# Decadal changes in the Canary Upwelling System as revealed by satellite observations: Their impact on productivity

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# Decadal changes in the Canary upwelling system as revealed by satellite observations: Their impact on productivity

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ABSTRACT

Satellite-derived sea-surface temperature (SST) data were used to study the variability of the Canary Upwelling Ecosystem-CUE (12 to 43N) over the last two decades of the 20$^{th}$ century. The analysis reveals well known patterns of climatology and seasonal variability in this upwelling system. In contrast to quasi-regular decadal oscillations of SST anomalies observed in the open ocean, the coastal variability during the 1980s–1990s was better described as a decadal scale shift of the upwelling regime intensity. The analysis of the upwelling index and coastal zonal gradient of SST showed that this shift occurred earlier (~1992) in the northern part of the CUE (off western Iberia) and some years later (~1995) off the northwest African coast. The long-term variability of upwelling-favorable wind forcing during the examined period provides reasonable explanations for the observed shift of the upwelling intensity and its timing for the whole CUE. Finally, changes in the productivity of several small pelagic fish species observed for the same period suggest that there was a response of the ecosystem to these changes.

## 1. Introduction

The Canary Upwelling Ecosystem (CUE), which includes the northwest African and the western Iberian coasts, is one of the four major eastern boundary upwelling systems of the World Ocean, and thus a very productive ecosystem and an active fishery. Fluctuations in the abundance of small pelagic fish species in this ecosystem have a serious impact in the socio-economy of the countries of the region. As a result of scientific interest and practical importance, the variability of the upwelling system on scales from synoptic to seasonal is reasonably well established (comprehensive review and list of references may be found in Arístegui *et al.,* 2004). However, information on longer-term fluctuations is limited due to the lack of sufficiently long, continuous time series of observations. There are only a few indications of decadal scale changes in the second half of the 20th century. Thus, Arfi (1985) reported that at 20N the 1960s was a decade of weaker upwelling, while in the

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1970s the upwelling index was stronger and then appeared to weaken in the early 1980s. Blanton *et al.* (1987) found that at 43N again the strongest upwelling was in the mid-1970s and the weakest in the early 1980s. Roy (1991) calculated the interannual variability of the Ekman transport between 13N–30N and showed that the mid-1970s was a period of relatively intense upwelling at all latitudes followed by upwelling index decrease through the 1980s. While important, these findings are based on sparse local datasets and do not reveal a detailed coherent spatio-temporal pattern of decadal changes over the whole extent of the Canary system. The only data suitable for this goal are satellite sea-surface temperature (SST) observations because of their good time-space resolution and global coverage. Satellite SST was widely used in previous studies of the Canary upwelling system. With only a short data time series available, however, the target of those studies was limited to the internal spatial fine structure of upwelling (e.g., fronts, eddies, filaments) and its fluctuations on synoptic to interannual timescales (e.g., Van Camp *et al.,* 1991; Nykjaer and Van Camp, 1994; Kostianoy and Zatsepin, 1996). Over twenty years of weekly global SST products are now available and these data provide a new opportunity to expand our investigation of upwelling variability toward longer time scales. Recent research confirms the usefulness of satellite-derived SST for studying decadal variability in large-scale oceanic frontal zones (Nakamura and Kazmin, 2003). In this study, zonal averaging of SST was used to filter out mesoscale variability in (zonally oriented) frontal zones and extract the gross features of decadal changes. Similarly, in our research we will apply meridional averaging to suppress complicated mesoscale features of the (meridionally oriented) upwelling system that tend to mask the basic pattern of decadal change.

There is no long-term and consistent biogeochemistry time series for the Canary coastal upwelling ecosystem (e.g., Aristegui *et al.,* 2004). Much of the available information concerning the biological component of the ecosystem is from fisheries studies (mainly landing data). Thus, further discussion of the fluctuations in productivity of the ecosystem will be based mainly on catch data of small pelagic resources.

Decadal fluctuations in the annual catches of small pelagic fish species (e.g., sardine and horse mackerel) along the Canary upwelling ecosystem have been observed in the last century (Bélveze and Erzini, 1983; Binet *et al.,* 1998; Kifani, 1998; ICES, 2002; Borges *et al.,* 2003; Aristegui *et al.,* 2004). Although important changes occurred in the exploitation of the resources off northeastern central Atlantic fishing grounds (e.g., Binet *et al.,* 1998), these fluctuations seem to be largely environmentally driven (e.g., Caddy and Garibaldi, 2000; Roy and Reason, 2001; Borges *et al.,* 2003), mainly related to the variability in the strength of upwelling.

The goals of the present investigation are: (1) to confirm the usefulness of satellite-derived SST data for studying decadal variability in the Canary upwelling system; (2) to describe the general local spatio-temporal pattern of decadal changes of Canary upwelling in the 1980s–1990s; (3) to associate observed decadal variability with fluctuations of atmospheric forcing; and (4) to evaluate the impact of decadal changes in coastal upwelling upon the ecosystem.

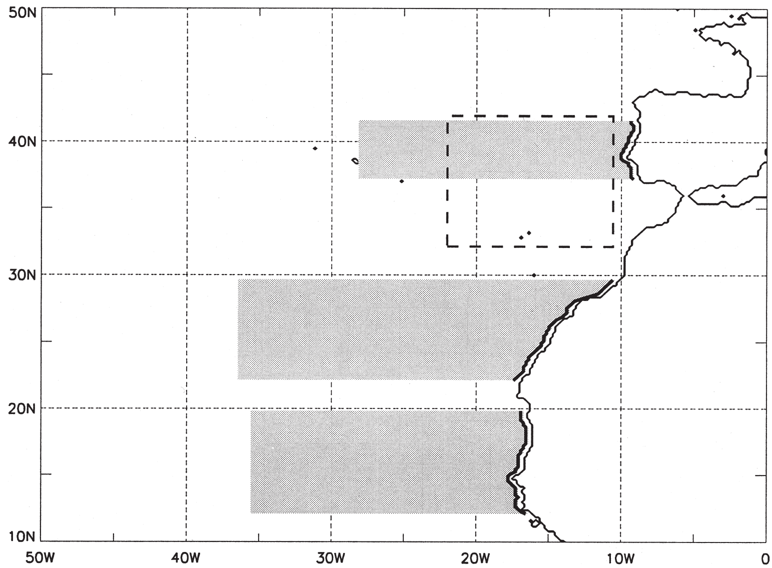


Figure 1. Study area. Solid bold lines along the coast and shaded areas indicate meridional and zonal extents of the three sub-areas where meridional averaging was applied. Dashed box indicates Azores front study sub-area.

## 2. Data and processing

In this study, we use weekly-mean multi-channel SST (MCSST) at approximately 18-km resolution based on the Advanced Very High Resolution Radiometer (AVHRR) night-time measurements. The MCSST data for the period 1982–2001 were prepared by the Rosenstiel School of Marine and Atmospheric Science of the University of Miami (Smith, 1992), based on global retrieval tapes of the National Oceanic and Atmosphere Administration/National Environmental Satellite Data and Information Service (NOAA/NESDIS). At each point on a global grid with 2048 by 1024 pixels, the SST product was computed as an average of all cloud-free measurements available for a particular week. Data void areas were then filled using Laplacian interpolation. Additional data processing was based on commonly used averaging and smoothing standard procedures. For our purposes, we cut the area limited by 10–50N latitude and 0–50W longitude from the global grid (Fig. 1). Further, weekly-mean SST was averaged over a month and seasonal SST was calculated for summer (July, August, September) and winter (December, January, February) for each year in the time series. Light spatial smoothing with a 3 by 3 pixel (approximately 0.5° latitude by 0.5° longitude) moving box average filter was applied to the original 18 km resolution data. All time series were smoothed with a 3-year moving average filter. For purposes of comparison with previous findings, 20-year monthly and seasonal SST climatologies were calculated. As an indicator of upwelling intensity, in this study we use an upwelling index defined as the SST difference between coastal (20 km to

40 km) and oceanic (500 km offshore) locations at the same latitude, and an upwelling index anomaly calculated by removing the mean from the time series. The stronger negative values of the index and its anomaly correspond to more intense upwelling. Since different authors use various oceanic locations as reference points to calculate upwelling indices, we made a number of calculations with reference points located within the range 400 km to 1500 km offshore. We find that the general patterns of the spatio-temporal variability of the index are similar within the range 400 km to 1000 km offshore.

In order to suppress mesoscale features and reveal general patterns of long-term variability in the three main parts of the upwelling system, we averaged SST meridionally along the coastline between 37–42N (Iberian coast with seasonal coastal upwelling), 22–30N (northwest African coast with year-round upwelling) and 12–20N (southern part of northwest African coast with seasonal upwelling), beginning from the coast and up to 2000 km offshore (Fig. 1, bold lines along the coast and shaded areas). The meridional averaging could be a source of errors in SST gradient estimates in high-gradient areas. However, in the present study it is appropriately used because in a macroscopic view frontal zones near the coast exhibit an alongshore (nearly meridional) orientation. Previous studies were successful in applying zonal averaging of SST to filter out mesoscale variability in frontal zones with a zonal orientation (e.g., Kazmin and Rienecker, 1996; Nakamura and Kazmin, 2003). The meridionally-averaged SST, $\bar{T}(x, t)$ was used to calculate an integral upwelling index (i.e., the difference between coastal and oceanic locations of the meridional averages of SST) for each subarea. Also, as an alternative indicator of upwelling intensity we use the magnitude of the zonal gradient of meridionally-averaged SST, $G(x, t) = \left|\partial(\bar{T})/\partial x\right|$.

The surface wind data were obtained from the U.S. National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project. The monthly mean meridional component of surface wind for the period of 1982–2001 was box-averaged over the approximately 2° latitude-wide coastal zones between 37–42N, 22–30N and 12–20N and then seasonal anomalies were calculated.

The North Atlantic Oscillation (NAO) winter (December–March) index, defined as the normalized sea level pressure difference measured in meteorological stations located at Gibraltar and Iceland (Jones *et al.,* 1997), was obtained from the Climate Research Unit of the University of East Anglia, U.K.

Sardine (*Sardina pilchardus*) catch time series for western Iberia were taken from the International Council for the Exploration of the Sea (ICES) "Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy" (ICES, 2003). We used only landings from the western coast of the Iberian Peninsula (43 to 37N). Recruitment (0-group, mainly immature fish with length $< 15$ cm) since 1978 was estimated by ICES from Virtual Population Analysis (VPA) for the whole Iberian stock (ICES, 2003). We then compute landings and recruitment estimations as the percentage of the maximum value of each time series. Small pelagic fish catch data by species for NW Africa were extracted from the Food and Agriculture Organisation (FAO) capture production 1950–

2001 database, which consists of landing data. The data used consist of information from the period 1970–2001 in Area 34-Subdivisions 1 and 3.1, which include information from an area between 9–36N latitude and from the coast to 20W longitude, assembled by the FAO's Regional Fishery Body CECAF (Commission for the Eastern Central Atlantic Fisheries). We then computed the contribution (percentage) of sardine and sardinellas (*Sardinella* spp.) for the total catch of small pelagic fish species in the region.

## 3. Climatology and seasonal cycle of upwelling system

In this section, mainly for the purpose of comparison with previous findings, we briefly present our calculations of the climatology and seasonal cycle of the upwelling index in the Canary system based on 20-year satellite SST measurements. Earlier, seasonal variability of this upwelling system was investigated in terms of the upwelling index, calculated from traditional *in situ* measurements (Wooster *et al.,* 1976) or 8-year satellite SST observations (Nykjaer and Van Camp, 1994), and of offshore Ekman transport (Wooster *et al.,* 1976; Nykjaer and Van Camp, 1994). In general, seasonal variability of the coastal upwelling in the study area is associated with meridional migration of the large-scale trade winds (basic upwelling forcing) band, which affects the northernmost part of the region in summer and moves southward in winter. Our results (Fig. 2) are quite consistent with previous research and clearly distinguish three main subareas of the upwelling system: (1) the Iberian coast between 37–43N where the upwelling season occurs mainly in summer; (2) the central part of the NW African coast between 21–32N where persistent upwelling throughout the year reaches its maximum intensity during fall and spring; and (3) the southernmost part of the NW African coast between 12–20N where upwelling occurs in winter and seasonality is most pronounced (due to replacement of trade winds in summer by monsoon winds, which advect warm water northward along the shore). During the winter season, the two subareas of the NW African coast tend to merge and form a spatially continuous upwelling region. The meridional profile of the 20-year mean upwelling index (Fig. 2-left, dotted line) indicates that in a climatological sense the whole area between 13–43N is affected by upwelling; i.e., the upwelling index is negative everywhere (except for an interruption at the Strait of Gibraltar). Thus, the satellite SST data reproduced reasonably well the known patterns of the climatology and seasonal variability in the Canary upwelling system and can be relied upon in further analyses.

## 4. Background larger-scale decadal variability pattern in the adjacent open ocean area

In this study, we concentrate on local decadal scale changes in the coastal Canary upwelling system. However, to understand the basic background pattern of decadal scale variability in the adjacent open ocean region (without any intention to contribute to the abundant literature on mechanisms of decadal change), we calculated SST anomalies (SSTA) at 1500 km offshore for the whole latitudinal extent of our study area. Latitude-

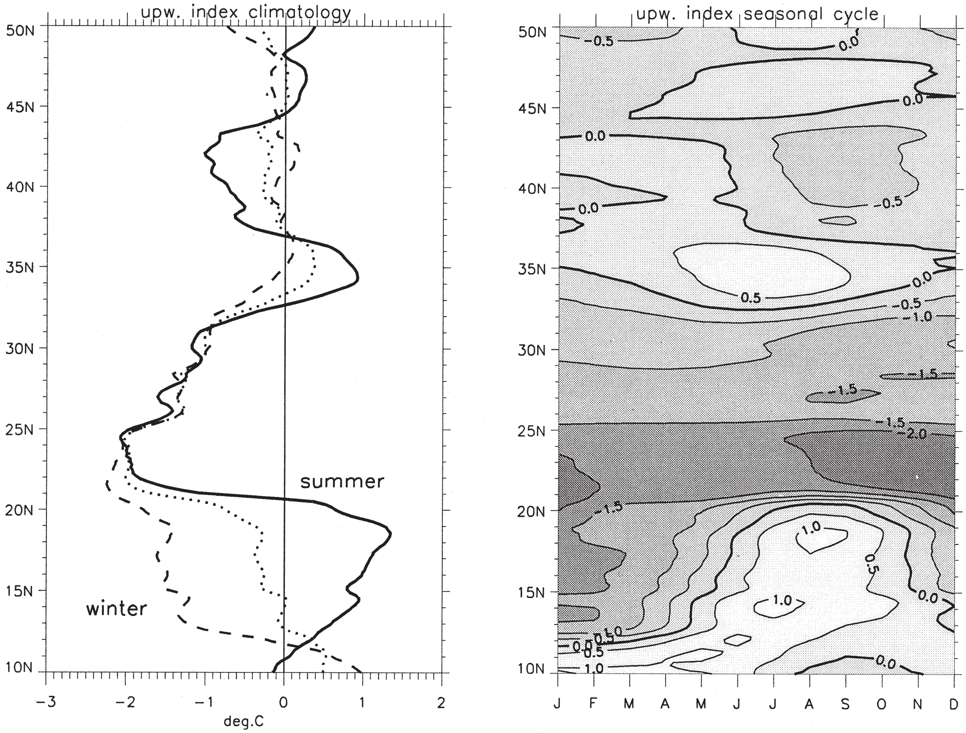


Figure 2. Meridional profiles of the upwelling index climatology (left panel): 20-year mean (dotted line), summer (solid line) and winter (dashed line), and (right panel) seasonal cycle of upwelling index (°C).

time sections of SSTA for summer and winter seasons are shown in Figure 3. Those plots reveal quasi-regular decadal-scale oscillations of SSTA typical for the northern Atlantic (e.g., Seager *et al.,* 2000; Marshall *et al.,* 2001), with cold anomalies in the early 1980s, early 1990s and early 2000s, and warm anomalies in the mid-1980s and mid 1990s.

Another indicator of large-scale decadal change is NAO. Our data confirm that mid-latitude SSTA was warm during low NAO index phases and cold during high phases (Kushnir, 1994). The NAO also plays an important role in long-term variability of winds across the North Atlantic and thus affects coastal upwelling intensity. Figure 4 shows time series of the NAO index (calculated as described in Section 2) for the period of 1960–2001. During the time span of our study, NAO reached one of its high-index extrema in the early 1990s with a sharp transition from the climatological mean in 1985–86 to a maximum positive anomaly in 1991–93. The same high-index extrema in the 1990s was also reported by Hurrell (1995). Although the 1990s values of the NAO index are not anomalous compared to longer records, they are unprecedented for the last half of the 20th century, but the sharp transition between negative NAO values in the 1960s and the highly positive NAO in the 1990s was unique (Jones, 2003). Many studies (e.g., Parsons and Lear,

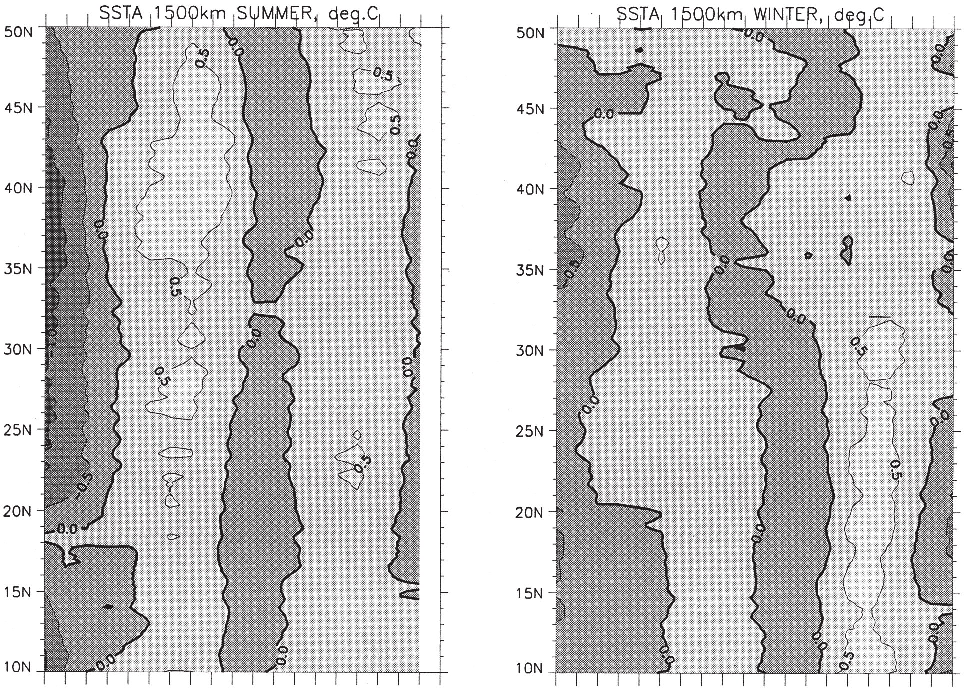


Figure 3. Latitude-time sections of (left panel) summertime and (right panel) wintertime SST anomaly (°C).

2001) linked long-term trends in the NAO with changes/fluctuations in the productivity of several components of marine ecosystems. For instance, Borges *et al.* (2003) found a decadal periodicity and synchrony between the NAO and wind conditions in the winter over the western Iberian coast, with an association between upwelling-favorable winds and a positive NAO index, which impacted negatively on sardine productivity after the early 1970s. Alvarez-Salgado (2003) also observed a close coupling between the decadal cycle of the NAO and the interannual variability of seasonal upwelling and downwelling patterns off NW Iberia.

## 5. Local decadal scale changes in upwelling system regime in 1980s–1990s

### *a. Overview of the pattern of decadal changes over the study area as seen in upwelling index distribution*

In this section we present an overview of the pattern of decadal scale changes in the upwelling index over the study area (Fig. 5). In contrast to the quasi-regular decadal oscillations of SSTA in the open ocean shown in the previous section, the pattern of upwelling index variability in the 1980s–1990s is better described as a decadal scale shift of upwelling regime intensity. Indeed, in summer when the upwelling season occurs on the

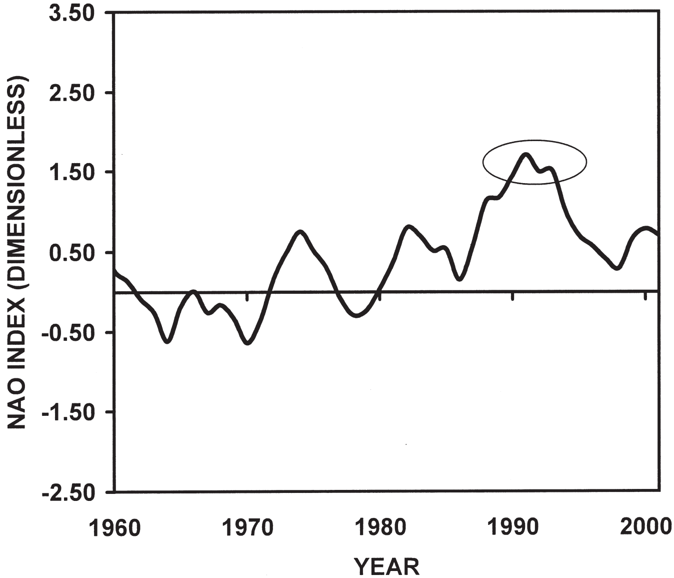


Figure 4. Five year running mean of the winter NAO index (December to March) calculated from the difference between the normalized sea level pressures at Gibraltar (Iberian Peninsula) and Reykjavik (Iceland). The circle corresponds to the high positive values observed during the early 1990s. (Source data: CRU-Univ. East Anglia).

western Iberian coast (37–42N) and the NW African coast (22–30N), for both areas we observed more than a 10-year (from at least 1982 to 1991–93) period of positive upwelling index anomaly (weaker upwelling), followed by an 8–10 year (from 1992–93 to 2001) period of stronger upwelling (negative index anomaly). On the Iberian coast an upwelling intensity during its weaker phase was almost constant, while on the northwest African coast (especially between 22–27N) pronounced extrema of upwelling index positive anomaly took place in the early 1980s. The strongest negative index anomaly (most intense upwelling) was reached around 1995–97 on the Iberian coast and in 1998–99 at the northwest African coast (the transition from weak to strong upwelling regime will be addressed in more detail in the next section). The intensity of upwelling during its stronger phase was not uniform in the meridional direction. Thus, on the Iberian coast two cores of stronger upwelling separated by an area of relatively weaker upwelling were located at approximately 38N and 41–42N. The northern core seems to be related to the location of a recurrent filament of cold upwelled waters at about 41N (Haynes *et al.,* 1993; Sousa, 1995). The southernmost core at 38N could be associated with the waters upwelled in the 'upwelling center' of Cape Roca ($\sim$ 39N) and their southward advection (Fiúza, 1983).

Similarly, on the northwest African coast stronger upwelling took place at 31–32N and especially at 24–25N. Both areas are known 'upwelling centers' adjacent to capes (Cap Sim and Cabo Bojador, respectively) where the strongest cyclonic wind-stress curl (which produces intense upwelling) is found (Parrish *et al.,* 1983; Bakun and Nelson, 1991).

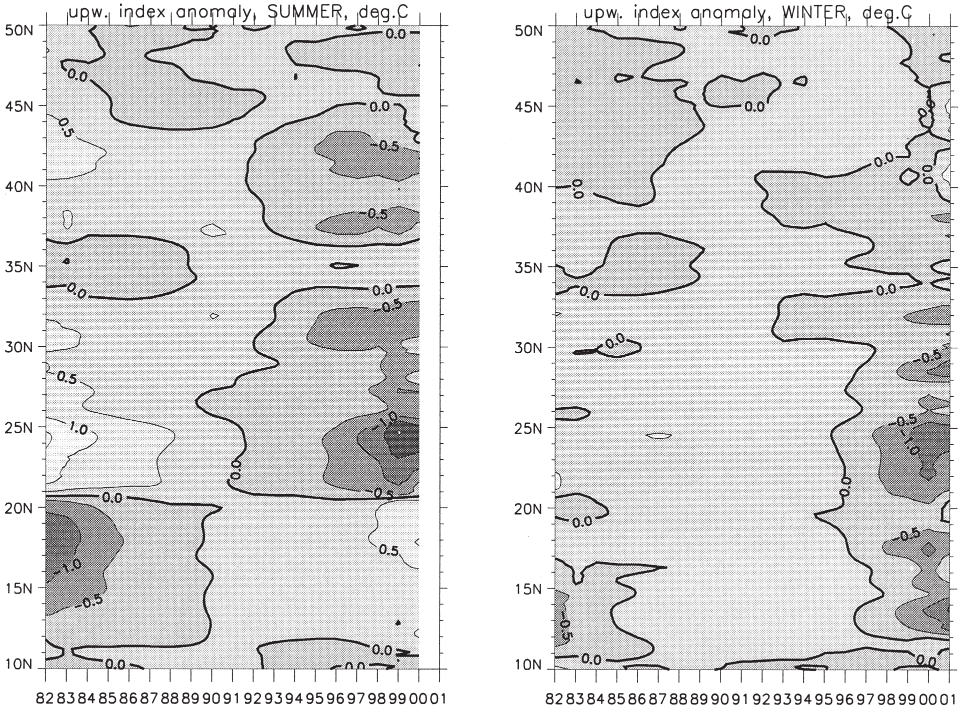


Figure 5. Latitude-time sections of (left panel) summertime and (right panel) wintertime anomalies of the upwelling index (°C).

The southern part of the Canary upwelling system between 12–20N displays strong seasonal variability and in summer (nonupwelling season) the SST at the coast is warmer than in the open ocean. Thus, the negative index anomaly observed in this area in the 1982–90 summer seasons means that in this period coastal waters were colder than the climatological mean. This may serve as an indication of decadal variability of the summer monsoon winds and associated northward advection of warm water along the coast.

Wintertime distribution of the upwelling index anomaly also reveals some interesting features, especially on the Iberian coastal zone. It is known that while some isolated upwelling events may occur on the Iberian coast in winter under favorable wind conditions, winter is still the climatological nonupwelling season and the winter upwelling index is close to zero (Fig. 2-right). However, after the shift of the upwelling regime from weak to strong in 1991–92, the winter upwelling index anomaly on the Iberian coast stays continuously negative. This suggests that during the strong phase of upwelling in 1992–2001, the Iberian coast was also under the conditions of weak but persistent upwelling in winter. Farther south along the entire extension of the northwest African coast from 30N to 12N the upwelling season is in the winter. Consequently, the shift of the upwelling regime intensity is evident through the whole meridional extent of this part of

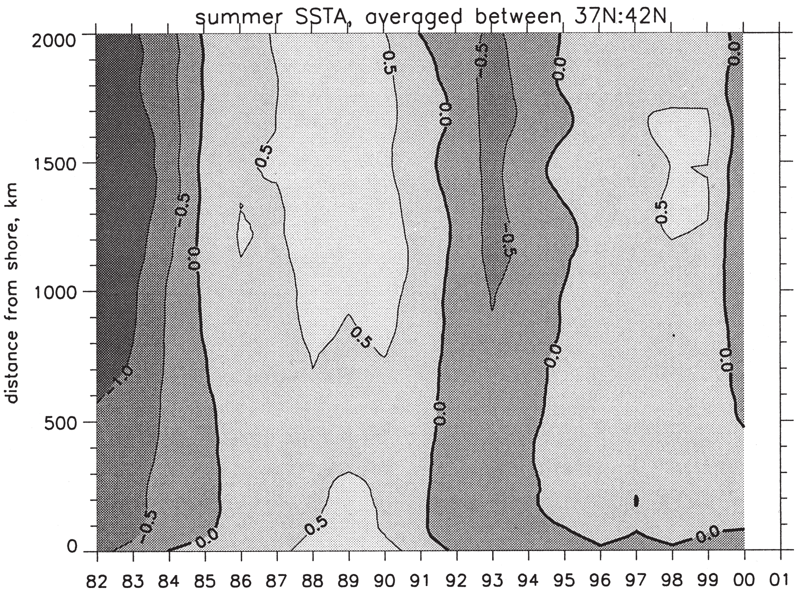


Figure 6. Longitude-time section of summertime meridionally averaged (37–42N) SST anomaly (°C).

the CUE, but the timing of the transition occurs later (1995–97) during wintertime than during summertime (1991–1992) in the area of permanent upwelling (22–30N) (Fig. 5). Also, it is worth noting that in the southernmost part of the Canary upwelling system during the winter upwelling season, the early 1980s was the period of stronger upwelling followed by more than 10 year-long weak upwelling conditions that, in turn, shifted to a strong upwelling phase like the rest of the system.

*b. Upwelling changes and local wind conditions in three main parts of ecosystem*

In this section we document a shift in upwelling intensity between the 1980s and the 1990s in terms of both the upwelling index and coastal zonal gradient of SST, separately in three main parts of the Canary upwelling system (i.e., northernmost and southernmost subareas with seasonal upwelling and a central region with year-round upwelling). In order to suppress numerous complicated mesoscale features of the upwelling system which tend to mask basic patterns of decadal scale variability, we averaged SST meridionally along the coastline between 37–42N, 22–30N and 12–20N, beginning from the coast and up to 2000 km offshore (Fig. 1), as described in Section 2. A sample of a longitude-time section of the summer anomaly of meridionally averaged SST for the Iberian coast is shown in Figure 6. This plot clearly illustrates the modification of SSTA patterns in coastal areas under the influence of the 1992–2000 intensified upwelling conditions. The open ocean area reveals quasi-regular decadal oscillations of SSTA (mentioned in Section 4), which tended to stretch out right to the coastline during the period of 1982–95. However, upwelling intensification after 1992–93 destroyed regular SST oscillations in the coastal area and resulted in the formation of a narrow (up to 100 km) coastal band of negative SSTA in 1995–2000, next to positive open ocean SSTA in the same period. This 'dipole' SSTA distribution pattern provided a strong negative anomaly of the upwelling index. A similar, though less pronounced, picture was observed in the other two subareas of the upwelling system.

While an upwelling index is a commonly used measure of upwelling intensity, an alternative indicator, e.g. coastal zonal gradient of SST, may also be useful. One of the most remarkable features of the coastal upwelling structure is coastal upwelling fronts (CUFs), or high SST gradient transition zones between the cold newly upwelled deep water mass located near the coastline and the transformed warmer water mass farther offshore (Kazmin, 1993). The CUFs are not permanent features of coastal upwelling structure: their formation is associated with upwelling events during the periods of intensification of upwelling-favorable winds. Thus, CUFs are essentially nonsteady, synoptic time-scale, local phenomena (though extremely strong and prolonged wind impulse may produce a continuous front along a significant portion of the upwelling coast). During their lifetime, lasting from a few days to 1–2 weeks, CUFs pass through the whole evolution cycle, including a frontogenesis phase, stationary state and relaxation (Kazmin *et al.,* 1990; Kazmin, 1993). However, in the macroscopic view, after spatio-temporal averaging over the upwelling-affected area, zonal gradients of SST near the coast may provide effective estimates of large-scale upwelling intensity. In cases of weak and sparse upwelling events during the upwelling season, averaging will produce very low or near-to-zero zonal SST gradients. On the other hand, in the case of intensified upwelling with strong and frequent upwelling events, we may expect strong zonal SST gradients even after heavy spatio-temporal averaging.

Another prominent feature of coastal upwelling structure is an oceanic upwelling frontal zone (OUFZ) that separates warmer open ocean surface water masses and colder transformed coastal water masses of upwelling origin (Kazmin, 1993). The OUFZ is an outcropped seasonal thermocline and is usually located near the shelf break; it is more steady than CUF, exists continuously during the upwelling season and, while it displays some changes in response to wind variability, is less indicative in the sense of coastal upwelling intensity.

We plotted the magnitude of zonal gradients of meridionally averaged SST as longitude-time sections for three upwelling system subareas (Fig. 7). These plots in terms of SST gradient provide even more evidence of the changes in upwelling patterns, which were described in Section 5a based on upwelling index variability. All three subareas display a similar pattern of temporal variability of SST gradient in the near-coast area: prolonged (over ten years) periods of near-zero gradient followed by sharp (1–2 years) switches to a strong gradient phase. However, the timing of this shift is different between subareas: it first occurs on the Iberian coast in 1992–94, and a few years later (in 1996–98) on the NW

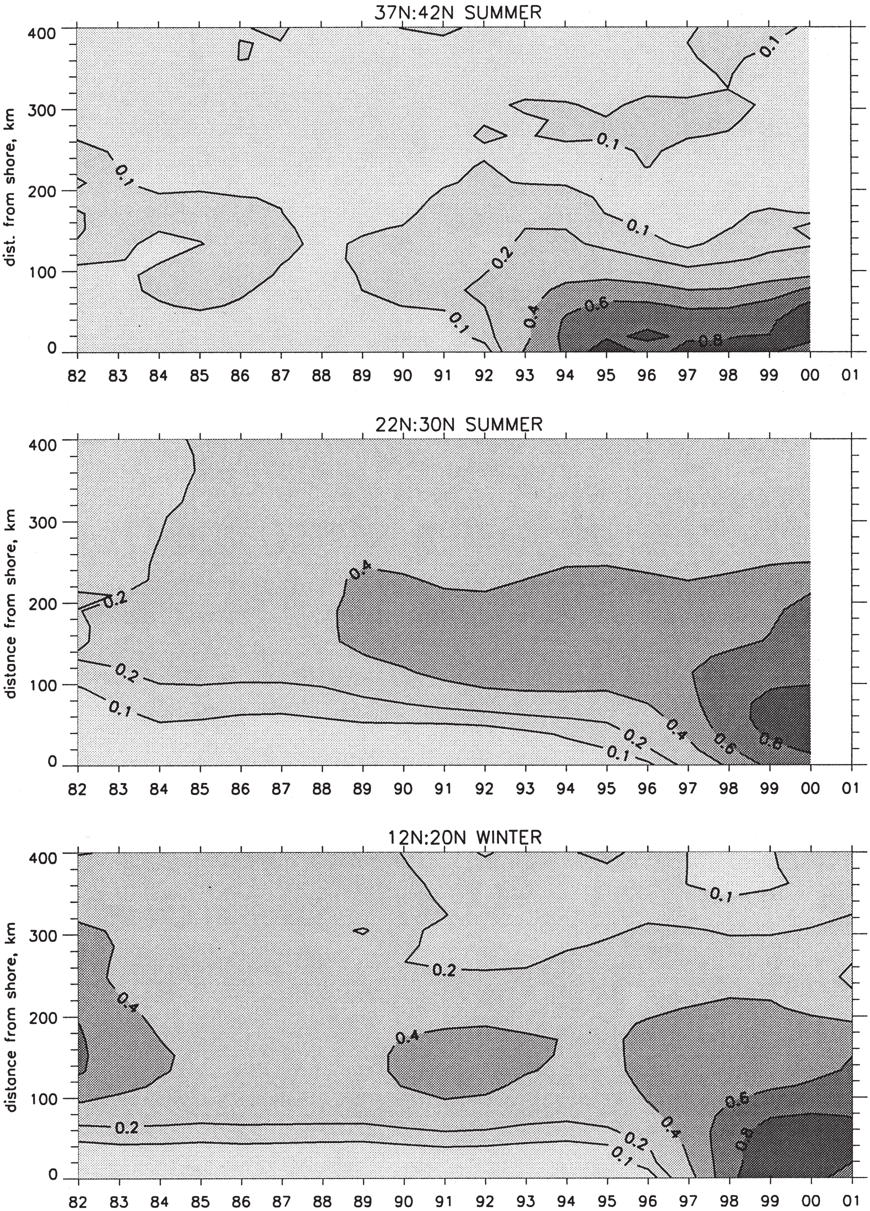


Figure 7. Longitude-time sections of the magnitude of the meridionally averaged SST zonal gradient between (top panel) 37–42N, summertime, (mid panel) 22–30N, summertime and (bottom panel) 12–20N, wintertime (G: °C/100 km).

African coast (simultaneously in the central, year-round upwelling area and in the southernmost, seasonal upwelling region). It is worth noting that in spite of heavy spatio-temporal smoothing, our satellite SST data were able to resolve some indications of the OUFZ as well. It appears as a wide, diffuse band (though not consistently time-continuous) of increased SST gradient with its core centered between 100–200 km offshore. This feature was better pronounced during the phase of weak upwelling and tended to merge with CUFs during the intensified upwelling period.

In order to document more accurately the timing of the shift in upwelling intensity and correlate it with changes in the local wind conditions, we plotted in Figure 8 for the Iberian coast (summer-bold solid line and winter-thin solid line) and for the central part of the NW African coast (summer-dashed line): (1) the upwelling index anomaly calculated from meridionally averaged SST, (2) the magnitude of the zonal gradient of meridionally averaged SST approximately 20 km offshore, and (3) the anomaly of the meridional component of surface winds, box averaged as described in Section 2 (only summertime is shown for the Iberian coast); positive/negative wind speed anomaly corresponds to weaker/stronger than the climatological mean wind. Wintertime patterns on the central NW African coast with year-round upwelling are similar to summertime distributions and are not shown; also not shown are figures for the southernmost subarea of the African coast, since during the winter upwelling season they almost mimic the central area pattern. Figure 8 displays, both in terms of the upwelling index and the SST gradient, a clear time lag of 3–4 years in the intensification of upwelling off the African coast compared with the Iberian coast. In terms of the SST gradient the upwelling intensity change looks like a sharp switch from near-zero to 0.8–1°C/100 km values over 2–3 years (Fig. 8 - mid plot), while the upwelling index anomaly demonstrates a more gradual transition from positive to negative values (Fig. 8 - top). It is interesting to note that while the negative anomaly of the upwelling index on the African coast was almost twice as strong as at the Iberian coast (Fig. 8 - top), the maximum SST gradient at both locations was of the same order of magnitude (Fig. 8 - mid). Wintertime distributions of the upwelling index anomaly and SST gradient on the Iberian coast (thin solid lines in Fig. 8 - top and mid plots) confirm that during the intensified upwelling phase in 1992–2001 this subarea in winter (climatologically nonupwelling season) was also experiencing weak but persistent upwelling conditions.

The first and most obvious explanation for the shift in upwelling intensity might be long-term variability of upwelling-favorable wind forcing. The temporal variability of the meridional component of surface winds for the two subareas (Fig. 8 - bottom plot) seems to be consistent with the observed pattern of upwelling intensity changes. Thus, extended periods of weak upwelling (1982–92 for the Iberian coast and 1982–96 for the African coast) coincide with the generally positive anomaly of the meridional wind, which tended to oscillate around the climatological mean with some occasional episodes of weak, negative values. However, on average the above mentioned periods had a positive wind anomaly, i.e., weaker wind. The period of positive wind anomaly was followed by a sharp

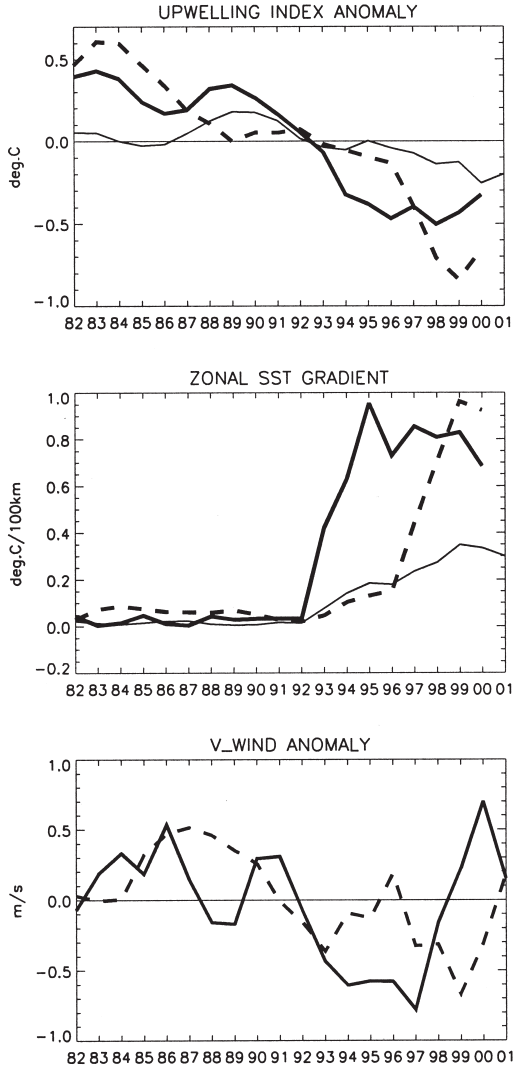


Figure 8. Meridional averages for the upwelling index (top panel), the magnitude of the coastal zonal SST gradient (mid panel), and the anomaly of meridional components of the surface wind (bottom panel). The bold solid line presents the values for the summer season on the Iberian coast (37N–42N) and the thin solid line the winter season in the same region. The dashed lines show the values for the summertime on the NW African coast (22N–30N).

transition to a strong negative anomaly (stronger upwelling-favorable winds), which, remarkably, first occurs on the Iberian coast in 1992–98, and only in 1996–2001 on the African coast, i.e., with the same time delay of the upwelling intensity shift. Intensification of upwelling started almost immediately with the increase of the negative wind anomaly,

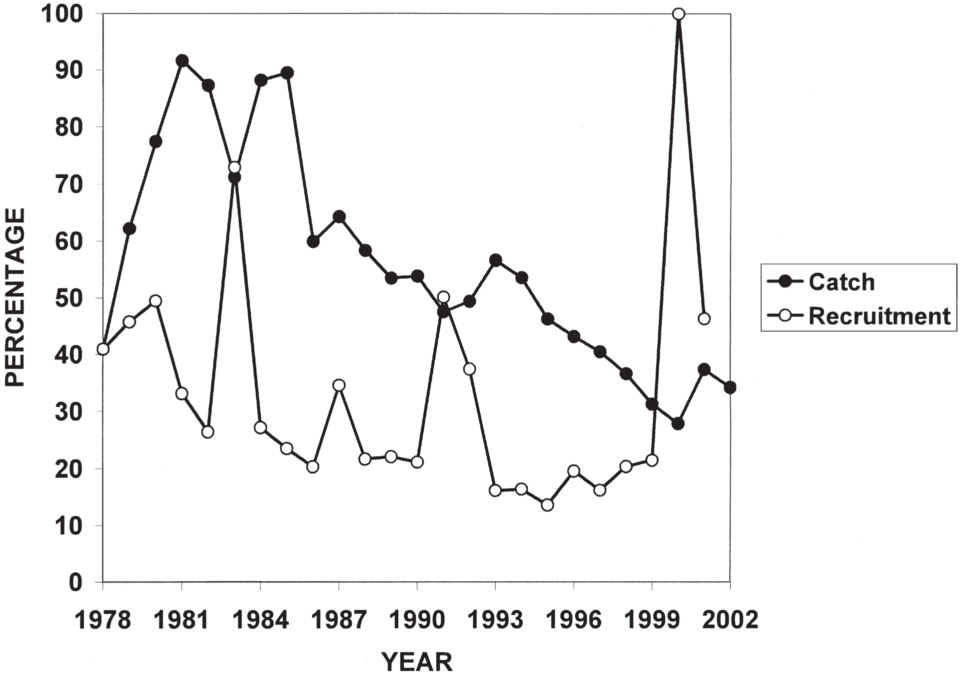


Figure 9. Sardine catches off western Iberia and recruitment estimates for the Iberian stock, as a percentage of the maximum value of each time series (data source: ICES, 2003).

which is consistent with the known short-time response of upwelling-to-wind forcing. There are also signs of an upwelling intensity decrease from the beginning of the weakening of the negative wind anomaly. Thus, long-term variability of wind forcing during the examined period provides a reasonable explanation for the observed shift of the upwelling intensity and its timing for the whole Canary system. Still, the nature of long-term local wind variations may be associated with decadal-scale, basin-wide processes. However, the analysis of the physical mechanisms of large-scale decadal wind variability, while important to explain the lag of approximately three years in the shift of upwelling intensity between the coasts off western Iberia and off northwest Africa, is out of scope of this investigation and will need further studies.

## 6. The impact of changes in upwelling intensity in ecosystem productivity

To access the impact of the abrupt change observed in the upwelling intensity in the Canary upwelling ecosystem we look for fluctuations in the productivity of small pelagic fish species (sardine and sardinella). In Figure 9 we present the annual catches (only landings for the western Iberia) and recruitment for the Iberian stock of sardine, both as percentages of the maximum value of the time series available. Since the end of the 1980s,

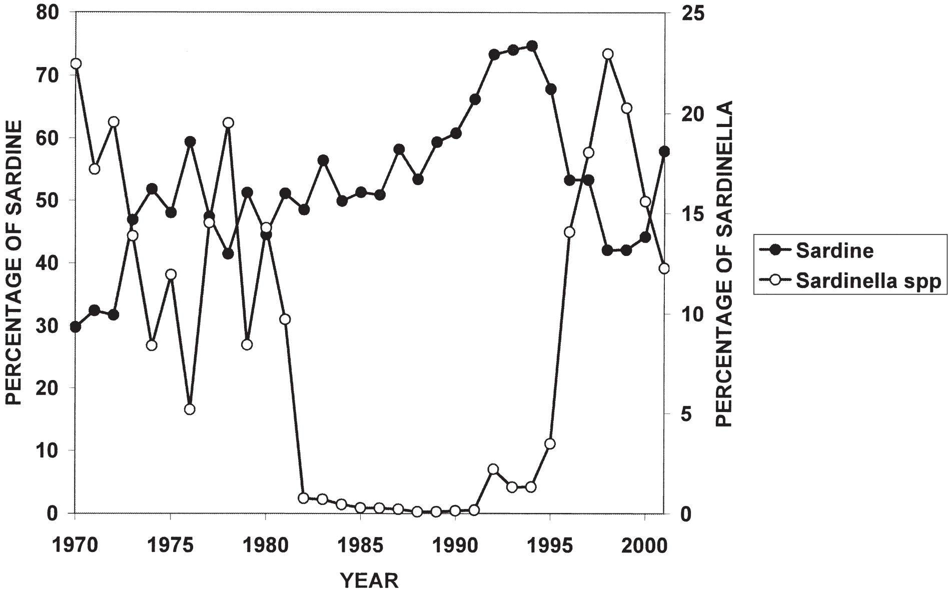


Figure 10. Percentage of sardine and sardinellas in the total catch of small pelagic fish in FAO-CECAF Area 34-Subdivisions 1 and 3.1 (data source: FAO capture production statistics).

a downward trend of the catches is clear and there is a systematic and pronounced decrease after 1993 which lasts until the end of the 1990s. The 1990s showed several of the lowest values for landings in the region since the 1940s. Recruitment values were steadily very low after 1993 and during the rest of the 1990s, presenting during this time the lowest values of all the recruitment time series available for this species.

However, off NW Africa there were clearer changes in the catches of sardine and sardinellas, associated with the abrupt change in the upwelling intensity around 1994–1995 as described previously. In Figure 10, it is evident that after 1994 the percentage of sardines in the total catches of small pelagic fish species suddenly dropped, from values of about 70% to values of about 40%. However, it is interesting to note that this decrease was accompanied by an abrupt increase in the contribution of sardinellas to the total catches, from values of almost 0% before 1994 to more than 20% in 1998. This important replacement of sardines by sardinellas is a clear example that drastic changes occurred in the biological community structure of the upwelling ecosystem associated with the changes described previously.

These results seem to contradict other studies that refer to the periods of high sardine productivity in the Canary Upwelling Ecosystem corresponding with enhanced coastal upwelling conditions (Belvèze and Erzini, 1983; Binet *et al.,* 1998; Roy and Reason, 2001). However, the results suggest that strong upwelling associated with an increase of upwelling during winter could explain the decrease of sardine productivity in the Canary Upwelling Ecosystem during the 1990s. According to the ‘optimal environmental window’ concept (Cury and Roy, 1989) under moderate upwelling conditions reproductive success is maximized, but under strong upwelling conditions excessive offshore transport and turbulent mixing occurs which limit the survival of larvae through their dispersion and disruption of food concentrations which are necessary for the success of larvae first feeding (Lasker, 1981; Cury and Roy, 1989). Additionally, Borges *et al.* (2003) found that when winter upwelling conditions overpass a certain limit, there is also lower catches of sardine, and this is explained by the negative impact of the oceanographic conditions on the recruitment. In fact our study revealed that there is an increase of upwelling intensity during the 1990s, both in summer and winter. Thus, during the 1990s, both of the effects of the limiting factors described previously were not minimized leading to a clear impact in the productivity and in the structure of the ecosystem.

The partial replacement of sardine for sardinellas could be linked to the fact that, at the least, *Sardinella aurita* has the capacity to change its reproductive strategy, in space and time, to avoid the variability of upwelling (Roy *et al.,* 1989; Roy, 1998; Demarcq and Fauré, 2000).

## 7. Summary and conclusions

We have presented evidence of decadal changes in the Canary coastal upwelling ecosystem based on the analysis of satellite SST data. We have shown that the currently available satellite-measured MCSST data can adequately depict the known patterns of the climatology and seasonal variability of the Canary Upwelling Ecosystem (CUE) and may be used for investigation of longer time-scale variability. The data are just long enough to capture decadal changes that occurred in the CUE over the last two decades of the 20th century. As an indicator of upwelling intensity we used both a traditional upwelling index and the magnitude of the coastal zonal gradient of SST. The latter proved to be very useful as an effective estimate of large-scale upwelling intensity.

Our basic finding is that, in contrast to quasi-regular decadal oscillations of SSTA in the open ocean, the pattern of upwelling variability in the 1980s–1990s is better described as a decadal scale shift of upwelling regime intensity from weak upwelling in 1980s to a stronger one in the 1990s.

In terms of both the upwelling index and the SST gradient, our analysis revealed a remarkable fact that there was a 3- to 4-year time lag between the intensification of the upwelling regime along the African coast (~1995–96) and along the Iberian coast (~1992–93).

Another important result is that the winter upwelling index anomaly on the Iberian coast has remained negative since the time of the shift in 1992–93 even though winter on the Iberian coast is climatologically the nonupwelling season. Thus the Iberian coast in winter was also experiencing weak but persistent upwelling during the 1992–2001 strong phase of upwelling, and because the winter is also the spawning season for small pelagic fishes (e.g., sardine) this could negatively impact their recruitment (Santos *et al.,* 2001; Borges *et al.,* 2003).

We found that long-term local variability of the upwelling-favorable meridional wind forcing during the examined period explains the observed shift of the upwelling intensity and its timing for the whole Canary system. Thus, the period of weak upwelling coincided with a generally positive anomaly of the meridional wind, while the set-up of a strong upwelling regime started almost immediately with the development of the strong negative meridional wind anomaly. This negative anomaly, remarkably, first occurred on the Iberian coast in 1992 and lasted until 1998, while on the African coast it started only in 1996 and persisted until 2001 (i.e., with the same time delay of the upwelling intensity shift). In both subareas the upwelling intensity maximum corresponded to the period of strongest negative wind anomaly. However, the nature of the long-term local wind variations is not quite clear. It may be associated with decadal-scale basin-wide processes, especially the NAO. In the context of our study, it is worth noting that during the time span considered here, the NAO reached one of its high-index extrema (with an unprecedented magnitude for the last half of the 20th century) in the early 1990s, with a sharp transition from near-climatological values through the 1960s–1980s to a maximum positive anomaly in 1991–94. These abrupt changes in the NAO index and associated transformation of large-scale wind patterns are temporally-consistent with the upwelling regime intensity shift described in our study. However, the possible correlation of local and basin-wide processes and their mechanisms is the subject for a separate study.

Our study reveals that the ocean ecosystem responds to abrupt changes observed in the upwelling intensity over the northeastern Atlantic (Iberia and NW Africa). Other studies based on fisheries/biological time series analyses also reveal that there were important changes in the 1990s in other components of the same ecosystem (e.g., Santos *et al.,* 2001; Stratoudakis *et al.,* 2003; ICES, 2002; Arístegui *et al.,* 2004). For instance, standardized data from 15 ichthyoplankton surveys show a decline in the mean probability of egg presence over the Portuguese continental shelf from the 1980s to the 1990s (Stratoudakis *et al.,* 2003). Comparable changes are observed in acoustically estimated distributions of sardine along the Portuguese coast (Santos *et al.,* 2002; ICES, 2002). Analysis of trawl data from acoustic surveys (1982–2000) has shown decadal differences in the depth distribution of sardine (being caught in deeper waters during the 1980s), changes in the maturation cycle of sardine, and changes in the distribution and abundance of other pelagic species. For example, bogue *Boops boops* and chub mackerel *Scomber japonicus* were caught in a wider area and more frequently during the 1990s (ICES, 2002). The reasons for the observed changes in the biological components of the ecosystem are not clearly understood, but the present study suggests that they could be, at least partially, climate driven. In fact, although management actions imposed on the Iberian stock of sardine to reduce fishing effort have contributed to reduce fishing mortality in recent years, the continuous decline of catches since 1985 cannot be explained by these measures alone, and one possible explanation could be the role of the environment in the dynamics of these species.

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