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Decadal environmental and ecological changes in the Canary Current Large Marine Ecosystem and adjacent waters: Patterns of connections and teleconnection

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ABSTRACT

In order to explore decadal changes in the Canary Current Large Marine Ecosystem (LME), wind and SST data collected by merchant ships are extracted from the Comprehensive Ocean Atmosphere Data Set (COADS) database from 1950 to 1995 within sixteen boxes along the Canary Current LME and adjacent waters from 10°N up to 43°N. Potential biases are reviewed and discussed when considering long-term changes and large spatial resolution. The heterogeneity of the seasonal patterns in the Canary current is described. Decadal environmental changes are explored using Sea Surface Temperature (SST) data. In the early and mid-1970s, an intensive cooling had a large latitudinal extension that affected the Canary Current LME and adjacent waters from Spain to Senegal. This cooling period was followed by a warming period, which started in the 1980s. Fisheries, fish stock abundance as well as fish population distributions have drastically changed during the last five decades. The sardine populations off Morocco widely fluctuated in a disconnected manner and a substantial increase in biomass was observed in fishing zone C (located between 20°N and 27°N) during the mid-1970s and mid-1980s. Several outbursts of fish populations (*Micromesistius poutassou*, *Macrorhamphosus scolopax* and *M. gracilis*, *Octopus vulgaris*, *Balistes carolinensis*) were observed during the last three decades in the Canary Current. In the case of the latter species it was connected with the outburst populations which took place in the Gulf of Guinea LME. Upwelling intensity and sea surface temperature are strongly linked and are thought to affect both spatial distribution and abundance of fish in the Canary Current LME. Ecosystems appear to be connected at very large scales through climatic teleconnection between the Northern and Central Atlantic but also between the Pacific and the Atlantic as the North Atlantic Oscillation (NAO) index and the El Niño Southern Oscillation (ENSO) events seem to have a major impact on the dynamics of the upwelling in the Canary Current.

THE CANARY CURRENT UPWELLING LME

The Canary Current LME is part of the eastern boundary of the central north Atlantic. This LME constitutes one of the four major upwelling systems of the world oceans. The main oceanographic features of this LME have been described in several papers dating from the 1970s. Wooster *et al.* (1976), using a compilation of merchant ship SST and wind data from 43°N to 7.5°N, summarized the seasonal patterns of the Canary Current coastal upwelling. In the mid 1970s, intensive process oriented studies were carried out along the coast to study the Canary Current upwelling with the main focus being off the Sahara coast between 20°N and 26°N (see Hempel 1982 for a collection of papers presenting detailed results of the CINECA [Cooperative Investigations of the Northern part of the Eastern Central Atlantic] program). The mean patterns of the circulation in the region were summarized by Mittelstaedt (1983) and Bas (1993). An updated review of the characteristics of upwelling in general, and of the Canary Current in particular, can be found respectively in Robinson and Brink (1998) and Barton (1998).

After the intensive process oriented studies carried out during the 1970s, most of the research and data collection effort was directed toward stock assessment and fisheries related studies. Except from some intensive surveys by the former GDR and USSR research groups off Mauritania, few oceanographic cruises have been carried out by the national fisheries research centres. To our knowledge, there is no long-term time series of subsurface data available. A network of coastal stations, where daily SST and (sometimes) nutrient data are collected, is maintained by several fisheries research centres along the coast (Cury and Roy 1991, Durand *et al.* 1998) but the accessibility of these data remains limited. The interannual and long-term variability of this LME over the last 40 years has not yet been summarized but several studies presented detailed information on the variability in a given area. Arfi (1985), using wind measurement at a coastal station, studied the variability of the wind-driven upwelling off Cape Blanc (Mauritania 21°N) from 1955 to 1982. The link between wind forcing and temperature fluctuations at 21°N was further explored by Ould-Dedah *et al.* (1999). An analysis of the interannual variability of the Senegalese upwelling (14°N) from 1963 to 1986 was presented by Roy (1989) using wind data from a coastal station. At a regional scale, Roy (1991) summarized the interannual variability of the wind induced upwelling process along the coast from 12°N to 30°N using merchant ship data. Using SST derived from AVHRR satellite data, Nykjaer and Van Camp (1994) presented a regional overview of the seasonal and interannual variability, over a limited period of time, from 1981 to 1991.

DATA USED

The present analysis gives an overview of the pattern of variability of the physical characteristics of the Canary Current LME and adjacent waters. Using an updated version of the CODE software (Mendelssohn and Roy 1996), wind and SST data collected by merchant ships are extracted from the COADS release 1-ab database (Woodruff *et al.* 1987) for sixteen rectangular boxes following the Canary Current upwelling coast from 10°N up to 43°N (Figure X-1). The shipping lanes from Europe to the Indian Ocean follow the shape of the West African coast south of 28°N; in these regions data density is high along the coast. Between 28°N to 32°N, the shipping lanes move offshore and data density sharply decreases. Further north, along the coast of Morocco, data density increases again and reaches a maximum off Spain and Portugal. The options regarding the source of the data selected by CODE were set in order to exclude all data from the former USSR vessels, a fishing fleet that was quite active in the 1980s and early 1990s off Mauritania. The activity of this fishing fleet was highly seasonal and concentrated over the shelf, while the shipping lanes are located further offshore. Blending these data with the merchant ship data can introduce a bias of the seasonal cycle because of the wind and SST cross-shore gradient. Both estimated wind (Beaufort scale) and measured wind (using an anemometer) data were selected. A correction factor was applied to the estimated wind data in order to avoid the introduction of a spurious trend due to the decreasing percentage of estimated wind data during the last twenty years. For each of the sixteen boxes,

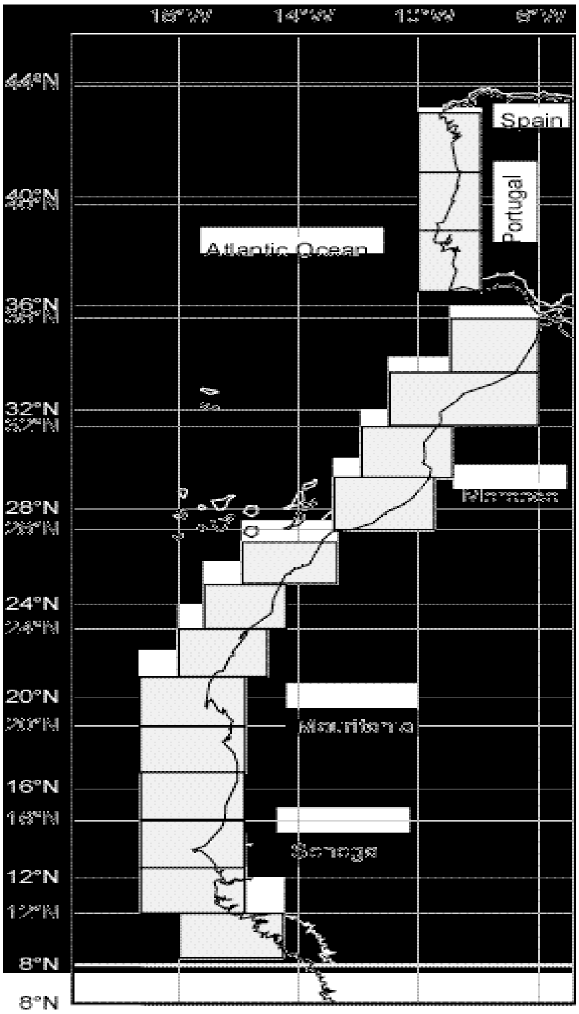

Figure X-1. The Canary Current LME and adjacent waters, from 46°N to 8°N. The 16 coastal boxes where the COADS data have been extracted are shaded.

monthly time series from 1950 to 1995, of SST, scalar wind speed and of a monthly Coastal Upwelling Index (CUI) are constructed. CUI is the offshore component of the wind induced Ekman transport and it is used as an index of the strength of the upwelling process (Bakun 1973). The mean monthly seasonal cycle of SST, scalar wind speed and CUI are calculated and are later used to compute monthly anomalies for each of the three parameters. Offshore SST (1400km from the coast) was also extracted from da Sylva *et al.* (1994) in order to compute time series of the offshore-coastal SST deficit and the corresponding mean seasonal cycle.

SEASONAL PATTERNS

The mean seasonal variability for the offshore-coastal SST deficit, SST and CUI are briefly analysed in this section. SST deficits greater than 2°C can be used to trace the seasonal and latitudinal variability of the upwelling (Figure X-2). The seasonal pattern of the SST deficit is similar to the general pattern first described by Wooster *et al.* (1976).

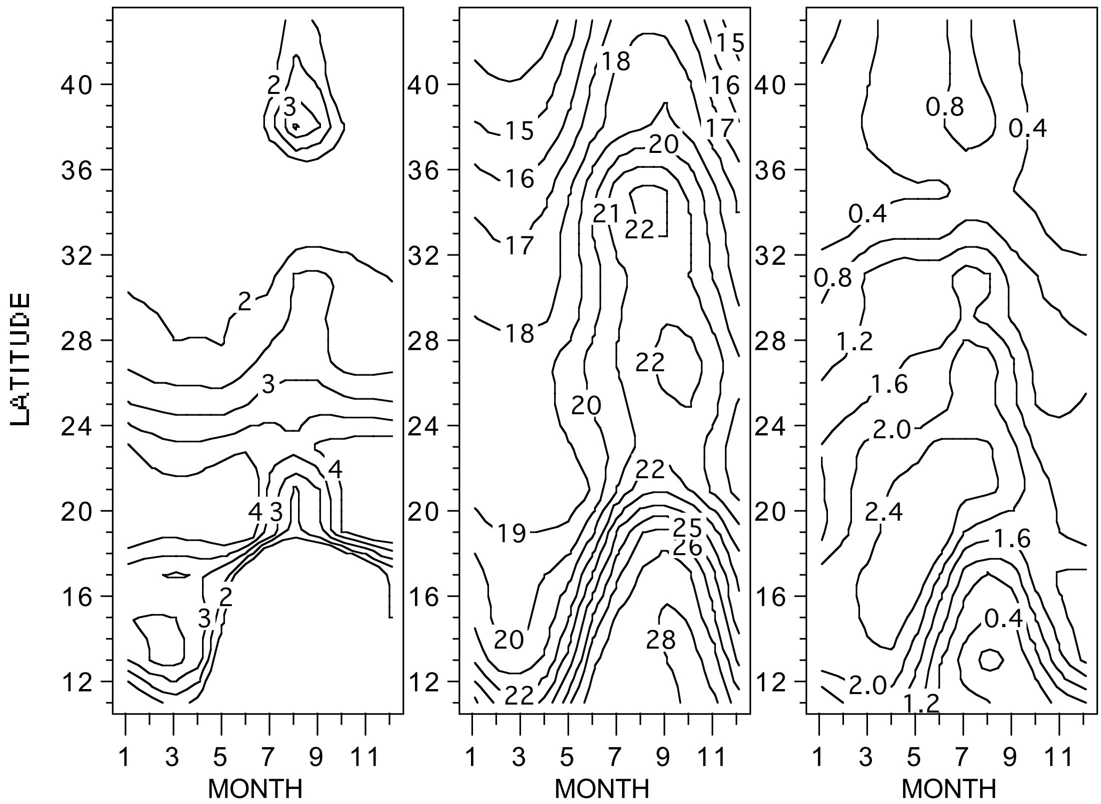

Figure X-2. Seasonal pattern of coastal SST deficit (°C, left panel), SST (°C, middle panel) and CUI ($m^3 \cong s^{-1} \cong m^{-1}$, right panel) along the coast of the Canary Current LME.

Upwelling is permanent between 19°N and 28°N. South of 21°N, upwelling occurs only in winter; the alternation of a winter upwelling season with a monsoon-type warm season strongly enhances the SST seasonal cycle. The positive SST deficit that occurs in summer between 28°N and 32°N, is the result of the northern Moroccan upwelling. Further north, between 32°N and 37°N, the orientation of the coast and the presence of the Gibraltar Straits are not upwelling favourable. North of 37°N, upwelling is active in summer off Portugal and Spain. In this region, upwelling disappears in winter, except during brief periods of favourable winds (Barton 1998). The seasonal pattern of SST (Figure X-2) is similar to the general pattern first described by Wooster *et al.* (1976).

The prominent feature is the strong seasonal variability south of 21°N. In that region, the amplitude of the seasonal cycle reaches 8°C between 14°N and 16°N. Data from coastal stations show that the amplitude of the seasonal cycle reaches up to 16°C (from 14°C in winter to 30°C in summer) in this area. Between 21°N and

29°N, the low amplitude of the SST seasonal cycle reflects the year-round persistence of the upwelling process. The CUI seasonal and latitudinal patterns over the region match closely the pattern described by Wooster *et al.* (1976) but with values up to 40 percent higher (Figure X-2). One possible cause of the difference between our estimation and the previous one is the correction factor that we applied to the COADS wind data in order to take into account the errors introduced by the use of the WMO1100 scale. This scale was used to convert wind data from Beaufort units to $m{\cong}s^{-1}$ and it tends to underestimate the winds for Beaufort numbers less than about 6 and overestimates for Beaufort numbers greater than 6. Off West Africa, a comparison between the corrected and uncorrected wind data shows that the mean value of the corrected wind can be from 10 to 15 percent higher than the uncorrected ones, depending on the percentage of wind data expressed in Beaufort units. This will lead to an increase of respectively 20 percent to 30 percent of the corresponding wind stress and CUI.

When comparing the spatio-temporal pattern of CUI with the pattern of coastal SST deficit, the global picture remains similar with a winter upwelling south of 19°N, a permanent upwelling between from 19°N to 28°N and a summer upwelling off the Portuguese and Spanish west coasts. CUI provides some indication of the seasonal pattern of the upwelling in the central region where upwelling is a permanent feature. In that region, the wind-induced upwelling is maximum in summer (July-August) and minimum in early winter (November-December).

DECADAL CHANGES IN THE ENVIRONMENT

SST

In the following section, SST is used to track changes in the intensity of the Canary Current LME upwelling. An intensification (relaxation) of the upwelling process enhances (reduces) the upward flux of cold water along the coast; the offshore extension of the cold upwelled water is also enhanced (reduced) during an intensification (relaxation) of the upwelling process. As a result, negative (positive) SST anomalies are expected during an intensified (relaxed) phase of the upwelling.

For each coastal box, monthly SST anomalies are derived from the monthly time series of SST. To get a synthetic view of the variability, monthly anomalies are then averaged by quarter of the year. The data are presented on a time/latitude diagram and smoothed to get the long-term pattern of the variability (Figure X-3). In the early and mid-1970s, an intensive cooling (negative SST anomalies) characterizes the variability of the SST anomalies during the first quarter (Figure X-3). It has a large latitudinal extension, affecting the Canary Current LME and adjacent waters from Spain to Senegal. South of 16°N, the low frequency variability is characterized by a succession of warm and cold periods. Between 16°N and 23°N, the variability appears to increase after the mid-1970s with a succession of warm and cold periods, similar to what is found further south. North of 23°N the variability decreases, the cooling of the 1970s being the major climatic event.

The SST anomalies' variability during the second quarter shares some common characteristics with the variability during the first quarter. There is an extensive cooling affecting the whole region in the 1970s but, while being less pronounced, this cooling appears to start in the mid 1960s and extends to the late 1970s. South of 16°N, the variability seems also to be characterized by a succession of warm and cold periods, but with a slightly different pattern than during the first quarter. Further north, a pronounced warm event developed in the early 1960s between 25°N and 43°N. Following the cooling of the 1970s, the variability north of 25°N remains weak with a slight warming.

During the third quarter, SST anomalies are characterized by a pronounced cooling extending from the mid-1960s to the mid-1980s. It affects the region north of 18°N up to 35°N. Another emergent pattern with a large latitudinal extension is the strong warming that developed north of 20°N during the late 1980s and early 1990s. From 1950 to 1965, the latitudinal variability is contrasted with warm anomalies in the central region (maximum intensity at 20°N) and cold anomalies at both high and low latitudes. During the fourth quarter, the global 1970s cooling pattern over the region is again a notable feature of the SST anomalies. It reaches its maximum intensity between 15°N and 30°N and extends from 1972 to 1975. A warming affecting all the Canary Current LME since the 1980s follows this cooling.

As a summary, time series in selected regions are presented to highlight the dominant patterns of variability of SST anomalies by quarter from 1950 to 1995 (Figure X-4.1 to X-4.4). The cooling in the 1970s is a major feature that has affected the whole region during and outside the upwelling seasons. The southern part of the regions presents a quite dynamic pattern of variability that is unique to the area. This is confirmed by a comparative analysis of the variability of SST anomalies times series using the standard deviation as an index of the variability (Figure X-5). It shows that the SST variability reaches a maximum during the first and second quarter in the southern part of the region. During the third and fourth quarters, the interannual variability is maximum around 20°N. This suggests that the variability of the upwelling strongly enhances the interannual variability of SST anomalies in the southern part of the Canary Current LME.

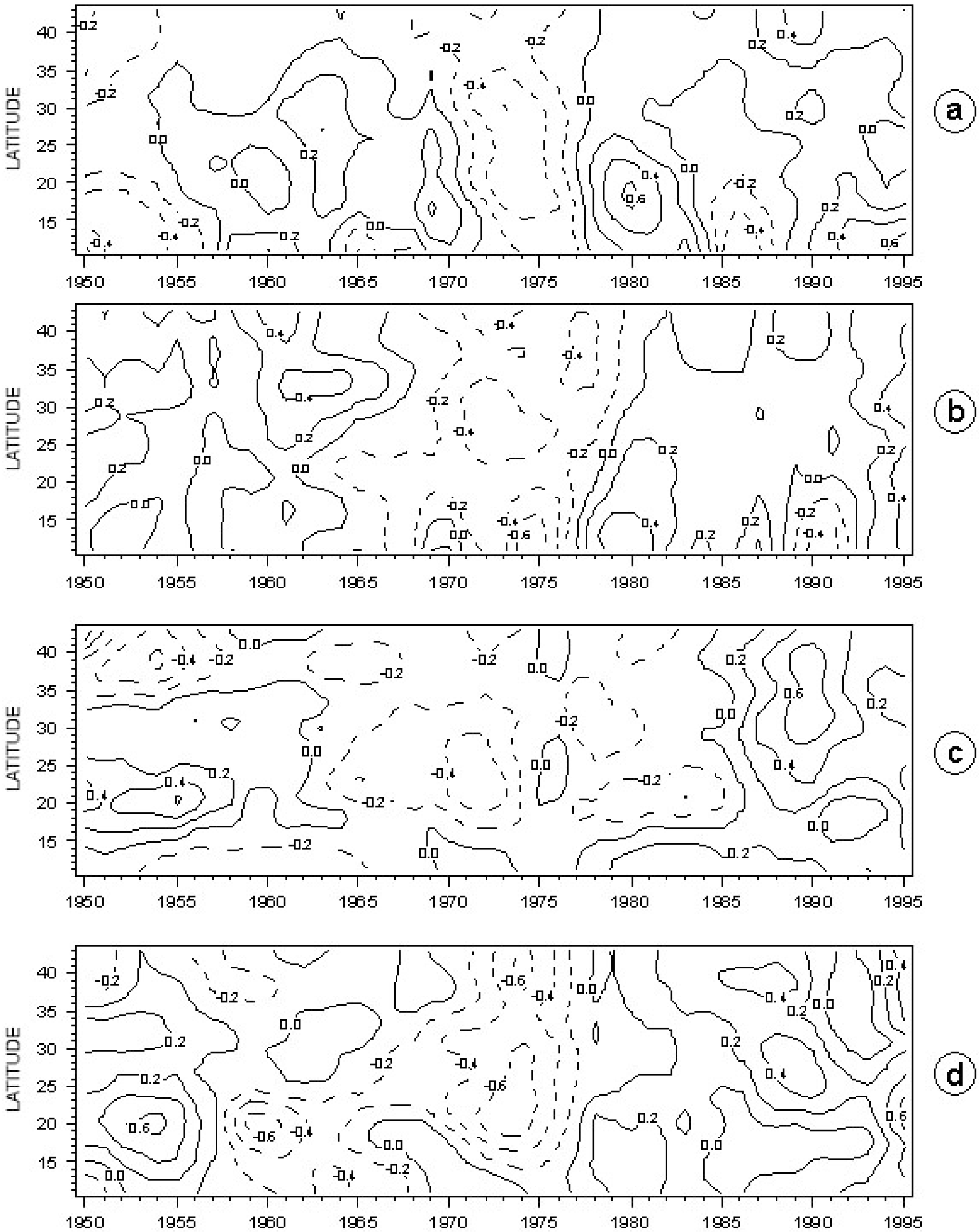

Figure X-3. Time/latitude (ºN) plot of SST anomalies (°C) in the Canary Current LME and adjacent waters from 43°N to 11°N and from 1950 to 1995 for the first (a), second (b), third (c) and fourth quarter (d).

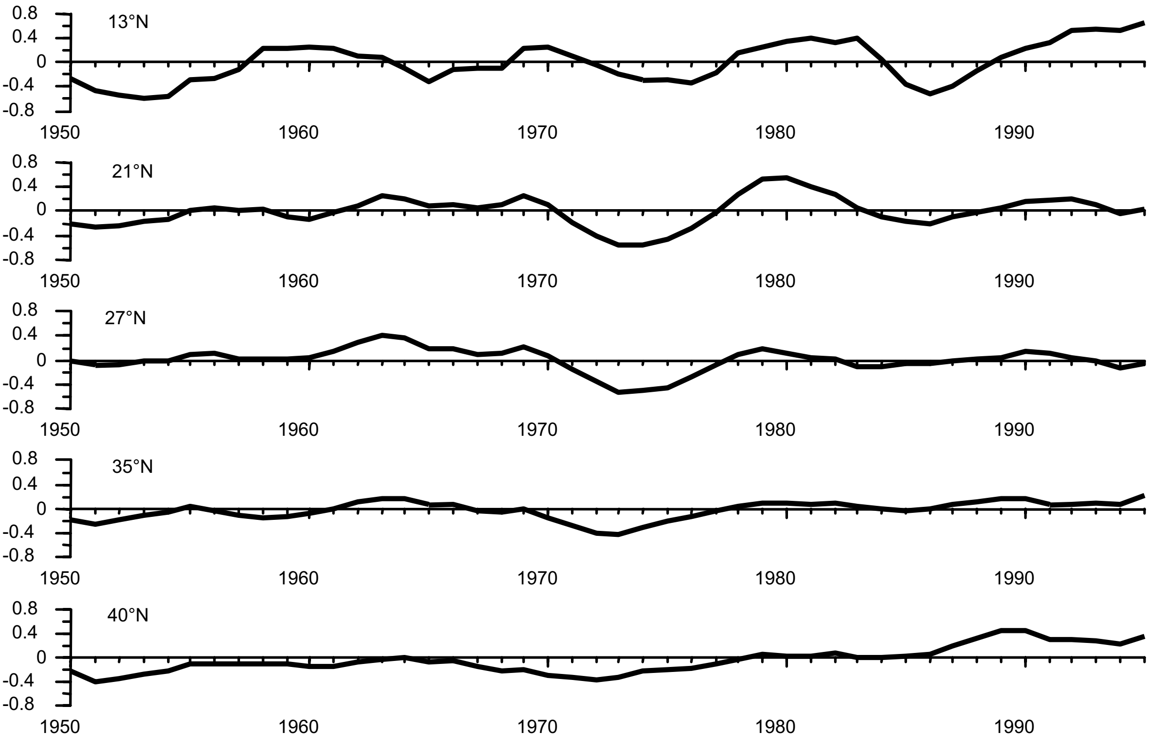

Figure X-4.1. Trend of the SST anomalies (°C) at selected latitudes in the Canary Current LME and adjacent waters during the first quarter, from 1950 to 1995.

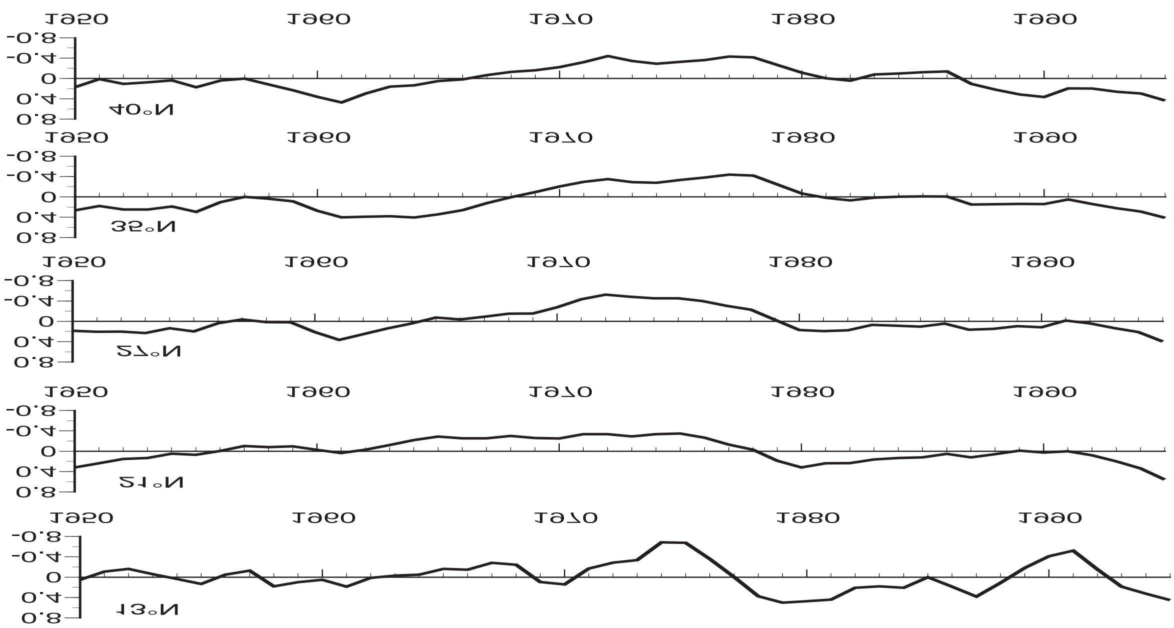

Figure X-4.2. Trend of the SST anomalies (°C) at selected latitudes in the Canary Current LME and adjacent waters during the second quarter, from 1950 to 1995.

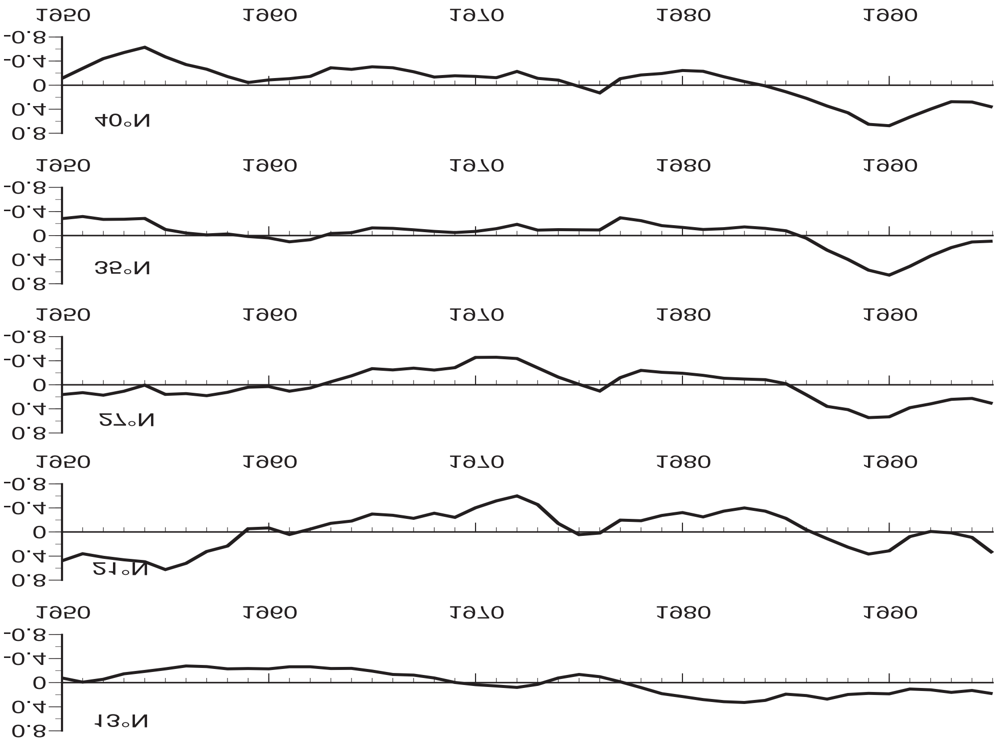

Figure X-4.3. Trend of the SST anomalies (°C) at selected latitudes in the Canary Current LME and adjacent waters during the third quarter, from 1950 to 1995.

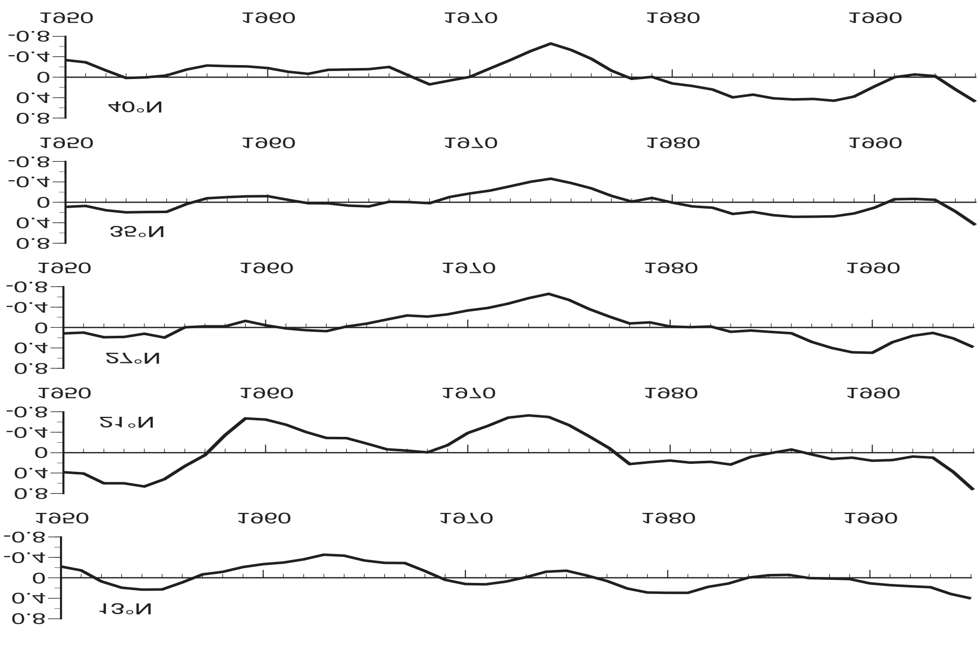

Figure X-4.4. Trends of the SST (°C) anomalies at selected latitudes in the Canary Current LME and adjacent waters during the fourth quarter, from 1950 to 1995.

Wind

Wind is the driving force of the upwelling process and interannual fluctuations or decadal trends of the alongshore wind component modulate the upwelling and can have drastic consequences on marine living resources. In the Canary Current LME, there are just a few stations where long-term time series of wind data are available and these data are not easily obtained. We had to rely on wind data extracted from the COADS database to set up an homogeneous set of time series over the region. Within the Canary Current, the wind speed monthly times series built using the COADS database are characterized by a pronounced upward trend over the last 40 years (Figure X-6). Before going further into the analysis, an evaluation of the intensity of the trend and a comparison over the region is performed. For each time series, the long-term trend is extracted by applying a low pass filter to the monthly time series. The trends appear to be similar within the region; they all are almost linear and show an increase of wind speed of about 20 percent over the last 40 years (Figure X-7). By normalizing the wind data within each coastal box, differences between the resulting trends become almost barely discernible (Figure X-7). Similar results were obtained by comparing low pass filtered quarterly wind data (Figure X-7); the slope of the quarterly trends is independent of the season being considered. Wind during winter increased as much as wind increased during summer. This analysis shows that the slope of the trend in the COADS wind data is surprisingly independent of both location and season. Coastal stations wind data show that there is an important inter-annual variability but none of the data that have been analysed shows a trend compatible with the COADS wind trend (Arfi 1985, Roy 1989). Using the COADS data, Roy and Mendelssohn (1998) showed that the correlation between the alongshore wind component and SST during upwelling seasons significantly increases when detrended wind data are used. These arguments raise some concern about the reality of the trend in the COADS wind data.

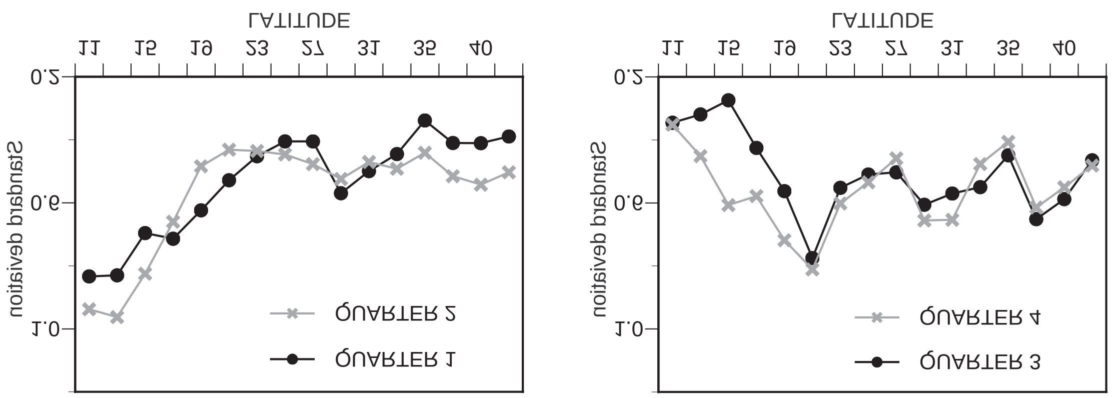

Figure X-5. Standard deviation of the quarterly time series (1950 to 1995) of SST anomalies in the Canary Current LME and adjacent waters from 11°N to 43°N.

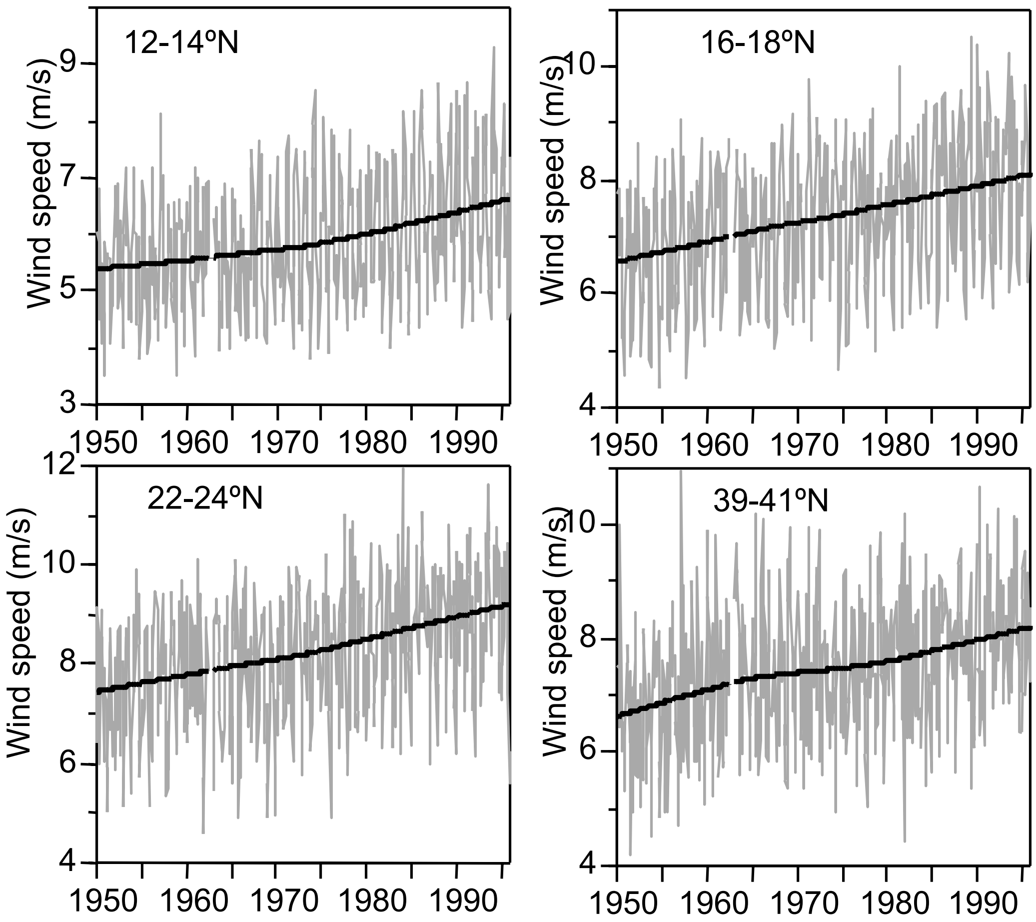

Figure X-6. Trend in the scalar wind speed (m≅s^{-1}) derived from the COADS database at several locations in the Canary Current LME and adjacent waters.

Furthermore, a 20 percent increase of wind speed results in a 40 percent increase of wind stress and of upwelling intensity according to the Ekman transport equation. Such a dramatic enhancement of the upwelling over the last 40 years would certainly have had an enormous impact on the ecosystem. Moreover such drastic environmental changes have never been observed in any upwelling systems and are not reflected in the other environmental time series. The reality of the COADS wind trends has been the subject of considerable debate (Cardone *et al.* 1990). Ward and Hoskins (1996), using pressure derived wind, showed that there is no statistically significant strengthening of the atmospheric circulation at a global scale; they concluded that a correction needs to be applied to the reported wind data in order to minimize the trend. On the other hand, Bakun (1990) proposed a mechanism whereby global greenhouse warming could intensify the alongshore surface wind.

Using analysed wind fields (a blend of pressure derived wind and ship reported wind), he gave evidence of a positive trend in the alongshore wind stress in several regions. No definitive agreement on the reality of the trends in the COADS wind data has been reached yet. Ward and Hoskins (1996) concluded that although there is no evidence for a global intensification of the circulation strength, regional patterns of upward and downward trends may also exist. Following these arguments, we considered that the upward trend in the COADS wind data in the Canary Current is an artifact and that wind data have to be detrended before being used. We are aware that removing the trend is based on a strong assumption, since possible natural causes such as Bakun's (1990) greenhouse effect on the coastal upwelling region are then not considered. A detailed understanding of the origin of the bias in the COADS data is a necessary step before being able to separate the natural long term variability from the data related bias.

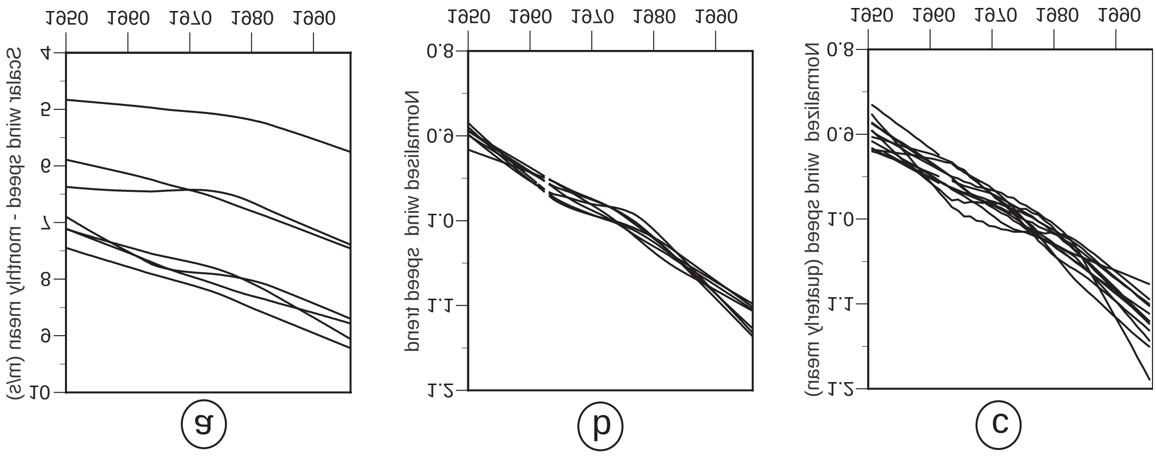

Figure X-7. a) Scalar wind speed trends (m≅s^{-1}) over the Canary Current LME and adjacent waters, monthly data from 1950 to 1995 and from 11°N to 43 °N ; b) Same as a) but with normalized wind speed data ; c) Trend of quarterly averaged wind data (1950 to 1995) in selected regions of the Canary Current LME and adjacent waters (15°N, 23°N, 40°N).

The detrended wind data are used to investigate the effect of the interannual variability of the wind on the upwelling strength by looking at the correlation between anomalies of SST and CUI. For each coastal box, quarterly means of SST and CUI anomalies are calculated from the monthly time series of SST and CUI (computed from the detrended wind data). For each coastal box, the correlation between the SST anomalies and the corresponding CUI anomalies are then calculated (Table X-1). As expected, the global pattern shows significant negative correlation coefficients between SST and CUI anomalies when upwelling is active: a strengthening of the alongshore wind (positive CUI anomalies) enhances the upwelling (negative SST anomalies). In the southern part of the region (between 10°N and 16°N), a significant part of the variability of SST anomalies is explained by the fluctuations of CUI anomalies during the first two quarters. North of 20°N (up to 28°N), upwelling is permanent and the correlation remains relatively high during the four quarters. North of 28°N, upwelling is active in summer and the correlation is high during the third and fourth quarters. Off Spain and Portugal, wind driven processes appear to be of major importance during the spring and summer upwelling seasons but also during the fourth quarter.

Table X-1. Correlation between quarterly averaged SST anomalies in the Canary Current LME and adjacent waters and the corresponding CUI anomalies, from 1950 to 1995 (* = p<0.05, ** = p<0.01).

Latitude	1st	2nd	3rd	4th
11°N	-0.43 **	-0.60 **	-0.35	-0.27
13°N	-0.49 **	-0.70 **	-0.05	-0.37 *
15°N	-0.49 **	-0.51 **	-0.19	-0.33
17°N	-0.59 **	-0.17	-0.47 **	-0.27
19°N	-0.48 **	-0.14	-0.43 **	-0.57 **
21°N	-0.53 **	-0.45 **	-0.20	-0.61 **
23°N	-0.46 **	-0.47 **	-0.47 **	-0.64 **
25°N	-0.51 **	-0.37 *	-0.43 **	-0.58 **
27°N	-0.42 **	-0.15	-0.57 **	-0.59 **
29°N	0.03	-0.33	0.02	-0.79 **
31°N	-0.25	-0.18	-0.51 **	-0.47 **
33°N	0.03	0.23	-0.47 **	-0.39
35°N	-0.13	0.19	-0.25	-0.50 **
38°N	0.00	-0.53 **	-0.47 **	-0.63 **
40°N	0.00	-0.40 **	-0.44 **	-0.60 **
42°N	-0.19	-0.37 *	-0.28	-0.61 **

TELECONNECTIONS

The North Atlantic Oscillation (NAO) characterizes a meridional oscillation in atmospheric mass with centres of action being the Icelandic low and the Azores high. It is most pronounced in amplitude and areal coverage during winter. NAO is an important contributor to the North Atlantic climatic variability (Hurrel 1995) and has a measurable impact on the North Atlantic ecosystem (Fromentin and Planque 1996).

The link between the NAO and the Canary Current and adjacent waters upwelling is investigated by looking at the correlation between quarterly averaged values of the NAO index and the corresponding SST anomalies over the regions (Table X-2). The NAO index is based on the difference of normalized sea level pressures between Ponta Delgada, Azores and Stykkisholmur, Iceland from 1865 through 1995. This index is slightly different from the winter version of the index that uses data from Lisbon. The Ponta Delgada station is chosen instead of Lisbon to adequately capture the NAO during the four quarters. A positive NAO index indicates stronger than average westerlies and anomalously high pressures across the sub-tropical Atlantic.

Negative and statistically significant ($p < 0.01$) correlations between NAO and SST anomalies off the Canary Current occur during the first and second quarters in the central region (between 18°N and 30°N), as well as during the fourth quarter north of 20°N. The inverse relationship indicates that negative (positive) SST anomalies are related to positive (negative) NAO anomalies. In the central region, this correlation suggests that an intensification of the westerlies (positive NAO index) across the sub-tropical Atlantic intensifies the upwelling favourable wind that also

Table X-2. Correlation between quarterly averaged SST anomalies in the Canary Current LME and adjacent waters and the corresponding NAO anomalies, from 1957 to 1995 (* = $p<0.05$, ** = $p<0.01$).

Latitude	1st quarter	2nd quarter	3rd quarter	4th quarter
11°N	0.02	-0.05	0.03	-0.19
13°N	-0.01	-0.10	0.04	-0.26
15°N	-0.16	-0.16	0.07	-0.38*
17°N	-0.37 *	-0.22	0.13	-0.35 *
19°N	-0.41 **	-0.31	0.04	-0.44 **
21°N	-0.30	-0.39 *	-0.01	-0.44 **
23°N	-0.48 **	-0.44 **	-0.06	-0.49 **
25°N	-0.60 **	-0.40 **	-0.22	-0.41 **
27°N	-0.56 **	-0.34 *	-0.29	-0.54 **
29°N	-0.01	-0.44 **	-0.20	-0.58 **
31°N	-0.15	-0.29	-0.17	-0.40 **
33°N	-0.09	-0.13	-0.04	-0.44 **
35°N	-0.20	-0.14	-0.05	-0.50 **
38°N	0.13	-0.31	-0.19	-0.57 **
40°N	0.26	-0.29	-0.24	-0.50 **
42°N	0.26	-0.24	-0.25	-0.50 **

enhances the upwelling process (negative SST anomalies). In the case of a relaxed meridional oscillation (negative NAO index), the weaker than average atmospheric circulation contributes to a relaxation of the Canary Current and adjacent waters upwelling (positive SST anomalies). In the northern region (north of 30°N), upwelling is not a dominant oceanographic process during the 4th quarter. An alternative mechanism accounting for the correlation between NAO and SST involves the intensification of the westerlies in early winter leading to a premature erosion of the thermocline and to a deepening of the surface mixed layer. Both the erosion of the thermocline and the deepening of the surface mixed layer result in negative SST anomalies.

Table X-3. Correlation between quarterly averaged SST anomalies in the Canary Current LME and the SOI anomalies during the fourth quarter of the preceding year, from 1957 to 1995 (* = $p<0.05$, ** = $p<0.01$).

Latitude	1st quarter	2nd quarter
11°N	-0.41 **	-0.46 **
13°N	-0.48 **	-0.47 **
15°N	-0.48 **	-0.54 **
17°N	-0.40 **	-0.51 **
19°N	-0.38 *	-0.48 **
21°N	-0.42 **	-0.38 *
23°N	-0.36 *	-0.21
25°N	-0.28	-0.15
27°N	-0.17	-0.19
29°N	-0.11	-0.25
31°N	-0.26	-0.28
33°N	-0.28	-0.24
35°N	-0.18	-0.16
38°N	-0.16	-0.09
40°N	-0.15	-0.03
42°N	-0.29	-0.04

Pacific El Niño SouthernOscillation (ENSO) events have a major impact on the world climate. In the tropical Atlantic, the SST and wind fields are regularly affected by Pacific equatorial variability (Hastenrath *et al.* 1987, Nobre and Shukla 1996). Large scale analyses have shown that the North Atlantic warms in response to the Pacific ENSO with a lag of about one or two seasons (3 to 6 months), the effect being stronger in the north-western part of the basin and during the boreal spring and early summer (Enfield and Mayer 1997). Furthermore, it appears that the Atlantic SST response to ENSO is a result of a reduction of the trade wind speeds (Enfield and Mayer 1997, Klein *et al.* 1999). In the Canary Current and adjacent waters, the wind being the driving force of the upwelling, an alteration of the trade wind activity has a pronounced effect on the ecosystem, thus one can expect to observe a connection between ENSO and the upwelling in the Canary Current. This is investigated by looking at the correlation between quarterly SST anomalies during the first semester and the Southern Oscillation Index (SOI) during the fourth quarter of the preceding year. In the southern part of the region (south of 19°N), the correlation is statistically significant ($p<0.01$) during the first and second quarters (Table X-3). As expected from the weakening of the trade wind that is associated with ENSO events, there is a negative correlation between SOI and SST anomalies: warm events in the Pacific (negative SOI) lead to the development of positive SST anomalies in the southern part of the Canary Current during late winter and early spring. Moreover, it appears that the correlation holds also for cold events in the Pacific (positive SOI), suggesting that there is a strong and permanent teleconnection between the coastal upwelling activity in the Atlantic and the state of the Pacific ocean. This link between ENSO and the Canary Current upwelling is explored in detail by Roy and Reason (2001). It is thought that the mechanism responsible for this remote forcing involves a tropospheric connection along 10°N-20°N between the

Atlantic and the Pacific resulting in an alteration of the Atlantic trade winds by the conditions over the Pacific ocean.

ECOLOGICAL PATTERN IN THE CANARY CURRENT LME

Fisheries and fish population patterns

Annual marine fish catch varied between 1.0 and 2.3 million tonnes from the 1970s to the 1990s in the Canary Current (FAO 1997a). Pelagic fish stocks, which represent approximately 70 percent of the total catch, are not over-exploited and their abundance has been shown to be driven by the strength of the upwelling (Binet *et al.* 1998, Kifani 1998). According to FAO (1997a) most of the demersal stocks are fully exploited in the Canary Current from Mauritania to Guinea-Bissau, and the catches have been decreasing substantially since the end of the 1980s.

Since the 1950s the exploitation of marine resources in the Canary Current has been subject to many changes. In the eastern central Atlantic a total of 25 distant-water fishing nations have exploited the marine resources using long-range fishing fleets (FAO 1997b, Maus 1997). Political changes in the Eastern European countries provoked important changes in the configuration of the exploitation in the Canary Current, particularly in the late 1980s and early1990s. Thus, between 20 percent and 50 percent of the total regional marine production has been harvested by foreign fleets, even though their catches, mainly pelagics, have been declining rapidly over the last few years, following the partial withdrawal of Eastern European and former USSR fleets from the west-African coast (FAO 1997a). In the Canary Current small-scale fisheries are particularly active in Senegal, and to a lesser extent in Mauritania. They have been exploiting both pelagic and demersal resources for several centuries (Chauveau 1991), and have recently improved drastically in their efficiency. In 1992, the small-scale fishery sector in Senegal was composed of 5,700 canoes and employed around 35,000 fishers who landed approximately 270,000 t of pelagic fish and 46,000 t of demersal fish (Ferraris *et al.* 1998). This makes the present Senegalese small-scale fishery far more socially and economically efficient than the industrial fishery sector.

Sardine (*Sardina pilchardus*) is mainly found off Morocco and sardinellas (*Sardinella aurita* and *S. maderensis*) further south off Mauritania and Senegal. Together with the horse mackerels (*Trachurus spp.*) they represent the predominant pelagic fish species. Drastic fluctuations of abundance have been observed for sardines, sardinellas and other pelagics during the last fifty years which have been linked to environmental changes (Cury and Roy 1991). Off Morocco, decadal patterns in the three fishing areas for sardine (zones A, B and C) seem to be disconnected as the sardine abundance appears to fluctuate in a different manner in the different fishing zones (Figure X-8). Fluctuations of sardine, linked to the upwelling, have been recorded in

Figure X-8. Catch of sardine in the three main fishing zones off Morocco (zone A=30°N-33°N, zone B=27°N-30°N, and zone C=20°N-27°N). (Data courtesy of INRH/Morocco) zone C since the mid-1970s (Binet *et al.* 1998). In this area, periods of high abundance have been associated with a southward expansion of the population as far as the Senegalese coast. Binet (1988) and Binet *et al.* (1998) hypothesized that an acceleration of the trade winds increased offshore and southward surface transport, enhanced the primary versus secondary production rate, and consequently favoured phytoplankton feeders such as sardine. Several hypotheses were recently proposed to explain the change in sardine abundance in areas A and B (Do-Chi and Kiefer 1996). Changes of the migrational tendencies, expansion of the stock, unfavourable environment in the traditional fishery zones affecting fish migration, and a southward shift in the centre of gravity of the sardine population due to climatic changes were the different mechanisms that were put forward to explain the changes observed in the traditional Moroccan sardine fishery.

Sardinellas (*Sardinella aurita* and *Sardinella maderensis*) have been mainly exploited by foreign fleets and by small-scale fisheries off Senegal. Acoustic surveys carried out in the Canary Current showed that sardinellas were very abundant, particularly off Mauritania, with biomass estimated to be about 4 million tonnes in 1992 (FAO 1997a). The two species of sardinella were moderately exploited until 1992. The exploitation has further decreased recently with the vanishing activity of the Eastern European fleets. Although the increase of the sardinella population off Mauritania, which represents the northern part of the species distribution, is barely detectable in any available catch statistics.

Fish population outbursts

In the Canary Current several species, known to be rare, developed such a huge biomass during several years that, in certain cases, they sustained important fisheries. Subsequently, they vanished in a relatively short time period. Off Morocco an outburst of *Micromesistius poutassou* was recorded in the 1960s, which later completely disappeared. In the 1970s *Macrorhamphosus scolopax* and *M. gracilis*, which have very different life-history traits, were found all along the Moroccan coast. In 1976 a first acoustic cruise estimated a potential of about one million tons between Cape Juby and Cape Spartel. The abundance decreased markedly in the 1980s and now the two species are rare.

Between 1972 and 1980 the large trigger fish (*Balistes carolinensis*) expanded its biomass to reach more than 1 million tonnes in the Gulf of Guinea. It also spread geographically from Ghana to Mauritania (Gulland and Garcia 1984): in the early 1970s this species was scarce in the Central Atlantic, the species was at maximum abundance at the end of the 1970s in the Gulf of Guinea and at the beginning of the 1980s in the Canary Current (Senegal). At the end of the 1980s this species almost disappeared from the West African ecosystems. While several authors believe that intensive exploitation drastically reduced the sparid communities and facilitated the outbreak of *Balistes* (Gulland and Garcia 1984), environmental changes could also have affected the trigger fish population dynamics (Caverivière 1991).

The octopus (*Octopus vulgaris*) population significantly increased in abundance in the mid-1960s in the Canary Current (Caddy and Rodhouse 1998). Three stocks of octopus are presently exploited by the Northern African industrial and small-scale fisheries off Dakhla, off Cape Blanc, and off Senegal. The prospective surveys conducted off Mauritania illustrate the rapid increase in biomass during the last thirty years: in 1966, 3.9 percent of octopus were found in the demersal surveys (for a total of 12 percent of cephalopods), compared to 75 percent of octopus in 1971 (90 percent of cephalopods) (Faure *et al.* 2000). In 1968 the octopus represented 10 percent of the commercial catches in Mauritania, 75 percent in 1971, and 84.6 percent in 1989 (approximately 50 percent of the fisheries' value). A substantial small-scale and industrial fishery really started in 1986 in Senegal as the octopus abundance increased in that area. The rapid emergence of the octopus in Mauritania in the late 1960s allowed historical yields between 45, 000 and 50,000 tonnes in the mid-1970s until the end of the 1980s. A rapid expansion of this stock was also observed off Morocco supporting catches that approximated 100,000 tonnes at the beginning of the 1980s. Off Senegal, the octopus stock apparently grew a bit later and was able to sustain an important fishery in the mid-1980s. A peak catch of 17,000 tonnes was recorded in 1986 whereas catches represented only a few hundred tonnes before. Altogether these three fisheries totalled between 40 to 90 000 tonnes from 1985 to 1995 but apparently the catch is rapidly decreasing off Cape Blanc and Dakhla. As in the case of the trigger fish, the outburst of the octopus in the Canary Current appears to be related to a lesser abundance of the sparid community due to strong fishing pressure (Gulland and Garcia 1984) which is supposed to have lowered larval mortality and competition for food (Caddy and Rodhouse 1998). Links between the environment and larval survival off the Banc d'Arguin have been demonstrated, as well as the links between upwelling intensity and the octopus abundance off Senegal and Mauritania (Faure *et al.* 2000; Inejih 2000).

DISCUSSION: CONNECTIONS, TELECONNECTIONS, AND THE LME

Demersal and pelagic fishes migrate seasonally off Mauritania and Senegal according to strong seasonal environmental patterns (Cury and Roy 1988, Fréon 1988). Interannual environmental variability also affects fish abundance and distribution. As noted previously a significant correlation exists between ENSO and upwelling intensity in the Canary Current. Using time series of pelagic fish catch (mainly sardine) in the Eastern Atlantic since 1950 (FAO 1997b) it is possible to quantify the patterns of abundance that occurred during the mid-1970s and the end of the 1980s. Periods of high abundance of sardine appear to be associated with ENSO variability (Figure X-9). Positive values of SOI are associated with enhanced

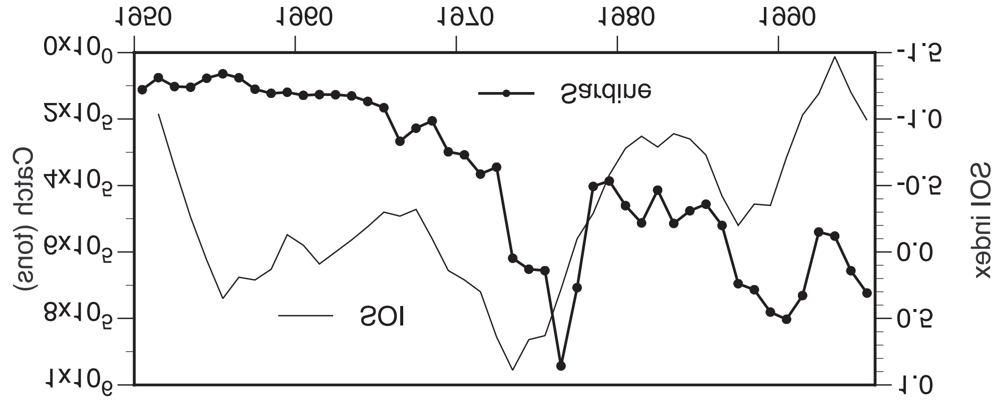

Figure X-9. Sardine catch in the Canary Current LME from 1950 to 1995 (from FAO 1997b) and smoothed SOI index.

upwelling and coincide with higher catch values. This shows that the interannual variability of both the environment and the fish populations in the Canary Current are related to global environmental signal acting through atmospheric teleconnections. Binet *et al.* (1998) found comparable results where environmental changes can modify fish population abundance and force ecological systems to spread or retract in space. It is noteworthy that the high abundance of Sardinellas at the beginning of the 1990s is associated with a period of higher temperatures, which in turn means that the habitat range for the southern fish species could potentially extend further north as the biomass increases.

During the last several decades the Canary Current was marked by important changes in the fish community which in turn strongly affected fisheries patterns. Species that experienced drastic changes have little in common. They occupy different habitats and have very different ecological requirements and life history traits (Longhurst and Pauly 1987). Many authors believe that the octopus and the trigger fish outbursts were due to a release of predator control on young stages (Longhurst and Pauly 1987) and that current annual fluctuations in recruitment and consequently landings are probably largely environmentally-driven (Caddy and Rodhouse 1998, Faure *et al.* 2000).

African coastal waters fish populations can migrate or spread towards large areas according to their relative abundance and to long-term environmental changes. The most extreme example is the trigger fish population, which apparently expanded from the Gulf of Guinea LME to the Canary LME. Distant ecosystems are connected through environmental teleconnections. The abundance of fish populations in the Canary Current can be related to indices such as the SOI. These teleconnections can potentially induce synchrony among fish populations inhabiting different LMEs. Synchronized patterns in pelagic fish populations have been observed in many distant ecosystems around the world (Schwartzlose *et al.* 1999), which suggests that these emerging patterns of decadal-scale variation are most probably driven by global climatic teleconnections (Klyashtorin 1998, Bakun 1998).

Strong environmental patterns are observed in the Canary Current LME. Drastic decadal patterns of changes in fish populations have also been observed. Even if it is difficult to identify the cause of these changes, it appears necessary to track and examine them at different scales, knowing that causes could be global as well as local.

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