3.3. Eastern boundary currents off North-West Africa

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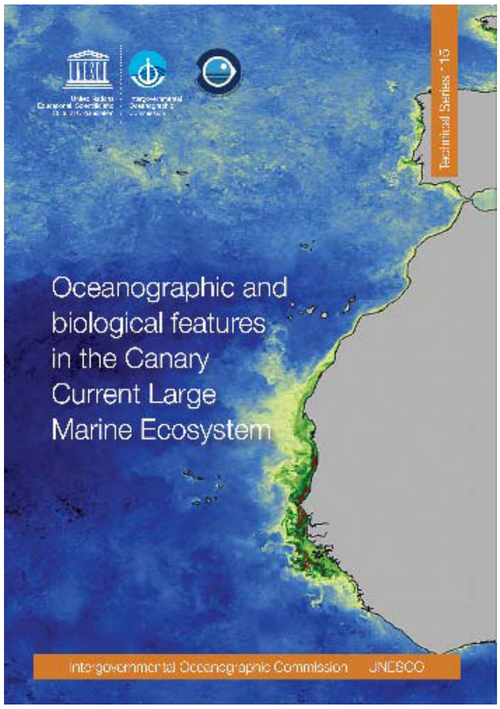

The report *Oceanographic and biological features in the Canary Current Large Marine Ecosystem* and its separate parts are available on-line at: http://www.unesco.org/new/en/ioc/ts115.

The bibliography of the entire publication is listed in alphabetical order on pages 351-379. The bibliography cited in this particular article was extracted from the full bibliography and is listed in alphabetical order at the end of this offprint, in unnumbered pages.

ABSTRACT

The Cape Verde Front (CVF) separates the North Atlantic subtropical gyre (NASG) from the north-eastern North Atlantic tropical gyre (NATG). Within the NASG, the Canary Current (CC) and the Canary Upwelling Current (CUC) comprise a relatively shallow (down to about 200-300 m) flow of North Atlantic Central Waters (NACW): the CC is found far offshore as a wide and poorly defined current while the CUC is a near-slope intense baroclinic jet linked to the coastal upwelling front. Within the top 300 m of the NATG, the along-slope Mauritania Current and the Cape Verde Current (CVC, a north-eastern extension of the North Equatorial Counter Current that broadly rotates around the Guinea Dome) carry South Atlantic Central Waters northwards. As a result, the frontal system is the site of intense along-slope flow convergence and offshore transport in the top 300 m of the water column. Further deep, down to some 500 m, the interior flow is very weak in both gyres, likely dominated by mesoscale features, except along the continental slope, where the northward Poleward Undercurrent (PUC) feeds through localized inputs from the interior ocean; in particular, within the NATG the CVC appears as responsible for southward transfer of NACW, across the CVF, which eventually reaches the PUC.

Keywords: Eastern boundary currents · Cape Verde Front · Canary Upwelling Current · Poleward Undercurrent · Guinea Dome · Canary Current Large Marine Ecosystem · Northwest Africa

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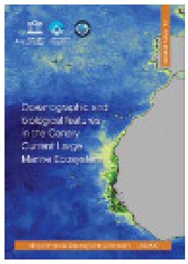

EASTERN BOUNDARY CURRENTS OFF NORTH-WEST AFRICA

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3.3.1. INTRODUCTION

From an oceanographic perspective, the Canary Current Large Marine Ecosystem (CCLME) may be divided in two major domains: the south-eastern boundary of the North Atlantic subtropical gyre (NASG) and the north-eastern North Atlantic tropical gyre (NATG) (Fig. 3.3.1). These two gyres are formed by surface and upper-thermocline waters – subducted from the sea surface at higher latitudes of both Atlantic hemispheres. The eastern margins of both gyres constitute the boundary current system off North-west Africa (NWA).

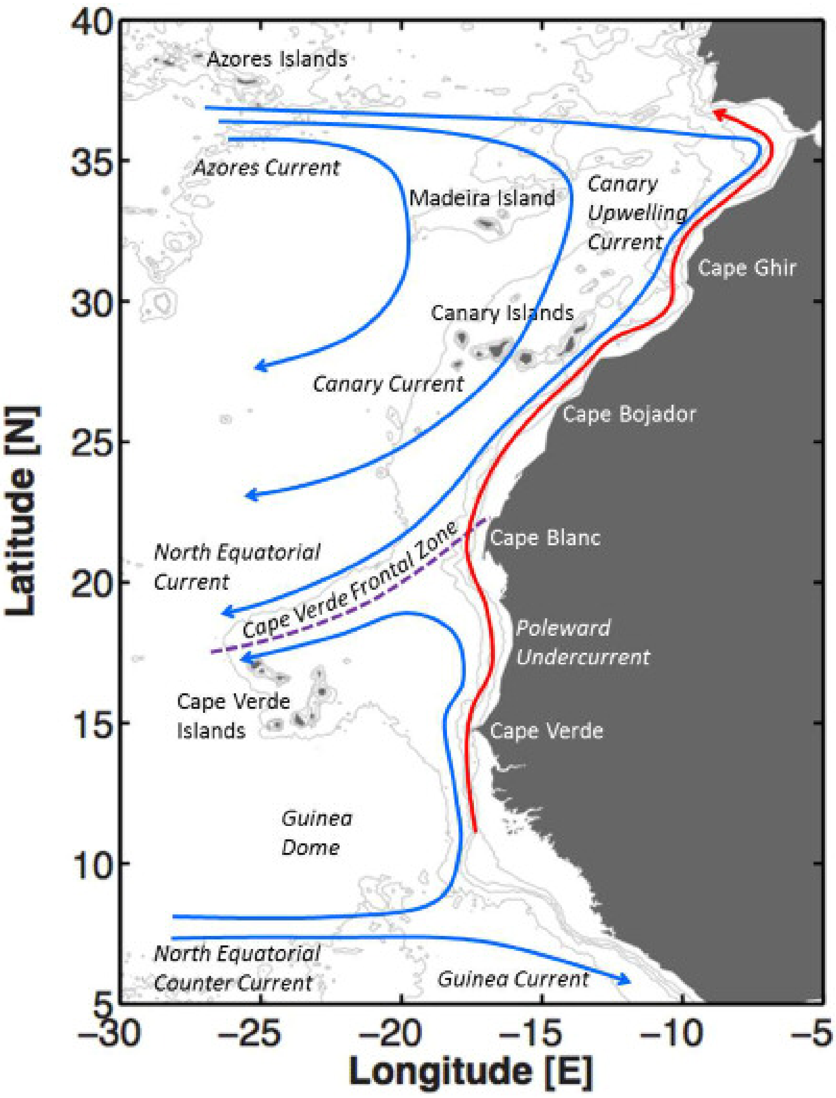

Figure 3.3.1. Scheme illustrating the main geographic features and mean oceanographic currents (italics) in the permanent thermocline of the CCLME; the red line shows the track of the Poleward Undercurrent.

The NASG waters come from the central North Atlantic (North Atlantic Central Waters, NACW) and enter the CCLME region following a relatively direct south-eastward path. The NATG waters, on the other hand, have their origin in the central South Atlantic (South Atlantic Central Waters, SACW) and take a much more intricate route to reach the CCLME: they cross the equatorial region mostly in the western Atlantic, off South America, and arrive to the eastern NATG through a system of zonal jets and recirculations north of the Equator (Rosell-Fieschi et al., 2015; Peña-Izquierdo et al., 2015). The two gyres, and associated water masses, are separated by the Cape Verde Front (CVF), a wide (4-6° of latitude) thermohaline front stretching roughly between Cape Blanc and the northernmost Cape Verde Islands (Fig. 3.3.1) (Zenk et al., 1991; Pérez-Rodríguez et al., 2001). Another frontal system, much shallower (at most 250 m) and narrower (1° of longitude), is found off the African continental slope, extending from the Gulf of Cadiz until Cape Blanc (Cape Vert) in boreal summer (winter) - this is the coastal upwelling front (CUF), separating stratified interior-gyre from more homogeneous slope waters.

In this article we examine the predominant geostrophic currents (annual and seasonal means) of these three upper-thermocline dynamic domains in the CCLME: the south-eastern NASG, the north-eastern NATG, and the upwelling region. We focus on the two main gyres and their seasonal variability, and also look at their connection with the upwelling system (further examined in Pelegrí and Benazzouz, 3.4 this book); other related circulation phenomena are addressed elsewhere in this volume: spatial distribution of water masses (Pastor et al., 3.2 this book) and mesoscale processes (Sangrà, 3.5 this book). For our analysis, we will use the 9-km resolution sea-surface-temperature (SST) and color Moderate Resolution Imaging Spectroradiometer (MODIS) data (2002-2014) from the National Aeronautics and Space Administration (NOAA, 2014) and the Etopo2v2 bathymetry (2’ resolution) (NGDC-NOAA, 2006). The wind data (2007-2014) is from the advanced scatterometer (ASCAT) on board the meteorological operational platforms of the Centre de Recherche et d'Exploitation Satellitaire (CERSAT, 2014). The velocity data (1992-2011) comes from the ECCO2 project (Estimating the Circulation and Climate of the Ocean, phase II), a general circulation model (Marshall et al., 1997) with 0.25° horizontal resolution and 50 vertical levels that uses realistic atmospheric forcing and assimilates satellite and in situ data (JPL-NASA, 2014).

3.3.2. ANNUAL-MEAN CURRENTS

3.3.2.1. The subtropical gyre

The NASG is a wind-induced anticyclone, formed by upper-thermocline North Atlantic waters with temperatures down to about 10°C (potential density anomalies about 27.3 kg m^{-3}), reaching some 700-800 m in the eastern boundary and 1000-1100 m in the western boundary (Kawase and Sarmiento, 1985; Machín et al., 2006a). The southeastern margin of the NASG comprises the eastward Azores Current (AC), the southward Canary Current (CC) and Canary Upwelling Current (CUC), and the westward North Equatorial Current (NEC) (Stramma, 1984) (Figs. 3.3.1 and 3.3.2). The NASG experiences wind-induced surface convergence and water subduction, i.e. waters originate near the sea surface and recirculate at depth following an anticyclonic path in near-geostrophic balance (Stommel, 1979; Luyten et al., 1983), so the vertical hydrographic structure reflects the latitudinal changes in the surface formation regions.

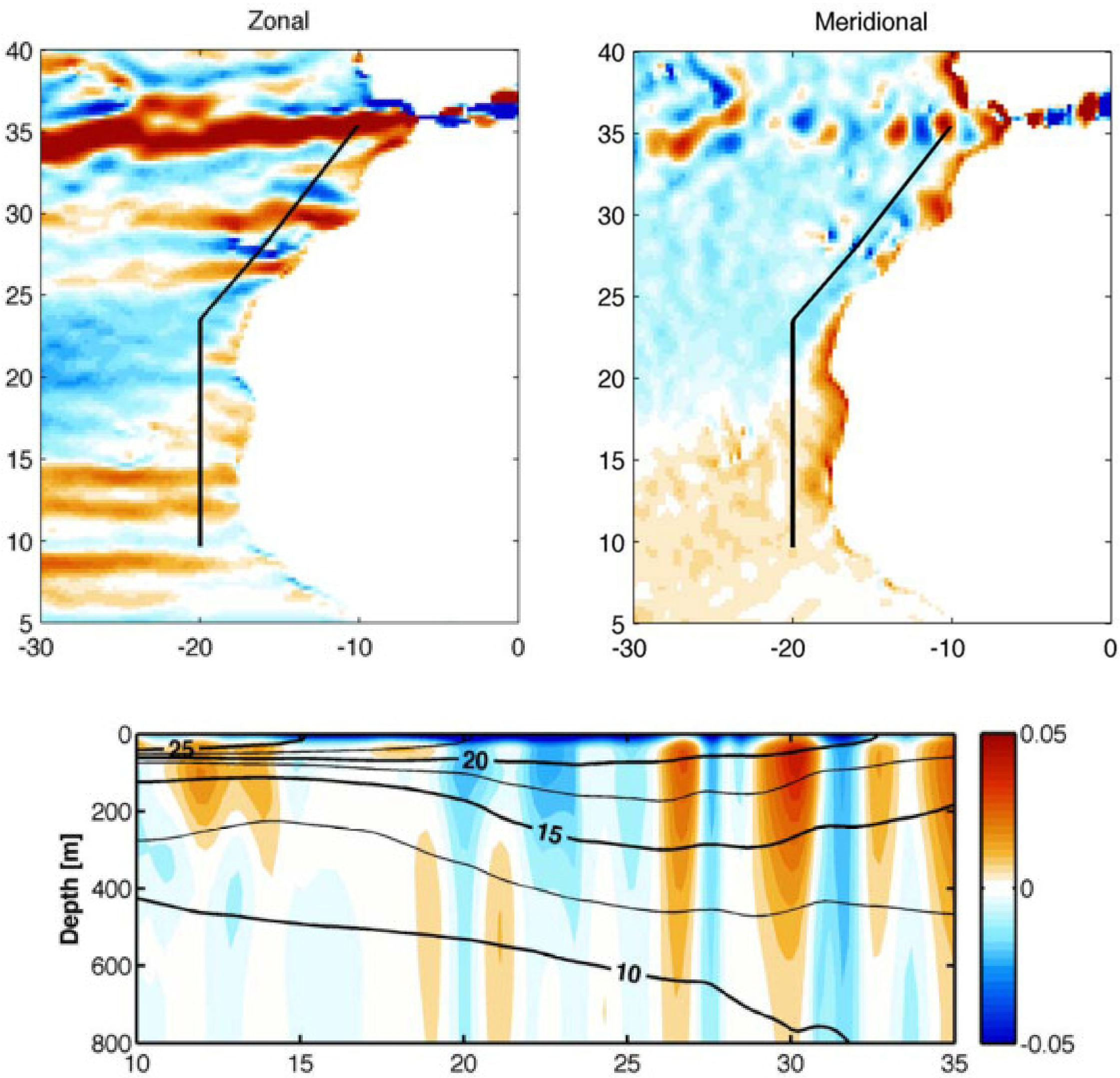

Figure 3.3.2. Mean annual velocities from the ECCO2 model (color-coded, positive values for eastward and northward components; m s^{-1}). Top panel: Zonal and meridional components at 200 m. Bottom panel: component normal to the section in the top panels; temperature (°C) is plotted as solid contours.

Most of the AC flows south as part of the NASG recirculation although about 1 Sv follows into the Mediterranean Sea (Candela, 2001) and another fraction, the Iberian Current, continues north during boreal winter (Haynes et al., 1993). Beyond the Azores Islands, the AC recirculates south as the interior CC (a mean transport of 1 Sv) and the coastal CUC (a mean transport of 1.5 Sv) (Laiz et al., 2012). The gentle eastward rise of the upper-thermocline leads to the southward flowing CC, with mean surface values less than 0.05 m s^{-1}. Closer to the African slope, typically within 2-5°, the upper portion of the water column (about 200 m) rises sharply as a result of wind-induced coastal upwelling, with the appearance of a relatively narrow (100-200 km) and intense (locally in excess of 0.25 m s^{-1}) coastal upwelling jet, the CUC or easternmost branch of the CC (Pelegrí et al., 2005a, 2006). The CUC begins in the Gulf of Cadiz, feeding directly from the AC, and is enhanced through water inflow from the ocean interior, in what is the classical upwelling vertical cell (Pelegrí and Benazzouz, 3.4 this book).

The Canary Islands are a major obstacle to the southward flow (Fig. 3.3.2). The CC follows the deep channels between the main islands, except for an offshore diversion in late boreal fall (Navarro-Pérez and

Barton, 2001; Pelegrí et al., 2005a), and the CUC streams between the eastern islands and the African coast (Hernández-Guerra et al., 2001, 2002). The CC and CUC extend south until near Cape Blanc, where they are fully diverted following the CVF. Between the slope and the CUC, we find the Poleward Undercurrent (PUC), an intense subsurface northward flow which is usually centred at 200-300 m but may occasionally extend from as deep as 800 m to the sea surface (Barton, 1989).

3.3.2.2. The tropical gyre

The NATG covers the zonal band south of the NASG, between the Equator and about 10°N, reaching Cape Blanc (21°N) along the eastern edge. It is a cyclonic region crossed by several seasonally changing zonal jets (Stramma and Schott, 1999; Rosell-Fieschi et al., 2015) (Fig. 3.3.2) – its cyclonic character, with the isothermals rising towards the Equator, is due to the wind-induced equatorial divergence and tropical-subtropical convergence (Castellanos et al., 2015). The eastern NATG extends down some 500 m, reaching down to about 10°C or potential densities of 27.15 kg m^{-3} (less dense than in the subtropical gyre because of its lower salinity), encircled by the westward NEC, the eastward North Equatorial Countercurrent (NECC) and Cape Verde Current (CVC), and the northward Mauritanian Current (MC) and PUC.

The eastward NECC ventilates the southern CCLME between May and December, with maximum zonal speeds of 0.5 m s^{-1} reaching beyond 10°N in August (Rosell-Fieschi et al., 2015). The CVC also flows east between 12°N and 17°N, down to about 300 m, before turning west south of the CVF (Peña-Izquierdo et al., 2015). Along the African slope, the MC is an extension of the NECC and, possibly, the north Equatorial Undercurrent. The PUC has also been found along the continental slope of the NATG during late boreal fall (Peña-Izquierdo et al., 2012), as a continuation of the Guinea Undercurrent (Mittelstaedt, 1976) and possibly the NECC (Rosell-Fieschi et al., 2015; Peña-Izquierdo et al., 2015).

The eastern NATG is classically associated to the south-eastern shadow zone of the NASG, a region which cannot be directly reached by the relatively young waters of the NASG (Luyten et al., 1983). As a result, the NATG thermocline waters are much older; their origin goes back to the subduction regions of the central South Atlantic Ocean and the intermediate waters that upwell near the Equator, reaching the NATG after an intricate path principally along the western Atlantic margin. The interior of the NATG, centred at about (10°N, 20°W) is occupied by the Guinea Dome (GD) (Siedler et al., 1992); the GD intensifies in summer as a result of the northward penetration of the Inter-Tropical Convergence Zone (ITCZ) and the South Atlantic High, bringing westward winds, surface water divergence and upwelling.

3.3.3. THE FRONTAL SYSTEMS

3.3.3.1. The Cape Verde frontal system

The eastern margins of the subtropical and tropical gyres are separated by the CVF, a wide (4-6° of latitude) frontal system with substantial gradients in temperature-salinity and even larger gradients in inorganic nutrients and dissolved oxygen (Pelegrí and Peña-Izquierdo, 4.1 this book), mirroring the remarkable differences between those regions where NACW and SACW are formed. However, the temperature and salinity fields are density-compensating – below the surface mixed layer, along any given density or depth level, the NACW is warmer and saltier than the SACW (Pastor et al., 3.2 this book) – so the cross-frontal density gradients are feeble. This leads to the NEC, a relatively weak along-front geostrophic current (annual-mean speeds less than 0.05 m s^{-1}), which stretches over several degrees of latitude in the top 300-400 m of the water column.

The confluence of southward (CC and, particularly, the CUC) and northward (PUC and MC) currents along the CVF is the locus of substantial along-shore convergence. This convergence drives chlorophyll- and inorganic-nutrient-rich waters, coming from the tropical gyre and the coastal upwelling region, into the south-eastern edge of the subtropical gyre. The load of inorganic nutrients helps maintain high primary production far from the coast, leading to a giant filament, which appears as a quite remarkable feature in colour satellite images (Fig. 3.3.3) (Gabric et al., 1993; Pastor et al., 2013). The CVF is an effective barrier between the NASG and the NATG but it also acts as a source of lateral mixing. The thermohaline horizontal gradients produce lateral subsurface intrusions (Zenk et al., 1991; Pérez-Rodríguez et al., 2001; Pastor et al., 2008) and the dynamic character of the front generates mesoscale features, in some instances detaching from the adjacent coastal upwelling front (Pastor et al., 2008).

3.3.3.2. The coastal upwelling front

The north-easterly winds along the African coastline cause offshore surface transport and cross-shore water divergence. The result is the CUF, a shallow (typically 200 m) but relatively intense frontal system, found permanently between the Gulf of Cadiz and Cape Blanc, and reaching Cape Vert between late fall and early spring (boreal seasons). The upwelling-frontal region contains the same offshore water masses (NACW/SACW in the subtropical/tropical gyres) yet it truly constitutes a distinct dynamic domain in the CCLME – the coastal transition zone (CTZ) (Barton et al., 1998). The frontal system is usually found offshore from the continental slope, giving rise to the coastal upwelling jet (speeds often in excess of 0.1 m s^{-1}); because of its upstream connection to the Azores Current, this jet constitutes the CUC. Between the CUC and the continental slope we find the relatively homogeneous upwelled waters, typically on top of the subsurface northward PUC.

The CUC and PUC constitute the true skeleton of the CCLME, connecting different latitudes along the CTZ by respectively conveying waters of northern and southern origin. The CUF is also a source of mesoscalar variability, both as eddies (Benítez-Barrios et al., 2011; Ruiz et al., 2014) and filaments (Hagen et al., 1996; Pelegrí et al., 2005b). The size of these eddies is typically the same as the width of the CUF but, west of Cape Bojador, they may be much larger – this happens in late fall as a result of an offshore recirculation which leads to a CUC local reversal (Pelegrí et al., 2005a; Laiz et al., 2012). These coastal eddies, together with those generated downstream of the Canary Islands, propagate westwards as Rossby waves (Sangrà et al., 2009; Mason et al., 2011). Additionally, part of the CUC deviates offshore as surface filaments, mainly at Cape Ghir and, to a lesser degree, off Cape Jubi and Cape Bojador (Hagen et al., 1996; Pelegrí et al., 2005b). For a detailed discussion on the dynamics and characteristics of the CTZ and the associated mesoscalar features, the reader is referred to Pelegrí and Benazzouz, 3.4 this book, and Sangrà, 3.5 this book.

3.3.4. SEASONAL VARIABILITY

The patterns of circulation in the NASG and, very particularly, the NATG display substantial seasonal variability. This is because of the latitudinal motion of the ITCZ and the accompanying high pressure centres (Azores High in the northern hemisphere and South Atlantic High in the southern hemisphere) – along 20°W, the ITCZ moves from 2°N to 14°N between February and August (Hastenrath and Lamb, 1977). In terms of wind forcing, the CTZ may be separated in three domains (all seasons are boreal): between Cape

Vert and Cape Blanc, with north-easterly winds during winter and doldrums and even westerlies during summer; between Cape Blanc and the Canary Islands, with permanent intense north-easterlies; and from the Canary Islands to the Gulf of Cadiz, where the north-easterlies are present all year long but intensify during summer (Fig. 3.3.3).

The changes in wind forcing have several major effects on (a) the intensity and extension of the CUC, (b) the connection between the AC and the CUC, (c) the intensity and extension of the PUC, (d) the recirculation patterns in the NATG, and (d) the flow convergence and offshore export along the CVF. To illustrate these changes we use the seasonal-mean outputs from the ECCO2 model (JPL-NASA, 2014), with the seasons defined as winter (December-February), spring (March-May), summer (June-August), and fall (September-November) (Figs. 3.3.4-3.3.6). In Figure 3.3.4 we present the cross-shore velocities along the same latitudinal section depicted in Fig. 3.3.2; in Figures 3.3.5 and 3.3.6 we show the meridional velocities across four longitudinal sections (30°N, 24°N, 18°N and 12°N), selected to illustrate the seasonal changes north of the Canary Islands, between Cape Blanc and the Canary Islands, and south of Cape Blanc.

3.3.4.1. Coastal upwelling

The remarkable latitudinal extent of the upwelling region shows up clearly in the SST maps (Benazzouz et al., 2014b) (Fig. 3.3.3). During summer and fall, a narrow band of cold upwelled waters extends from the Gulf of Cadiz to Cape Blanc; between Cape Blanc and the Canary Islands, where the winds are most intense, the influence of upwelling reaches far offshore, visible as a second band of surface waters with intermediate SSTs. During winter and spring upwelling reaches Cape Vert, but the band of upwelled waters is much narrower south of Cape Blanc; north of the Canary Islands upwelling still exists but this is hardly visible in the SST images, particularly in winter, because of the relatively low offshore SSTs.

The seasonal variation in the vertical structure of the CUF and the associated CUC may be appreciated from the vertical zonal sections in Figures 3.3.5 and 3.3.6. The CUF is present all year long north of Cape Blanc, 2-4° away from the coast between Cape Blanc and the Canary Islands; during fall, at 30°N and off the slope, the near-surface meridional currents are particularly intense, reflecting a local recirculation south of Cape Ghir (see section 3.3.4.3 below). South of Cape Blanc the CUF is only visible in spring, at 18°N, suggesting that the SST fall and winter patterns (Fig. 3.3.3) correspond to very shallow structures.

3.3.4.2. The Azores Current and the Canary Upwelling Current

The Gulf of Cadiz halts the upstream CUC flow, so the supply necessarily has to come from the AC (Pelegrí et al., 1997, 2005a, 2006; Machín et al., 2006b; Laiz et al., 2012). North of the Canary Islands, the AC transport into the CTZ is larger during winter-spring (2.8 Sv) than during summer-fall (1.9 Sv) (Laiz et al., 2012), possibly because of substantial offshore recirculations (fall and winter panels, Fig. 3.3.4).

The southward transport between the eastern Canary Islands and the continental slope does not change much throughout the year: 1.5 Sv during winter-spring as compared with 1.6 Sv during summer-fall (Laiz et al., 2012). Nevertheless, as a result of local recirculations, the flow through this eastern passage turns north in October-December (Hernández-Guerra et al., 2001, 2002; Laiz et al., 2012).

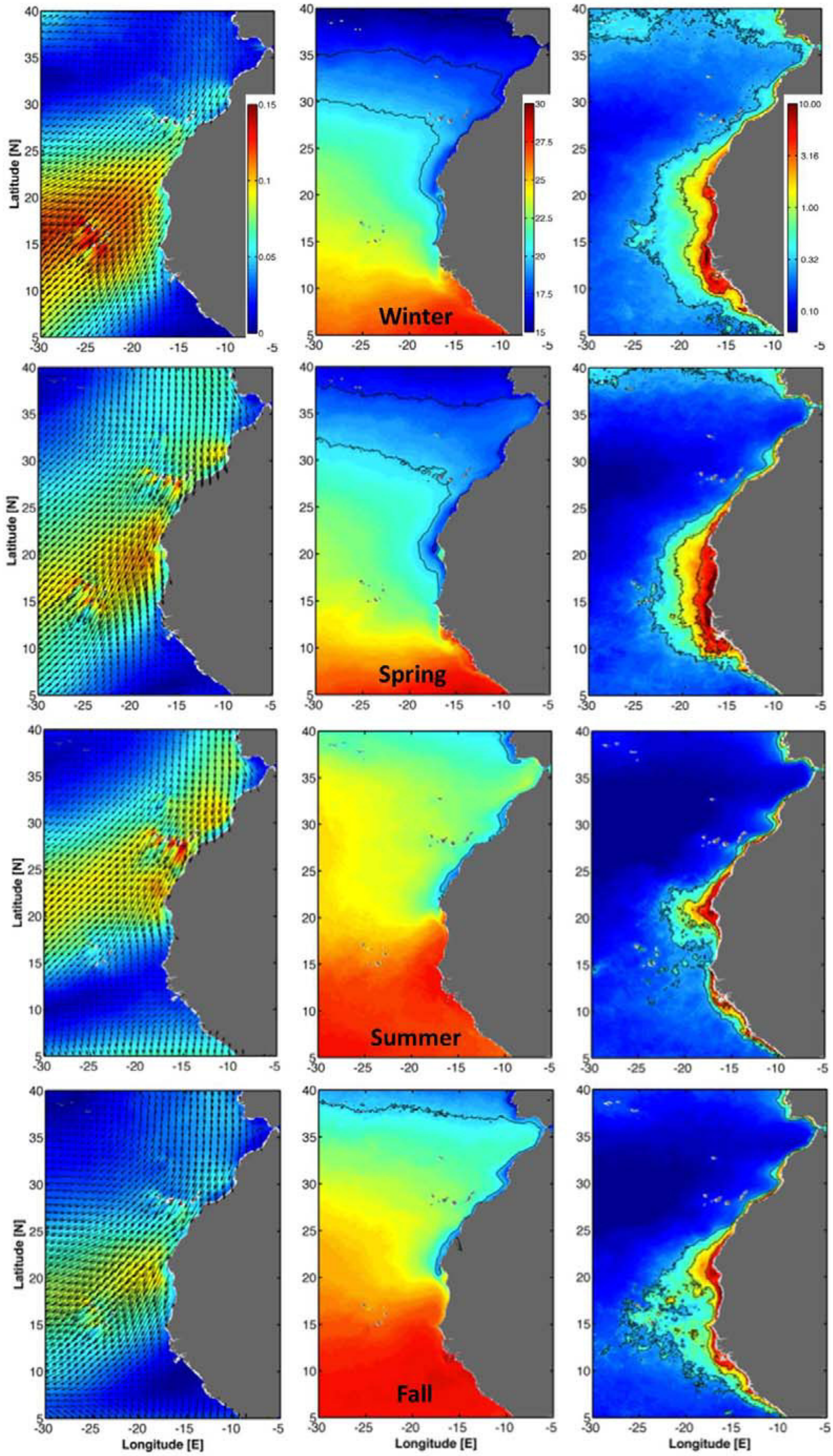

Figure 3.3.3. Boreal season distributions in the CCLME (winter, spring, summer and fall, from top to bottom) of (left) surface winds (m s^{-1}), (middle) SST (°C), and (right) near-surface chlorophyll-a (mg m^{-3}).

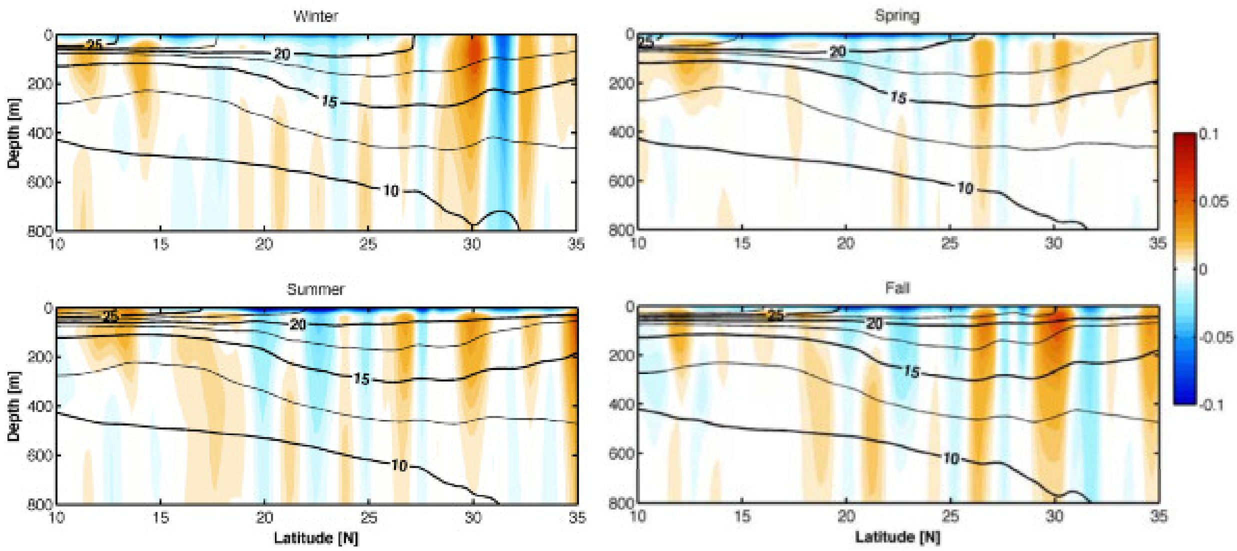

Figure 3.3.4. Mean seasonal distributions of the cross-slope velocity (normal to the meridional section in Figure 3.3.2) as deduced from the ECCO2 model (color-coded, with positive values for onshore velocities; m s^{-1}); temperature (°C) as solid contours.

3.3.4.3. The Poleward Undercurrent

The ubiquity and importance of the PUC is clear in the annual-mean meridional velocity maps (Fig. 3.3.2). The seasonal velocity fields across the four zonal sections confirm the latitudinal continuity of the PUC all along NWA – except south of Cape Blanc during boreal spring (Figs. 3.3.5 and 3.3.6). South of Cape Vert the PUC does not extend very deep, except possibly in boreal summer, and is located further offshore – this surface flow may actually be identified as the northward MC. North of Cape Blanc, the PUC intensifies through onshore intakes located north and south of the Canary Islands and near the CVF (Fig. 3.3.4). During boreal summer and fall, the PUC is particularly intense at 30°N because of a local cyclonic recirculation south of Cape Ghir (Fig. 3.3.6) – during these seasons the northward flow extends to 800 m, as a result of the propagation of intermediate waters (Machín and Pelegrí, 2009; Machín et al., 2010).

3.3.4.4. Circulation in the north-eastern tropical gyre

The results from the model suggest a boreal summer-fall intensification of the CVC (flowing east through 20°W, between 11°N-18°N; Fig. 3.3.4) and the NECC (north through 12°N, west of 20°W; Figs. 3.3.5 and 3.3.6); this coincides with the boreal late-summer and fall growth of the PUC and MC (Lazaro et al., 2005). In boreal winter and spring the GD weakens and the NATG currents decrease.

Because of the semi-enclosed character of the circulation and the weak currents, water parcels have long residence times within the basin, e.g. a parcel moving at 0.1 m s^{-1} would travel less than 800 km in three months, so that the renovation rate depends on the way the Lagrangian pathways are affected by the seasonally changing circulation (Peña-Izquierdo et al., 2015).

3.3.4.5. Flow convergence at the Cape Verde front

According to the model, the zonal band occupied by the CVF (18°N to 21°N) is characterized by year-long near-surface convergence and offshore export, with maximum values during summer and, particularly, fall (Fig. 3.3.4); this result is in agreement with Pastor et al. (2008), who found CVF-related convergence and export to increase from 0.6 Sv to 3.0 Sv between spring and fall. The summer-fall increase in along-slope convergence contrasts with the sea surface color images, where the high surface chlorophyll values occupy their maximum extension during winter and spring (Fig. 3.3.3), see also Pastor et al. (2013); this is likely caused by the seasonal increase in nutrient supply south of Cape Blanc, due to high coastal upwelling and river discharge, brought north by the surface MC.

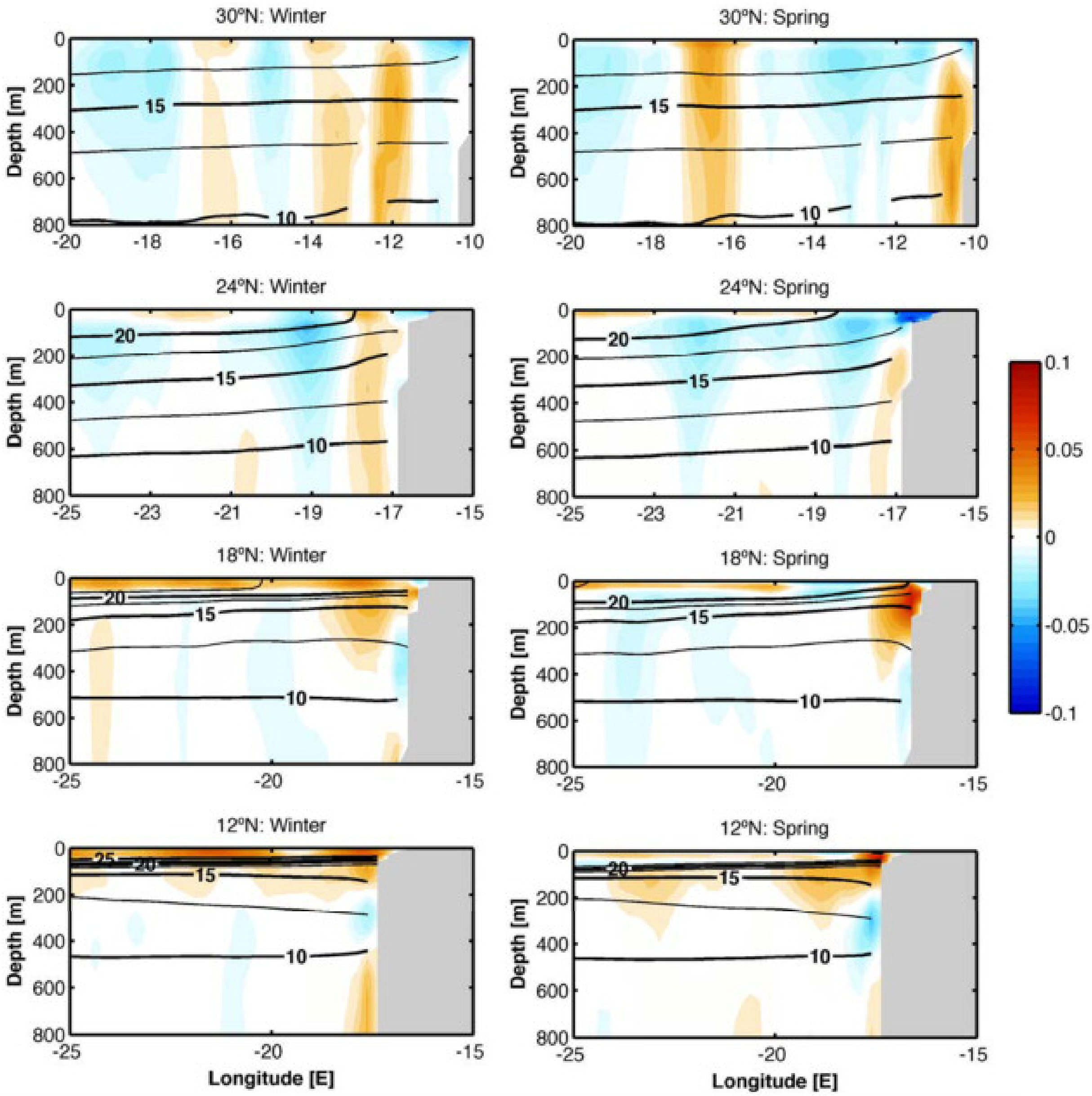

Figure 3.3.5. Mean boreal winter (left) and spring (right) distributions of the meridional velocity along zonal sections (30°N, 24°N, 18°N and 12°N; from top to bottom) as deduced from the ECCO2 model (color-coded, with positive values for onshore velocities; m s^{-1}); temperature (°C) as solid contours.

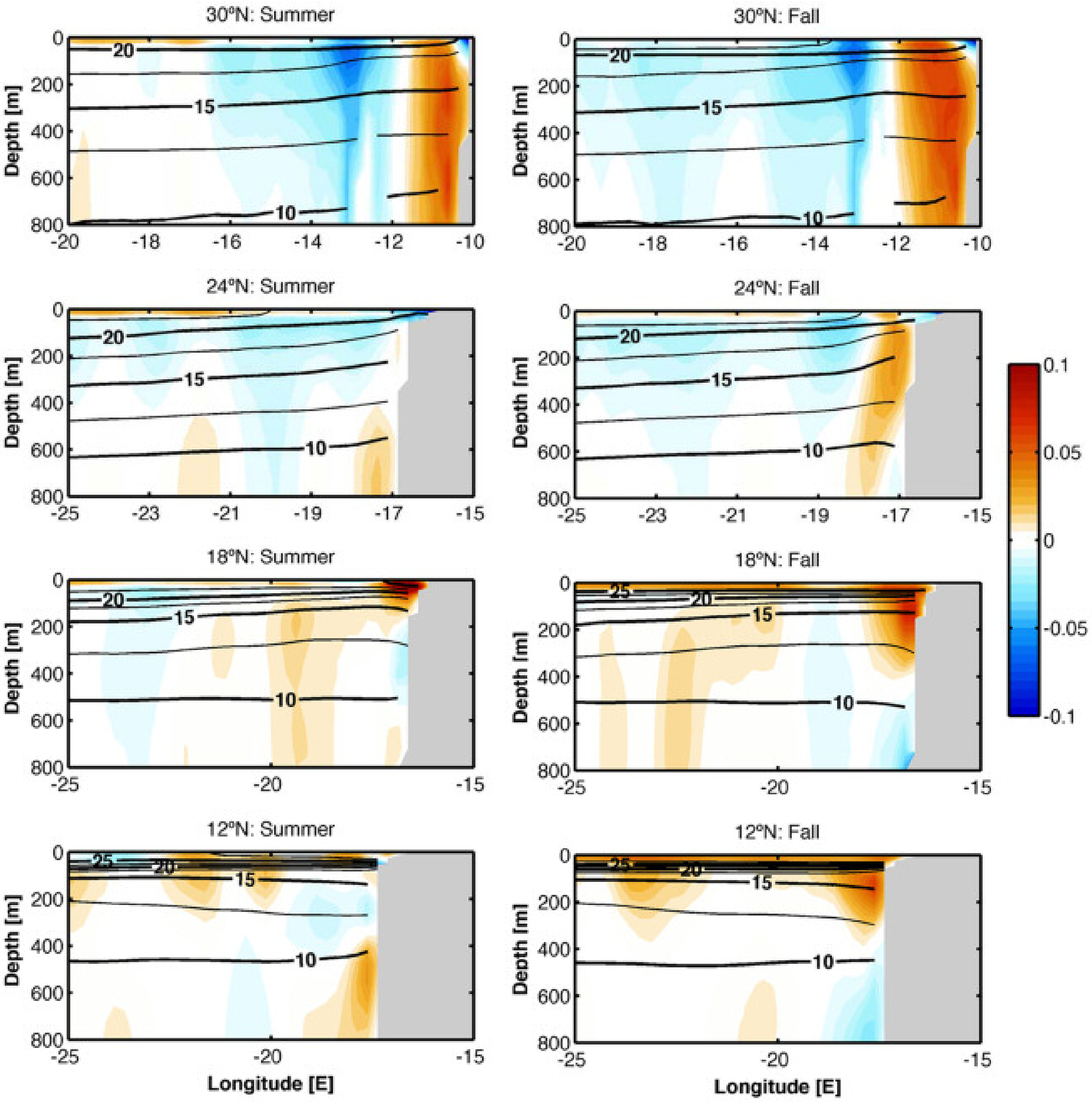

Figure 3.3.6. Mean boreal summer (left) and fall (right) distributions of the meridional velocity along zonal sections (30°N, 24°N, 18°N and 12°N; from top to bottom) as deduced from the ECCO2 model (color-coded, with positive values for onshore velocities; m s^{-1}); temperature (°C) as solid contours.

3.3.5. CONCLUSIONS

The characteristics of the CCLME are controlled by the encountering of the eastern limb of two major ocean gyres: the NASG and the NATG (Fig. 3.3.7). Both these gyres bring water from the interior ocean to the CTZ, where it recirculates meridionally thanks to a system of along-slope currents, predominantly southward in the NASG and northward in the NATG – the two gyres converge into the CVF, where water is expulsed back to the interior ocean. Therefore, despite the presence of offshore meridional currents – the CC in the northern gyre and the cyclonic motions around the GD in the southern gyre – the eastern boundary structure that connects both gyres is the latitudinal current system along the CTZ.

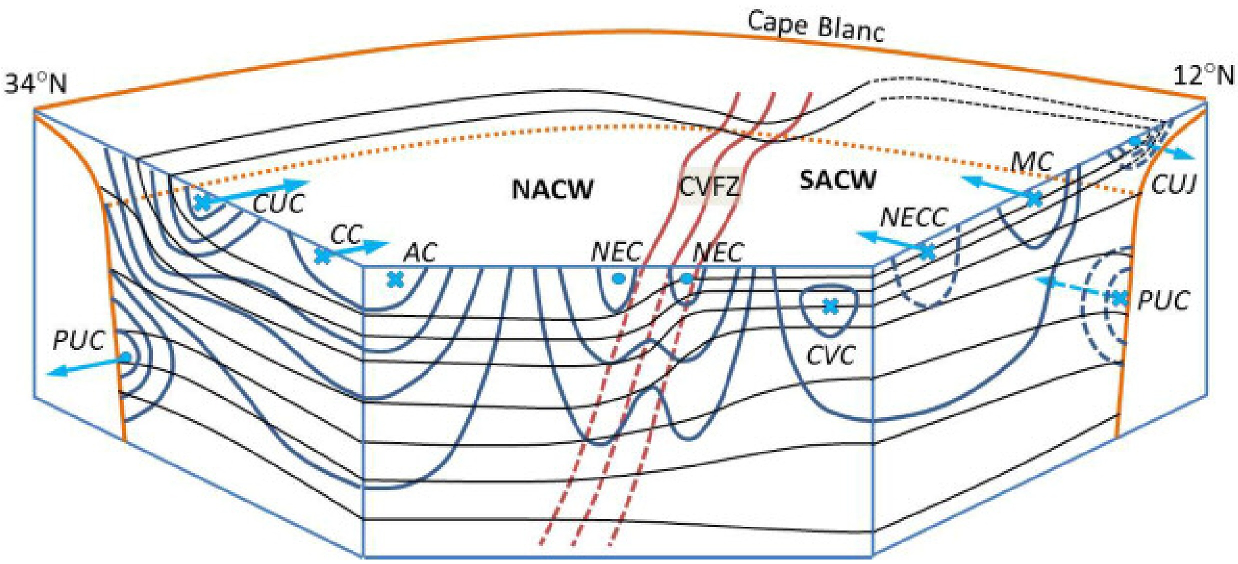

Figure 3.3.7. Cartoon for the principal geostrophic currents in the CCLME, with isopycnals (black lines) and isotachs (blue lines; dashed lines denote seasonal flows); the arrows mark the locus of the peak currents.

The system of along-slope currents is composed by the CUC, flowing south between the Gulf of Cadiz and Cape Blanc, and the PUC, streaming north as a near-surface current until Cape Vert and as a subsurface current till the Gulf of Cadiz and beyond. The way these two currents interact between themselves and with the interior flow is what sets the system of eastern boundary currents (Pelegrí et al., 2005a). Such interaction occurs through both upstream input – the AC for the CUC and the MC for the OUC – and along-track exchange – the vertical upwelling cell for the CUC (Pelegrí and Benazzouz, 3.4 this book) and the interaction between the GD and the CTZ for the PUC.

Our understanding of these boundary systems has greatly increased through the availability of field and satellite observations, as well as thanks to high-resolution numerical circulation models. It could be argued that we now understand the predominant large-scale patterns and their seasonality (Fig. 3.3.8) and are left to learn the inter-annual and longer time-scale variability (Pastor et al., 2013; Benazzouz et al., 2014a, b; Peña-Izquierdo et al., 2015). However, many questions on the annual- and seasonal-mean transports remain open, particularly those related to the exchange of properties across the frontal systems, the way the frontal systems interact among each other, and the spatial and temporal variability of the PUC.

What sets the cross-slope location of both CUC and PUC? What are the principal mechanisms for cross-frontal exchange? What happens with the CUC and MC-PUC in the intersection between the CVF and the CUF? What drives the spatial and temporal variability of the PUC? How the offshore and coastal upwelling systems shape the mean currents in the NATG? What drives localized flow reversals, such as the fall reversal east of the Canary Islands? How are the mean transports affected by the generation of vortices at the frontal systems and their posterior westward propagation? All these questions remain a challenge for the present and future generations of oceanographers.

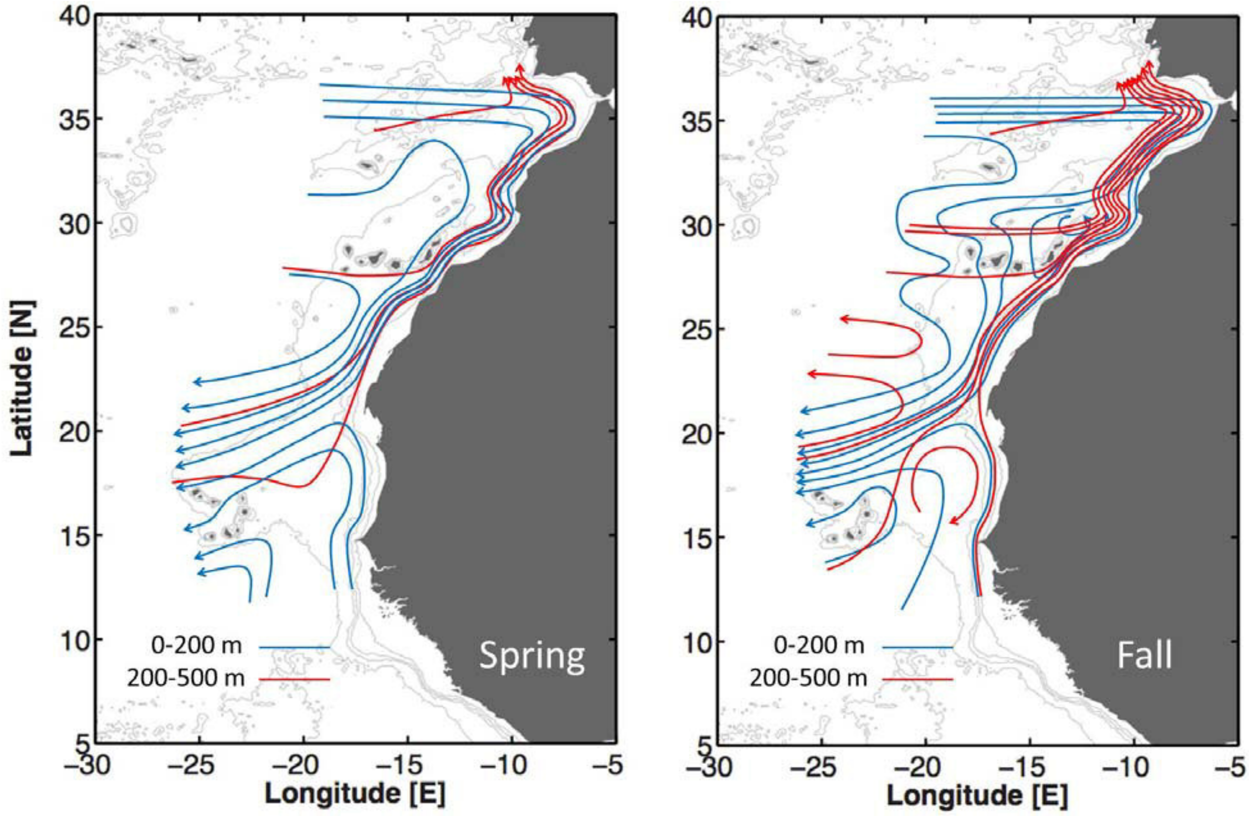

Figure 3.3 8. Scheme with the principal near-surface (50-200 m, in blue) and subsurface (200-500 m, in red) geostrophic currents in the CCLME, as deduced from the ECCO2 model: boreal spring (left) and fall (right).

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