Chapter 23.   OCEANOGRAPHY AND FISHERIES OF THE CANARY CURRENT/IBERIAN REGION OF THEEASTERN NORTH ATLANTIC (18a,E)

JAVIER ARÍSTEGUI

University of Las Palmas de Gran Canaria

XOSÉ A. ÁLVAREZ-SALGADO

CSIC, Instituto de Investigacións Mariñas, Vigo

ERIC D. BARTON

University of Wales, Bangor

FRANCISCO G. FIGUEIRAS

CSIC, Instituto de Investigacións Mariñas, Vigo

SANTIAGO HERNÁNDEZ-LEÓN

University of Las Palmas de Gran Canaria

CLAUDE ROY

Centre IRD de Bretagne, Plouzané

ANTONIO M.P. SANTOS

Instituto de Investigaçao das Pescas e do Mar, Lisboa

Contents

1.   Introduction

The eastern boundary of the North Atlantic subtropical gyre extends from the northern tip of the Iberian Peninsula at 43°N to south of Senegal at about 10°N, approximately the range of displacement of the Trade wind band (Fig. 23.1). It is one of the four major eastern boundary upwelling systems of the world ocean, and thus an area of intensive fisheries activity. The meridional shift of the Trade wind system causes seasonal upwelling in the extremes of the band, while in the central region upwelling is relatively continuous all year round (Wooster et al., 1976). Superimposed on the seasonal variation, short-term variability in wind direction and intensity may induce or suppress upwelling, affecting the dynamics of the ecosystem. At long-term scale, decadal fluctuations in fisheries landings - particularly north of 20°N- have been related to environmental changes due to the North Atlantic Oscillation (NAO) (Borges et al., 2003). In the southern part of the region, the influence of the El Niño Southern Oscillation (ENSO) may be also responsible of some of the recorded inter-annual variability in fisheries landings (Roy and Reason, 2001).

The upwelling region is separated into two distinct areas - the Iberian coast and the Northwest African coast- with apparently little continuity in the flow between them. This is caused by the interruption of the coastline at the Strait of Gibraltar, which allows the exchange of water between the Mediterranean Sea and the Atlantic Ocean. The continental shelf of the whole region is the most extensive of any eastern boundary current and persistent hydrographical features are associated with the topography of the shelf. Several submarine canyons are distributed along the Iberian margin, acting as sites for coastal sediment deposition, the Nazaré canyon being the most significant depocenter. At the northern part of the Iberian coast, the Rías Baixas represent a singular ecosystem, which transforms the 3D-variability of continental shelf waters into 2D-variability, causing an amplification of the biogeochemical signals. Large filaments of coastal upwelled water stretch offshore from the numerous capes and promontories, exchanging water and biological properties with the ocean boundary. The exchange is particularly noticeable along the giant filaments of Cape Guir and Cape Blanc, which stretch up to several hundred kilometres into the open ocean, transporting rich-organic matter waters into the impoverished oligotrophic waters of the subtropical gyre. Another singularity of this eastern boundary system is the presence of the Canary Archipelago, close to the NW African coast, which interrupts the main flow of the Canary Current and introduces large mesoscale variability, mainly in the form of vortex streets downstream of the islands (Arístegui et al., 1994). Island eddies and upwelling filaments interact to exchange water properties, acting as an efficient route for transporting organic matter to the open ocean.

Research effort has been unevenly distributed through the whole region. The western and northern coasts of the Iberian Peninsula have been extensively studied from the hydrographic and dynamic point of view (Barton et al., 1998). However, most of the field studies on carbon and nutrient biogeochemistry in the Iberian margin concentrate in the Galician and Cantabrian coast (42°–44°N, 5–10 °W), at the boundary between the temperate and subpolar regimes of the North Atlantic. There, intensive research was supported during the past decade by the European scientific community in the frame of several research projects, like "The

Control of Phytoplankton Dominance" (Figueiras et al., 1994; Moncoiffé et al., 2000), MORENA (Multidisciplinary Oceanographic Research in the Eastern Boundary of the North Atlantic; Fiuza et al., 1998; Pérez et al., 1999; 2001), or OMEX II (Ocean Margin Exchange; Joint and Wassmann, 2001; Huthnance et al., 2002; Joint et al., 2002; van Weering and McCave, 2002).
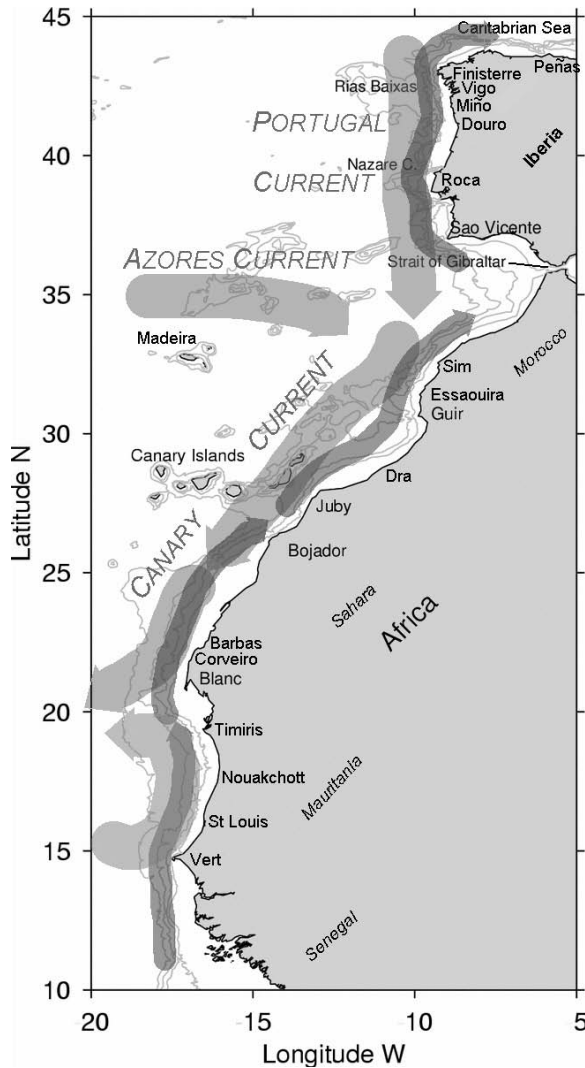

Figure 23.1 Fig. 23.1. Chart of the Eastern North Atlantic Iberian and NW African margin indicating locations referred to in the text. The 200, 1000, 2000 and 3000 m isobaths are shown. A schematic summer current regime is shown by broad, light arrows representing surface flows and narrower, dark arrows representing the poleward slope undercurrent. Seasonal variation of the currents is discussed in the text.

The upwelling region of NW Africa was intensively studied in the 1970s, during the International Decade of Ocean Exploration (IDOE), under the international programme of Cooperative Investigation of the Northern Part of Eastern Central Atlantic (CINECA; Hempel, 1982), but almost ignored during the 1980s. Some interdisciplinary studies, focused on the export of organic matter from the NW Africa upwelling into the open ocean, were however carried out during the last decade in the Canary Current region. These were the cases of the French EUMELI (Eutrophic, Mesotrophic, Oligotrophic) project (Morel, 1996), and the European Canaries-Coastal Transition Zone (Barton et al., 1998) and CANIGO (Canary Islands, Azores, Gibraltar Observations; Parrilla et al., 2002) projects.

In this chapter, we present a review bringing together for the first time up-to-date knowledge on inter-disciplinary aspects of the oceanography and fisheries of the eastern boundary of the North Atlantic. Our synthesis provides a global view of the trophic functioning of these coastal ecosystems. Aspects covered range from nutrient dynamics, through production and respiration, to fish populations and fisheries, all of which are affected by processes that occur on distances from mesoscale to large scale and vary over periods from days to decades.

2.   The coastal upwelling system in Iberia and NW Africa

2.1   Temporal and spatial variability

The surface circulation off Iberia (Fig. 23.1), far away from the main currents of the North Atlantic Ocean, has been systematised by Pelíz and Fiúza (1999). They coined it the 'Portugal Current System' (although Iberian would be more inclusive) because of similarities with the 'California Current System'. The oceanic side of the Iberian basin is occupied by the weak 'Portugal Current' (PC), which flows southwards year round from 45°–50°N and 10°–20°W, at the interface between the areas of influence of the North Atlantic Current and the Azores Current (Krauss, 1986). The circulation pattern is more complex at the ocean margin, showing a marked seasonal variability defined by the coastal wind regime of the area either in the western (Huthnance et al., 2002) and northern coast (van Aken, 2002). During spring and summer (from March–April to September–October) north-easterly winds (Fig. 23.2a) predominate in the Iberian basin (Wooster et al., 1976; Bakun and Nelson, 1991), producing the southward flowing 'Portugal Coastal Current' at the surface (<100m) and the northward flowing 'Portugal Coastal Under Current' (PCUC) at the slope. In contrast, during the rest of the year, south westerly winds are predominant, provoking a reversal of the surface circulation to form the 'Portugal Coastal Counter Current (PCCC)' which flows northward from the surface to 1500m depth, including the propagation of the Mediterranean Overflow Water along the western and northern Iberian slope. The existence of a poleward surface flow during the autumn and winter months in the Iberian slope was described first by Wooster et al. (1976) and subsequently found by Frouin et al. (1990) and Haynes and Barton (1990) in the western Iberian coast and by Pingree and Le Cann (1990) in the Cantabrian coast.
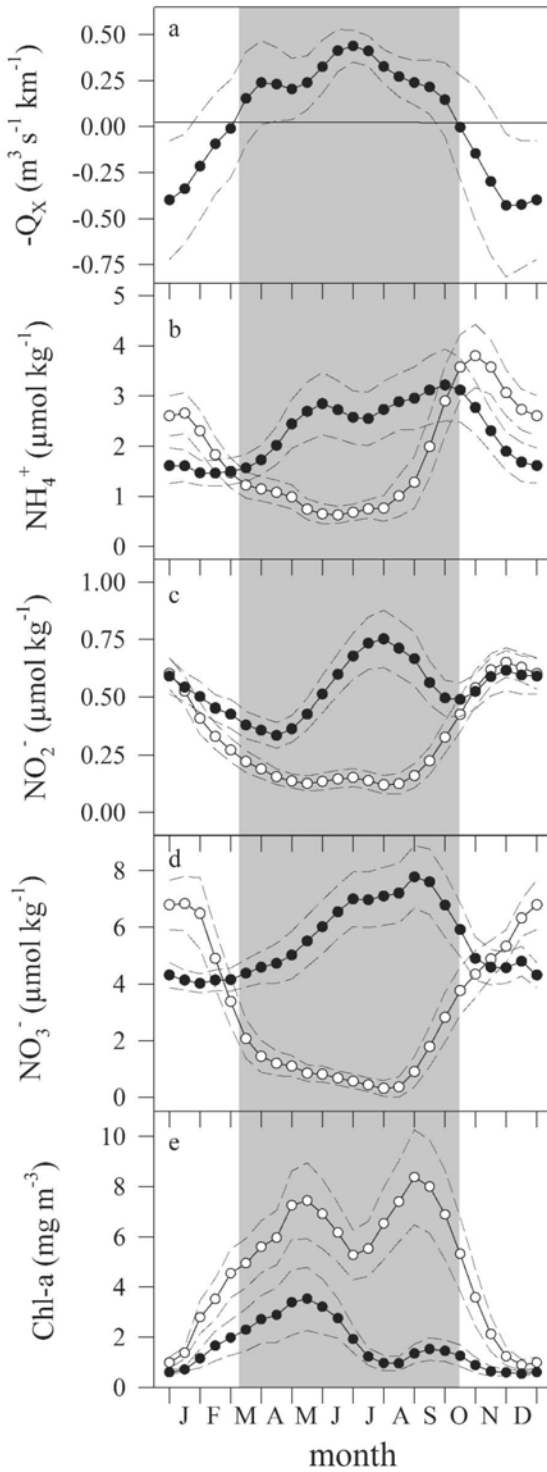
Figure 23.2   Seasonal cycles of (a) offshore Ekman transport ($-Q_x$, $m^3\ s^{-1}\ km^{-1}$) in a $2°\times2°$ geostrophic cell centred at 43°N 11°W; (b) surface and bottom ammonium (NH_4^+, µmol kg^{-1}); (c) nitrite (NO_2^-, µmol kg^{-1}); (d) nitrate (NO_3^-, µmol kg^{-1}); and (e) Chlorophyll (mg m^{-3}) in the coastal upwelling ecosystem of the Ría de Vigo. Shaded area: spring-summer upwelling season. Black circles in panel a: 1987–96 fortnightly average; black circles in panels b–e: 1987–96 fortnightly bottom average; white circles in panels b–e: 1987–96 fortnightly surface average; dashed lines: average ± std.

The Portugal Coastal Current is associated with seasonal coastal upwelling at the Iberian margin, and the export of coastal surface waters to the open ocean, especially at the recurrent upwelling centres and filaments along the western Iberian coast (e.g. Fiúza, 1983; McClain et al., 1986; Sousa and Bricaud, 1992; Haynes et al., 1993; Pelíz and Fiúza, 1999). On the contrary, the PCCC is associated with downwelling on the coast, and the piling of coastal waters onto the Portuguese (Pelíz and Fiúza, 1999), Galician (e.g Castro et al., 1997; Álvarez–Salgado et al., 2003) and Cantabrian (e.g Bode et al., 1990; Fernández et al., 1993) coasts. Anticyclonic eddies, named SWODDIES ('Slope Water Oceanic Eddies') by Pingree and Le Cann (1992), detach from the PCCC at certain points along the Cantabrian coast and inject slope water into the southern Bay of Biscay, affecting its kinematics (Pingree, 1994) and biogeochemistry.

The extension and intensity of the seasonal upwelling and downwelling favourable periods varies strongly from year to year (Fig. 23.2a), describing a decadal cycle linked to the NAO. Whereas the onset of the upwelling season can occur within two months, from the beginning of April to the end of May, its cessation falls within a period of just one month, from middle September to middle October. However, this seasonal cycle only explains about 10% of the variability of the wind regime off NW Spain, whereas >70% of the variability arises from periods <30 days (Álvarez–Salgado et al., 2002; 2003). In fact, the upwelling season off NW Spain is described well as a succession of upwelling/relaxation events of period 1–3 wk (Blanton et al., 1987; Silva, 1992; Álvarez–Salgado et al., 1993). It is also remarkable that due to the different orientation of the western and northern coasts (Fig. 23.1), northerly winds produce upwelling off the western coast whereas easterly winds do it off the northern coast. The orientation of the coast changes abruptly north of Cape Finisterre, in such a way that both northerly and easterly winds are upwelling favourable there (McClain et al., 1986; Torres et al., 2003). Similar considerations apply to Cape Sao Vicente and the coast of southern Portugal (Fiúza 1983; Relvas and Barton, 2002).

The coastal upwelling region from Gibraltar to Cape Blanc is maintained by the presence of favourable northeasterly winds throughout the year, although winds and upwelling are more intense during the summer months. Between Cape Blanc and Cape Vert, the upwelling has a marked seasonal periodicity, reaching its peak of intensity during winter. In contrast with the Iberian coast, the NW African coast is largely influenced by the general circulation of the North Atlantic subtropical gyre, particularly by its eastern branch, termed the "Canary Current". The Canary Current flows equatorward while interacting with the coastal upwelling waters. It detaches from the coast near Cape Blanc (21° N), flowing westward at the latitude of Cape Vert (15° N). South of Cape Blanc a large permanent cyclonic recirculation develops as a consequence of the offshore displacement of the Canary Current (Fig. 23.1). Nearshore in winter, a narrow equatorward flow develops over the shelf in response to upwelling forced by the southward migration of the trade wind band (e.g. Hughes and Barton, 1974).

Several studies (e.g. Stramma and Siedler, 1988; Siedler and Onken, 1996) have described the seasonal variability of the Canary Current, confirming the existence of water inflow from the open ocean into the coastal upwelling region north of the Canary Islands. The coupling between the coastal and open ocean waters at the Canary- Coastal Transition Zone (Canary-CTZ) region, has been addressed in

more recent works (Pelegrí et al., 1997; Barton, 1998; Barton et al., 1998; Hernández Guerra et al., 2001; 2002; Pelegrí et al., 2003), in which it is shown how the water recirculates south along the continental slope, where quasi-permanent filaments stretch offshore and exchange water properties with island eddies (Arístegui et al., 1997; Barton et al., 1998).

Flow reversals in the main flow have been observed close to the upwelling-Canary CTZ, during late-fall and winter (Navarro-Pérez and Barton 2001; Hernández Guerra et al. 2002). These flow diversions, probably caused by a weakening of the trade winds south of Cape Guir (Pelegrí et al. 2003), allow the presence of a northward flow from Cape Blanc to Cape Juby, and consequently an offshore spread of organic matter produced in upwelling waters near the Canary Islands region (Arístegui et al. 1997). Pelegrí et al. (2003) suggested that the Canary region is characterised by the presence of two cells transporting upwelled waters into the open ocean. The first one would be the standard vertical cell, present in all upwelling systems, with Ekman offshore transport responding to the wind variations. The second one would be the horizontal circulation cell originated by the impinging of open ocean water north of Cape Guir, which is closed by the offshore export of water through several upwelling filaments and the flow diversion at Cape Guir. The joint action of both cells would cause this upwelling region to be a key region for export of organic matter and nutrients to the open ocean.

2.2.   Water masses and nutrients

The distribution of water masses in the region has been summarized by Barton (1998). Most of the region, from Cape Finisterre to Cape Blanc, is dominated by North Atlantic Central Water (NACW), responsible for the fertility of the coast during upwelling processes, although there is considerable variation in this water mass with latitude. Eastern North Atlantic Central Water (ENACW) of subtropical (13°C–15°C) and subpolar (11°C–13°C) origin (Fiúza, 1984; Ríos et al., 1992; Fiúza et al., 1998) extends from 50–100m (marked by a salinity maximum, >35.9) to 450–750 m depth (marked by a salinity minimum, <35.4), depending on latitude. Subtropical (σ_θ <27.1) ENACW lays above subpolar (σ_θ >27.1) off the western Iberian coast and north of the Canary region, so nutrient–poorer (0–6 µM of nitrate) subtropical waters upwell first, and nutrient–richer (6–10 µM of nitrate) subpolar ENACW enters the shelf only during strong upwelling events. Additionally, a variety of subpolar ENACW, the so–called 'Bay of Biscay Central Water' (BBCW), characterized by 12°C and 6 µM of nitrate, dominates the central waters domain off the Cantabrian coast (Treguer et al., 1979; Fraga et al., 1982; Botas et al., 1989). A subsurface front between subtropical ENACW and BBCW forms in the surrounding of Cape Finisterre (Fraga et al., 1982), although it experiences a seasonal displacement from south of the River Miño in early spring to west of Cape Peñas in late autumn (Fig. 23.1; Castro, 1997). There is also evidence that BBCW can intermittently upwell off the western Iberian coast during the summer (Álvarez–Salgado et al., 1993).

Subtropical ENACW is transported northward year round, by the PCUC during the upwelling season and by the PCCC during the downwelling season. A southward displacement of the origin of the subtropical ENACW which arrives to the Galician coast has been inferred from a progressive increase of salinity and tem-

perature and a decrease of nutrients from the early spring to the winter mixing period (Ríos et al., 1992; Álvarez–Salgado et al., 1993; 2003). On the other hand, subpolar ENACW is conveyed southwards by the oceanic PC and it mixes laterally with the northward flowing PCUC and PCCC being eventually conveyed northwards at the slope (Pérez et al., 2001).

During the spring–summer period, surface (0–100 m) eutrophic coastal waters (affected by intermittent coastal upwelling) and surface oligotrophic surrounding ocean waters are separated by a slope front in the northern Iberian coast (Marañón and Fernández, 1995) but connected throughout upwelling centres and filaments at the wider coastal transition zone (CTZ) of the western coast (Haynes et al., 1993). In contrast, during the autumn–winter period, eutrophic coastal and oceanic waters are separated by the oligotrophic subtropical waters carried by the PCCC, which occupies the CTZ.

The variability (from weekly to interannual) of nutrient levels in the coastal domain has been studied in detail by Nogueira et al. (1997) in the Ría de Vigo (Fig. 23.1), a large (2.5 km^3) coastal embayment that behaves as an extension of the shelf (Figueiras et al., 2002). The seasonal evolution of inorganic nitrogen (Fig. 23.2b–d) allows clear definition of the spring–summer upwelling period, when nitrate levels are the highest in the cold bottom layer, because of intermittent coastal upwelling, and the lowest in the warm surface layer, because of efficient utilisation of upwelled nitrate by coastal phytoplankton populations. At the short–time–scale of an upwelling episode (1–3 wk), the sequence consists of upwelling of nitrate rich ENACW followed by nutrient consumption during the subsequent upwelling relaxation (Pérez et al., 2000a). The autumn–winter downwelling period is characterised by high nitrate levels throughout the water column, being maximum in the surface layer in association with continental runoff and intense regeneration processes. The importance of regeneration during the autumn–winter period is indicated by the succession of ammonium, nitrite and nitrate maxima in the surface layer, separated by ~1 month, which is characteristic of nitrification processes (Wada and Hattori, 1991). The succession of ammonium, nitrite and nitrate maxima also occurs in the bottom layer during the spring–summer period, indicating that regeneration processes are also important in the bottom layer, as will be shown below.

In the Iberian CTZ, during the spring–summer period, surface nutrient levels are detectable only where upwelling centres and filaments develop, being specially intensified in the surroundings of Cape Finisterre, where surface nitrate can reach up to 6 µM (Fraga, 1981; McClain et al., 1986; Castro et al., 1994). On the contrary, during the autumn–winter period, the CTZ is occupied by the PCCC that transports northwards warm (>15°C), salty (>35.8) and nutrient poor (<2 µM nitrate, >0.2 µM nitrite) subtropical waters (Bode et al., 1990; Castro et al., 1997; Álvarez–Salgado et al., 2003). This has important implications for the development of the spring bloom in the CTZ, because reduced nutrient levels transported by the PCCC do not allow massive chlorophyll accumulation as in the coastal and ocean domains.

The nutrient regime in coastal waters of NW Africa is conditioned by the presence of two different water masses. A marked front at 21°N (Cape Blanc) separates the NACW from the slightly cooler, less saline, and richer in nutrients South Atlantic Central Water (SACW). The boundary between these two water masses

is convoluted, variable in position and characterised by intense mixing and inter-leaving processes (Fraga, 1974; Barton and Hughes, 1982; Minas et al., 1982; Barton, 1987; Hagen and Schemainda, 1987). South of Cape Blanc, the SACW is advected northward along the inshore side of the cyclonic recirculation to meet the equatorward flow of the Canary Current. Beyond this front, the northward propagation of SACW depends mainly on the poleward undercurrent, which is associated with the coastal upwelling. Hughes and Barton (1974) and Gardener (1977) traced this poleward flow between 16° and 28°N, and at depths of 200 to 400 m over the continental slope. Since the SACW is richer in nutrients than the NACW, a meridionally decreasing nutrient gradient is apparent in the northward flowing waters (Table 1). Off Mauritania (~18°N), high nutrient concentrations are observed at surface, probably related to the doming in the centre of the cyclonic recirculation. However, according to Minas et al. (1982), this is a region of anomalously low productivity and chlorophyll concentrations in relation to the observed nutrient concentrations.

TABLE 1.
Nutrient concentrations (in μmol kg^{-1}) observed in waters upwelled in the NW Africa and NW Iberia upwelling system.

	T (°C)	NO$_3^-$	PO$_4^{3-}$	SiO$_2$	Reference
NW AFRICA					
CapeTimiris-Nouakchott	14	20	1.5	10	Minas et al .. 1982
Cape Blanc - Cape Corveiro	15.5	14–15.5	0.9–1.0	6.5–7.5	Minas et al., 1982
Cape Sim, Cape Guir (summer)	14.5	8–9	0.6–0.7	4–5	Minas et al., 1982
NW IBERIA					
Galicia (May 91)	11.8±0.3	8±1	0.5±0.1	3.5±0.9	Castro et al., 2000
Galicia (July 84)	11.9–12.8	7±2	0.5±0.1	3.0±0.7	Castro et al., 2000
42°18'N, 8°57'W	12–13	9–12	0.5–0.8	5–10	Álvarez-Salgado et al., 1993

Compared to other eastern boundary regions in which upwelling takes place, the source waters off NW Africa are somewhat poorer in nutrients but richer in oxygen, largely as result of the global scale circulation (Codispoti et al., 1982). This could explain some of the differences in productivity and regeneration rates found, for instance, between the NW Africa and the Peruvian upwelling systems (Minas et al. 1982). However, differences in local topography, together with dissimilar seasonal cycles in the nutrient regimes, a larger interannual variability in Peru, a higher wind stress and turbidity in NW Africa, are all factors that must be considered in understanding the spatial-temporal variability in the productivity regimes of these regions.

Nutrient assimilation and regeneration ratios in the NW African coast are in general high, as in other coastal upwelling regions, although there are significant regional differences, particularly in silicon supply. Minas et al. (1982) have hypothesized that silicon limitation is a function of the geomorphology and dynamics of the coast. In the Moroccan upwelling, silicon, which should in theory be limiting

because it is present in low concentrations in the source waters, is frequently in excess, due to high regeneration processes. In the Mauritanian upwelling, between Cape Timiris and Nouakchott, Herbland and Voituriez (1974) have shown that silicon is the first nutrient to be exhausted. Apparently, regeneration on this narrow shelf cannot compensate for the high demand. This region differs from more northern zones with wider shelves, such as Capes Dra and Corveiro, where regeneration compensates for the silicon deficiencies of the upwelling source waters. Indeed, Friederich and Codispoti (1982) made a detailed study of dissolved silicon regeneration over the shelf off Cape Corveiro, and observed that silicon regeneration in upwelling waters exceeded the inorganic nitrogen regeneration rate in spite of low (<1) Si/NO_3 ratios in the source water. This finding agrees with similar results obtained from the NW Iberian upwelling (Álvarez-Salgado et al. 1997)

High ammonia concentrations and high regenerations rates are frequently found in the inner shelf of the African coast (Codispoti and Friederich 1978; Minas et al 1982; Head et al. 1996). As a result of high wind stress, which produces mixing in the whole water column, ammonia is homogeneously distributed in the turbid inshore waters. This distribution contrasts with other coastal upwelling systems, which are less affected by strong wind regimes and present more stratified water columns. The turbidity, which may result also from aeolian dust deposition blown into the sea from the Sahara desert, produces a poor light regime for phytoplankton, which may inhibit ammonia uptake, in spite of high concentrations (Huntsman and Barber, 1977; Codispoti et al., 1982). Head et al. (1996), however, did not find any correlation between integrated primary production rates and light intensity in the inshore waters off the coast of Morocco, despite a two-fold variation in the latter.

2.3.   Primary production

The seasonal and event–scale variability of coastal winds and upwelling in the Iberian and NW African coasts determines 1) the limiting nutrient flux to the photic layer; 2) the efficiency of utilisation of the limiting nutrient; 3) the fraction of the primary production required to maintain the metabolism of the pelagic ecosystem; and 4) the fate of the excess 'new' production: net transference to higher trophic levels, off–shelf export or deposition on shelf sediments, with subsequent benthic mineralization processes, reinjection of nutrients into the water column and eventual promotion to the photic layer.

The effect of spring–summer upwelling and autumn–winter downwelling periods in the productivity of the Iberian margin is illustrated by the 1987–1996 seasonal cycle of chlorophyll–*a* (Chl–*a*) in the Ría de Vigo (Fig. 23.2e; Nogueira et al., 1997). Apart from the spring and autumn Chl–*a* maxima, characteristic of any temperate ecosystem, Chl–*a* levels remain relatively high throughout the summer because of nutrient fertilisation by coastal upwelling. In addition, the spring and autumn Chl–*a* maxima occur within the transitional periods of onset and cessation of the upwelling season (Fig. 23.2a), respectively, determining the fate of the accumulated Chl–*a:* off–shelf export *versus in situ* mineralization (Álvarez–Salgado et al., 2003).

Although dramatic changes occur over space and time scales of a few kilometres and days, a seasonal pattern of gross primary production (P) rates in the Iberian

margin can be drawn from field observations (Bode et al., 1994; 1996; Tenore et al., 1995; Bode and Varela, 1998; Teira et al., 2001; Joint et al., 2002; Álvarez–Salgado et al., 2003, Tilstone et al., 2003). The highest, but very variable, P rates are recorded during the spring and summer (1.0–8.0 g C m^{-2} d^{-1}) and the lowest in winter (~0.2 g C m^{-2} d^{-1}), as expected in any temperate coastal upwelling system. However, the succession of 1–3 wk coastal wind stress/relaxation cycles produces a remarkable short–time–scale variability in P rates during the seven months of the upwelling season (Fig. 23.3). The expected decrease of P rates from the inner shelf to the open ocean is also observed in the Iberian margin yearound (Tenore et al., 1995; Joint et al., 2002; Álvarez–Salgado et al., 2003; Tilstone et al., 2003), except when the PCCC occupies the CTZ between the spring bloom and the onset of the upwelling season (April–May), when P rates can be higher in the PCCC than in coastal waters (Álvarez–Salgado et al., 2003; Tilstone et al., 2003). These authors argue that this is because downwelling on the coast, generated by the PCCC, forces the sinking of coastal phytoplankton, mainly diatoms, into the aphotic layer.
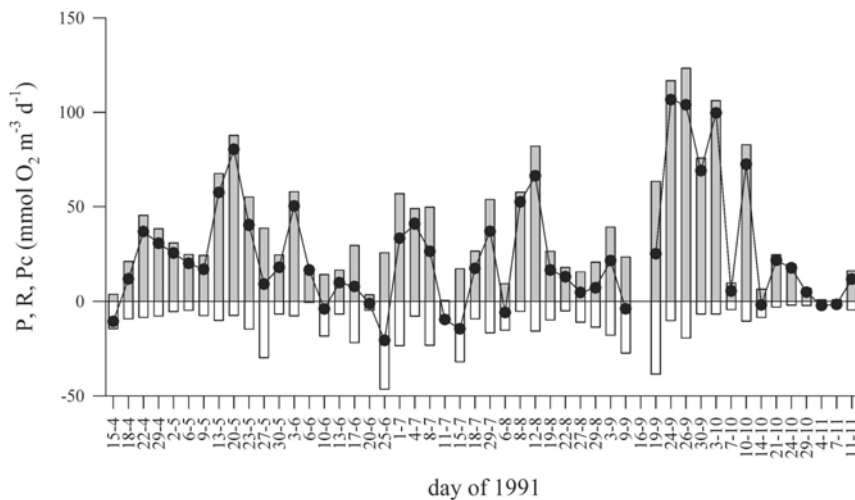

Figure 23.3 Short–time scale (3–4 days) evolution of community respiration (*R,* white bars), gross primary production (*P,* black bars) and net community production (*Pc,* black circles), in surface waters of the coastal upwelling ecosystem of the Ría de Vigo, from April to November 1991 (all rates in mmol O$_2$ m^{-3} d^{-1}).

Recently, the seasonal cycle of primary production in the Iberian margin (from 42° to 44°N) has been addressed by Joint et al. (2002), who produced monthly averages of net production (Pn), derived from satellite chlorophyll and 24 hours *in situ* [14]C incubations. They concluded that the average Pn for shelf waters during the 1998–2000 upwelling season was 1.5 g C m^{-2} d^{-1}. This value coincides with average net community production (Pc), estimated from 24 h in vitro oxygen experiments, over the upwelling season for the area of the Rías Baixas (Moncoiffé et al., 2000). Since the mean ratio of oxygen net community production/ gross production (Pc/P)

for the upwelling season is ~0.6 (Moncoiffé et al., 2000), P in the Iberian margin should be ~2.5 g C m^{-2} d^{-1} for the upwelling season. Assuming a P of 2.5 g C m^{-2} d^{-1} during 225 days of upwelling period and a P of 0.2 g C m^{-2} d^{-1} during 140 days of downwelling period (see above, and Fig. 23.2) the average annual P value in the Iberian upwelling system would be 590 g C m^{-2} y^{-1}.

Average microbial respiration in the photic layer represents ~40% of P (Fig. 23.4), although it ranges from <10% in spring and during summer upwelling events to >100% (net heterotrophy) during upwelling relaxation periods (Serret et al., 1999; Moncoiffé et al., 2000; Teira et al., 2001; Barbosa et al., 2001). The coupling between small phytoplankton (<20μm) and microzooplankton activities causes these relatively high microbial respiration rates. Small phytoplankton (<20 μm) usually accounts for >50% of P (Bode et al., 1994, Tilstone et al., 1999; 2003; Joint et al., 2001a) and microzooplankton, which can reach a biomass equivalent to 60% of phytoplankton biomass during upwelling relaxation on the shelf, is able to graze 40–80% of the chlorophyll standing stocks and ~60% of the daily P (Fileman and Burkill, 2001; Tilstone et al., 2003). Dominance of large phytoplankton (>20 μm), particularly diatoms, is restricted to the spring bloom and during strong upwelling events at the inner shelf (Varela et al., 1991; Bode et al., 1994; Abrantes and Moita, 1999; Tilstone et al., 1999, Cachâo and Moita, 2000). Upwelling relaxation and downwelling favours diatom sinking at these sites (Figueiras et al., 1994, Fermín et al., 1996, Castro et al., 1997; Tilstone et al., 2000), contributing to enhanced nutrient mineralization in bottom shelf waters (Álvarez–Salgado et al., 1993; 1997; Prego and Bao, 1997). It has been argued that microzooplankton herbivory is an important source of dissolved organic matter (DOM) in the sea (Strom et al., 1997; Nagata, 2000), and the correlation found between a hetrotrophic/autotrophic microplankton assemblage and the concentration of DOM in the Iberian margin supports this view (Joint et al., 2001b). The possible role of microzooplankton grazing in DOM production is further reinforced by the fact that bacteria do not remove all DOM produced during an upwelling–relaxation cycle (Barbosa et al., 2001), while DOM released by phytoplankton, which is a small fraction (~6%) of P (Teira et al., 2001; Morán et al., 2002a), is not enough to satisfy the bacterial demand of labile carbon (Morán et al., 2002a; 2002b). Zooplankton grazing impact on phytoplankton seems to be rather moderate, ~5% of phytoplankton stock and ~10% of P (Barquero et al., 1998; Halvorsen et al., 2001), even though previous studies in the Rías Baixas indicated that zooplankton could consume the entire daily phytoplankton production (Hanson et al., 1986). Results of model simulations (Slagstad and Wassmann, 2001) also produce P values >2 g C m^{-2} d^{-1} under upwelling conditions and emphasise the predominant role played by small flagellates in P and by microzooplankton in grazing.
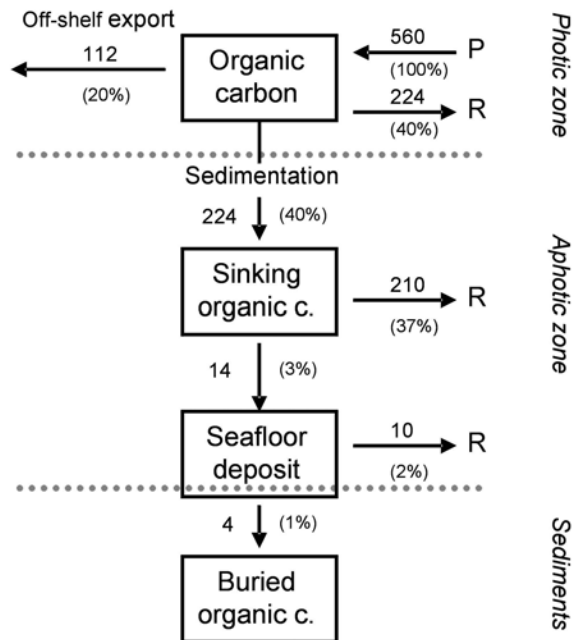
Figure 23.4 Tentative organic carbon budget of the NW Iberian margin, from 42° to 44°N, during the upwelling season. All fluxes are expressed in gC m^{-2} and are referred to an average P of 560 gC m^{-2} over the upwelling season. This value results from multiplying 2.5 gC m^{-2} d^{-1} (the average daily P) times 225 days (average duration of the upwelling season).

New production (New P) has been also estimated in shelf waters between 42° and 44°N combining upwelling rates, bottom shelf temperatures and ENACW nutrient–temperature relationships (Álvarez–Salgado et al., 2002). Shelf New P, fuelled exclusively by upwelled ENACW, was relatively low (0.5 ± 0.15 g C m^{-2} d^{-1} for the 1982–1999 period) and, consequently, it represents ~20% of P. These low New P rates compared with other coastal upwelling systems are attributable to reduced continental inputs during the upwelling season, low nutrient levels in upwelled ENACW, and low average coastal winds because of the 1–3 wk wind stress–relaxation cycles. Therefore, although P rates, ~2.5 g C m^{-2} d^{-1}, are among the expected values for an upwelling system (e.g. Barber and Smith, 1981; Brown and Field, 1986; Minas et al., 1986; Pilskan et al., 1996) the average *f*–ratio (=New P/P) of ~0.2 over the upwelling season seems to be very low.

The succession of periodic 1–3 wk wind stress–relaxation cycles throughout the upwelling season is the reason behind both the high productivity and the low *f*–ratio of the Iberian margin. A well-described spatial sequence in coastal upwelling systems is initiated with upwelling of nutrient–rich subsurface waters near coast and continues with progressive nutrient consumption during seaward displacement of the upwelled water parcel (e.g. MacIsaac et al., 1985; Dugdale and Wilkerson, 1989). In the Iberian upwelling, this 'spatial sequence' is also a periodic 'time se-quence' (Pérez et al., 2000a), which determines that the Iberian margin periodi-

cally switches from net autotrophy to net heterotrophy (high microbial respiration) producing a low average f–ratio.

Compared to the Iberian region, recent studies on primary production in the NW African region are scarce, and annual integrated rates have to be estimated from local studies on individual cruises. Compiled P values in the NW Africa upwelling region (Table 2) yields an average annual estimate of 2.4 g C m^{-2} d^{-1}, which coincides with P estimates from the NW African coast, computed from satellite chlrorophyll and averaged photosynthetic parameters (Longhurst et al., 1995; Morel et al., 1996). On a yearly basis, this estimate (874 g C m^{-2} y^{-1}) is about 50% higher than the average annual P value in the Iberian upwelling system (590 g C m^{-2} y^{-1}). Although the NW Africa estimate may be biased in time (since many of the studies correspond to the spring and summer periods), the difference in magnitudes is mainly caused by the strong seasonality in the Iberian upwelling, compared to the more continuous upwelling off NW Africa. Indeed, the average P values for the upwelling season in the Iberian margin (spring-summer) coincide with the annual average values from NW Africa.

TABLE 2.
Compiled daily primary production values in coastal waters from the Northwest Africa upwelling system (a), and average annual primary production for the Iberia and NW Africa coastal upwelling regions (b).

(a)Region	Latitude (N)	Season	Daily Primary Production g C m^{-2} d^{-1}			Reference
			Average	Min.	Max.	
C.Sim-C.Ghir	31.5–30.5	Summer	2.4	0	4.2	Minas et al., 1982
C.Sim-C.Ghir	31.5–30.5	Winter	1.3	0.2	2.5	Minas et al., 1982
C.Sim-C.Ghir	31.5–30.5	Summer	1.3	0.6	2.8	Grall et al., 1982
C.Sim-C.Ghir	31.5–30.5	Autumn	1.5	1	2.5	Head et al., 1996
C.Jubi-C.Bojador	28.5–26.5	Summer	3.1	1.3	5.3	Basterretxea and Arístegui, 2000
C.Juby-C.Bojador	28.5–26.5	Summer	2.4			Minas et al., 1982
C.Corveiro-C.Blanc	22.0–21.0	Spring	2.4	0.8	5.0	Huntsman and Barber, 1977
C.Corveiro-C.Blanc	22.0–21.0	Spring		1.1	3.4	Lloyd, 1971
C. Blanc	21.0	Spring	1.15	0.3	2.6	Schulz, 1982
C. Blanc	21.0	Spring	0.96	0.2	1.8	Schulz, 1982
C. Blanc	21.0	Summer	1.62	0.4	3.6	Schulz, 1982
C.Timiris-Nouakchott	19.5–18.0	Spring	3.9	1.6	4.3	Minas et al., 1982
NW Africa upwelling	31.5–18		2.4 ± 1.5			

(b)Region	Latitude (N)	Annual Prim. Production g C m^{-2} y^{-1}	Data	Reference
Iberia upwelling	43.0–41.0	590	In situ	This work
NW Africa upwelling	31.5–18.0	874	In situ	Several authors
Iberia and NW Africa	43.0–15.0	732	Satellite based	Longhurst et al., 1995

Regional variability in P in the NW Africa region probably results from differences in nutrient regimes, although the lack of detailed studies in the region preclude identification of clear spatial-temporal patterns as in other eastern-boundary

uwelling regions. The highest annual P rates are presumably produced between Cape Barbas and Cape Blanc, where the more nutrient-rich SACW is available as source water, and upwelling is produced year round (Minas et al., 1982). Yet, local topographic and environmental factors may be responsible of short-term changes in the nutrient regime and primary production. Codispoti (1981) concluded from a study comparing different coastal upwelling regions, that, in contrast with other upwelling regions, much of the nutrient variability off NW Africa occurs on the scale of several days. In agreement with this, Grall et al. (1992) described large spatial variations in P (from 0.8 to 2.8 g C m^{-2} d^{-1}) off Morocco, between Cape Sim and Cape Guir, which were correlated to short (~3 days) but intense wind pulses. He also observed that the centre of the upwelled water migrated from the inner shelf to the shelf break as the upwelling progressed, probably reflecting the off-shore intensification of the Cape Guir filament. In a more recent study, Arístegui and Harrison (2002) observed also a similar large daily variability in P (1.1 to 2.8 g C m^{-2} d^{-1}) and chlorophyll a (25–94 mg m^{-2}), following a drifting buoy along the Cape Guir filament, during 7 days of consecutive measurements.

2.4.   Shelf-ocean exchange of organic matter

The excess production of any coastal upwelling system can be 1) transferred to higher trophic levels (section 4); 2) transported downwards to the coastal sediments, where it can experience mineralization in the dark water column and sediments or be buried (section 2.6); and 3) exported to the adjacent open ocean.

The shelf–ocean exchange of organic matter is enhanced during the productive upwelling season, especially at sites where large filaments develop. Several recurrent filaments are distributed all along the Iberian coast (Sousa and Bricaud, 1992; Haynes et al., 1993; Pelíz and Fiúza, 1999), although only the filament off the Rías Baixas has been studied from a biogeochemical point of view (Joint and Wassmann, 2001). One of the most relevant conclusions of that process–orientated study is that fresh dissolved and particulate organic materials are exported in equal amounts to the ocean by the upwelling filament (Álvarez–Salgado et al., 2001). Total organic carbon export by the filament off the Rías Baixas was estimated to be ~100 g C m^{-2} during the upwelling season, a number that is very close to the New P estimate of 0.5±15 g C m^{-2} d^{-1} (=110±30 g C m^{-2}) by Álvarez–Salgado et al. (2002), suggesting that, at the time scale of the upwelling season, a significant fraction of the New P is exported to the adjacent ocean (Fig. 23.4). On the contrary, during the unproductive downwelling season (winter), the PCCC acts as an insulator between shelf and ocean waters, confining coastal primary production on the shelf and enhancing sedimentation and *in situ* mineralization (Castro et al., 1997; Álvarez–Salgado et al., 2003). Recent estimates of particle residence times (average: from 26 days in the early summer upwelling season to 113 days in winter) in surface waters of the NW Iberian margin support this view (Schmidt et al., 2002a).

Transitional periods, from the upwelling to the downwelling season, are especially important for the fate of coastal P because they occur at the time of the spring and autumn phytoplankton blooms (Fig. 23.2a,e). In this manner, a coastal bloom under upwelling conditions might be exported to the adjacent ocean, while

a bloom under downwelling conditions would sediment on the shelf, being eventually processed by the benthic communities (Álvarez–Salgado et al., 2003).

Since ~40% of P is recycled in the photic layer by the microbial component and ~20% is exported (Fig. 23.4), the remaining 40% of P would be respired in the aphotic layer and the sediments. Estimates of vertical fluxes of organic matter from the photic layer (Fernández et al., 1995; Bode et al., 1998; Hall et al., 2000) provide values between 19 and 50% of P, although extremely low values of 4–9% may occur during strong upwelling events and prolonged relaxation periods (Bode et al., 1998; Olli et al., 2001). Strong upwelling precludes the development of phytoplankton on the shelf because off–shelf export of upwelled water is enhanced. Prolonged relaxation favours small phytoplankton (Joint et al., 2001a, Tilstone et al., 2003), microbial recycling (Fileman and Burkill, 2001) and high retention of particulate material in the upper 200m (Riser et al., 2001) at the expense of export and sinking (Olli et al., 2001).

Off NW Africa, numerous upwelling filaments are distributed along the coastal-offshore upwelling boundary (Fig. 23.5). These filaments may arise for one or a combination of several factors: baroclinic instability of the coastal current, irregularities in coastline and bottom topography, coastal convergence caused by wind stress, and the interaction of the coastal region with offshore eddies (Brink and Cowles, 1991; Strub et al., 1991; Barton, 1998). The latter process is very common south of the Canary Archipelago, where island eddies are sequentially spun off downstream the islands. However, only two of the filaments (the Cape Guir and Cape Blanc filaments) remain as major permanent features, even during non-favourable upwelling winds, and thus represent key sites for the export of organic matter to the open ocean waters of the subtropical gyre.
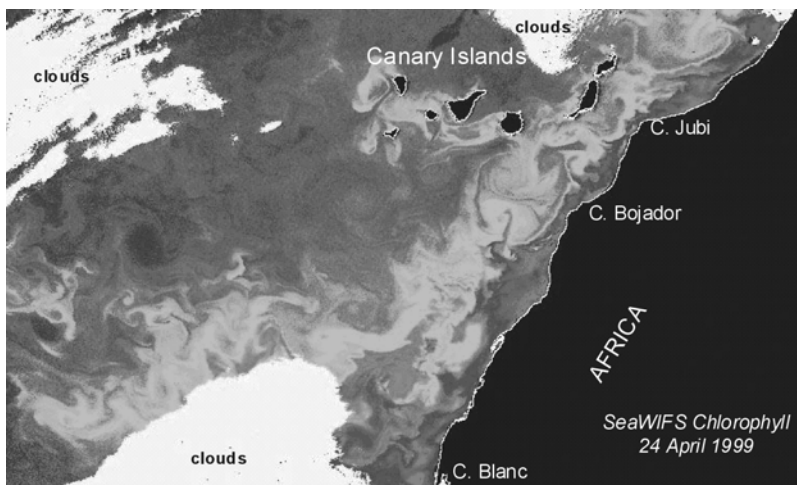

Figure 23.5 F SeaWIFS chlorophyll image from the Canary Islands region (24 April, 1999), showing the presence of numerous cyclonic and anticyclonic eddies downstream the islands. The eddy field extends southward down to the latitude of Cape Blanc, where the Canary Current detaches from the coast and flows westward. As a reference, green colour represents chlorophyll values >1 mg m^{-3} and red colour corresponds to values >3 mg m^{-3}

The Cape Guir filament has been documented in several studies (Mittlestaedt, 1991; Hernández Guerra and Nykjaer, 1997; Pelegrí et al., 2003) as a recurrent feature, which may extend several hundred kms offshore (Fig. 23.5), transporting particulate organic carbon (POC). The impact of POC export by the Cape Guir filament has been observed as far as 700 km from the filament origin, well into the subtropical gyre province, by means of deep-water sediment traps deployed northwest of La Palma, the easternmost island of the Canaries (Neuer et al., 2002). The filament presumably represents also a significant oceanic route for the transport of excess dissolved organic and inorganic nutrients produced in the coastal upwelling waters. García-Muñoz et al. (2003) calculated a net offshore export of nitrate of 2.6 kmol s^{-1} by this filament, during non-favourable upwelling conditions. This value is much larger than the offshore Ekman transport (0.4 kmol s^{-1} of nitrate) that would take place in an upwelling system along a shore distance of 10 km, equivalent to the filament width. However, although the offshore transport of filaments is usually significantly larger than Ekman transport (e.g. Kostianoy and Zatsepin, 1996) the return flow of filament water into the coastal upwelling jet may reduce the impact of the overall offshore transport. This was observed in an upwelling filament stretching between Cape Juby and Cape Bojador during August 1993 (Navarro Pérez and Barton, 1998). The filament extended approximately 150 km offshore, wrapping around a cyclonic eddy of 100 km diameter, before returning shoreward. Most of the particulate organic matter exported by this filament was returned by the recirculation path of the filament (Basterretxea and Arístegui, 2000).

Off Mauritania, the giant Cape Blanc filament appears as a persistent low-temperature and high-chlorophyll feature, extending several hundred kms offshore. The filament is linked to the convergence of NACW and SACW at the Cape Vert frontal zone. At this site, the large-scale circulation pattern induces the upwelling centre to shift towards the shelf break area, allowing phytoplankton to achieve maximal growth rates in oceanic waters. According to Gabric et al. (1993) this filament exports more than 50% of New P to oceanic waters. Deep-water sediment traps deployed during the EUMELI project at a mesotrophic station located >500 km off Cape Blanc (Bory et al. 2001) recorded biogenic fluxes higher than other stations in the Atlantic Ocean (Jickells et al., 1996; Wefer and Fischer, 1993). The temporal variability of these fluxes seemed to be linked to westward surface currents, which are likely to transport seaward carbon-rich waters from the coastal upwelling. Nevertheless, a large interannual variability is appreciable in the downward particle flux, presumably caused by climatic changes (Bory et al., 2001). Similar interannual variability was appreciated in particle fluxes recorded off Cape Guir (Neuer et al., 2002).

2.5.   *The coastal upwelling as a source–sink of CO_2*

The behaviour of coastal upwelling systems as sources or sinks of CO_2 to the atmosphere depends on the balance of two opposing tendencies. On one side, the higher the nutrient concentration of the source water, the higher is its partial CO_2 pressure (pCO_2). On the other, the higher the P rates (enhanced by the nutrient input), the higher must be the reduction of pCO_2 in the surface layer (e.g. Watson, 1995; Borges and Frankignoulle, 2002a).

With these simple considerations in mind, the water masses and the dynamics of the Iberian margin would favour its behaviour as a CO_2 sink. First, nutrients and, consequently, pCO_2 levels of upwelled ENACW are relatively low (400–500 µatm) compared with the aged central waters of the South Atlantic, the Indian and the Pacific Ocean. Second, the intermittency of coastal upwelling in the Iberian margin allows efficient utilisation of upwelled nutrients, leading to P rates comparable with other coastal upwelling systems, where the nutrient loads of upwelled waters are much higher.

Surface pCO_2 measurements in the western Iberian margin (Pérez et al., 1999; Borges and Frankignoulle, 2001; 2002a,b) confirm this general view. Despite seasonal upwelling, surface pCO_2 undersaturation occurs throughout the spring and summer, except at the Cape Finisterre upwelling centre throughout the upwelling season (Borges and Frankignoulle, 2002b) and along the northern Portuguese coast during strong upwelling events (Pérez et al., 1999). Shelf waters off the Rías Baixas are usually undersaturated because of the combination of outwelling of pCO_2 equilibrated/undersaturated waters from the rías and the considerable width of the continental shelf compared with the Cape Finisterre area (Borges and Frankignoulle, 2002a). It should be highlighted that the 'outwelled' water from the rías is just upwelled ENACW that experiences pCO_2 reduction during seaward displacement from the inner to the outer part of these embayment. However, Álvarez et al. (1999) followed the variability of surface pCO_2 levels along a transect from the central Ría de Vigo to the middle shelf, from May 1994 to September 1995, observing pCO_2 supersaturation in the inner shelf and the ría under strong upwelling conditions. Moreover, bottom regeneration associated with the intensive culture of mussels on hanging ropes in the Ría de Arousa, which increases the pCO_2 of upwelled ENACW, together with enhanced flushing rates in the rias, do not allow P to reduce pCO_2 below the atmospheric level during the upwelling season of 1989 (Rosón et al., 1999).

During the autumn and winter period, pCO_2 undersaturation is associated with low salinity continental waters, which allow a sequence of stratification, Chl–a accumulation and pCO_2 decrease. On the contrary, pCO_2 supersaturation occurs anywhere continental runoff is reduced, because the aged shelf bottom waters enter in contact with the atmosphere as a result of irradiative loss and strong vertical mixing (Fiúza et al., 1998; Vitorino et al., 2002a). Equilibrium with the atmosphere or slight undersaturation is usually found in the high salinity subtropical waters occupying the CTZ and the surrounding ocean year-round (Pérez et al., 1999; Borges and Frankignoulle, 2002a).

Borges and Frankignoulle (2002b) computed air–sea exchange fluxes of CO_2 on the western Iberian shelf from 42° to 44°N yielding a net influx in the range of –2.3 to –4.7 mmol C m^{-2} d^{-1} during the upwelling season and of –3.5 to –7.0 mmol C m^{-2} d^{-1} on an annual basis, using different formulations of the CO_2 exchange coefficient. A similar calculation made by Álvarez et al. (1999) off the Ría de Vigo, using the lower flux estimate, yielded a net influx from about –0.1 mmol C m^{-2} d^{-1} in the middle ría to –2.0 mmol C m^{-2} d^{-1} in the middle shelf during the upwelling season. CO_2 uptake is maximum at the time of the spring and autumn blooms, when influxes up to –4.3 mmol C m^{-2} d^{-1} were recorded in the middle shelf. On the contrary, the area acted as a CO_2 source during the winter, with maximum fluxes of 2.3 mmol C m^{-2} d^{-1} again in the middle shelf. In a more recent study, Gago et al. (2003)

found that the inner Ría de Vigo is usually a CO_2 source to the atmosphere, except in December.

Recent studies in the NW Africa upwelling near the Canary Islands region, have identified the coastal upwelling as a weak CO_2 source, with average carbon fluxes of 0.5 mmol m^{-2} d^{-1} (Santana-Casiano et al., 2001; Pelegrí et al., 2003). Yet, most of these studies were performed during autumn and winter, when winds are low to moderate and upwelling is weaker than the rest of the year. It is therefore plausible that during strong upwelling events and higher productivity, the system behaves as a carbon sink, as off the north Iberian coast.

Upwelling filaments can support an important export of excess inorganic carbon in the upwelling region to the open ocean, providing carbon uptake by phytoplankton is not large enough to decrease significantly the pCO$_2$ along the filament extension. Pelegrí et al. (2003) observed a net surface flux of CO_2 from the coast to the open ocean through the Cape Guir filament, during October 1999. The calculated biological consumption of CO_2 along the filament was low enough to allow supersaturation of CO_2 in the warmer open ocean waters, increasing the net flux of CO_2 to the atmosphere.

2.6. Benthic production and sediment processes

The fate of phytogenic organic materials exported from shelf surface waters to the sea floor depends on the supply of organic matter, the preservation conditions, the dilution with terrigenous sediments and the near bed hydrodynamics (van Weering et al., 2002). In this sense, the role of the Galician Rías Baixas in the north Iberian margin (42–43°N), is significant, because they trap the terrestrial input from their 6800 km^2 drainage basin (Araújo et al., 2002; Dias et al., 2002a) and export endogenous detritus to the adjacent shelf (Prego, 1994; Rosón et al., 1999; Pérez et al., 2000a). In the northern Portuguese coast, the river Douro (Fig. 23.1), with the largest drainage basin of the Iberian Peninsula, constitutes the main sediment source for both the coarse material deposited close to the coast and the active mud belts of fine–grained materials in the middle shelf off northern Portugal, especially during winter high floods (Drago et al. 1998). Further south, several submarine canyons, and particularly the Nazaré canyon, which intersects the entire continental shelf (Fig. 23.1), are sites where export of shelf sediments to the Iberian Abyssal Plain is likely enhanced (van Weering et al., 2002). Regarding the near bed hydrodynamics, the predominantly along–shore flow of the 'Portugal Current System' at the western Iberian margin, favours summer offshore export in the surface layer, with onshore compensation below, and a winter onshore component through the water column with some offshore export being confined to the bottom layer (Drago et al., 1998; Vitorino et al., 2002a). Consequently, resuspension and transport of shelf fine sediments in bottom nepheloid layers (BNLs), occur mainly in the alongshore direction (Dias et al., 2002a; Oliveira et al., 2002). Any export to the adjacent ocean is confined to the shelf edge during the summer but it is enhanced during the winter, when resuspension is maximum (Vitorino et al., 2002b). Well–developed BNLs are observed at the shelf break during winter storms, likely making a significant contribution to the off–shelf export (McCave and Hall, 2002) when detach from the slope in the form of intermediate nepheloid layers (Oliveira et al., 2002). In the case of the middle–shelf Douro mud patch, fine sediments are

resuspended and transported northwards during the winter to meet the outer shelf mud patch off the Rías Baixas, because the plateau west of the Douro acts as a barrier to off–shelf export (Dias et al., 2002b; Jouanneau et al., 2002).

Intense biogeochemical processes occur at the sediment–water interface of the 42°–43°N region during the upwelling season, as a consequence of the enhanced productivity of the Rías Baixas (Tilstone et al., 1999; Moncoiffé et al., 2000; Pérez et al., 2000a), the outwelling of detritus, and the onshore compensating flow in bottom shelf waters, which favours particle retention. Upwelled ENACW experiences a remarkable nutrient enrichment, which is maximum for water parcels in direct contact with shelf sediments (Fraga, 1981; Álvarez–Salgado et al., 1993; Prego et al., 1999). The agreement between the spatial distributions of organic carbon and silica debris in sediments and the corresponding nutrient salts in the overlying water (López–Jamar et al., 1992; Prego and Bao, 1997) confirm the benthic origin of this enrichment. It has been observed that nutrient enrichment increases progressively throughout the upwelling season (Álvarez–Salgado et al., 1993) and from the outer to the inner shelf (Álvarez–Salgado et al., 1997), being maximum inside the Rías Baixas (Prego et al., 1999). This nutrient enrichment increases P rates by 'secondary recycling' and dampens the temporal and spatial variability in nutrient conditions seen when driven exclusively by upwelling.

Schmidt et al. (2002b) observed that whereas the Iberian margin between 43° and 44°N is not an efficient depocenter, rapid sedimentation appears to be more important on the shelf and slope of the 41°–43°N area at a time scale of 100 days. In this sense, van Weering et al. (2002) obtained organic carbon burial rates of 1.0–34.3 g C m^{-2} y^{-1} for the shelf and 0.01–0.69 g C m^{-2} y^{-1} for the slope off the Rías Baixas. In contrast, carbon burial rates up to 182 g C m^{-2} y^{-1} were observed at the Nazaré canyon, mainly on the upper and middle canyon, from where it is episodically released to the deep sea (van Weering et al., 2002).

Estimates of organic carbon deposition rates at the sediment–water interface (~14 g C m^{-2} y^{-1}; Epping et al., 2002) are low compared with the relatively high P rates (~560 g C m^{-2} y^{-1}; Fig. 23.4) of the NW Iberian shelf during the upwelling season. Since ~40% of P is deposited on the shelf and the near bed hydrodynamics favours particle retention -organic carbon deposition on the deep ocean is only ~20% of that on the shelf (Epping et al., 2002)- most of the organic carbon delivered to the sea floor (~87%) has to be mineralised at the sediment–water interface to produce the observed nutrient enrichment in bottom shelf waters. Finally, ~30% of organic carbon deposited in the sediments is buried and ~70% experiences mainly aerobic oxidation, although denitrification is important (up to 50%) on the inner shelf (Epping et al., 2002), in the rías (Dale and Prego, 2002) and in the canyons (Epping et al,. 2002), where higher sedimentation rates occur. Considering that these deposition rates are representative of the upwelling season and assuming that continental inputs (Álvarez–Salgado et al., 2002) and off–shelf export of sediments is negligible, the tentative carbon balance for the NW Iberian shelf off the Rías Baixas presented in Figure 23.4 can be completed. This situation contrasts with the preponderant role previously assigned to continental shelves as organic carbon sinks but agrees with the most recent assessments which point out shelves primarily as mineralization sites (de Haas et al., 2002).

Along the NW African coast, the high wind stress and strong equatorward and cross-shelf currents may prevent accumulation of organic matter in sediments,

where aerobic respiration dominates. In fact, concentrations of particulate organic matter in the nearshore are in the lower range of coastal upwelling regions, with a predominance of particles <50 μm (Lenz, 1982). Nevertheless, there is a trend towards increasing accumulation rates of organic material from north to south, which partly reflects a southward increase of productivity, but also an input of clay minerals by the Senegal River and better preservation of organic matter from plankton or land plants in these fine grained sediments (Seibold, 1982).

Relexans et al (1996) studied the biological and chemical characteristics of sediments sampled at three different sites along a trophic gradient from the eutrophic waters of the Mauritanian upwelling to the oligotrophic open ocean waters of the subtropical gyre. As expected, they observed a general decrease, from eutrophic to oligotrophic waters in POC, macromolecular contents, biomass and metabolic activities in microbenthos, reflecting the fertility of the water column above the sediments. However, while POC fluxes at the sediment water interface ranged from 1 g C $m^{-2}y^{-1}$ (oligotrophic) to >20 g C $m^{-2}y^{-1}$ (eutrophic), carbon mineralization rates varied only 3 fold: from 1.7 gC $m^{-2}y^{-1}$ in the oligotrophic station, to an average 5 g C m^{-2} y^{-1} in the eutrohic region. These results led Relexans and coworkers (1996) to suggest a more efficient utilization of the vertical carbon supply in deep oceanic waters than in the shallower shelf of the upwelling system. Yet, organic carbon flux rates near the shelf bottom may be higher than fluxes computed from surface productivity and empirical relationships of decrease of POC with depth, indicating that a large fraction of the nearshore material is resuspended (Bory et al., 2001; Neuer et al., 2002). This material may be lost out from the system by cross-shelf advective transport. Particularly, high offshore carbon export rates have been observed in the region associated with the Cape Blanc filament (e.g. Gabric et al., 1993).

The sediments off Cape Guir represent an important depocenter site (Henderiks et al., 2002). Nevertheless sedimentation rates in the Moroccan coast may actually be low compared with the offshore transport. Head et al., (1996) carried out a carbon flux study in this region, following drifting arrays deployed in the core of the filament during 7 days. These authors estimated from in situ P measurements and shallow sediment traps, that the *f*-ratio (export flux/total P; Eppley and Peterson 1979) ranged from 0.16 to 0.24. These ratios are significantly lower than those seen in other coastal regions during periods of active upwelling (Codispoti et al., 1982; Dugdale et al., 1990), indicating that remineralization rates are very high in the upper water column, or the offshore export is higher than in other regions, or both. The high offshore export hypothesis is strongly supported by recent studies, which ascribe a key role in the off-shelf transport of organic matter to the Cape Guir filament (Neuer et al., 2002: García Muñoz et al., 2003; Pelegrí et al., 2003). The distribution of surface-sediment analysis underlying the Cape Guir filament mirrors the surface gradients in temperature and chlorophyll observed from satellite images. Total organic carbon, benthic foraminifera and *Globigerina* shells decrease from coastal sediments to open ocean sediments (Meggers et al., 2002). Moreover, the occurrence of coccolithophorids (Sprengel et al., 2002), diatom and foraminifera species (Abrantes et al., 2002), characteristic of high productivity coastal areas, in deep sediment traps deployed several hundred of kms offshore, reflects the export capacity of the Cape Guir filament.

3.   The Canary Islands Coastal Transition Zone

South of Cape Guir, the Canaries archipelago (28°N) spans the transition zone between the NW Africa coastal upwelling waters and the open ocean waters of the subtropical gyre. The sharpest changes in primary production (Basterretxea and Arístegui, 2000; Fig. 23.6), as well as in the distributions of particulate and dissolved organic carbon (Arístegui et al. 2003), are found in the eastern sector of the region, close to the upwelling region. The zonal gradient extends however for the width of the Archipelago's area of influence (>300 km) because of the recurrence of mesoscale eddies and fronts, induced by island disturbance of wind and currents (Barton et al. , 1998). Eddies are spun off in the form of vortex streets, extending southward to about 22° N, where the Canary Current detaches from the coast and flows westwards. While drifting southward, eddies may interact with the coastal upwelling waters and act as a route to export organic matter to the oligotrophic open ocean (Fig. 23.5).
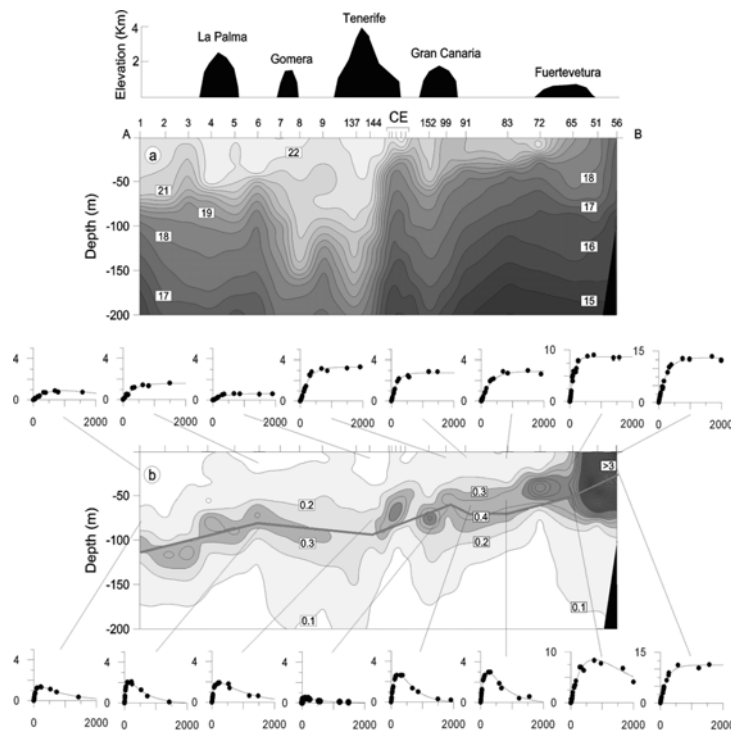

Figure 23.6   Contour plots of temperature (°C; middle panel, a) and chlorophyll (mg m^{-3}; lower panel, b) along a transect extending from the African coast to the open ocean subtropical gyre, south of the Canary Islands (upper panel). Dashed lines indicate the location and depth of photosynthesis (P; mgC mg^{-1} chla h^{-1}) - irradiance (E; μmol m^{-2} s^{-1}) experiments; grey line marks depth of 1% surface irradiance. Notice the high range of variation in the photosynthetic parameters along the coastal-open ocean gradient, comparable to latitudinal ranges observed in basin-scale studies. The chlorophyll maximum coincides with the depth of 1% surface irradiance along the whole section. (Adapted from Basterretxea and Arístegui, 2000)

3.1. Interaction of island eddies and upwelling filaments

The temporal and spatial variability in plankton biomass, community structure, and metabolic activities in the Canaries-Coastal Transition Zone (CTZ) region, largely results from the mesoscale variability generated by the perturbation of the main flow by the islands (Fig. 23.7). Wind and current shear at the flanks of the islands enhance plankton productivity and respiratory activity, by increasing vertical mixing and nutrient availability in surface waters (Hernández- León, 1988; Arístegui et al., 1989; Hernández-León, 1991; Arístegui and Montero, 2003). Additionally, Ekman pumping on the wind shear boundaries of the islands produces convergence and divergence fronts (Barton et al., 2000), which affect plankton distribution and productivity. Divergence fronts induce upwelling of deep nutrient-rich water, increasing primary production and chlorophyll (Basterretxea et al., 2002).
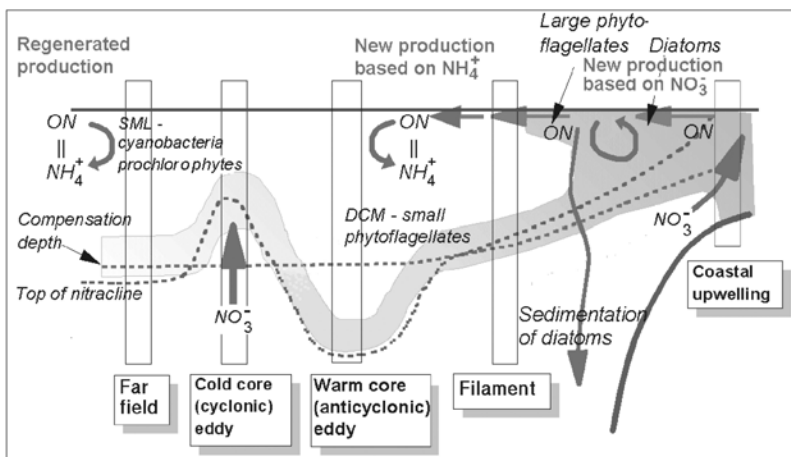

Figure 23.7 Schematic of vertical processes along the NW Africa-Canaries CTZ region. Vertical rectangles indicate typical situations. The *Far-field* nitracline lies below the compensation depth for phytoplankton growth, and so production is low, carried out by pico- or nanoplankton, and likely sustained by recycled ammonium. *Cyclonic eddies* lift isopycnals and nitracline relative to compensation depth, so locally stimulating new production. *Anticyclonic eddies* depress isopycnals and nitracline, deepening the deep chlorophyll maximum (*DCM*) below the compensation depth. Counter paired cyclonic and anticyclonic eddies act as a two-way "biological pump" enhancing the formation and vertical transport of organic matter in the water column. The DCM intensifies toward the coast and higher nitrate concentrations are exposed a above the compensation depth. In the *Upwelling* region the nitracline reaches the surface mixed layer, resulting in high production of diatoms, converting nitrate into Organic Nitrogen (*ON*). These diatoms sink or are eaten as upwelled water moves offshore in the *Filament,* leaving large phytoflagellates as the dominant producers, supported by recycled ammonia from the organic matter transported by the filament. (Modified from Barton et al., 1998)

Downstream of the islands, cyclonic and anticyclonic eddies are generated, by a combined mechanism of flow perturbation and Ekman pumping (Arístegui et al., 1994; 1997; Barton et al., 2000). These eddies exchange water properties between themselves and with the coastal upwelled waters at its offshore boundary or in upwelling filaments (Fig. 23.8). In their early digenetic stages, island eddies present

strong vertical transport of water in their cores to compensate for the ageostrophic movement. Cyclonic eddies enhance primary production by upwelling nutrient-rich thermocline waters into the euphotic zone. Primary production in the core of cyclonic eddies may increase several fold in magnitude compared with the ambient waters (Basterretxea and Arístegui, 2000). As in coastal upwelling, high nutrient concentrations favour the growth of larger cells, like diatoms, increasing considerably the chlorophyll content inside cyclonic eddies, associated with a shift from small to large phytoplankton cells (Barton et al. 1998; van Lenning 2000). Conversely, anticyclonic eddies collect and downwell surface water, deepening the mixed layer and the chlorophyll maximum to depths well below the euphotic zone (>100 m) (Arístegui et al., 1997). These eddies may act as effective organic carbon pumps, sequestering dissolved and particulate organic carbon from the nearby waters and sinking it into the dark ocean. Overall, counter-paired eddies behave as a two-way biological pump, accelerating the production and transport of organic matter in the water column (Arístegui and Montero, 2003).
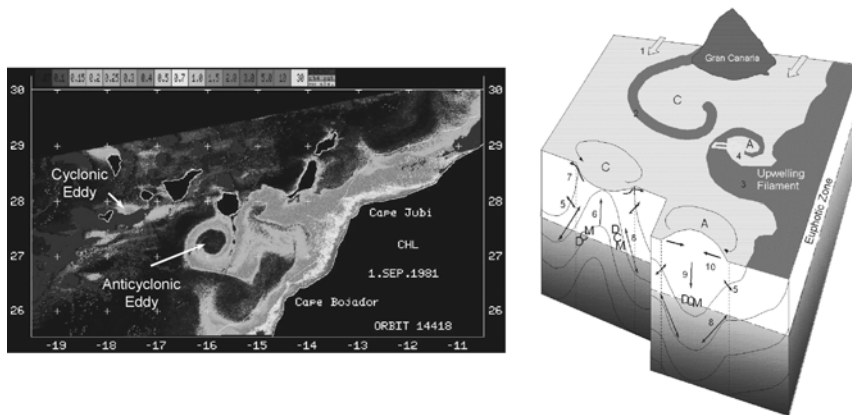

Figure 23.8   (a) CZCS chlorophyll image from the Canary Islands region (1 September 1981), showing the entrainment of high-chlorophyll water from an upwelling filament by an anticyclonic island eddy. (b) Schematic diagram showing vertical and horizontal fluxes associated with island-generated cyclonic (C) and anticyclonic (A) eddies downstream Gran Canaria Island. (1) Mean surface flow and wind direction; (2) advection of high-chlorophyll coastal water during cyclonic eddy formation; (3) entrainment of high-chlorophyll water upwelled from the African coast by anticyclonic eddy; (4) lateral exchange of chlorophyll between the periphery and the eddy centre; (5) diapycnal mixing; (6) upwelling or uplifting of the thermocline; (7) outward radial advection; (8) isopycnal mixing; (9) downwelling or deepening of the thermocline; (10) inward radial advection. DCM = Deep Chlorophyll Maximum. (Panel b, adapted from Arístegui et al., 1997)

Anticyclonic eddies are revealed by SST or chlorophyll like-pigments images thanks to the entrainment of cold, chlorophyll-rich waters when interacting with cyclonic eddies or upwelling filaments stretching from the African coast (Hernández Guerra et al., 1993; Arístegui et al., 1997; Barton et al., 1998; Pacheco and Hernández Guerra, 1999). Satellite images show that anticyclonic eddies detached from the eastern islands of the Archipelago, occasionally interact with the

offshore boundary of the coastal upwelling, entraining upwelled water and extending the filament further offshore (Fig. 23.8). The exchange of water and organic matter between filaments and eddies may be extended to the open ocean waters of the subtropical gyre, by successive interactions between cyclonic and anticyclonic eddies all along the Canaries-CTZ region. This has been confirmed by a drifting lagrangian buoy deployed in the core of a filament near Cape Juby, which followed a westward trajectory to the open ocean, crossing the Canaries-CTZ while spinning around several island eddies (Barton et al., unpubl.). Nevertheless, the water mass characteristics and their associated biological properties must be drastically modified along the way from the coastal upwelling to the open ocean, by mixing of cyclonic and anticyclonic eddy surface waters with different bio-chemical properties, and by vertical displacements of isopycnals and downwelling/ upwelling processes, associated with eddies.

   The biological effects of upwelling filaments on open ocean waters depend in large part on the source coastal water that is advected offshore. Arístegui and Montero (2003) observed that the Cape Juby filament could either transport water with large phytoplankton cells and low community respiration, or water with high respiratory rates associated with smaller cells. These contrasting differences in the composition and metabolism of the transported organic matter may be explained by a different origin of the filament waters, and the time that these waters take to be advected offshore. Significant differences in nutrients and chlorophyll concentrations, and phytoplankton composition, have been described also for an upwelling filament in the California Current upwelling system (Chavez et al., 1991; Jones et al., 1991). These authors attributed a different origin of the upwelled water along the coastal jet to interpret the chemical and biological differences in the upwelling filament sampled during two different cruises.

3.2.   Carbon imbalance in the Canary region

The advection of upwelling waters into the Canary region has important consequences not only by prompting changes in plankton community structure, but also by altering the metabolic balance of the region. The average seasonal P in the Canary region varies more than one order of magnitude, from ~0.1 g C m^{-2} d^{-1} in autumn to >1 g C m^{-2} d^{-1} in spring (Basterretxea, 1994; Basterretxea and Arístegui, 2000). Comparatively, the average integrated community respiration (R) rates are higher and the range of variation (2 fold) lower: from 1.3 g C m^{-2} d^{-1} in summer to 2.3 g C m^{-2} d^{-1} in spring (Arístegui and Montero, 2003). The annual average P/R ratio for the region is <0.5, and only approximates equilibrium during late winter/ early spring, when phytoplankton blooms (Arístegui and Montero, 2003). These results agree with most of the studies on plankton metabolism in the subtropical Northeast Atlantic, where net hetetotrophy (P<R) seems to be the dominant state for the surface planktonic community (Duarte et al., 2001; González et al., 2001, Arístegui and Harrison, 2002). Nevertheless, heterotrophy is considerably larger in the Canary region, where R may at times be more than ten-fold higher than P (Arístegui and Montero, 2003).

   Although cyclonic eddies contribute to increase P and R in the region, frequent loadings of organic matter from the coastal upwelling would be necessary to balance the high R rates measured in the Canary region. Satellite images show the

yearly recurrence of high-chlorophyll filaments invading the Canary region (Arístegui et al., 1997; Pacheco and Hernández Guerra, 1999), and thus spreading organic matter into the open ocean waters. Neuer et al (2002) observed a marked seasonal correlation between carbon fluxes collected in 3 moored sediment traps deployed along the Canaries CTZ region (up to 250 km offshore) and the variability in the intensity of the NW Africa upwelling system. They concluded that particle fluxes in all the traps were affected by particle dispersion from the upwelling filaments of Cape Juby and Cape Guir. Apart from the particulate carbon export, upwelling filaments may export dissolved organic carbon too, as demonstrated by García-Muñoz et al. (2003). Most of the exported particulate and dissolved organic matter is thought to be respired in the Canary region, although some must be transported, by means of eddy exchange, to the oligotrophic waters of the subtropical gyre, where R is consistently higher than P (Duarte et al., 2001; González et al., 2001; Serret et al., 2002).

3.3.   Upwelling filaments and fish larvae survival

Filaments in the Canary region are also known to transport neritic fish larvae to the open ocean acting as a strong tracer of the movement of upwelled water (Rodríguez et al., 1999). Considerable interannual variability is observed in the predominance of fish larvae groups, presumably reflecting different environmental conditions in the upwelling system or different source waters. In a 1993 survey immediately south of the Canaries archipelago, 94% of the neritic larvae were captured in the offshore extension of a filament, the two most common species being sardine (*Sardina pilchardus;* 27.6%) and anchovy (*Engraulis encrasicolus;* 7.5%). In contrast, in 1999, the dominant clupeid species in the area was *Engraulis encrasicolus* (J.M. Rodríguez com. pers.). In 2001 the situation had reversed to its earlier state of dominance by *Sardina pilchardus* (Hernández-León et al., unpubl.). In 1993, the mean length of sardine larvae increased along the filament suggesting that the high zooplankton biomass inside the filament could maintain their growth.

As with phytoplankton, filaments transport zooplankton species originating on the shelf to the open ocean. However, while chlorophyll decreases sharply beyond the shelf break, due to decreasing nutrient concentration and grazing (Basterretxea and Arístegui, 2000), zooplankton show high biomass in the oceanic domain as result of their longer generation times and longevity (Hernández-León et al., 2002). Indices of feeding, metabolism and growth progressively decrease along the offshore extension of the filament, suggesting that advection, rather than local enrichment processes inside the filament, are mostly responsible for the high biomass. Additionally, a change in feeding behaviour takes place between coastal waters and the open ocean. Over the shelf edge zooplankton are mostly herbivorous but they gradually change their diet to fulfil their metabolic demands with non-pigmented food (e.g., microzooplankton) as they move to the ocean (Hernández-León et al., 2002).

In the sense of Bakun's (1996) triad of enrichment, concentration and retention, filaments can act as either retentive or dispersive agents. Coastal upwelling provides the basic enrichment necessary for a favourable reproductive habitat while fronts between upwelled and oceanic water provide a means of concentration. Filaments, by providing a transport mechanism to remove neritic fish eggs and

larvae from the area of their continental shelf spawning to the open ocean, may act dispersively. On the other hand, the Canary Islands filament near Cape Juby has been shown to be entrained around a quasi-permanent cyclonic eddy (Barton et al., 1998; Navarro-Pérez and Barton, 2001). Filament waters may so be returned to the continental shelf on a time scale of 7–10 days by the cyclonic circulation (Navarro-Pérez and Barton, 1998). The filament in this case acts retentively and provides a nursery within which the larvae may grow before returning to their shelf environment (Rodríguez et al., 1999).

Moreover, both cyclonic and anticyclonic eddies spun off the islands may interact with the filament to entrain upwelled water carrying larvae (Rodríguez et al., 2001), in some cases facilitating their transport from the African coast to near shore of the islands. Since zooplankton accumulates near the islands, (Hernández-León, 1991), it has been suggested that the interaction between filaments and eddies enhances recruitment there. Recent studies (Hernández-León et al., unpubl.) suggest a connection between the dominant species in the African upwelling area, their larvae transported in the filaments, and the presence of their juveniles in the fishing catch around the islands. This genetic refreshing from the African coast is thought to promote the high fish abundances sometimes observed around the Canaries Archipelago.

4. Fish and fisheries

4.1. Link with the environment

Off the Iberian Peninsula, the long-term changes in alongshore winds during recent decades are related to the NAO, and lead to variations in the patterns of upwelling in the region and decadal fluctuations in the annual catch of sardine (Borges et al., 2003). Both sustained and intermittent northerly winds, and therefore upwelling, during the winter spawning season have a negative impact on sardine (*Sardina pilchardus*) and horse mackerel (*Trachurus trachurus*) recruitment and catches the following year, even if adequate upwelling conditions occur later during the summer upwelling (feeding) season (Santos et al., 2001).

South of 36°N, variability of recruitment is poorly understood due to the lack of adequate data. However, several patterns relating the environment with fish abundance or reproductive strategies have been documented (Cury and Roy, 1991; Durand et al., 1998). A comparative analysis of the spawning pattern of the major small pelagic species in the Canary Current shows that there is no correspondence between the spawning seasons of sardine and sardinellas (*Sardinella aurita* and *S. maderensis*) and the occurrence of upwelling (Roy et al., 1989; 1992). In some areas spawning occurs during the upwelling season (Senegal) and in other areas outside the upwelling season (Morocco) or when upwelling activity reaches a seasonal minimum (Sahara). Rather than being associated with the maximum upwelling intensity, it appears that the timing of spawning is associated with the occurrence of wind speed of about 5–6 m s^{-1} (Roy et al., 1992). This wind speed range corresponds to the optimal wind conditions for recruitment success, as defined by Cury and Roy (1989). This correspondence between the spawning peaks and the optimal wind value for recruitment success illustrates the long-term adaptation of small pelagic fish reproductive strategies to the environment.

The dynamics of the Morrocan sardine fisheries was studied in great detail by Belvèze and Erzini (1983) and Belvèze (1991). Three main populations of sardine are found along the northwest African coastline. An analysis of the catches over the last 40 years showed that these three populations have distinct patterns of abundance variability (Kifani, 1998). The boundaries between the three populations are located approximately at 27°N and 34°N, but these stocks migrate latitudinally in relation to the seasonal dynamics of upwelling in the region. These migrations have a minor effect on the fisheries occurring in the southern part of the region. However, the migration of the central sardine stock to the upwelling area that develops in summer north of Cape Guir (29°N) is a major component of the dynamics of the traditional Moroccan fishery that operates north of 30°N (Belvèze and Erzini, 1983; Belvèze, 1991). The intensity of this migration appears to be linked to the strength of the upwelling, with higher catches being recorded during years of enhanced upwelling. Sustained upwelling is thought to enhance primary production and sardine feeding condition in summer north of Cape Guir, resulting in a strengthening of the migration flux and consequently higher catches by the fishery. The traditional Moroccan fishery collapsed in the early 1990s following a constant decline of the catches since the mid-1970s. The reason for this collapse is still an unresolved issue and several hypotheses have been proposed (Do-Chi and Kiefer, 1996). Changes of the migration pattern, unfavourable environment in the traditional fishery zones affecting fish migration, a southward shift in the centre of gravity of the sardine population due to climatic changes were the different mechanisms that were put forward. However, in the early eighties, Belvèze and Erzini (1983) expressed concern about the persistent decline of the catches that they observed in the traditional fishery areas. They linked this decline to a reduced sardine summer migration related to a decrease of the upwelling favourable wind recorded at a coastal station (Essaouira, 31°30' N). They predicted that if the observed tendencies persisted, a geographical concentration of the central stock between 24°N and 30°N could likely occur and severely impact the fisheries operating at the geographical boundaries of the stock. It is worth noting that this scenario, proposed in the early eighties, adequately anticipated what happened during the following decade.

The southernmost sardine population is mainly exploited by foreign fishing fleets, most of them from Eastern Europe. The catch record showed a pattern of drastic booms and bursts with two major peaks in the late seventies and late eighties during which annual catches reach 600000 t. It is recognised that these periods of enhanced catches were associated with a dramatic increase of the abundance and with a significant southward extension of the southern population (Binet, 1997; Kifani, 1998). During the two periods of high abundance, significant sardine catches were recorded as far south as Cape Vert (14°N). There is an apparent synchrony between the two outbursts of the southern sardine population and periods of enhanced upwelling in the central Canary Current region, around 24°N (Binet, 1997; Roy and Reason, 2001).

The highly seasonal activity of the upwelling off Mauritania and Senegal (between 22°N and 14°N) induces profound changes in the biological community structure: the ecosystem shifts from tropical to a sub-tropical influence within a few months. Abrupt seasonal shifts in the environment induce a pronounced seasonal migration of the major pelagic and demersal fish stocks between Senegal,

Mauritania and the Sahara region. The following example illustrates how the seasonal dynamic of the upwelling impacts on the latitudinal distribution of the fish, on the fishing activities, as well as on the fish landings. The appearance of a migrant population of thiof (*Epinephelus aeneus*) along the north coast of Senegal is related to the onset of the Senegalese upwelling, which takes place between November and May (Cury and Roy, 1988). Anomalies of SST data collected at coastal stations were used to characterize the upwelling intensity. Using CPUE in the two main landing ports (Saint-Louis and Kayar, 15°-16°N) a mean lag of about one month was found between the occurrence of the upwelling and the arrival of the thiof off Kayar (Fig. 23.9a). The migration of the thiof from Mauritania to Senegal appears to be not only related to the onset of the Senegalese upwelling but is also linked to the relaxation of the upwelling off northern Mauritania (Fig. 23.9b).
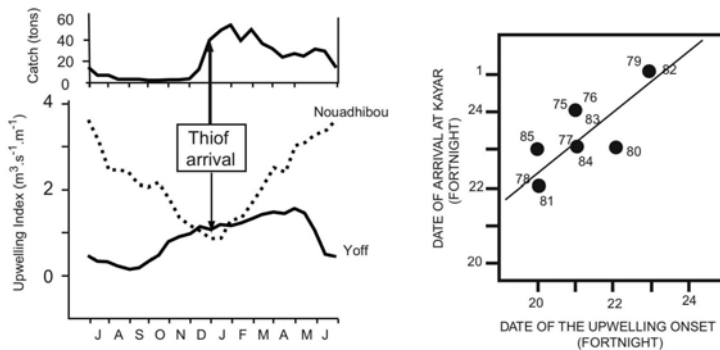

Figure 23.9 (a) the relationship between the seasonal arrival of Thiof at Kayar and the onset of the upwelling (1975–1985). (b) Mean monthly upwelling (m^{-3} s^{-1} m^{-1}) indices at Yoff (Senegal) and Nouadhibou (Mauritania) and mean monthly thiof catches (tons) at Kayar. (Adapted from Cury and Roy, 1988).

The effect of the environment on the Canary Current fish populations and fisheries has been investigated using production models incorporating an environmental variable in addition to fishing effort (Fréon et al., 1993). These models have been successfully applied to several pelagic stocks in the region (Fréon, 1983; 1988). In the case of Senegal for instance, the abundance of the sardinella stock appears to be related to the interanual variations of a wind derived upwelling index. Off Morocco, the variability of the upwelling has a significant impact on the catchability of sardine in the northern region.

4.2.   *Major patterns of changes off the Iberian Peninsula*

In the northern part of the Canary Current, there is evidence of changes in fish distribution and community structure related to an increase of water temperature. Air and sea temperatures over most of the NE Atlantic increased since the late 1980s by at least 0.4° C per decade (Dias et al., 1992; Brander et al., 2003). Over

the same period extensive northward shifts in distribution of commercial and non-commercial fish species occurred from southern Portugal to northern Norway (Brander et al., 2003). Off the Iberian Peninsula, there is evidence that warm water species have been extending their range to southern Portugal with, during the last decade, an increase of species whose distribution was previously limited to the Mediterranean and/or NW Africa (Brander et al., 2003). Quero et al. (1998) observed also that a variety of tropical species have systematically extended their ranges northward along the European continental slope since the early 1960s.

Decadal fluctuations in the catches of small pelagic fishes species off the western Iberian Peninsula were observed in the last century (Borges et al., 2003; Cendrero, 2002; ICES, 2002). Sardine landings in Portugal peaked in the 1930s and especially in the 1960s, when landing reached an historical maximum of 158000t. Landings in Spain also presented high values in the 1960s. At the end of the 1960s and beginning of 1970s there was an important decline in the landings of the two countries. However, the major decline was recorded in the main sardine fishing grounds north of 41° N, while in the southern areas there was a slight increase (ICES, 2002). After the abrupt decline at the end of the 1960s, the Portuguese landings in the northern region remained stable until 1994 with values around 45000t, followed by a slight decrease of the catches during the following period (ICES, 2002). Since 1985, sardine catches off Galicia (Spain) have been declining continuously with an historical low recorded in 1999–2000 (ICES, 2002).

Using information from eggs and larvae surveys during the period 1985–2000, Stratoudakis et al. (2003) found significant changes in the distribution of sardine eggs and larvae off Portugal. They showed that the area where fish eggs are encountered significantly decreased from 11800 km^2 in 1988 to around 7200 km^2 in late 1990s. This decline is related to a marked reduction in egg abundance in the northern Portuguese spawning grounds, and corresponds to changes observed in the distribution of larvae. The pattern of change is coherent with changes observed in sardine catches off northwestern Iberia, and is also corroborated by changes in the area of distribution and abundance of sardine estimated by Portuguese and Spanish acoustic surveys (Stratoudakis et al., 2002; 2003; ICES, 2002). Other documented changes in northern Portugal during the 1980s and 1990s, include a reduction of the abundance of sardine larger than 16 cm and a decrease in the length at first maturation (Stratoudakis et al., 2002).

4.3.   Fisheries in the NW African coast

Total landings in the NW Africa region fluctuated between 1.3Mt and 2.6Mt over the last 30 years. As in the other three major eastern boundary currents, fisheries landings in the region are based on pelagic fish species which represent 70% of the total catches on average (Fig. 23.10). Catches of pelagic species are dominated by the sardine. Its contribution to the total pelagic catches peaked in 1977, sharply declined in the late seventies and showed a constant positive trend up to the mid 1990s when it suddenly dropped to pre mid-1970s levels (Fig. 23.11). These fluctuations are thought to be the result of environmental fluctuations as well as changes in the exploitation (Binet et al., 1998; Roy and Reason, 2001). Demersal catches peaked in the early 1970s with a maximum of 440000t in 1974 (Fig. 23.10). The persistent negative trend that characterises the demersal catches since the early

1980s is an indication that most of the demersal fish populations are fully exploited in the region (FAO 1997).
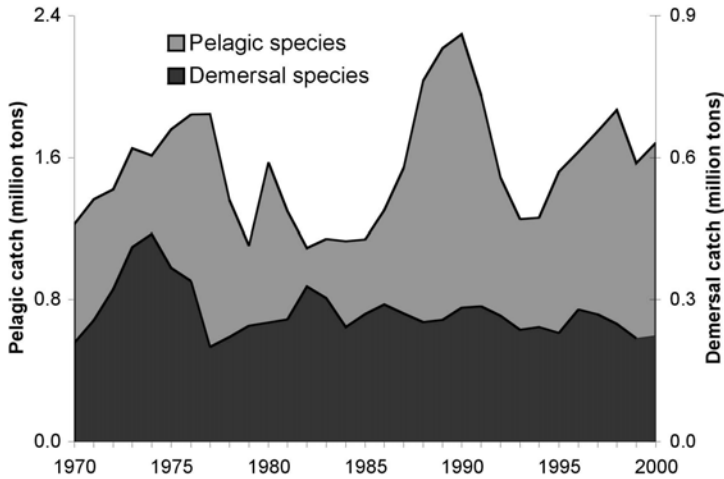

Figure 23.10   Annual catches of pelagic and demersal fish species in the Canary Current region from 1970 to 2000. Source: CECAF (Eastern Central Atlantic) capture production 1970–2000 from FAO.
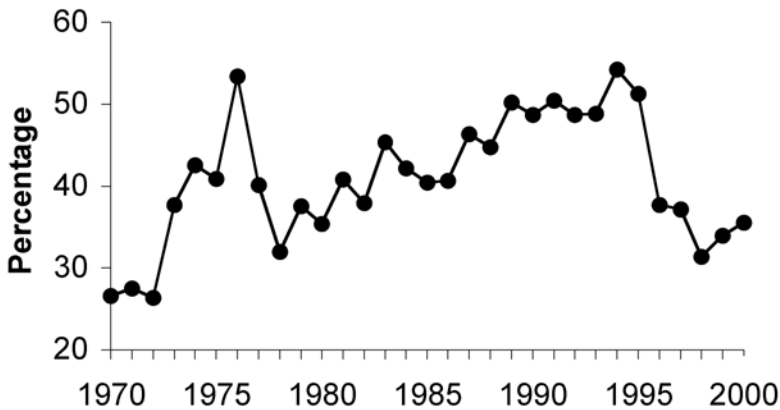

Figure 23.11   Contribution of the European sardine (*Sardina pilchardus*) to the total pelagic catches in the Canary Current from 1970 to 2000. Source : CECAF (Eastern Central Atlantic) capture production 1970–2000 from FAO.

   Drastic changes in the exploitation occurred over the last 50 years. Both small scale and industrial-type fisheries have drastically expanded over the whole region by taking advantage of technological changes. Artisanal fisheries in West Africa have been in operation for centuries. Since the early 1960s, they have considerably improved their efficiency by increasing their size, integrating new technologies such as outboard engines and new fishing gears (Chauveau, 1991). The regional

importance of the artisanal sector is best illustrated by the Senegalese small-scale fisheries which drastically "mutated" over the last 30 years to become as socially and economically efficient as the industrial fishery sector (Kébé, 1994). With a fleet of about 5000 motorized canoes, this fleet provides employment to about 35000 fishermen. Total catches reached 270000t of pelagic fish and 46000t of demersal fish in the early 1990s (Ferraris et al., 1998). During the 1970s and 1980s, exploitation by foreign nations was particularly active in the Canary Current region with a total 25 long-range fishing fleets operating mainly in the central part of the region (FAO, 1997; Maus, 1997). This pattern changed drastically in the 1990s following the political transformation in the Eastern European countries. By targeting mostly pelagic species, these fleets contributed up to 50% of the total regional marine catches, but their contribution has been declining rapidly since the early 1990s, with the partial withdrawal of Eastern European and former USSR fleets from West Africa (FAO 1997).

4.4.   Fish population outburst in the Canary Current

In the Canary Current several species that were known to be rare, developed huge biomass during several years then suddenly vanished in a relatively short time period. Off Morocco an outburst of blue whiting (*Micromesistius poutassou*) was recorded in the 1960s, which later disappeared. In the 1970s snipefishes (*Macrorhamphosus scolopax* and *M. gracilis*)*, which have very different life-history traits, were found all along the Moroccan coast. In 1976, a biomass of about 1 Mt was estimated during an acoustic survey. In the 1980s, the abundance was drastically reduced and today the two species are rarely encountered.

In the late 1960s, trigger fish (*Balistes carolinensis*) was scarce in the Central Atlantic. Between 1972 and 1980, the biomass of this species drastically increased in the Gulf of Guinea to reach more than 1 Mt. This increase in abundance was associated with a wide geographical spreading that reached the southern part of the Canary Current, south of 20°N (Gulland and Garcia, 1984). Off Senegal, the peak in abundance was recorded in the early 1980s. A sharp decline in abundance followed the outburst of the population and at the end of the 1980s this species almost disappeared from the different ecosystems. While several authors believe that the fisheries-induced reduction of the sparid communities facilitated the outburst of the trigger fish (Gulland and Garcia, 1984), environmental changes may also have affected the trigger fish population dynamics (Caverivière, 1991).

The octopus (*Octopus vulgaris*) population increased significantly in abundance in the mid-1960s in the Canary Current (Caddy and Rodhouse, 1998). Three stocks of octopus are presently exploited by both industrial and artisanal fisheries off southern Morocco, Mauritania and Senegal. The rapid emergence of the octopus in Mauritania in the late 1960s led to historical yields of 52900t and 45600t recorded in 1976 and 1987, respectively. During recent years, the production has decreased to about 20000 t (Faure et al, 2000). A rapid expansion of the stock was observed off Morocco with catches reaching 100000t at the beginning of the 1980s. In the mid 1980s, octopus abundance started to increase off Senegal and both the local small-scale and industrial fisheries shifted a significant part of their activity to target this highly economically valuable resource. A peak catch of 17000t was recorded in 1986 whereas catches represented only a few hundreds tonnes before.

Altogether the combined catches in the Canary Current fisheries ranged between 40000t and 90000t from 1985 to 1995. During recent years, catches off southern Morocco and Mauritania have been drastically reduced (Inejih, 2000). Like 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 caused by strong fishing pressure (Gulland and Garcia 1984), which is supposed to lower larval mortality and competition for food in the octopus (Caddy and Rodhouse 1998).

5.   Decadal environmental changes

Wooster et al. (1976), using a compilation of merchant ship SST and wind data from 43°N to 7.5°N, summarised the seasonal patterns of the Canary Current coastal upwelling. In the mid 1970s, intensive process oriented studies were carried 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 program). After the intensive process oriented studies carried 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 (see Cury and Roy, 1991 and Durand et al., 1998 for details) but the accessibility of these data remains limited.

There is an abundant literature on the decadal climatic variability in the subtropical and Northern Atlantic basin (Enfield and Mayer, 1997; Seager et al., 2000; Eden and Jung, 2001; Marshall et al., 2001). However, most of these analyses are performed on relatively low spatial resolution dataset and one can wonder how much of the coastal signal is diluted within the broad oceanic signal. Several studies presented detailed information on the variability in a given area. Arfi (1985), using wind and sea surface temperature measurements 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. High-resolution SST data from satellite, available since the early 1980s, have also been used to investigate the SST structure and the variability over the shelf of the Canary Current (Nykjaer and Van Camp, 1994; Hernandez Guerra and Nykjaer, 1997; Demarcq and Faure, 2000).

In the northern part of the Canary Current, a significant change on the monthly wind distribution pattern on the Portuguese west coast occurred during the period of 1947–1991, namely an increase in the frequency and intensity of upwelling-favourable winds in winter (Borges et al., 2003). During the spring-summer season, several authors noticed an increasing trend in the alongshore wind time series off the Iberian Peninsula (Dickson et al., 1988; Bakun, 1990; 1992). However, contrary results were reported from the analysis of wind and sea surface temperature ob-

servations (1947 to 1992) at the meteorological station of Cape Carvoeiro (Dias et al., 1996) and from daily atmospheric pressure data (1966 to 1999) off Galicia (Lavín et al., 2000). Pérez et al. (1995; 2000b) found a good correlation between the thermohaline properties of ENACW and the wind stress, the cumulative river discharge and the NAO index, illustrating the close coupling between water mass formation and climate change in the North Atlantic.

The interannual and long-term variability in the shelf domain of the Canary Current has not yet been summarised. To get an overview of the main pattern of variability at the surface, we extract SST data collected by merchant ships from the COADS database (Woodruff et al., 1987) from 1950 to 1995 within sixteen boxes along the Canary Current coast from 10°N up to 43°N (Fig. 23.12). The shipping line from Europe to the Indian Ocean follows the shape of the West African coast south of 28°N, and so in these regions data density is high along the coast. Between 28°N and 32°N, the shipping line moves 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. To avoid potential biases due to seasonal changes in the data distribution, observations from former USSR fishing fleet which was quite active in the 1980s and early 1990s in the central region were excluded. For each of the sixteen boxes, monthly SST time series from 1950 to 1995 are constructed. Monthly SST anomalies are computed by subtracting the monthly climatology from the 1950–1995 monthly time series.

SST anomalies can be used to track changes in the intensity of the upwelling. 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 intensification (relaxation) of the upwelling process. As a result, negative (positive) SST anomalies are expected during an intensified (relaxed) phase of the upwelling.

To get a synthetic view of the variability, monthly anomalies are then averaged by quarter. The data are presented on a time/latitude diagram and smoothed to get the long-term pattern of the SST variability (Fig. 23.13). In the early and mid-1970s, an intensive cooling (negative SST anomalies), characterised the variability of the SST anomalies during the first quarter (Fig. 23.13). It had a large latitudinal extension, affecting the whole Canary Current coastal domain from Spain to Senegal. South of 16°N, the low frequency variability was characterised by a succession of warm and cold periods. Between 16°N and 23°N, the variability appeared to increase after the mid-1970s with a succession of warm and cold periods, similar to further south. North of 23°N the variability decreases, the cooling of the 1970s being the major climatic event.

The variability of SST anomalies during the second quarter shares some common characteristics with that during the first quarter. There was an extensive cooling affecting the whole region in the 1970s but, although less pronounced, this cooling appeared to start in the mid 1960s and extended to the late 1970s. South of 16°N, the variability was also characterised 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.
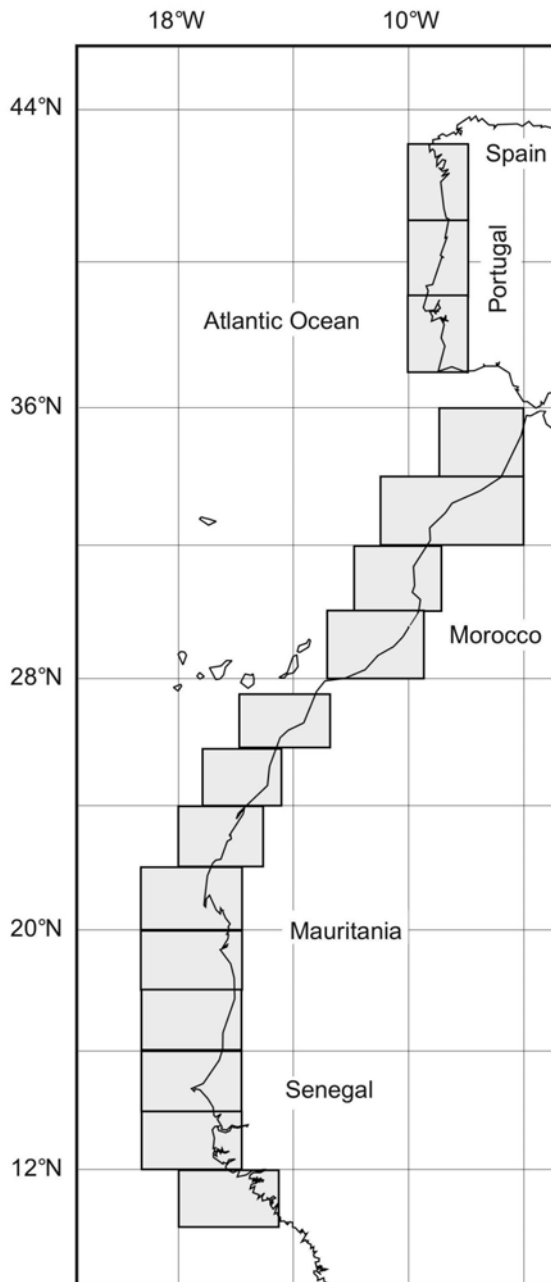
Figure 23.12 Location of the 16 coastal boxes where SST time-series have been built using data extracted from COADS.
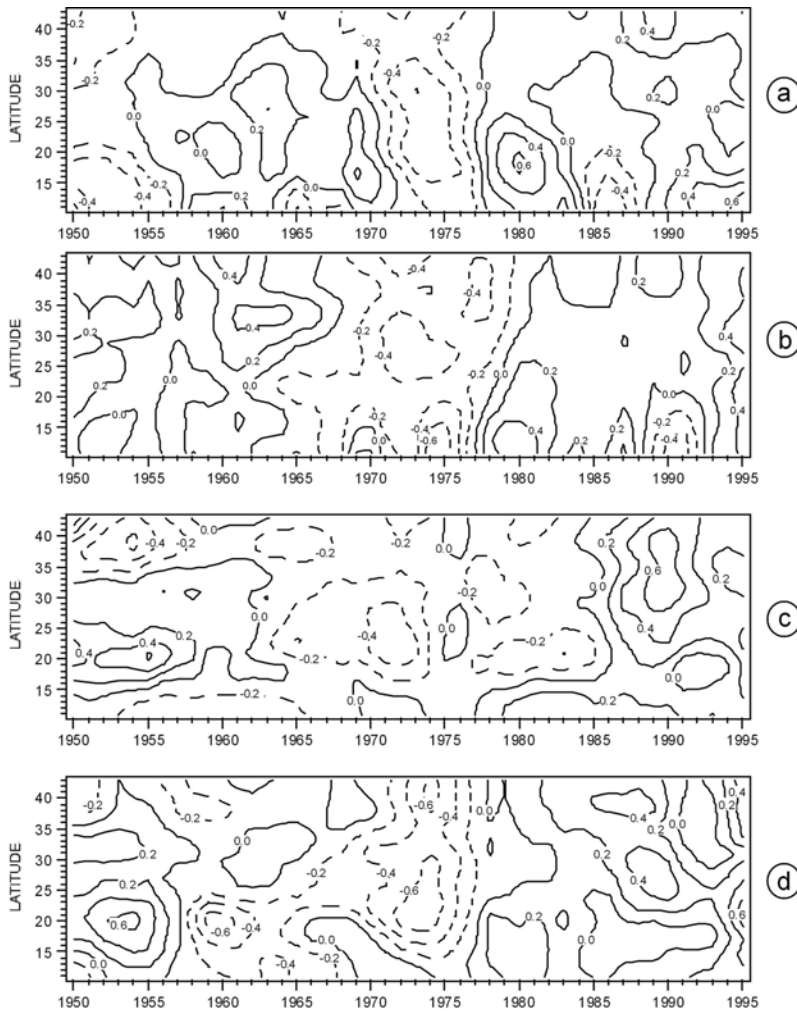
Figure 23.13   Time/latitude plot of SST anomalies (°C) in the Canary Current/Iberia from 43°N to 11°N and from 1950 to 1995 for the first (a), second (b), third (c) and fourth quarter (d).

During the third quarter, SST anomalies were characterised by a pronounced cooling from the mid-1960s to the mid-1980s. It affected the region north of 18°N up to 35°N. Another emergent pattern with large latitudinal extent was the strong warming developing north of 20°N during the late 1980s and early 1990s. From 1950 to 1965, the latitudinal variability 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 was again one of the salient features of the SST anomalies. It reached maximum intensity between 15°N and 30°N from 1972 to 1975. A warming affecting all the Canary Current since the 1980s followed this cooling.
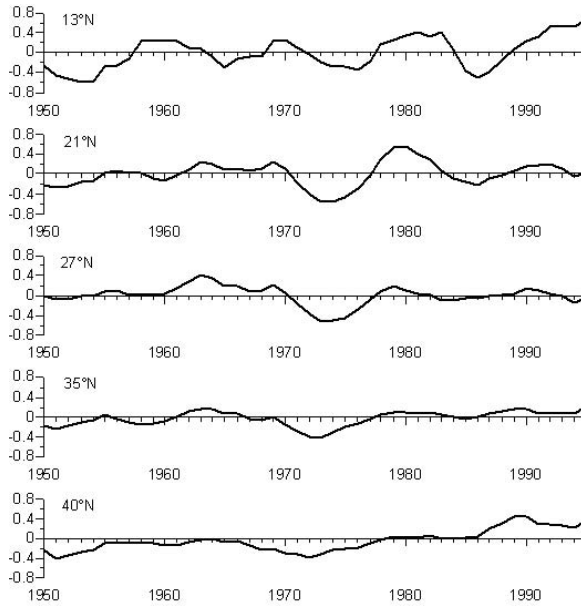
Figure 23.14a Trend of the SST anomalies (°C) at selected latitudes in the Canary Current/Iberia during the first quarter, from 1950 to 1995
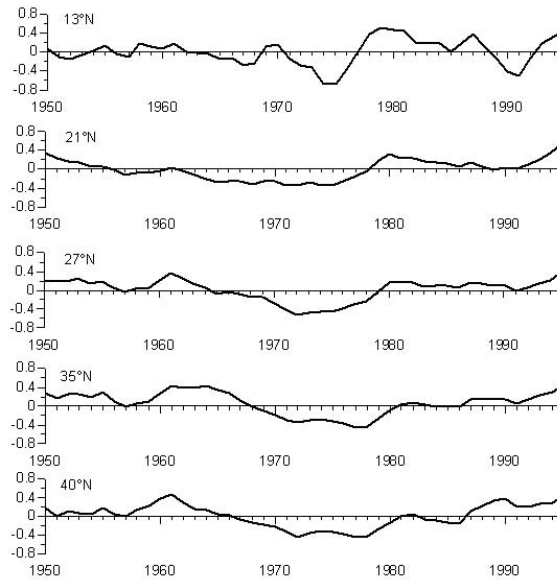

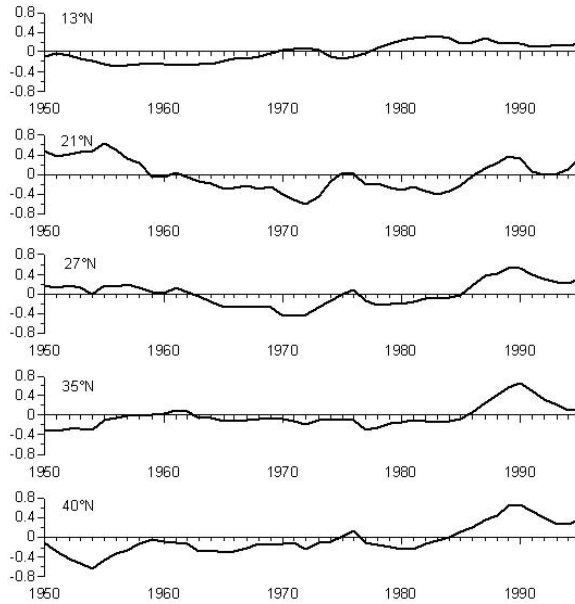Figure 23.14b Trend of the SST anomalies (°C) at selected latitudes in the Canary Current/Iberia during the second quarter, from 1950 to 1995

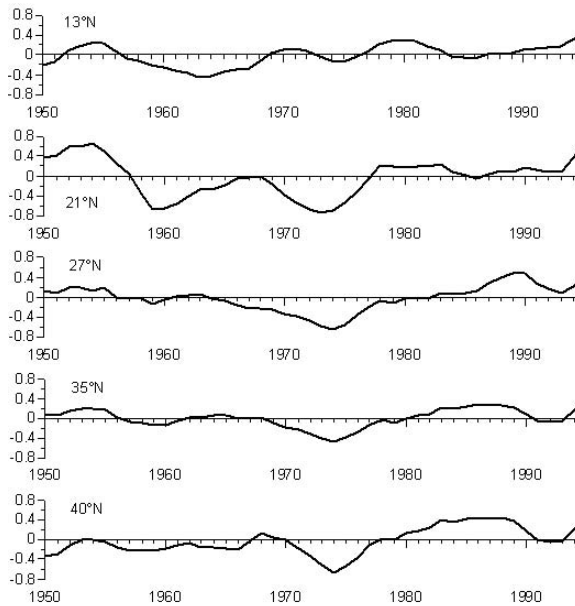Figure 23.14c Trend of the SST anomalies (°C) at selected latitudes in the Canary Current/Iberia during the third quarter, from 1950 to 1995

Figure 23.14d Trend of the SST anomalies (°C) at selected latitudes in the Canary Current/Iberia during the fourth quarter, from 1950 to 1995

In summary, time series in selected regions are presented to highlight the dominant patterns of variability of SST anomalies by quarter from 1950 to 1995 (Fig. 23.14a to 23.14d). The cooling in the 1970s is a major feature. It affected the whole region during and outside the upwelling seasons (Binet, 1997). The southern part of the region presents a quite dynamic pattern of variability unique to the area. This is confirmed by a comparative analysis of the variability of SST anomaly time series using the standard deviation as an index of the variability (Fig. 23.15). 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.
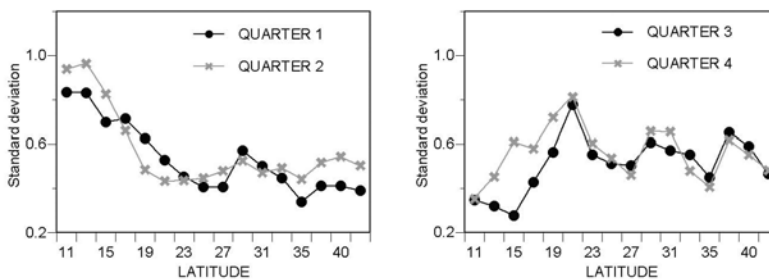
Figure 23.15   Trend of the SST anomalies (°C) at selected latitudes in the Canary Current/Iberia during the fourth quarter, from 1950 to 1995

5.1.   *Link with the North Atlantic Oscillation (NAO)*

The North Atlantic Oscillation (NAO) characterises 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, Marshall et al., 2001) and has a measurable impact on the North Atlantic ecosystem (Fromentin and Planque, 1996).

The link between the NAO and the Canary Current 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 3). 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.

TABLE 3.
Correlation between quarterly averaged SST anomalies in the
Canary Current 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 **

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 induces an intensification of the upwelling
favourable wind and 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 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 may result
in negative SST anomalies.

5.2   ENSO Teleconnection

Pacific El-Nino/Southern-Oscillation (ENSO) events have a major impact on the
world climate. In the tropical Atlantic, the SST and wind fields are regularly af-
fected by Pacific equatorial variability (Hastenrath et al., 1987, Nobre and Shukla,
1996; Enfield and Mayer, 1997). Large-scale analyses have shown that the North
Atlantic warms in response to the Pacific ENSO with a lag of about 3 to 6 months,

the effect being apparently stronger in the north-western part of the basin and during the boreal spring and early summer (Enfield and Mayer, 1997). The origin of this lag is not clear, but Klein et al. (1999) argue that the El Nino warming signal is communicated to the tropical Atlantic via a reduction in surface latent heat flux associated with reduced trade winds. In the Canary Current, the wind is the driving force of the upwelling and an alteration of the trade wind activity has a pronounced effect on the ecosystem, thus one can expect to observe a strong connection between ENSO and the coastal upwelling. 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 quarter of the year (Table 4). As expected from the weakening of the Atlantic 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 teleconnection between the coastal upwelling activity in the Atlantic and the state of the Pacific Ocean. This link between ENSO and the Canary Currrent upwelling has been explored in details 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 (Enfield and Mayer, 1997).

TABLE 4.
Correlation between quarterly averaged SST anomalies in the Canary Current 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

6.   Synthesis and future research

Considerable information has been gathered on biogeochemical cycles and fisheries of the eastern boundary of the subtropical gyre of the North Atlantic, but knowledge of some space and time scales, of some areas and of certain seasons is lacking. For example the northwestern Iberian margin has been intensively studied whereas southern Iberia is much less well known. The dynamics and biogeochemistry of much of the African coast have been little sampled. Some basic questions about seasonal variation remain. The winter downwelling regime off Iberia is poorly known. Recent evidence suggests the development of a previously unrecognized surface poleward counterflow in the Canaries region during winter, despite favourable, albeit weaker, Trade winds than in summer. It has been hypothesized that this is linked to a horizontal re-circulation associated with the Cape Guir filament, which would have major consequences for carbon fluxes in the area. Large scale, high resolution, multidisciplinary surveys, such as have been made in the California Current, would throw much light on these issues and their implications.

Both the NW African coast and the Canary Islands region are considered important sources of primary productivity. Although most of the organic matter produced is thought to be respired in the surface waters of the eastern boundary of the Canary Current, the interplay between island eddies and upwelling filaments may enhance the export of coastal enriched water to the oligotrophic open ocean. This would explain the strong imbalance between phytoplankton production (P) and community respiration (R) observed in the subtropical gyre, where the P/R ratio is normally <1. However, little is still known about the relative importance of vertical sedimentation of organic carbon in the coast vs. offshore transport, the nature of the organic matter exported (e.g. dissolved vs. particulate), or the different mechanisms of filament-eddy exchange through the Canaries Coastal Transition Zone. Multi-disciplinary oceanographic studies should be strongly supported in order to achieve the basic knowledge of the functioning of these complex coastal ecosystems in order to test and validate trophic and biogeochemical models.

South of Gibraltar much knowledge of the coastal upwelling ecosystem was obtained during the intensive studies of the 1970s, but recent research has been largely (though not entirely) confined to coastal regions in relation to fisheries and dynamics of fish populations. Major changes like the redistribution of Moroccan sardine populations and outbursts of octopus and other species underline profound changes in the ecosystem over the last 30 years. In a context of global climate change, escalating fisheries exploitation and increasing pressure on coastal resources, the need for further intensive study and greater understanding of the system is clear if it is to be managed in a sustainable way. The requirement is for a dual approach of more systematic and detailed observational programs that take advantage of advances in remote sensing and instrumentation, coupled with the development of linked numerical modeling that combines knowledge of ocean dynamics, the ecosystem, fisheries and proper management of the ecosystem.

Acknowledgements

Bibliography

Abrantes, F. and M.T. Moita, 1999. Water column and recent sediment data on diatoms and cocco-lithophorids off Portugal confirm sediment record of upwelling events. *Oceanol. Acta,* **22,** 319–336

Abrantes, F., H. Meggers, S. Nave, J. Bollman, S. Palma, C. Sprengel, J. Henderiks, A. Spies, E. Salgueiro, M.T. Moita and S. Neuer, 2002. Fluxes of micro-organisms along a productivity gradient in the Canary Islands region (29°N): implications for paleoconstructions. *Deep Sea Res. II,* **49,** 3599–3629.

Álvarez, M., E. Fernández and F.F. Pérez, 1999. Air–sea CO_2 fluxes in a coastal embayment affected by upwelling: physical versus biological control. *Oceanol. Acta,* **22,** 499–515.

Álvarez–Salgado, X.A., G. Rosón, F.F. Pérez and Y. Pazos, 1993. Hydrographic variability off the Rías Baixas (NW Spain) during the upwelling season. *J. Geophys. Res.,* **98,** 14447–14455.

Álvarez–Salgado, X.A., C. G. Castro, F.F. Pérez and F. Fraga, 1997. Nutrient mineralization patterns in shelf waters of the Western Iberian upwelling. *Cont. Shelf Res.,* **17,** 1247–1270.

Álvarez–Salgado, X.A., M.D. Doval, A.V. Borges, I. Joint, M. Frankinouglle, E.M.S. Woodward and F.G. Figueiras, 2001. Off–shelf fluxes of labile materials by an upwelling filament off the NW Iberian upwelling system. *Prog. Oceanogr.,* **51,** 321–339.

Álvarez–Salgado, X.A., S. Beloso, I. Joint, E. Nogueira, L. Chou, F.F. Pérez, S. Groom, J.M. Cabanas, A.P. Rees and M. Elskens, 2002. New Production of the NW Iberian shelf during the upwelling season over the period 1982–1999. *Deep Sea Res. I,* **49,** 1725–1739.

Álvarez–Salgado, X.A., F.G. Figueiras, F.F. Pérez, S. Groom, E. Nogueira, A. Borges, L. Chou, C.G. Castro, G. Moncoiffé, A.F. Ríos, A.E.J. Miller, M. Frankignoulle, G. Savidge and R. Wollast, 2003. The Portugal Coastal Counter Current off NW Spain: new insight on its biogeochemical variability. *Prog. Oceanogr.,* **56,** 281–321.

Araujo, M., J. Jouanneau,, P. Valerio, T. Barbosa, A. Gouveia,, O. Weber, A. Oliveira, A. Rodrigues and J. Dias, 2002. Goechemical tracers of northern Portuguese estuarine sediments on the shelf. *Prog. Oceanogr.,* **52,** 277–297.

Arfi, R. 1985. Variabilité inter-annuelle d'un indice d'intensité des remontées d'eaux dans le secteur du Cap-Blanc (Mauritanie). *Canad. J. Fish. Aquat. Sci.,* **42,** 1969–1978.

Arístegui, J. and W.G. Harrison, 2002. Decoupling of primary production and community respiration in the ocean: implications for regional carbon studies. *Aquat. Microb. Ecol.,* **29,** 199–209.

Arístegui, J. and M. F. Montero, 2003. Temporal and spatial changes in microplankton respiration and biomass in the Canary Islands: the effect of mesoscale variability. *J. Mar. Sys.* (accepted)

Arístegui, J., S. Hernández-León, M. Gómez, L. Medina, A. Ojeda and S. Torres, 1989. Influence of the wind on neritic plankton around Gran Canaria. In *Topics in Marine Biology.* Ros, J.D., ed., *Sci. Mar.,* **53,** 223–229.

Arístegui, J, P. Sangrà, S. Hernández-León, M. Cantón, A. Hernández_Guerra and J. L. Kerling, 1994. Island-induced eddies in the Canary Islands. *Deep-Sea Res. I,* **41,** 1509–1525.

Arístegui, J., P. Tett, A. Hernández-Guerra, G. Basterretxea, M.F. Montero, K. Wild, P. Sangrà, S. Hernández-León, M. Cantón, J.A. García-Braun, M. Pacheco and E.D. Barton, 1997. The influence of island-generated eddies on chloropyll distribution: a study of mesoscale variation around Gran Canaria. *Deep-Sea Res. I,* **44,** 71–96.

Arístegui, J, E.D. Barton, M.F. Montero, M. García-Muñoz and J. Escánez. 2003. Organic carbon distribution and water-column respiration in the NW Africa-Canaries Coastal Transition Zone. *Aquat. Microb. Ecol.* (in press)

Bakun, A., 1990. Global climate change and intensification of coastal ocean upwelling. *Science,* **247,** 198–201.

Bakun, A., 1992. Global greenhouse effects, multi-decadal wind trends, and potential imapcts on coastal pelagic fish populations. *ICES Marine Science Symposia,* **195,** 316–325.

Bakun, A., 1996. Patterns in the ocean: ocean processes and marine population dynamics. Calif. Sea Grant College Syst. Univ. Calif., La Jolla, 323p.

Bakun, A., C.S. Nelson, 1991. The seasonal cycle of wind–stress curl in subtropical eastern boundary current regions. *J. Phys. Oceanogr.,* **21,** 1815–1834.

Barber, R.T. and R.L. Smith, 1981. Coastal Upwelling Ecosystems. In: *Analysis of marine ecosystems,* Longhurst, A.R. ed., Academic press, New York, pp. 31–68.

Barbosa, A.B., H.M. Galvao, P.A. Mendes, X.A. Álvarez–Salgado, F.G. Figueiras and I. Joint, 2001. Short–term variability of heterotrophic bacterioplankton during upwelling off the NW Iberian margin. *Prog. Oceanogr.,* **51,** 339–359.

Barquero, S., J. A. Cabal, R. Anadón, E. Fernández, M. Varela and A. Bode, 1998. Ingestion rates of phytoplankton by copepod size fractions on a bloom associated with an off–shelf front off NW Spain. *J. Plankton Res.,* **20,** 957–972.

Barton, E. D., 1987. Meanders, eddies and intrusions in the thermohaline front off northwest Africa. *Deep Sea Res.,* **24,** 1–6.

Barton, E. D., 1998. Eastern boundary of the North Atlantic: Northwest Africa and Iberia. Coastal segment (18,E). In *The Sea,* Vol. 11, Robinson, A. R. and K. H. Brink, eds, John Wiley and Sons, Inc., New York, pp. 633–657.

Barton, E. D. and P. Hughes, 1982. Variability of water mass interleaving off NW Africa. *J. Mar. Res.,* **40,** 963–984.

Barton, E. D., J. Arístegui, P. Tett, M. Cantón, J. García-Braun, S. Hernández-León, L. Nykjaer, C. Almeida, J. Almunia, S. Ballesteros, G. Basterretxea, J. Escánez, L. García-Weil, A. Hernández-Guerra, F. Ópez-Laatzen, R. Molina, M. F. Montero, E. Navarro-Pérez, J. M. Rodríguez, K. van Lenning, H. Vélez and K. Wild, 1998. The transition zone of the Canary Current upwelling region. *Prog. Oceanogr.,* **41,** 455–504.

Barton, E.D., G. Basterretxea, P. Flament, E.G. Mitchelson-Jacob, B. Jones, J. Arístegui and H. Felix, 2000. Lee region of Gran Canaria. *J. Geophys. Res.,* **105,** 17173–17193.

Basterretxea, G., 1994. Influencia de las estructuras oceanográficas mesoescalares sobre la producción primaria en la región Canaria. PhD. Thesis. University of Las Palmas de Gran Canaria, 113 pp.

Basterretxea, G. and J. Aristegui, 2000. Mesoscale variability in phytoplankton biomass distribution and photosynthetic parameters in the Canary-NW African coastal transition zone. *Mar. Ecol. Prog. Ser.,* **197,** 27–40.

Basterretxea, G., E.D. Barton, P. Tett, P. Sangrà, E. Navarro-Pérez and J. Aristegui, 2002. Eddy and DCM response to wind-shear in the lee of Gran Canaria. *Deep-Sea Research I,* **49,** 1087–1101

Belvèze, H., 1991. Influence des facteurs hydroclimatiques sur la pêcherie marocaine de petits pélagiques côtiers. In *Les pêcheries ouest-africaines: variabilité, instabilité et changement.* Cury, P. and C. Roy, eds., ORSTOM, Paris.

Belvèze, H. and K. Erzini, 1983. The influence of hydroclimatic factors on the availability of the sardine (Sardina pilchardus, Walbaum) in the Moroccan Atlantic fishery. In *Proceedings of the expert consul-*

tation to examine changes in abundance and species composition of neritic fish resources G.D. Sharp and J. Csirke, eds., FAO, Fish. Rep. 291, pp. 285–327.

Binet, D., 1997. Climate and pelagic fisheries in the Canary and Guinea currents 1964–1993: the role of trade winds and the southern oscillation. *Oceanol. Acta,* **20,** 177–190.

Binet, D., B. Samb, M.T. Sidi, J.J. Levenez and J. Servain, 1998. Sardine and other pelagic fisheries changes associated with multi-year trade wind increases in the southern Canary current. In *Global versus local changes in upwelling systems,* Durand, M.H., P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly, eds., ORSTOM Editions, Paris, pp. 211–233.

Blanton, J.O., K.R. Tenore, F.F. Castillejo, L.P. Atkinson, F.B. Schwing and A. Lavín, 1987. The relationship of upwelling to mussel production in the rías on the Western coast of Spain. *J. Mar. Res.,* **45,** 497–511.

Bode, A. and M. Varela, 1998. Mesoscale estimations of primary production in shelf waters: a case study in the Golfo Artrabo (NW Spain). *J. Exp. Mar. Biol. Ecol.,* **229,** 111–131.

Bode, A., E. Fernández, J.A. Botas and R. Anadón, 1990. Distribution and composition of suspended particulate matter related to a shelf–break saline intrusion in the Cantabrian Sea (Bay of Biscay). *Oceanol. Acta,* **13,** 219–228.

Bode, A., B. Casas and M. Varela, 1994. Size–fractioned primary productivity and biomass in the Galician shelf (NW Spain): Netplankton versus nanoplankton dominance. *Sci. Mar.,* **58,** 131–141.

Bode, A., B. Casas, E. Fernández, E. Marañón, P. Serret and M. Varela, 1996. Phytoplankton biomass and production in the shelf waters off NW Spain: spatial and seasonal variability in relation to up-welling. *Hidrobiologia,* **341,** 225–234.

Bode, A., M. Varela, S. Barquero, M.T. Álvarez–Osorio and N. González, 1998. Preliminary studies on the export of organic matter during phytoplankton blooms off La Coruña (North–western Spain). *J. Mar. Biol. Ass. U.K.,* **78,** 1–15.

Borges, A.V. and M. Frankignoulle, 2001. Short–term variations of the partial pressure of CO_2 in surface waters of the Galician upwelling system. *Prog. Oceanogr.,* **51,** 283–302.

Borges, A.V. and M. Frankignoulle, 2002a. Aspects of dissolved inorganic carbon dynamics in the upwelling system off the Galician coast. *J. Mar. Sys.,* **32,** 181–198.

Borges, A.V. and M. Frankignoulle, 2002b. Distribution of surface carbon dioxide and air-sea exchange in the upwelling system off the Galician coast. *Global Biogeochem. Cycles,* **16,** 10.1029/2000GB001385.

Borges, M. F., A. M. P. Santos, N. Crato, H. Mendes and B. Mota, 2003. Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions. *Sci. Mar.,* **67**Suppl.1, 235–244.

Bory, A., C. Jeandel, N. Leblond, A. Vangriesheim, A. Khripounoff, L. Beaufort, C. Rabouille, E. Nicolas, K. Tachikawa, H. Etcheber and P. Buat-Ménard, 2001. Downward particle fluxes within different productivity regimes off the Mauritanian upwelling zone (EUMELI program). *Deep Sea Res. I,* **48,** 2251–2282.

Botas, J.A., E. Fernández, A. Bode and R. Anadón (1989). Water masses off the Central Cantabrian coast. *Sci. Mar.,* **53,** 755–761.

Brander, K., G. Blom, M. F. Borges, K. Erzini, G. Henderson, B.R. MacKenzie, H. Mendes, J. Ribeiro, A.M. P. Santos and R. Toresen, 2003. Changes in fish distribution in the eastern North Atlantic; are we seeing a coherent response to changing temperature?. *ICES Marine Science Symposia,* **219,** 261–270.

Brink, K.H. and T.J. Cowles, 1991. The Coastal Transition Zone Experiment. *J. Geophys. Res.,* **96,** 14637–14647.

Brown, P.C. and J.C. Field, 1986. Factors limiting phytoplankton production in a neashore upwelling area. *J. Plankton Res.,* **8,** 55–68.

Cachâo, M. and M.T. Moita, 2000. *Coccolithus pelagicus* a productivity proxy related to moderate fronts off Western Iberia. *Mar. Micropaleontol.,* **39,** 13–155

Caddy, J.F. and P.G. Rodhouse, 1998. Cephalopod and groudfish landings: evidence for ecological change in global fisheries. *Rev. Fish Biol. Fish.,* **8,** 431–444.

Castro, C.G., 1997. Caracterización química del agua subsuperficial del Atlántico Nororiental y su modificación por procesos biogeoquímicos. Ph.D. Thesis, University of Santiago, 244 pp.

Castro, C.G., F.F. Pérez, X.A. Álvarez–Salgado, G. Rosón and A.F. Ríos, 1994. Hydrographic conditions associated with the relaxation of an upwelling event off the Galician Coast (NW Spain). *J. Geophys. Res.,* **99,** 5135–5147.

Castro, C.G., X.A. Álvarez–Salgado, F.G. Figueiras, F.F. Pérez and F.Fraga, 1997. Transient hydrographic and chemical conditions affecting microplankton populations in the coastal transition zone of the Iberian upwelling system (NW Spain) in September 1986. *J. Mar. Res.,* **55,** 321–352.

Castro, C.G., F.F. Pérez, X.A. Álvarez-Salgado and F. Fraga, 2000. Coupling between thermohaline and chemical fields during two contrasting upwelling events off the NW Iberian Peninsula. *Cont. Shelf Res,,* **20,** 189–210.

Caverivière, A., 1991. L'explosion démographique du baliste (Balistes carolinensis) en Afrique de l'Ouest et son évolution en relation avec les tendances climatiques. In *Pêcheries ouest-africaines: variabilité, instabilité et changement,* Cury P. and C. Roy, eds., Orstom Editions, Paris, pp. 354–367.

Cendrero, O., 2002. Sardine and anchovy crises in northern Spain: natural variations or an effect of human activities?. *ICES Marine Science Symposia,* 215:279–285.

Chauveau, J.P., 1991. Les variations spatiales et temporelles de l'environnement soci-économique et l'évolution de la pêche maritime artisanale sur les côtes ouest-africaines. Essai d'analyse en longue période: XVè-XXè siècle. In *Pêcheries ouest-africaines: variabilité, instabilité et changement.* Cury P. and C. Roy, eds., ORSTOM Editions, Paris, pp. 14–25.

Chavez, F.P., R.T. Barber, P.M. Kosro, A. Huyer, S.R. Ramp, T.P. Stanton and B. Rojas de Mendiola, 1991. Horizontal transport and the distribution of nutrients in the coastal transition zone off Northern California: effects on primary production, phytoplankton biomass and species composition. *J. Geophys. Res.,* **96 (C8),** 14833–14848.

Codispoti, L.A., 1981. Temporal nutrient variability in three different upwelling regions. In *Coastal upwelling,* Richards, F.A., ed., Coastal and Estuarine Sciences 1, Washington D.C., pp. 209–220.

Codispoti, L.A. and G.E. Friederich, 1978. Local and mesoscale influences on nutrient variability in the northwest African upwelling region near Cabo Corbeiro. *Deep Sea Res.,* **25,** 751–770.

Codispoti, L.A., R. C. Dugdale and H. J. Minas, 1982. A comparison of the nutrient regimes off Northwest Africa, Peru and Baja California. *Rapp. Proc. Reun. Cons. Int. Expl. Mer.,* **180,** 184–201.

Cury, P. and C. Roy, 1988. Migration saisonnière du thiof (Epinephelus aeneus) au Sénégal : influence des upwellings sénégalais et mauritaniens. *Oceanol. Acta,* **11,** 1, 25–36.

Cury, P. and C. Roy, 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. *Canad. J. Fish. Aquat. Sci.,* **46,** 670–680.

Cury, P. and C. Roy (eds), 1991. Pêcheries ouest-africaines: variabilité, instabilité et changement. ORSTOM Editions, Paris, 525p.

Dale, A.W. and R. Prego, 2002. Physico–biogeochemical controls on benthic–pelagic coupling of nutrient fluxes and recycling in a costal upwelling system. *Mar. Ecol. Prog. Ser.,* **235,** 15–28.

Demarcq, H. and V. Faure, 2000. Coastal upwelling and associated retention indices from satellite SST. Application to Octopus vulgaris recruitment. *Oceanol. Acta,* **23,** 391–408.

De Hass, H., T.C.E. van Weering and H. de Stigter, 2002. Organic carbon in shelf seas: sinks or sources, processes and products. *Cont. Shelf Res.,* **22,** 691–717.

Dias, C. A., A. Amorim and M. das Dores Vacas, 1992. Sea-surface temperature: seasonal variation between the Iberian coast and the Madeira Islands, 1981–1987. *ICES Marine Science Symposia,* **195,** 177–186.

Dias, C. A., G. Pestana, E. Soares and V. Marques, 1996. Present state of sardine stock in ICES Divisions VIIIc and IXa. Working Document to the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy, 17 pp.

Dias, J., R. Gonzalez, C. Garcia and V. Diaz del Río, 2002a. Sediment distribution patterns on the Galicia–Minho continental shelf. *Prog. Oceanogr.* **52,** 215–231.

Dias, J., J. Jouanneau, R. Gonzalez, M. Araujo, T. Drago, T., C. Garcia, A. Oliveira, A. Rodrigues, J. Vitorino and O. Weber, 2002b. Present day sedimentary processes on the northern Iberian shelf. *Prog. Oceanogr,* **52,** 249–259.

Dickson, R. R., P. M. Kelly, J. M. Colebrook, W. S. Wooster and D. H. Cushing, 1988. North winds and production in the eastern North Atlantic. *J. Plankton Res.,* **10,** 151–169.

DoChi, T. and D.A. Kiefer, 1996. Workshop on the coastal pelagic resources of the upwelling ecosystem of Northwest Africa: research and predictions, Casablanca 15–17 April 1996. FAO:TCP/MOR/4556(A)

Drago, T., A. Oliveira, F. Magalhaes, J. Cascalho, J. Jouanneau and J. Vitorino, 1998. Some evidences of northward fine sediment transport in the northern Portuguese continental shelf. *Oceanol. Acta,* **21,** 223–231.

Duarte, C.M., S. Agustí, J. Arístegui, N. González and R. Anadón, 2001. Evidence for a heterotrophic subtropical northeast Atlantic. *Limnol. Oceanogr.,* **46,** 425–428.

Dugdale, R.C. and F.P. Wilkerson, 1989. New production in the upwelling center at Point Conception, California: Temporal and spatial patterns. *Deep Sea Res.,* **36,** 985–1007.

Dugdale, R.C., F.P. Wilkerson and A. Morel, 1990. Realization of new production in coastal upwelling areas: a means to compare relative performance. *Limnol. Oceanogr.,* **35,** 822–829.

Durand, M-H., P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly (eds), 1998. Global versus local changes in upwelling systems. Editions ORSTOM Paris. 594pp.

Eden, C., and T. Jung, 2001. North Atlantic interdecadal variability: Oceanic response to the North Atlantic Oscillation (1865–1997). *J. Climate,* **14,** 676–691.

Enfield, D. B., and D. A. Mayer, 1997. Tropical Atlantic sea surface temperature variability and its relation to El Nino–Southern Oscillation. *J. Geophys. Res.,* **102,** 929–945.

Epping, E., C. Van der Zee, K. Soetaert and W. Helder, 2002. On the oxidation and burial of organic carbon in sediments of the Iberian margin and Nazare Canyon (NE Atlantic). *Prog. Oceanogr.,* **52,** 399–431.

Eppley, R.W. and B.J. Peterson, 1979. Particulate organic matter flux and plankton new production in the deep ocean. *Nature,* **282,** 677–680.

FAO, 1997. Review of the state of world fishery resources: marine fisheries. FIRM/C920, Fisheries Circular N°920.

Faure, V., C.A. Inejih, H. Demarcq and P. Cury, 2000. The importance of retention processes in upwelling areas for recruitment of Octopus vulgaris: the example of the Arguin Bank (Mauritania). *Fish. Oceanogr.,* **9,** 343–355.

Fermín, E. G., F.G. Figueiras, B.Arbones and M.L. Villarino, 1996. Short–time evolution of a Gymnodinium catenatum population in the Ría de Vigo. *J. Phycol.,* **32,** 212–221.

Fernández, E., J. Cabal, J.L. Acuña, A. Bode, J.A. Botas and C. García–Soto, 1993. Plankton distribution across a slope current–induced front in the southern Bay of Biscay. *J. Plankton Res.,* 15, 619–641.

Fernández, E., E. Marañón, J. Cabal, F. Álvarez and R. Anadón, 1995. Vertical particle flux in outer shelf waters of the southern Bay of Biscay in summer 1993. *Oceanol. Acta,* **18,** 379–384.

Ferraris J., K. Koranteng and A. Samba, 1998. Comparative study of the dynamics of small-scale marine fisheries in Senegal and Ghana. In *Global versus local changes in upwelling systems:* Durand M.H., P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly, eds., Editions ORSTOM, Paris, pp. 447–464.

Figueiras, F.G., K. Jones, A.M. Mosquera, X. A. Álvarez–Salgado, A. Edwards and N. MacDougall., 1994. Red tide assemblage formation in an estuarine upwelling ecosystem: Ría de Vigo. *J. Plank Res,* **16,** 857–878.

Figueiras, F.G., U. Labarta and M. J. Fernández Reiriz, 2002. Coastal upwelling, primary production and mussel growth in the Rías Baixas of Galicia. *Hydrobiologia,* **484,** 121–131.

Fileman, E. and P. Burkill, 2001. The herbivorous impact of microzooplankton during two short–term Lagrangian experiments off the NW coast of Galicia in summer 1998. *Prog. Oceanogr.,* **51,** 361–383.

Fiúza, A.F.G., 1983. Upwelling patterns off Portugal. In *Coastal upwelling.* Suess, E. and J. Thiede, eds., pp. 85–98

Fiúza, A.F.G., 1984 Hidrología e dinámica das augas costeiras de Portugal. Ph.D. Thesis, University of Lisbon, 294 pp.

Fiúza, A.F.G., M. Hamann, I. Ambar, G. Díaz del Río, N. González and J.M. Cabanas, 1998. Water masses and their circulation off western Iberia during May 1993. *Deep Sea Res.,* **45,** 1127–1160.

Fraga, F., 1974. Distribution des masses d'eau ans l'upwelling de Mauritanie. *Téthys,* **6,** 5–10

Fraga, F., 1981. Upwelling off the Galician coast, northwest Spain. In *Coastal upwelling.* Richards, F.A., ed., Washington, DC, pp. 176–182.

Fraga, F., C. Mouriño and M. Manríquez, 1982. Las masas de agua en las costas de Galicia: junio–octubre. Resultados Expediciones Científicas, **10** ,51–77.

Fréon, P., 1983. Production models as applied to sub-stocks depending on upwelling fluctuations. In *Proceedings of the expert consultation to examine changes in abundance and species composition of neritic fish resources.* Sharp, G. D. and J. Csirke, eds., FAO, Fish. Rep. 291 (3), 1047–1064.

Fréon, P. 1988. Réponses et adaptations des stocks de clupéidés d'Afrique de l'ouest à la variabilité du milieu et de l'exploitation : Analyse et réflexion à partir de l'exemple du Sénégal. Etudes et Thèses, ORSTOM, 287 pp.

Fréon, P. Mullon, C. and Pichon, G. 1993. CLIMPROD: Experimental interactive software for choosing and fitting surplus production models including environmental variables. *FAO Computerized information series,* 5, 76 pp.

Friederich, G.E. and L.A. Codispoti, 1982. Some factors influencing dissolved silicon distribution over the Northwest African shelf. *Rapp. Proc. Reun. Cons. Int. Expl. Mer.,* **180,** 205.

Fromentin, J.-M., and B. Planque, 1996. Calanus and environment in the eastern North Atlantic. II. Influence of the North Atlantic Oscillation on C. Finmarchicus and C. Helgolandicus. *Mar. Ecol. Prog. Ser.,* **134,** 111–118.

Frouin, R., A.F.G. Fiúza, I. Ambar and T.J. Boyd, 1990. Observations of a poleward surface current off the coasts of Portugal and Spain during winter. *J. Geophys. Res.,* **95:** 679–691.

Gabric, A.J., L. García, L. van Camp, L. Nykjaer, W. Eifler and W. Schrimpf, 1993. Offshore export of shelf production in the Cape Blanc giant filament as derived from CZSC imagery. *J. Geophys. Res.,* **98,** 4697–4712.

Gago, J., M. Gilcoto, F.F. Pérez and A.F. Ríos, 2003. Short-term varibility of fCO$_2$ in seawater and air-sea CO$_2$ fluxes in a coastal upwelling system (Ría de Vigo, NW Spain). *Mar. Chem.,* **80,** 247–264.

García Muñoz, M., J. Arístegui, J.L. Pelegrí, A. Antoranz, A. Ojeda and M. Torres, 2003. Exchange of carbon and nutrients by an upwelling filament off Cape Guir (NW Africa). *J. Mar. Sys.* (accepted)

Gardener, D., 1977. Nutrients as tracer of water mass structure in the coastal upwelling of Northwest Africa. In *A voyage of Discovery,* Angel, M., ed., Pergamon Press, Oxford and N.Y., 712 pp.

González, N., R. Anadón, B. Mouriño, E. Fernández, B. Sinha, J. Escánez and D. de Armas, 2001. The metabolic balance of plankton community in the N Atlantic Subtropical Gyre: the role of mesoscale instabilities. *Limnol. Oceanogr.,* **46,** 946–952.

Grall, J.R., P. Le Corre, P. Treguer, 1982. Short-term variability of primary production in coastal upwelling of Morocco. *Rapp. Proc. Reun. Cons. Int. Expl. Mer.,* **180,** 221–227

Gulland, J.A. and S. Garcia, 1984. Observed patterns in multispecies fisheries. In *Exploitation of marine communities.* R.M. May, ed., Dahlem Konferenzen. Berlin, Heidelberg, New-York, Tokyo, Springler-Verlag, pp. 155–190.

Hagen, E. and R. Schemainda, 1987. On the zonal distribution of South Atlantic Central Water (SACW) along a section off Cape Blanc, Northwest Africa. *Oceanol. Acta,* vol. special, **6,** 61–70

Hall, I.R., S. Schmidt, I.N. McCave and J.L. Reyss, 2000. Particulate matter distribution and 234Th/238U disequilibrium along the Northern Iberian Margin: implications for particulate organic carbon export. *Deep Sea Res., 47,* 557–582.

Halvorsen, E., A.G. Hirst, S.D. Batten, K.S. Tande and R.S. Lampitt, 2001. Diet and community grazing by copepods in an upwelled filament off the NW coast of Spain. *Prog. Oceanogr., 51,* 399–421.

Hanson, R.B., M. T. Álvarez–Osorio, R. Cal, M.J. Campos, M. Roman, G. Santiago, M. Varela and J. A. Yoder, 1986. Plankton response following a spring upwelling event in the Ría de Arosa, Spain. *Mar. Ecol. Prog. Ser., 32,* 101–113.

Hastenrath, S., L. C. de Castro and P. Aceituno, 1987: The Southern Oscillation in the Atlantic sector. *Contrib. Atmos. Phys., 60,* 447–463

Haynes, R. and E.D. Barton, 1990. A poleward flow along the Atlantic coast of the Iberian Peninsula. *J. Geophys. Res., 95,* 11425–11441.

Haynes, R., E.D. Barton and I. Pilling, 1993. Development, persistence and variability of upwelling filaments off the Atlantic coast of Iberian Peninsula. *J. Geophys. Res., 98,* 22681–22692.

Head, E.J.H., W.G. Harrison, B.D. Irwin, E.P.W. Horne and W.K.W. Li, 1996. Plankton dynamics and carbon flux in an area of upwelling off the coast of Morocco. *Deep Sea Res. I, 43,* 1713–1738

Hempel G., 1982, The Canary current: studies of an upwelling system. Introduction. *Rapp. Proc. Reun. Cons. Int. Expl. Mer., 180,* 7–8.

Hendericks, J., T. Freudenthal, H. Meggers, S. Nave, F. Abrantes, J. Bollmann and H.R. Thierstein, 2002. Glacial-interglacial variability of particle accumulation in the Canary Basin: a time-slice approach. *Deep Sea Res. II, 49,* 3675–3705.

Herbland, A. and B. Voitiurez, 1974. La production primaire dans l'upwelling mauritanien enmars 1973. *Cah. ORSTOM, sér. Océanogr., 12,* 187–201.

Hernandez Guerra, A. and L. Nykjaer, 1997. Sea surface temperature variability off North-West Africa. *Int. J. Remote Sens., 18,* 2539–2558.

Hernández-Guerra, A., J. Arístegui, M.Cantón and L. Nykjaer, 1993. Phytoplankton pigments patterns in the Canary Islands as determined using Coastal Zone Colour Scanner Data. *Int. J. Remote Sens., 14,* 1431–1437.

Hernández-Guerra, A., F. López-Laatzen, F. Machín, D. de Armas and J. L. Pelegrí, 2001. Water masses, circulation and transport in the eastern boundary current of the North Atlantic subtropical gyre. *Sci. Mar., 65 (S1),* 177–186.

Hernández-Guerra, A., F. Machín, A. Antoranz, J. Cisneros-Aguirre, C. Gordo, A. Marrero-Díaz, A. Martínez, A. Ratsimandresy, A. Rodríguez-Santana, P Sangrá, F. López-Laatzen, G. Parrilla and J. L. Pelegrí, 2002. Temporal variability of mass transport in the Canary Current. *Deep-Sea Res. II* (in press).

Hernández-León, S. 1988. Gradients of mesozooplankton biomass and ETS activity in the wind-shear area as evidence o fan island mass effect in te Canary Islands waters. *J. Plankton Res., 10,* 1141–1154

Hernández-León, S. 1991. Accumulation of mesozooplankton in a wake area as a causative mechanism of the "Island-mass effect". *Mar. Biol., 109,* 141–147.

Hernández-León, S., C. Almeida, L. Yebra, J. Arístegui, 2002. Lunar cycle of zooplankton biomass in subtropical waters: biogeochemical implications. *J. Plankton Res., 24,* 935–939.

Hughes, P. and E. D. Barton, 1974. Stratification and water mass structure in the upwelling area off northwest Africa. *Mém. Soc. Roy. Sciences Liège,* 6 sér., **X,** 31–42.

Huntsman, S.A. and R.T. Barber, 1977. Primary production off northwest Africa: the relationship to wind and nutrient conditions. *Deep-Sea Res. I, 24,* 25–33.

Hurrell, J. W., 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science, 269,* 676–679.

Huthnance, J.M., H.M.V.Aken, M. White, E.D. Barton, B. Le Cann, B., E.F. Coelho, E., E.A. Fanjul, P. Miller and J. Vitorino, 2002. Ocean margin exchange–water flux estimates. *J. Mar. Sys.,* **32,** 107–137.

ICES, 2002. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy. ICES CM 2002/ACFM:6, 474 pp.

Inejih, C. A., 2000. Dynamique spatio-temporelle et biologie du poulpe (Octopus vulgaris) dans les eaux mauritaniennes: modélisation de l'abondance et aménagement des pêches. Thèse de doctorat. Université de Bretagne Occidentale, Brest, 155pp.

Jickells, T.D., P.P. Newton, P. King, R.S. Lampitt and C. Boutle, 1996. A comparison of sediment traps record of particle fluxes from 19° to 48° in the Northeast Atlantic and their relation to surface water productivity. *Deep Sea Res. I,* **43,** 971–986.

Joint, I. and P. Wassmann, 2001. Lagrangian studies of the Iberian upwelling system–an introduction. A study of the temporal evolution of surface production and fate of organic matter during upwelling an and off the NW Spanish continental margin. *Prog. Oceanogr.,* **51,** 217–221.

Joint, I., A.P. Rees and E.M.S. Woodward 2001a. Primary production and nutrient assimilation in the Iberian upwelling in August 1998. *Prog. Oceanogr.,* **51,** 303–320.

Joint, I., M. Inall, R. Torres, F.G. Figueiras, X.A. Álvarez–Salgado, A.P Rees and E.M.S. Woodward, 2001b. Two lagrangian experiments in the Iberian upwelling system: tracking an upwelling event and an off–shore filament. *Prog. Oceanogr.,* **51,** 221–248.

Joint, I., S.B. Groom, R. Wollast, L. Chou, G.H. Tilstone, F.G. Figueiras, M. Loijens and T.J. Smyth., 2002. The response of phytoplankton production to periodic upwelling and relaxation events at the Iberian shelf break: estimates by the 14C method and by satellite remote sensing. *J. Mar. Sys.,* **32,** 219–238.

Jones, B.H., C.N.K. Mooers, M.M. Rienecker, T. Stanton and L. Washburn, 1991. Chemical and biological structure and transport of a cool filament associated with a jet-eddy system off northern California in July 1986 (OPTOMA21). *J. Geophys. Res.,* **96 (C12),** 22207–22225

Jouanneau, J., O. Weber, T. Drago, A. Rodrigues, A. Oliveira, J. Dias, C. Garcia, S. Schmidt and J. Reyss, 2002. Recent sedimentation and sedimentary budgets on the western Iberian shelf. *Prog. Oceanogr.,* **52,** 261–275.

Kébé, M., 1994. Principales mutations de la pêche artisanale maritime sénégalaise. In *L'évaluation des resources exploitables par la pieche artisanale sénégalaise.* Barry-Gérard M.B., T. Diouf and A. Fonteneau., tome 2. ORSTOM Editions, Paris, 43:58.

Kifani S., 1998. Climate dependant fluctuatiosn of the Moroccan sardine and their impact on fisheries. In *Global versus local changes in upwelling systems.* Durand M.H., P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly, eds., Editions ORSTOM Paris, 235–248.

Klein, S. A., B. J. Soden and N.-C. Lau., 1999. Remote Sea Surface Temperature Variations during ENSO: Evidence for a Tropical Atmospheric Bridge. *J. Climate,* **12,** 917–932.

Kostianoy, A.G. and A.G. Zatsepin, 1996. The west African coastal upwelling filaments and cross-frontal water exchange conditioned by them. In *The coastal ocean in a global change perspective,* Djenidi, S., ed., *J. Mar Sys.,* **7,** 349–359

Krauss, W., 1986. The North Atlantic Current. *J. Geophys. Res.* **91,** 5061–5074.

avín, A., G. Díaz del Rio, G. Casas and J. M. Cabanas, 2000. Afloramiento en el noroeste de la Península Ibérica. Índices de afloramiento para el punto 43° N, 11° O, Periodo 1990–1999 [Upwelling in the NW of the Iberian Peninsula. Upwelling indexes at 43° N, 11° W, between 1990–1999]. Datos y Resúmenes Instituto Español de Oceanografia (15), 25 pp.

Lenz, J., 1982. Particulate organic matter off Northwest Africa: size distribution and composition in relation to shore distance and depth. *Rapp. Proc. Reun. Cons. Int. Expl. Mer.,* **180,** 234–238.

Lloyd, I.J., 1971. Primary production off the coast of north-west Africa. *J. Cons. Int. Explor. Mer,* **33,** 312–323.

Longhurst, A., S. Sathyendranath, T. Platt and C. Caverhill, 1995. An estimate of global primary pro-
duction in the ocean from satellite radiometer data. *J. Plankton Res.,* **17,** 1245–1272.

López–Jamar, E., R.M. Cal, G. González, R.B. Hanson, J. Rey, G. Santiago and K.R. Tenore, 1992.
Upwelling and outwelling effects on the benthic regime of the continental shelf off Galicia, NW
Spain. *J. Mar. Res.* **50,** 465–488.

MacIsaac, J.J., R.C. Dugdale, R.T. Barber, D. Blasco, and T.T. Packard, 1985. Primary production cycle
in an upwelling center. *Deep Sea Res,* **32,** 503–529.

Marañón, E. and E. Fernández, 1995. Changes in phytoplankton ecophysiology across a coastal upwell-
ing front. *J. Plankton Res.,* **10,** 1999–2008.

Marshall, J., Y. Kushnir, D. Battisti, P. Chang, A. Czaja, R. Dickson, J. Hurrell, M. McCartney, R.
Saravanan and M. Visbeck, 2001. North Atlantic Climate variability: phenomena, impacts and
mechanisms. *Int. J. Climat.,* **21,** 1863–1898.

Maus, J., 1997. Sustainable fisheries information management in Mauritania. PhD thesis. Ecosystem
analysis and Management Group. University if Warwick, Coventry, 269pp.

McCave, I. and I. Hall, 2002. Turbidity of waters over the Northwest Iberian continental margin. *Prog.
Oceanogr.,* **52,** 299–313.

McClain, C.R., S.–Y. Chao, L.P. Atkinson, J.O. Blanton and F.F. de Castillejo, 1986. Wind–driven
upwelling in the vicinity of Cape Finisterre, Spain. *J. Geophys. Res.,* **91,** 8470–8486.

Meggers, H., T. Freudenthal, S. Nave, J. Targarona, F. Abrantes and P. Helmke, 2002. Assessment of
geochemical and micopaleontological sedimentary parameters as proxies of surface water properties
in the Canary Islands region. *Deep Sea Res. II,* **49,** 3631–3654.

Minas, H.J., L.A. Codispoti and R.C. Dugdale, 1982. Nutrients and primary production in the upwelling
region off Northwest Africa. *Rapp. Proc. Reun. Cons. Int. Expl. Mer.,* **180,** 148–183.

Minas, H.J., M. Minas and T.T. Packard, 1986. Productivity in upwelling areas deduced from
hydrographic and chemical fields. *Limnol. Oceanogr.,* **31,** 1182–1206.

Mittlelstaedt, E., 1991. The ocean boundary along the northwest African coast: circulation and
oceanographic properties at the sea surface. *Prog. Oceanogr.,* **26,** 307–355.

Moncoiffé, G., X.A. Álvarez–Salgado, F.G. Figueiras and G. Savidge, 2000. Seasonal and short time–
scale dynamics of microplankton community production and respiration in an inshore upwelling
system. *Mar. Ecol. Prog. Ser.,* **196,** 111–126.

Morán, X.A.G., J.M. Gasol, C. Pedrós–Alió and M. Estrada, 2002a. Partitioning of phytoplankton
organic carbon production and bacterial production along a coastal–offshore gradient in the NE
Atlantic during different hydrographic regimes. *Aquat. Microb. Ecol.,* **29,** 239–252.

Morán, X.A.G., M. Estrada, J.M. Gasol and C. Pedrós–Alió, 2002b. Dissolved primary production and
the strength of phytoplankton–bacterioplankton coupling in contrasting marine regions. *Microb.
Ecol.,* **44,** 217–223.

Morel, A., 1996. An Ocean flux study in eutrophic, mesotrophic and oligotrophic situations: the
EUMELI program. *Deep-Sea Res. I,* **43,** 1185–1190.

Morel, A., D. Antoine, M. Babin and Y. Dandonneau, 1996. Measured and modeled primary
production in the northeast Atlantic (EUMELI JGOFS program): the impact of natural variations in
photosynthetic parameters on model predictive skills. *Deep-Sea Res. I,* **43,** 1273–1304.

Nagata, T. 2000. Production mechanims of dissolved organic matter. In *Microbial ecology of the oceans*
Kirchman, D.L., ed., Wiley and Sons, New York, pp. 121–152.

Navarro-Pérez, E. and E. D. Barton, 1998. The physical structure of an upwelling filament off the
north-west African coast during August 1993. In *Benguela dynamics: impacts of variability of shelf –
sea environments and their living resources,* Pillar, S.C., C.L. Moloney, A.I.L. Payne and F.A. Shilling-
ton, eds., *S. Afr. J. Mar. Sci.,* **19,** 61–74

Navarro-Pérez, E. and E. D. Barton, 2001. Seasonal and interannual variability of the Canary Current.
Sci. Mar., **65 (S1),** 205–213.

Neuer, S., T. Freudenthal, R. Davenport, O. Llinás, and M.J. Rueda, 2002. Seasonality of surface water properties and particle flux along a productivity gradient off N.W. Africa. *Deep Sea Res. II,* **49,** 3561–3576.

Nobre, P. and J. Shukla, 1996. Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate,* **9,** 2464–2479.

Nogueira, E., F.F. Pérez and A.F. Ríos, 1997. Modelling thermohaline properties in an estuarine up-welling ecosystem (Ría de Vigo: NW Spain) using box–Jenkins transfer function models. *Est. Coast. Shelf Sci.,* **44,** 685–702.

Nykjaer L. and L. Van Camp, 1994. Seasonal and interannual variability of coastal upwelling along Norhwest Africa and Portugal from 1981 to 1991. *J. Geophys. Res.,* **99,** C7, 14197–14207.

Oliveira, A., J. Vitorino, A. Rodrigues, J. Jouanneau, J. Dias and O. Weber, 2002. Nepheloid layer dynamics in the northern Portuguese shelf. *Prog. Oceanogr.* , **52,** 195–213.

Olli, K., C.W. Riser, P. Wassmann, T. Ratkova, E. Arashkevich and A. Pasternak, 2001. Vertical flux of biogenic matter during a Lagrangian study off the NW Spanish continental margin. *Prog. Oceanogr,* **51,** 443–466.

Ould-Dedah, S., W.J. Wiseman Jr. and R.F. Shaw, 1999. Spatial and temporal trends of sea surface temperature in the northwest African region. *Oceanol. Acta,* **22,** 265–279.

Pacheco, M. and A. Hernández-Guerra, 1999. Seasonal variability of recurrent phytoplankton pigment patterns in the Canary Islands area .. *Int. J. Remote Sens.,* **29,** 1405–1418.

Parrilla, G., S. Neuer, P.-Y. Le Traon and E. Fernández-Suárez, 2002. Topical studies in oceanography : Canary Islands Azores Gibraltar Observations (CANIGO). Volume 1: Studies in the northern Canary Islands basin. *Deep Sea Res. II,* **49,** 3409–3413

Pelegrí, J. L., P. Sangrà and A. Hernández-Guerra, 1997. Heat gain in the eastern North Atlantic subtropical gyre. In *The mathematics of models for climatology and environment,* Díaz J. I., ed., NATO ASI Series, Vol. I 48, Springer-Verlag, Berlin, pp. 419–436.

Pelegrí, J. L., J. Arístegui, L. Cana, M. González-Dávila, A. Hernández-Guerra, S. Hernández-León, A. Marrero-Díaz, M. F. Montero, P. Sangrà and M. Santana-Casiano, 2003. Coupling between the open ocean and the coastal upwelling region off Northwest Africa: Water recirculation and offshore pumping of organic matter. *J. Mar. Sys.* (accepted)

Pelíz, A.J. and A.F.G. Fiúza , 1999. Temporal and spatial variability of CZCS–derived phytoplankton pigment concentrations off the western Iberian Peninsula. *Int. J. Remote Sens.,* **20,** 1363–1403.

Pérez, F.F., A.F. Ríos, B.A. King and R.T. Pollard, 1995. Decadal changes of the O-S relationship of the Eastern North Atlantic Central Water. *Deep-Sea Res.,* **42,** 1849–1864.

Pérez, F.F., A.F. Ríos and G. Rosón, 1999. Sea surface carbon dioxide off the Iberian Peninsula (NE Atlantic Ocean). *J. Mar. Sys.,* **19,** 27–46.

Pérez, F.F., X.A. Álvarez–Salgado and G. Rosón, 2000a. Stochiometry of nutrients (C, N, P and Si) consumption and organic matter production in a coastal inlet affected by upwelling. *Mar. Chem.,* **69,** 217–236.

Pérez, F.F., R.T. Pollard, J.F. Read, V. Valencia, J.M. Cabanas and A.F. Ríos, 2000b. Climatological coupling of the thermohaline decadal changes in Central Water of the Eastern North Atlantic. *Sci. Mar.,* **64,** 347–353

Pérez, F.F., C.G. Castro, X.A. Álvarez–Salgado and A.F. Ríos, 2001. Coupling between the Iberian basin–scale circulation and the Portugal boundary current system. A chemical study. *Deep Sea Res I,* **48,** 1519–1533.

Pilskan, C.H., J.B. Paduan, F.P. Chavez, R.Y. Anderson and W.M. Berelson, 1996. Carbon export and regeneration in the coastal upwelling system of Monterey Bay, central California. *J. Mar. Res.,* **54,** 1149–1178.

Pingree, R.D., 1994. Winter warming in the southern bay of Biscay and Lagrangian Eddy kinematics from a deep–drogued argos buoy. *J. Mar. Biol. Ass. U.K.,* **74,** 107–128.

Pingree, R.D. and B. Le Cann, 1990. Structure, strength and seasonality of the slope currents in the bay of Biscay region. *J. Mar. Biol. Ass.U.K.,* **70,** 857–885.

Pingree, R.D. and B. Le Cann, 1992. Three anticyclonic Slope Water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. *Deep Sea Research II,* **39,** 1147–1175.

Prego, R., 1994. Nitrogen interchanges generated by biogeochemical processes in a Galician Ria. *Mar. Chem.,* **45,** 167–176.

Prego, R. and R. Bao, 1997. Upwelling influence on the Galician coast: silicate in shelf water and underlying surface sediments. *Cont. Shelf Res.,* **17,** 307–318.

Prego, R., M.C. Barciela and M. Varela, 1999. Nutrient dynamics in the Galician coastal area (North-western Iberian Peninsula): Do the Rias Bajas receive more nutrient salts than the Rías Altas?. *Cont. Shelf Res,* **19,** 317–334.

Quero, J-C., M-H. Du Buit and J-J. Vayne, 1998. Les observations de poissons tropicaux et le réchauffement des eaux dans l'Atlantique européen. *Oceanol. Acta,* **21,** 345–351.

Relexans, J.-C., J. Deming, A. Donet, J.-F. Gaillard and M. Sibuet, 1996. Sedimentary organic matter and micro-meiobenthos with relation to trophic conditions in the tropical northeast Atlantic. *Deep Sea Res. I,* **43,** 1343–1368.

Relvas, P. and E. D. Barton, 2002. Mesoscale patterns in the Cape São Vicente (Iberian Peninsula) upwelling region. *J. Geophys. Res.,* 107(C10), 3164, doi:10.1029/2000JC000456, 2002.

Ríos, A.F., F.F. Pérez and F. Fraga, 1992. Water masses in upper and middle North Atlantic Ocean east of Azores. *Deep Sea Res. I,* **39,** 645–658.

Riser, C.W., P. Wassmann, K. Olli and E. Arashkevich, 2001. Production, retention and export of zooplankton faecal pellets on and off the Iberian shelf, north–west Spain. *Prog. Oceanogr,* **51,** 423–441.

Rodríguez, J.M., S. Hernández-León and E.D. Barton, 1999. Mesoscale distribution of fish larvae in relation to an upwelling filament off Northwest Africa. *Deep Sea Res. I* , **46,** 1969–1984

Rodríguez, J.M., E.D. Barton, L. Eve and S. Hernández-León, 2001. Mesozooplankton and ichtyoplankton distribution around Gran Canaria, an oceanic island in the NE Atlantic. *Deep Sea Res. I* , **48,** 2161–2183

Rosón, G., X.A. Álvarez–Salgado and F.F. Pérez, 1999. Carbon cycling in a large coastal embayment affected by wind–driven upwelling. Short–time–scale variability and spatial differences. *Mar. Ecol. Prog. Ser.,* **176,** 215–230.

Roy, C., 1989. Fluctuations des vents et variabilité de l'upwelling devant les côtes du Sénégal. *Oceanol. Acta,* **12,** 361–369.

Roy, C. and C. Reason. 2001. ENSO related modulation of coastal upwelling in the eastern Atlantic. *Prog. Oceanogr,* **49,** 245–255.

Roy, C., P. Cury, A. Fontana and H. Belvèze. 1989. Stratégies spatio-temporelles de la reproduction des clupéidés des zones d'upwelling d'Afrique de l'Ouest. *Aquat. Liv. Resources,* **2,** 21–29.

Roy, C., P. Cury and S. Kifani, 1992. Pelagic fish recruitment success and reproductive strategy in upwelling areas : environmental compromises. In *Benguela Trophic Functioning.* Payne, A.I.L., Brink, K.H., Mann, K.H. and R. Hilborn, eds., *S. Afr. J. Mar. Sci.,* **12,** 135–146.

Santana-Casiano, J.M., M. González-Dávila, L.M. Laglera-Baquer and M.J. Rodriguez-Somoza, 2001. Carbon dioxide system in the Canary region during October 1995. *Sci. Mar.,* **65,** 41–49.

Santos, A. M. P., M. F. Borges and S. Groom, 2001. Sardine and horse mackerel recruitment and upwelling off Portugal. *ICES J. Mar. Sci.,* **58,** 589–596.

Schmidt, S., L. Chou and I.R. Hal, 2002a. Particle residence times in surface waters over the north–western Iberian Margin: comparison of pre–upwelling and winter periods. *J. Mar. Sys.* **32,** 3–11.

Schmidt, S., T.C. van Weering, J.L. Reyss and P. van Beek, 2002b. Seasonal deposition and reworking at the sediment–water interface on the northwestern Iberian margin. *Prog. Oceanogr,* **52,** 331–348.

Schulz, S., 1982. A comparison of primary production in upwelling regions off Northwest and Southwest Africa. *Rapp. P. –v. Reún. Cons. Int. Explor .Mer,* **180,** 202–204.

Seager, R., Y. Kushnir, M. Visbeck, N. Naik, J. Miller, G. Krahmann, and H. Cullen, 2000. Causes of Atlantic Ocean climate variability between 1958 and 1998. *J. Climate,* **13,** 2845–2862.

Seibold, E., 1982. Sediments in upwelling areas, particularly off Northwest Africa. *Rapp. Proc. Reun. Cons. Int. Expl. Mer.,* **180,** 315–322.

Serret, P., E. Fernández, F.A. Sostres, and R. Anadón, 1999. Seasonal compensation of microbial production and respiration in a temperate sea. *Mar. Ecol. Prog. Ser.,* **187,** 43–57.

Serret, P., E. Fernández and C. Robinson, 2002. Biogeographic differences in the net ecosystem metabolism of the open ocean. *Ecology,* **83,** 3225–3234.

Siedler, G. and R. Onken, 1996. Eastern recirculation. In *The warmwatersphere of the North Atlantic Ocean,* W. Krauss, ed., Gebrüder Borntraeger, Berlin, pp. 339–364.

Silva, A.J., 1992. Dependence of upwelling related circulation on wind forcing and stratification over the Portuguese northern shelf. International Council for the Exploitation of the Sea, Council Meeting, Hydrography Committee C17, 1–12.

Slagstad, D. and P. Wassmann, 2001. Modelling the 3–D carbon flux across the Iberian margin during the upwelling season in 1998. *Prog. Oceanogr,* **51,** 467–497.

Sousa, F.M. and A. Bricaud, 1992. Satellite-derived phytoplankton pigment structures in the Protuguese upwelling area. *J. Geophys. Res.,* **97,** 11343–11356.

Sprengel, C., K-H. Baumann, J. Henderiks, R. Henrich and S. Neuer, 2002. Modern coccolitophore carbonate sedimentation along a productivity gradient in the Canary Islands region: seasonal export production and surface accumulation rates. *Deep Sea Res. II,* **49,** 3577–3598.

Stramma, L. and G. Siedler, 1988. Seasonal changes in the North Atlantic subtropical gyre. *J. Geophys. Res.,* **93,** 8111–8118.

Stratoudakis, Y., A. Morais, A. Silva, V. Marques and C. A. Dias, 2002. Sardine distribution, abundance and population structure off Portugal: acoustic surveys in 1984–2000. Working Document to the Working Group On the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy. ICES CM 2002/ACFM:6, p. 473

Stratoudakis, Y., M. Bernal, D. Borchers and M. F. Borges, 2003. Changes in the distribution of sardine eggs and larvae off Portugal, 1985–2000. Fisheries Oceanography, **12,** 49–60

Strom, L.S., R. Benner, S. Ziegler and M.J. Gagg, 1997. Planktonic grazers are a potentially important source of marine dissolved organic carbon. *Limnol. Oceanogr.,* **42,** 1364–1374.

Strub, P.T., P.M. Kostro and A. Huyer, 1991. The nature of cold filaments in the California Current System. *J. Geophys. Res.,* **96 (C8),** 14743–14768.

Teira, E., P. Serret and E. Fernández, 2001. Phytoplankton size–structure, particulate and dissolved organic carbon production and oxygen fluxes through microbial communities in the NW Iberian coastal transition zone. *Mar. Ecol. Prog. Ser.,* **219,** 65–83.

Tenore, K.R., M. Alonso–Noval, M. Álvarez–Osorio, L.P. Atkinson, J.M. Cabanas, R.M. Cabal, H.J. Campos, F. Castillejo, E.J. Chesney, N. González, R. B. Hanson, C.R. McClain, A. Miranda, M.R. Roman, J. Sanchez, G. Santiago, L. Valdes, M. Varela and J. Yoder, 1995. Fisheries and oceanography off Galicia, NW Spain: Mesoscale spatial and temporal changes in physical processes and resultant patterns of biological productivity. *J. Geophys. Res.,* **100,** 10943–10966.

Tilstone, G.H., F. G. Figueiras, E.G. Fermín and B. Arbones, 1999. Significance of nanophytoplankton photosynthesis and primary production in a coastal upwelling system (Ría de Vigo, NW Spain). *Mar. Ecol. Prog. Ser.,* **183,** 13–27.

Tilstone, G.H., B.M. Míguez, F.G. Figueiras and E.G. Fermín, 2000. Diatom dynamics in a coastal ecosystem affected by upwelling: coupling between species succession, estuarine circulation and biogeochemical processes. *Mar. Ecol. Prog. Ser.,* **205,** 23–41.

Tilstone, G.H., F.G. Figueiras, L.M. Lorenzo and B. Arbones, 2003. Phytoplankton composition, photosynthesis and primary production during different hydrographic conditions at the NW Iberian upwelling system. *Mar. Ecol. Prog. Ser.,* **252,** 89–104.

Torres, R., E.D. Barton, P. Miller and R. Fanjul, 2003. Spatial patterns of wind and sea surface temperature in the Galician upwelling region, *J. Geophys. Res.,* 108(C4), 3130, doi: 10.1029/2002JC001361, 2003.

Tréguer, P., P. Le Corre and J.R. Grall, 1979. The seasonal variations of nutrients in the upper waters of the Bay of Biscay region and their relation to phytoplankton growth. *Deep–Sea Res.,* **26A,** 1121–1152.

Van Aken, H.W., 2002. Surface currents in the bay of Biscay as observed with drifters between 1995 and 1999. *Deep–Sea Res. I,* **49,** 1071–1086.

Van Lenning, K., 2000. Variability in biomass and structure of phytoplankton populations in the Canary Islands waters, as determined by HPLC analyses of pigments. PhD. Thesis. University of Las Palmas de Gran Canaria, 270 pp.

Van Weering, T.C. and I.N. McCave, 2002. Benthic processes and dynamics at the NW Iberian margin: an introduction. *Progr. Oceanogr., 52,* 123–128

Van Weering, T.C., H. de Stigter, W. Boer and H. de Haas, 2002. Recent sediment transport and accumulation on the NW Iberian margin. *Prog. Oceanogr.,* **52,** 349–371.

Varela, M., G. Diaz del Río, M. T. Álvarez–Osorio and E. Costas, 1991. Factors controlling phytoplankton size class distribution in the upwelling area of the Galician continental shelf (NW Spain). *Sci. Mar.,* **55,** 505–518.

Vitorino, J.O., J.M. Jouanneau and T. Drago, 2002a. Winter dynamics on the northern Portuguese shelf. Part I: physical processes. *Prog. Oceanogr.,* **52,** 129–153.

Vitorino, J.O., J.M. Jouanneau and T. Drago, 2002b. Winter dynamics on the northern Portuguese shelf. Part 2: bottom boundary layers and sediment dispersal. *Prog. Oceanogr.,* **52,** 155–170.

Wada, E. and A. Hattori, 1991. Nitrogen in the sea: forms, abundances and rate processes. CRC Press, Boca Raton.

Watson, A.J., 1995. Are upwelling zones sources or sinks of CO_2?,. In *Upwelling in the ocean. Modern processes and ancient records.* C.P. Summerhayes, K.–C. Emeis, M. V. Angel, R. L. Smith and B. Zeitzschel, eds, Wiley Sons, pp. 321–336.

Wefer, G. and G. Fisher, 1993. Seasonal patterns of vertical particle flux in equatorial and coastal upwelling areas of the eastern Atlantic. *Deep Sea Res. I,* **40,** 1613–1645.

Woodruff, S.D., R.J. Slutz, R. L. Jenne and P. M. Steurer, 1987. A Comprehensive Ocean-Atmosphere Data-Set. *Bull. Amer. Meteor. Soc.,* **68,** 1239–1250.

Wooster, W.S., A. Bakun and D.R. McLain, 1976. The seasonal upwelling cycle along the eastern boundary of the North Atlantic. *J. Mar. Res.,* **34,** 131–141.