Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy" (ICES, 2001). Nevertheless for the time series analysis, we used only the Portuguese sardine catches (Catch) of the western land-

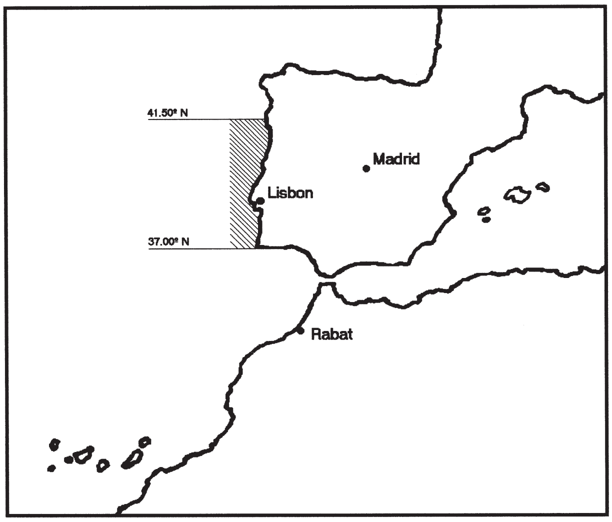

FIG. 1. – Map of the area under study - the Portuguese west coast (shaded).

ing ports from 1946 to 1991, in order to coincide with the length of the wind time series.

Landings of the sampled harbours were grouped, to represent catches from the western coast of Portugal from Minho River (41.5ºN) to Cape S. Vicente (37.0ºN). Figure 1 illustrates the studied area. The southern coast of Portugal (subdivision IXa South-Algarve) was not included in the present study due to the different oceanographic features that prevail in the area (e.g. Relvas and Barton, 2002).

Historical fishing effort directed to sardine, in number of purse-seines operating, indicates that 350-400 boats were fishing during 1950-60s. In the seventies the fleet number was drastically reduced by 50%, apparently as a result of a prolonged lack of sardine availability (Pestana, IPIMAR, unpublished data).

New technologies were introduced in the purse seine fleet, which facilitated mobility and detection of schools, consequently increasing its fishing power. In spite of this, the mean number of seine operations per day per boat has decreased, from the usual two sets performed during 1940-1960 to the performance since the 1970s of only one operation per day per boat as indicated in the official Portuguese statistics published from 1941 to 1999. Following a recruitment failure observed during the 1990s, Portugal introduced, in 1997, strict management measures forcing the purse-seine fleet to reduce fishing effort by: (i) an overall limitation in the number of fishing days (180 days per year, and a week-end ban); (ii) an overall quota reduction of about 10% of the fishing days per year; (iii) a closure of the purse- seine fishery in the northern part of Portugal from the 15th of February to 15th of April; and, finally, (iv) a yearly quota reduction by fishermen regional organization, which have been distributed in daily catch limits by boat (ICES, 2002).

The fleet behaviour and management measures introduced in late 1990s indicate that in general, along the period of study (1946-1991), fishing effort has been adjusted with some time delay, to the existing high or low sardine abundance in the area.

Therefore our assumption that sardine catch variability is a proxy of changes in recruitment, with a certain time lag, seems to be rather plausible. The lag will depend mainly of the purse seine catch selection pattern which is the result of: (i) the area where the schools are found (closer to or farther away from the nurseries); and (ii) the distribution of the fishery by season relative to the timing of sardine recruitment.

To explore the relationship between sardine recruitment and catch data, we used the available recruitment (0-group) data series from 1978 to 1999 as estimated by ICES (2001) from Virtual Population Analysis (VPA). The analytical assessment used fishery dependent data (commercial catch-at-age) and fishery independent data (acoustic survey abundance-at-age, egg survey spawning biomass).

Composition of sardine commercial catch-at-age by ICES sub-divisions corroborates that in the studied area (western Portugal) juveniles are available to the fishery (ICES, 2001 and 2002). Thus, the yield variability of the commercial catches should represent recruitment variability.

Statistical analysis

The statistical time series analysis of data was performed using standard correlation and spectral methods (for reference see, e.g. Brockwell and Davis, 1991). The analysis of the sample autocorrelation functions of each series allowed the study of their memory structure. The estimated spectra allowed the study of the periodic behaviour and inter-decadal dynamics of the series. The results obviously depend on the length of the data series, which for this study is 45 years. The analysis of the sample cross correlation functions, allowed the investigation of the statistical relationships between catches and meteorological variables. The computations and graphics were performed with PcGive (Hendry *et al.*, 2000) and GiveWin (Doornik *et al.*, 2001), specialized time series modules of the OxMetrics™ package.

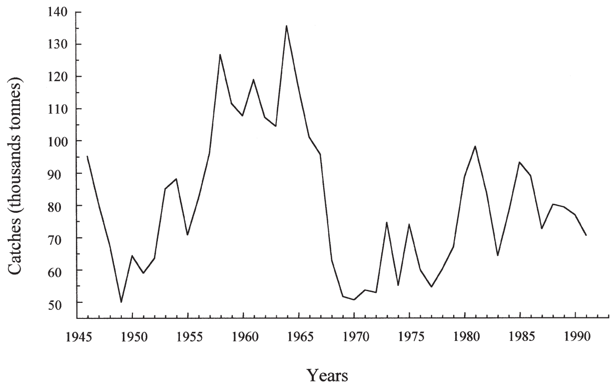

FIG. 2. – Sardine catch in ICES subdivisions IXa Central-North and IXa Central-South in the period 1946-1991.

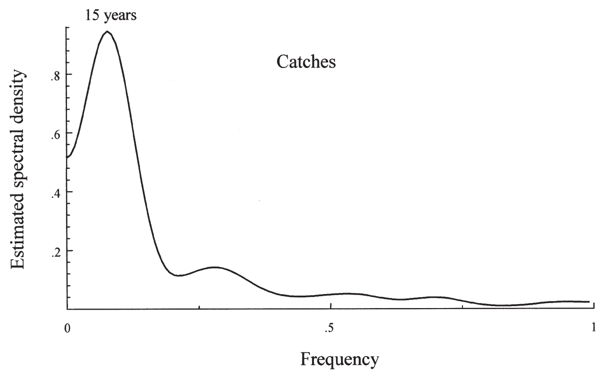

FIG. 4. – Smoothed periodogram of sardine landings obtained with a Parzen window (m = 25).

RESULTS

Sardine catch

By simple visualization of the catch time series (Fig. 2), we detect two stages in the annual catch of the species under study: one high catch stage in the period before the late 1960s and a low catch stage from then on. We may assume that the series is stationary, both in mean and variance. A memory structure is apparent in the series, although this needs to be further investigated by autocorrelation and spectral methods.

Figure 3 plots the sample autocorrelation function (ACF) for time lags 1 through 20 years. The two horizontal lines show significance limits at a 95% confidence. Significant autocorrelation coefficients appear up to the time lag of 14 years. This indicates that values at each period receive an influence of values occurring up to 14 years before, probably longer.

In order to complement this analysis, Figure 4 shows the sample spectrum for the same time series. The spectrum was estimated by smoothing the periodogram with a Parzen window with lag parameter m = 25 (see, e.g. Brockwell and Davis, 1991, Chapter 9). The estimated spectrum decomposes the movement of the series in various sinusoidal waves of different frequencies and shows the relative strength of each frequency oscillation. The lower frequencies (at left) measure the contribution of long-run oscillations and the high frequencies (at right) measure the contribution of short-run oscillations. A peak at a low frequency is apparent in the pictures. This peak occurs at a frequency implying a period of about 15 years. Due to the sample size, this estimate cannot be made more precise. However, a clear conclusion emerges: catches display long-run movements with strong memory.

Sardine catch and recruitment

Sardine recruitment data series is available from 1978 to 1999, but the annual catch in yield is available for a longer period. In order to perform retrospective analyses, we assume that the variability of the recruitment or year-class strength is included in the catch variability displaced by some years later. The year-to-year changes of the catch are explained

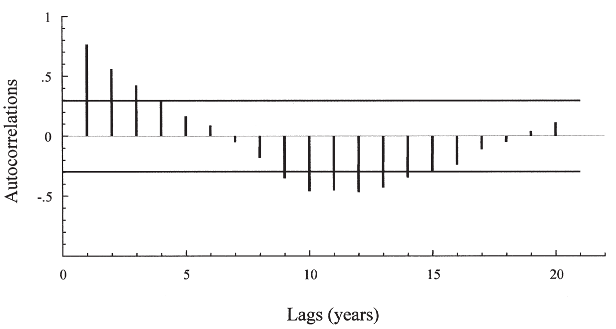

FIG. 3. – Sample autocorrelation function (ACF) for the 1946-1991 sardine catch time series in ICES subdivisions IXa Central-North and IXa Central-South. The two horizontal bands represent the limits of significance at 5% level.

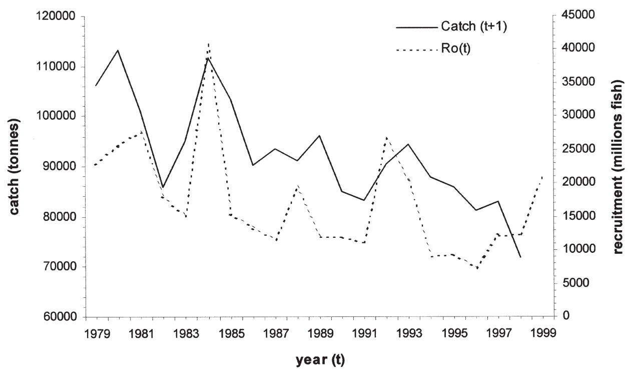

FIG. 5. – Sardine recruitment at 0-age-group ($R0_{(t)}$) and commercial catches of sardine one year after (t+1).

TABLE 1. – Correlation matrix of the estimated linear association between recruitment ($R_{0(t)}$) and commercial catches of sardine (*Sardine pilchardus*) at different time lags. ***Significant at the 0.1% level, **Significant at the 1% level, *Significant at the 5% level, NSNon-significant

	$R_{0(t)}$
$R_{0(t)}$	1.000
$Catch_{(t)}$	0.243 NS
$Catch_{(t+1)}$	0.711 ***
$Catch_{(t+2)}$	0.514 *

by the incoming year class strength, by the amount of biomass of the older year classes left in the sea in the previous year, and by the fishing mortality rate changes (Gulland, 1983). In fact, the sardine recruitment to this fishery is highly variable (Fig. 5).

We thus need to explore the time delay between sardine recruitment and its turnover as reflected in the catch some years later. We computed the correlations between recruitment and catches at different time lags. The strongest correlation is the one between recruitment as 0-group and total catch one year later (Table 1 and Fig. 5). This is consistent with the selection pattern estimated from the catch-at-age structure for this area, in which the fish at age-group 1 is already fully recruited to the fishery (see e.g. ICES, 2002).

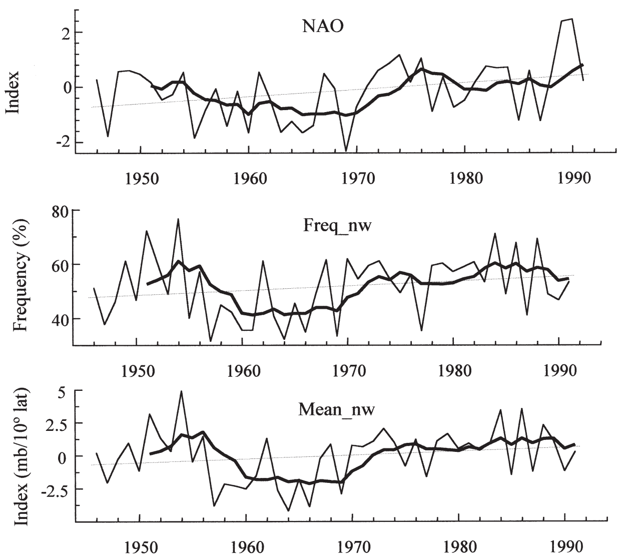

FIG. 6. – NAO and wind conditions time series during winter (January-March) from 1946 to 1991: (a) NAO index; (b) frequency of northerlies (Freq_nw); and (c) wind intensity (Mean_nw) index. Note that in the present study a positive Mean_nw value means that the wind direction is from the north (northerly wind) and a negative value means that the wind blows from south (southerlies). On each graph, the solid light line represents the original data, the bold line represents the smoothed data obtained with a 5 years moving average filter, and the dashed straight line represents the estimated linear trend.

TABLE 2. – Correlation matrix of the estimated linear association between North Atlantic Oscillation (NAO) index, mean northern wind (Mean_nw) index, northern wind frequency (Freq_nw), and sardine catches (Catch). ***Significant at the 0.1% level, **Significant at the 1% level, *Significant at the 5% level, NSNon-significant (*p*-value is presented within square brackets).

	NAO	Mean_nw	Freq_nw	Catch
NAO	1.000			
Mean_nw	0.522***	1.000		
Freq_nw	0.464***	0.938***	1.000	
Catch	-0.274 NS [0.0649]	-0.430**	-0.359*	1.000

NAO and wind

Figure 6 displays upwelling favourable winds (northerlies) during winter (January-March), as measured by their intensity (Mean_nw) and frequency (Freq_nw). Both series show an increasing trend more apparent after the mid 1950s. It is also clear from these series that a shift in the wind conditions occurred in the beginning of the seventies. From 1957 until 1970, the Mean_nw index was mainly negative (southerlies) and the frequency of the northerlies (Freq_nw) was almost always under 50%. After 1970, the opposite happened. These changing trends in the wind conditions during the winter were in phase with the NAO index trends, as shown also in Figure 6. When NAO remained predominantly in a highly positive phase (mid 1970 to mid 1995), the wind patterns favoured increasing upwelling conditions (increasing frequency and intensity of the northerlies over the west coast of Portugal).

Table 2 presents the correlation matrix of estimated linear association between the NAO index, mean northern wind index, and northern wind frequency. Sardine catches are also included for later reference. NAO and the winter wind data series from 1946 to 1991 are significantly correlated, and the variable that reveals the strongest correlation with the NAO index is the mean northern wind index.

Figure 7 shows the scatter-plots and the corresponding regression lines between the NAO index and the wind variables. These graphs visually corroborate the previous results, showing that favourable upwelling winter wind conditions (high mean northern wind and high northern wind frequency) are associated with positive NAO index. On the contrary, negative NAO index is associated with absence or weaker northerlies.

Figure 8 displays the estimated spectra of the two wind variables under consideration obtained again

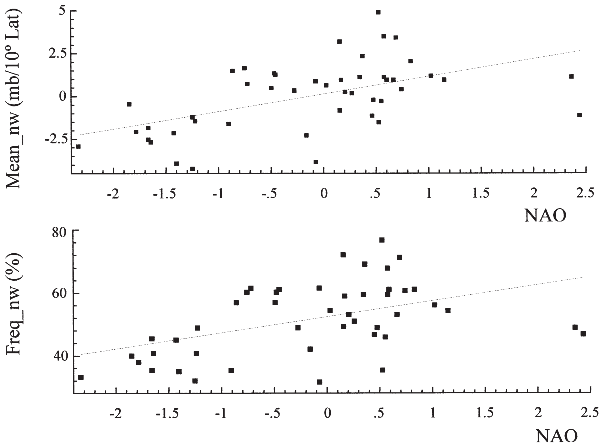

FIG. 7. – Linear regression plots between the NAO index and the winter (January-March) wind conditions from 1946 to 1991: (a) NAO vs. mean northern wind index (Mean_nw) index, and (b) NAO vs. northern wind frequency (Freq_nw).

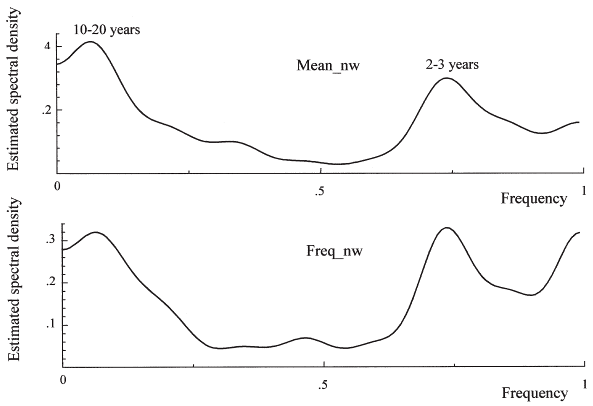

FIG. 8. – Smoothed periodogram for the winter (January-March) wind conditions from 1946 to 1991: (a) mean northern wind (Mean_nw) index, and (b) northern wind frequency (Freq_nw).

by applying a Parzen window with m = 25. These spectra are remarkably similar. They suggest long-term periods of about 10-20 years and short-term periods of about 2-3 years of favourable winter upwelling conditions. van Loon and Rogers (1978) and Hurrell (1995) observed similar behaviour on the NAO.

Sardine catches, NAO and wind

The two catch stages observed in Figure 2 coincide with the alternate phases exhibited by the NAO index. In fact, NAO exhibited a downward trend from the early 1940s until the early 1970s, and a sharp reversal has occurred after the 1970s, when NAO initiated a dominant positive phase. As we have shown previously, the wind conditions, which favour local upwelling during sardine spawning season, occurred during the NAO positive phase and led to a low catch period. On the other hand, during NAO negative phase the northern winds are absent or very weak corresponding to a high catch period.

Given the complexity of the relationship between the physical environment and the biological dynamic processes, potentially observable associations are expected to be noisy and fraught with multiple dimensions from local to large-scale processes. As we try to uncover these possible interactions and construct a simple and potentially useful environmental indicator for sardine recruitment, we do not expect to visualize strong statistical associations, but only signals that may depict the underlying processes of the physical-biological interactions.

The statistical linear associations we estimated, between the meteorological variables (winter wind conditions and NAO) and sardine catches (Table 2), single out mean northern wind index (Mean_nw) as the variable that reveals the strongest association with the Catch series.

Since wind condition variables can have delayed effects on catch, we studied the sample cross correlation between the variables Mean_nw and Catch. Figure 9 plots the cross correlation function showing the statistical linear association between these variables, for delays from 1 to 8 years. Significant negative coefficients appear for lags 0 through 1, only. Since wind series are constructed for winter months and catches are predominant in summer, these lags correspond to a delay of approximately six months (lag 0) and approximately 18 months (lag1). This is a striking result, showing that winter upwelling favourable winds have a negative effect on catches, and that this effect is strongest in a period of about six to 18 months, roughly corresponding to the lag we previously identified for the turnover of recruitment into catch.

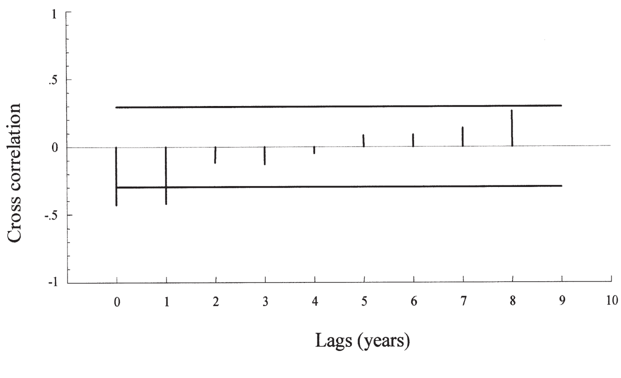

FIG. 9. – Estimated cross correlations between catches and mean northern winds at different time lags. The two horizontal bands represent the limits of significance at 5% level.

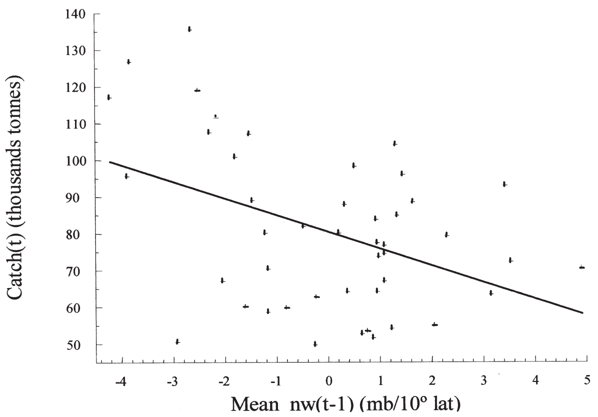

FIG. 10. – Catches *versus* north wind-mean (Mean_nw) index one year before. Note that in the present study a positive Mean_nw value means that the wind direction is from the north (northerly wind) and a negative value means that the wind blows from south (southerlies).

Figure 10 shows the scatter-plot and the regression line of Catch versus Mean_nw. Table 3 presents the regression statistics. The obtained determination coefficient is $R^2 = 0.180$ and the association is statistically significant (p-value = 0.0036).

We visualize (Fig. 10) that most observations fall on an almost rectangular triangle with base parallel to the abscissa line, vertical side parallel to the ordinates line, and third side a diagonal decreasing from low winds to high winds. This picture is much more illuminating than the simple linear association revealed by the regression line. We notice a clear phenomenon of heteroeskedasticity: the dispersion of the catch variable changes as the wind changes. For southerly winds (negative values) or lower values of the Mean_nw index, sardine catch data are widely scattered. However, for higher values of the index, catches are bound to a lower maximum. Thus, strong northerly wind conditions seem to force the recruitment to be low, but they do not explain recruitment variability when these conditions are absent or weaker (values to the left on the x-axis of Fig. 10). Consequently, the striking and most potentially useful result is that when the winter upwelling exceeds a limit and gets stronger (x-axis values on the right side of Fig. 10), then the recruitment, one year later, is forced to be lower by the physical adverse oceanographic conditions in the western Portuguese area.

DISCUSSION

Periodicity and synchrony

We detected two long term periods or oscillations in the sardine catch time series: one high stage in the period before the late 1960s and a low stage from then onwards. By the retrospective sardine catch time series analysis we found long run movements with strong memory with periods of about 15 years. This is evidence of decadal periodic cycles in sardine abundance off Portugal. At the same time wind and NAO time series have shown approximately the same decadal periodicity as observed in the sardine catches. The three variables under analysis, NAO, northern wind and catch have shown synchrony in their cycles. At a regional scale we observed that winter northern wind conditions have increased since the 1970s. This increase is confirmed to be associated with the NAO positive phase, since we estimated a statistical significant correlation between NAO and both the northern wind frequency and the mean northern wind index. Sardine catch and winter northern wind conditions also presented significant correlations.

We estimated by sample cross correlation analysis that the time lag between the catch in yield and recruitment is about one year. Cross correlation analysis between mean northern wind index and the catch time series data resulted in a time lag of one year. Both results are very useful to infer retrospectively about recruitment variability, when only catch records are available, and to estimate its relationships with the atmospheric indexes.

TABLE 3. – Regression statistics considering *Catch* at year *t* as a linear function of *Mean_nw* index at year *t* – 1.

Variable	Coefficient	Std.Error	t-value	t-prob	Part R^2
Constant	80480.0	2998.2	26.842	0.0000	0.9437
Mean_nw	-4537.6	1475.3	-3.076	0.0036	0.1803

$R^2 = 0.18032$ F(1,43) = 9.4595 [0.0036] s = 20111.4
RSS = 1.739221473e+010 for 2 variables and 45 observations

Importance of trend wind versus catch

Will the wind conditions during winter and related ocean processes (coastal upwelling) be an important factor for the recruitment pattern of sardine that spawns at the west coast of Portugal? We think it plays an important role as expressed by the regression of the catches versus mean north winds. However, this regression explains only 20% of the variance reflecting that the phenomenon probably will be better modelled using a non-linear relationship. Nevertheless, the negative trend describing the linear association of catch and wind (Fig. 10) is significant and presents already evidence of the influence of environmental changes (upwelling favourable wind conditions occurring during winter in the Portuguese west coast) on sardine recruitment variability.

The process is linked with the impact of upwelling conditions at the spawning grounds on the survival of eggs and larvae during the spawning season (Santos *et al.*, 2001). In *situ* experiments to measure sardine egg and larvae transport in the Northern Portuguese egg retention area were put in place during Winter 2000, under IPIMAR's Project SURVIVAL. Preliminary results (Santos *et al.*, 2000) confirmed that coastal winter upwelling events were in place, as well as that offshore transport of larvae and eggs was occurring.

Regime shifts

The regularity of the physical processes on the Northern Portuguese shelf and slope expressed by the wind strength and corresponding upwelled waters seem to be modulate by the North Atlantic Oscillation. In our work we confirm what Dickson *et. al.* (1988) already indicated was happening since the 1970s. These authors described how the increased northerly winds during the 1970s were coupled with increasing upwelling off Portugal, a decline in zooplankton and phytoplankton in the North Atlantic and declines in the catch of sardines off Portugal.

Whether one adheres to the regime shift concept that there are relatively rapid changes in the community structure, which suggests that these changes can be linked to other changes in the planktonic invertebrates (Soutar and Isacc, 1974; Reid *et al.*, 2001), or accepts only the probability of auto-correlation around decadal time scales, it is evident that recruitment variability is not only dependent on the spawning stock biomass, and that recruitment predictions based on uncorrelated, white noise, distributions will rapidly degrade. These physical interactions might be seen as the density independent element of recruitment variability (Steele, 1996). Understanding the effects of environment on recruitment is difficult but necessary, given that we can thereby improve the knowledge of the relationships between spawning stock and recruitment (see Shepherd *et al.*, 1984). These relationships are complex and according to Rothschild (1991, 2000), the complexity lies in the high dimensional environment and in the non-linear population dynamics response. To circumvent this difficulty it is necessary to understand the physical-biological and the spatial-temporal species dynamics of the different ecosystems of the ocean. For example Bakun (1996) suggested that upwelling intensity was linked to large-scale climatic effects, thus linking climate change to the rate of nutrient transport into the eutrophic upper ocean layer, and ultimately to changing primary production.

The regime shift concept implies that the different regimes have an inherent stability, as we have observed in our present study: two different stable regimes of about twenty years, one prior to the 1970s and another since then. This is linked to the large-scale winter climate variability in the North Atlantic region, expressed by the North Atlantic Oscillation (NAO). In this study we found highly significant correlation between NAO and wind conditions off Portugal during winter (Table 2).

During the early 1990s, the NAO evolved to positive values higher than ever recorded earlier and this was reflected in more intense winter upwelling conditions in Portugal west coast, leading to the lowest values (1991-1996) ever observed in the recorded recruitment since 1978 (Santos *et al.*, 2001; ICES, 2002).

Fisheries management implications

The concept of physical environment or climatic forced fish productivity regime shifts needs to be conceptually further explored in population dynamics and fisheries management.

If the carrying capacity of the stock periodically changes, then the historically based levels of spawning stock biomass (SSB) and recruitment (R) are no longer appropriate to serve as long term biological reference limits, unless these references are worked out according to physical variables explaining the temporal pattern of the region. The Californian and Japanese sardine population-environment relationships are particularly well studied (Kawasaki 1992, Lluch-Belda *et al*. 1989, Wada and Jacobsen, 1998). In some of such cases, such as the Californian sardine, harvest control rules that take into account the environmental indices are already in place, to adjust harvest during the transitional periods between the different productivity regimes.

In the west coast of Portugal, our study shows that the use of a wind index is very promising and should be taken into account in the analysis of past spawning stock biomass versus recruitment relationships, to define the historical long-term biological reference limits according to each productivity regime and, if the wind index is monitored, to be used in the context of harvest control rules in future fishery management plans.

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