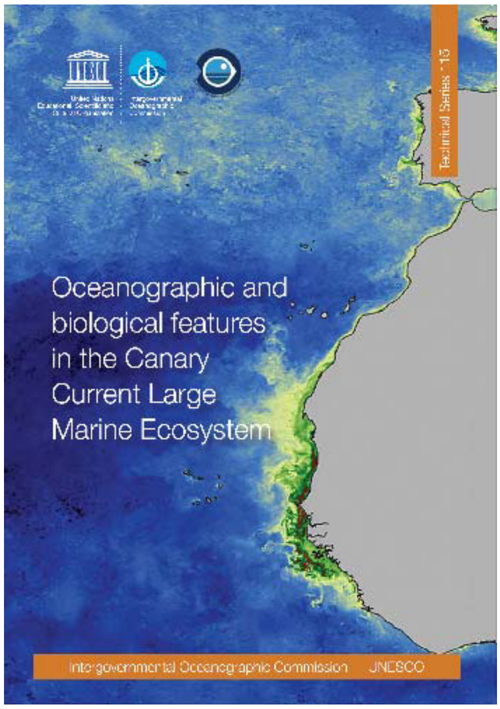
4.1. Inorganic nutrients and dissolved oxygen in the Canary Current Large Marine Ecosystem

For bibliographic purposes, this article should be cited as:
Pelegrí, J. L. and Peña-Izquierdo, J. 2015. Inorganic nutrients and dissolved oxygen in the Canary Current Large Marine Ecosystem. In: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. Valdés, L. and Déniz-González, I. (eds). IOC-UNESCO, Paris. IOC Technical Series, No. 115, pp. 133-142. URI: http://hdl.handle.net/1834/9183.

The publication should be cited as follows:
Valdés, L. and Déniz-González, I. (eds). 2015. *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. IOC-UNESCO, Paris. IOC Technical Series, No. 115: 383 pp. URI: http://hdl.handle.net/1834/9135.



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.

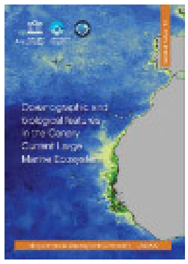
The bibliography of the entire publication is listed in alphabetical order on pages 351-379. The bibliography cited in this particular article was extracted from the full bibliography and is listed in alphabetical order at the end of this offprint, in unnumbered pages.

ABSTRACT

Inorganic nutrients increase with depth as a result of the enhanced remineralization of organic matter with aging waters (the time since they were last near the sea surface), and the opposite happens with dissolved oxygen (except within the saturated surface mixed layer). In the Canary Current Large Marine Ecosystem there is also a marked latitudinal gradient, with the Cape Verde Front separating relatively nutrient-poor and oxygen-rich subtropical waters from the nutrient-rich and oxygen-poor tropical waters. Along a latitudinal band off North-West Africa, coastal upwelling brings the subsurface waters towards the sea surface, locally raising the inorganic nutrient levels. This becomes an important lateral source to both gyres, especially to the nutrient-poor subtropical one, taking place through lateral mixing (mainly as a result of the instability of the coastal-upwelling baroclinic jet) and localized coastal filaments (in those regions, typically capes, where the coastal flow converges and offshore advection takes place). In the southernmost portion of our domain, within tropical waters, there is also high (wind-induced) offshore primary production. This, together with the slow ventilation of the subsurface waters, leads to much enhanced remineralization, producing a region with very low oxygen and high inorganic nutrient levels, the oxygen minimum zone of the North Atlantic Ocean.

Keywords: Cape Verde Front · Inorganic nutrient supply · Biogeochemical processes · Spatial distributions · Oxygen minimum zone · Canary Current Large Marine Ecosystem · Northwest Africa

IOC TECHNICAL SERIES, No. 115, pp. 133-142. URI: http://hdl.handle.net/1834/9183. 2015



INORGANIC NUTRIENTS AND DISSOLVED OXYGEN IN THE CANARY CURRENT LARGE MARINE ECOSYSTEM

Josep L. PELEGRÍ and Jesús PEÑA-IZQUIERDO

Institut de Ciències del Mar, CSIC. Spain

4.1.1. INTRODUCTION

The temporal and spatial distribution of inorganic nutrients (IN) and dissolved oxygen (DO) in the ocean responds to the combined effect of physical and biogeochemical processes. Within the surface euphotic layer, primary production (PP) is limited by the availability of sunlight and IN – if the irradiance exceeds some minimum threshold, the higher the flux of IN the higher the PP, hence restraining the maximum IN concentration. The surface waters are typically DO-saturated, as a result of the equilibrium in the partial pressures of oxygen across the air-sea interface – the greater the water temperature, the larger the saturated DO concentration. Within surface waters, as a result of high PP, the concentration of DO may exceed its saturation value.

Below the euphotic depth – in practice meaning below the surface mixed layer and the seasonal thermocline – respiration generally exceeds PP. As a result, organic matter produced at the sea surface gets remineralized in the subsurface layers, along the trajectory of water parcels, and the concentration of IN and DO arises from the interplay between the rate of water supply (bringing upstream concentrations of IN, DO and organic matter) and the local rate of remineralization (which depends largely on water temperature). Therefore, the concentration of IN and DO in subsurface waters reflects both biogeochemical (original IN and DO concentrations at the surface formation regions, the amount of organic materials in these surface waters, and the remineralization processes along the water path) and hydrodynamic (the way the subsurface layers connect to the surface ocean, and the patterns of circulation within the subsurface layers) processes (Fig. 4.1.1).

We begin this article by briefly reviewing how the dynamics of the Canary Current Large Marine Ecosystem (CCLME), together with air-sea exchange and biogeochemical processes, influences the distribution of IN and DO. Afterwards, we continue with a description of the IN and DO spatial distributions, both as horizontal and vertical maps and property-property diagrams, and end up briefly discussing the relevance of the different physical and biogeochemical processes within the CCLME.

4.1.2. PHYSICAL AND BIOGEOCHEMICAL DOMAINS

The CCLME has three well differentiated hydrographic regions: the North Atlantic subtropical gyre (NASG), the north-eastern extension of the North Atlantic tropical gyre (NATG), and the upwelling region off North-west Africa (NWA) (Pelegrí and Peña-Izquierdo, 3.3 this book). The dynamic differences among these regions set distinct biogeochemical domains.

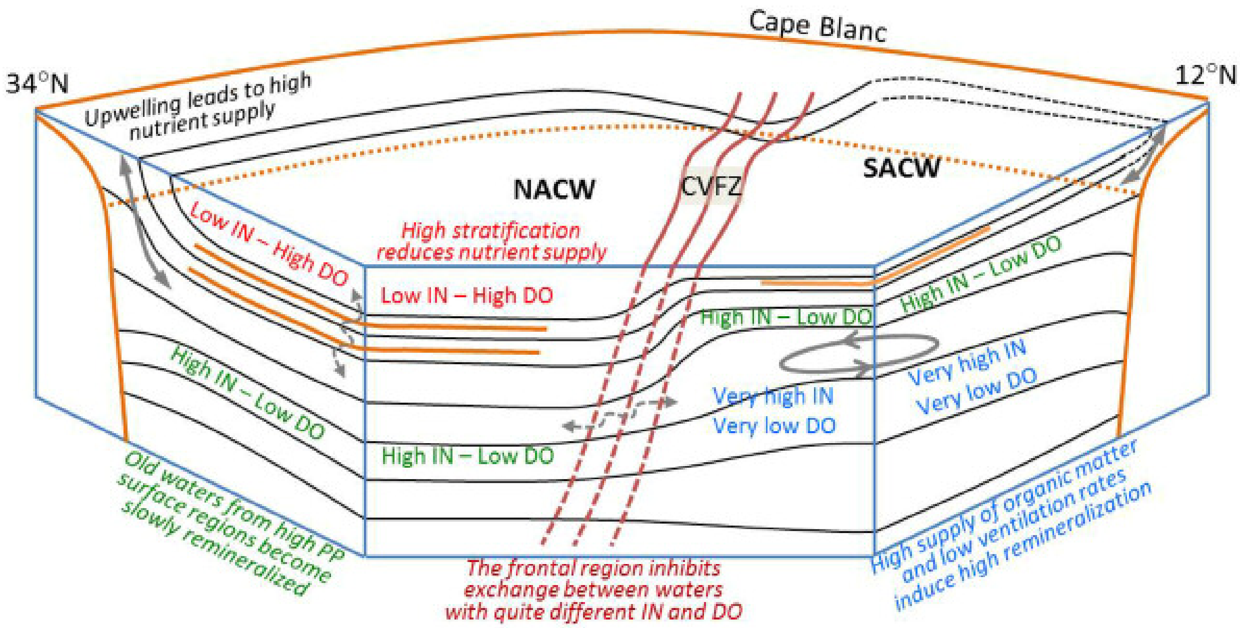


Figure 4.1.1. Schematics of the main processes affecting the distributions of IN and DO in the CCLME, with the isopycnals (black lines) and the main fluxes (advective, solid arrows; diffusive, dashed arrows); the horizontal yellow lines emphasize the role of stratification to inhibit the vertical fluxes.

The NASG is an anticyclonic (clockwise) gyre, constituted by upper-thermocline North Atlantic Central Waters (NACW), with a very intense western boundary current (Gulf Stream) and a much weaker eastern boundary flow (Canary Current system). The anticyclonic flow causes the isopycnals to sink towards the central-western part of the gyre, restricting the connection between the subsurface layers and the euphotic zone; the gyre reaches down to about 600-700 m in the eastern margin and 1000 m in the western margin. Most important, the gyre is a region of water subduction: the sea-surface winds change from intense easterlies at low latitudes to intense westerlies at high latitudes, causing the surface Ekman transport to be convergent and the surface waters to penetrate (subduct) into the subsurface layers (Stommel, 1979; Luyten et al., 1983). The subsurface waters are brought back to the sea surface along the western limb of the gyre, associated with the Gulf Stream and its northern extension (North Atlantic Current), or through relatively slow vertical mixing and boundary upwelling processes. This has two major consequences. First, the surface NASG is an oligotrophic zone. The interior of the gyre is a very low PP region, with shallow subsurface waters having very low nutrient levels except intermittently, near its boundaries, because of lateral inputs through mesoscale activity and thermohaline intrusions. Second, the deeper subsurface layers of the gyre are connected to the sea surface at its margins; in particular, surface to subsurface advection takes place at high latitudes of the northern North Atlantic Ocean, in regions with very high seasonal PP (the spring bloom of the North Atlantic). These surface waters are loaded with organic matter which, after subduction, becomes progressively remineralized and lead to the North Atlantic nutrient- bearing stratum. The deeper the subsurface layer, the higher the nutrient level, up to a maximum located in those layers that outcrop near the loci of maximum westerly winds (approximately defined by the 10°C isothermal); further north the surface waters do not subduct (Sarmiento et al., 1982; Kawase and Sarmiento, 1985).

At latitudes less than Cape Blanc, we find a poorly ventilated upper-thermocline: the shadow zone of the NASG (Luyten et al., 1983), a shallow upper-thermocline (down to about 500 m) which is not directly reached by waters of subtropical origin. As a consequence, this region becomes a north-eastern extension of the NATG, occupied by relatively old South Atlantic Central Water (SACW); the boundary between the NACW and SACW constitutes the Cape Verde Front (CVF) (Zenk et al., 1991), stretching approximately between Cape Blanc and the Cape Verde Islands (15°N-17°N). Because of their old age and the influence of intermediate waters originating in the southern ocean, SACW is distinguished by relatively high IN and low DO concentrations. Additionally, during summer the southern part of this region (between about 8°N and 13°N) experiences wind-induced surface divergence which leads to offshore upwelling. The result is the Guinea Dome, the main supplier of nutrients to the euphotic zone (Pastor et al., 2013). During boreal winter the dome weakens but is accompanied by a narrow band (typically less than 100 km) of shallow (down to about 100 m) coastal upwelling (Pelegrí and Benazzouz, 3.4 this book). The high levels of PP in the Guinea Dome and coastal upwelling regions, together with their low ventilation rate, cause high rates of remineralization and accentuate the characteristics of the SACW, leading to the appearance of a DO minimum and IN maximum zone (Karstensen et al., 2008; Stramma et al., 2008).

The upwelling region off NWA is the result of the year-long northeasterly winds (Pelegrí and Benazzouz, 3.4 this book). These winds induce offshore surface transport which, together with the coastal constraint, brings nutrient-rich subsurface waters to the euphotic zone and gives rise to a coastal band of enhanced PP – the coastal transition zone, typically extending about 2-4° offshore from the continental slope (Barton et al., 1998). Other consequences are the rising of the isopycnals towards the sea surface, leading to the coastal upwelling front with its associated alongshore current (Canary Upwelling Current, CUC), and the creation of alongshore pressure gradients, which sustain the Poleward Undercurrent (PUC) between the frontal system and the slope (Barton, 1989). The CUC and PUC are the true eastern boundary currents of both NASG and NATG, behaving as alongshore water and nutrient conveyors between the Gulf of Cadiz and Cape Vert and providing high spatial and temporal coherence to the whole CTZ (Pelegrí et al., 2005, 2006; Peña-Izquierdo et al., 2012; Benazzouz et al., 2014; Pelegrí and Peña-Izquierdo, 3.3 this book).

The presence of three dynamic regions results in substantial differences in DO and IN within the CCLME (Fig. 4.1.1). The DO concentration is set at the sea surface through gas exchange with the atmosphere and by PP. Cooling of surface waters reduces the partial pressure of oxygen, hence capturing it from the atmosphere (physical pump); enhanced high PP may cause the surface waters to become oversaturated in DO. Both factors lead to a decrease of DO in warm and nutrient-poor offshore surface waters, and a DO increase in the cold and nutrient-rich coastal upwelling band. Sea surface warming further increases vertical stratification, inhibiting vertical diffusion of IN and DO. In subsurface waters, the enhanced remineralization of organic matter is the main cause for a decrease in DO concentrations and an increase in IN. In highly productive and poorly ventilated areas, such as in the Guinea Dome, the sinking of organic matter and the enhanced water-residence times may lead to a substantial decrease in DO concentration and an increase in IN, resulting in the development of an oxygen minimum zone (OMZ).

4.1.3. SPATIAL DISTRIBUTIONS

In this section we use the temperature, IN and DO fields from the World Ocean Atlas 2013 database (WOA-13, 2013), with a 1° latitude-longitude resolution. We use phosphate to illustrate the spatial IN distributions (Figs. 4.1.2 to 4.1.4), and silicate in the property-property scattered plots (Figs. 4.1.5 and 4.1.6).

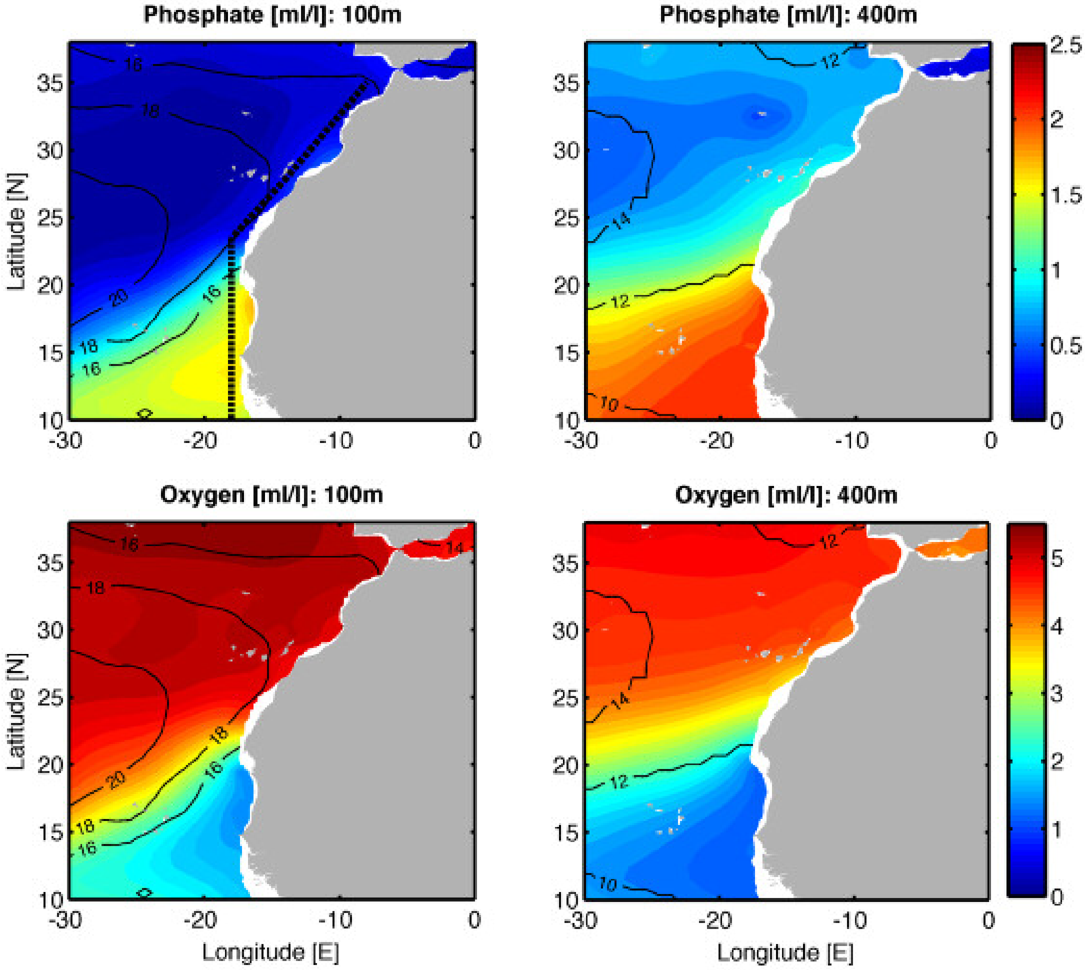


Figure 4.1.2. Annual-mean distributions of phosphate (top) and DO (bottom) concentrations (ml l^{-1}) at 100 m (left) and 400 m (right), with temperature (°C) superimposed as solid contours.

The transition between the tropical and subtropical gyres is clear in the mean annual temperature, IN and DO distributions along a section parallel to the African slope (Fig. 4.1.3). The depth of the upper thermocline (down to 10°C) doubles from the NATG to the NASG. The CVF is evident in the temperature field but the latitudinal IN and DO gradients are even sharper due to the high remineralization in the eastern tropical region (latitudes less than 22°N) and the increased ventilation with latitude along the eastern NASG. The DO distributions show the existence of a local maximum at low latitudes (10-12°N) and shallow depths (200-300 m); this reflects the different regimes in the upper (down to 300 m) and lower (300-500 m) SACW, with the upper layer being oxygenated by the equatorial system of zonal jets and the lower layer subject to very reduced ventilation (Peña-Izquierdo et al., 2015).

The differences between the subtropical and tropical regions are also clear in the annual-mean temperature, IN and DO distributions along zonal sections at different latitudes (Fig. 4.1.4). Those sections in the NASG (30°N and 24°N in Fig. 4.1.4) show a deep thermocline (reaching 800 m at 30°N), with relatively low IN and high DO concentrations, indicative of recently ventilated waters. The CTZ is characterized by the uplifting of isothermals and IN contours; the rise of DO contours is not evident because of the increased air-sea exchange within the cooler coastal waters. Within the NATG (18°N and 12°N in Fig. 4.1.4), the thermocline only extends to about 500 m, with a subsurface IN maximum and DO minimum evidencing much older water masses. The intensity and offshore extent of the IN/DO concentrations increases/decreases with decreasing latitude, with DO reaching below 1.5 ml l^{-1} near the coast at 12°N, as part of the North Atlantic OMZ (Karstensen et al., 2008; Stramma et al., 2008).

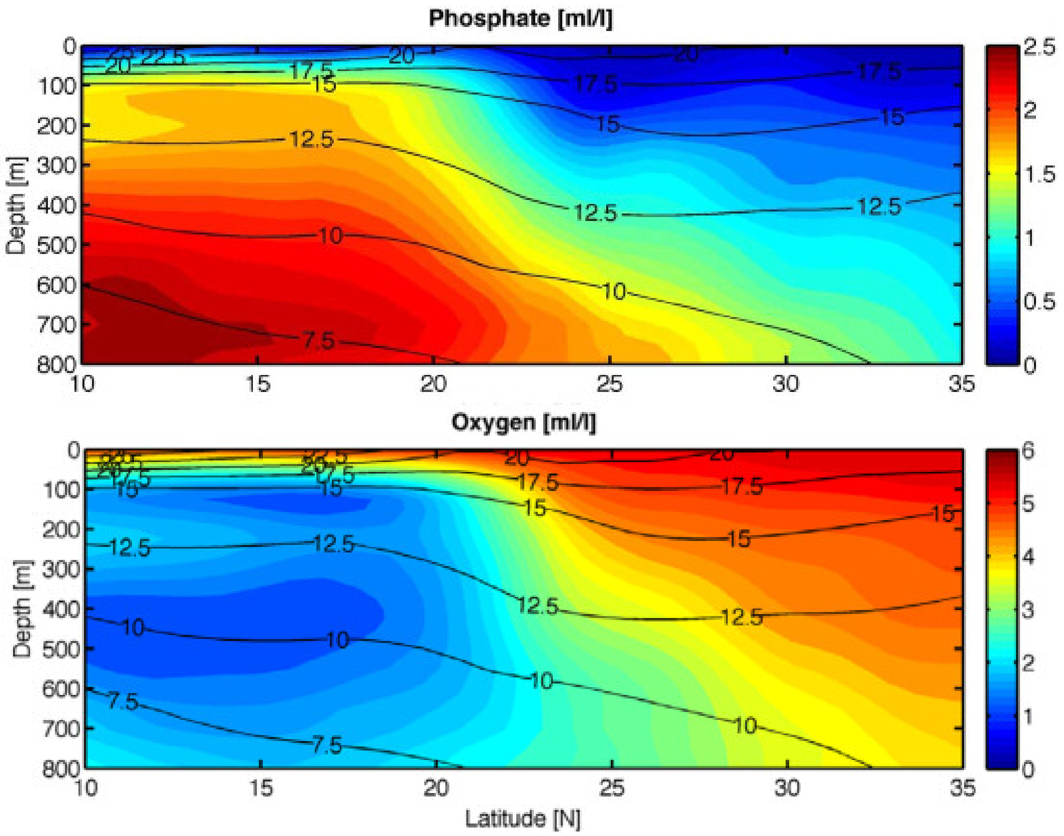


Figure 4.1.3. Annual-mean distributions of phosphate (top) and DO (bottom) concentrations (ml l^{-1}) along the meridional section in the top-left panel of Fig. 4.1.2, with temperature (°C) superimposed as solid contours.

Since we present the mean annual fields, and coastal upwelling develops in the NATG only during boreal winter, the upwelling band is visible only in the NASG, extending about 2-3° from the continental slope. It is interesting to note the deeper location of the IN maximum (700-800 m) as compared with the DO minimum (400-500 m), reflecting the along-slope northward propagation of nutrient-rich intermediate waters (Machín et al., 2006; Machín and Pelegrí, 2009).

Several decades of observations (Stramma et al., 2008; Brandt et al., 2010) have revealed an expansion and deoxygenation of the world OMZs, with dramatic implications for the highly productive eastern boundary marine ecosystems – all OMZs present hypoxic conditions, with lethal DO concentrations for half of the marine species (Vaquer-Sunyer and Duarte, 2008). The North Atlantic OMZ is the least hypoxic of all the OMZs but its rate of oxygen decline is at least twice faster than any other OMZ (Stramma et al., 2008). This growth in the loss of habitat is threatening the sustainability of the valuable pelagic fisheries and marine ecosystems in the region (Arístegui et al., 2006; Stramma et al., 2012).

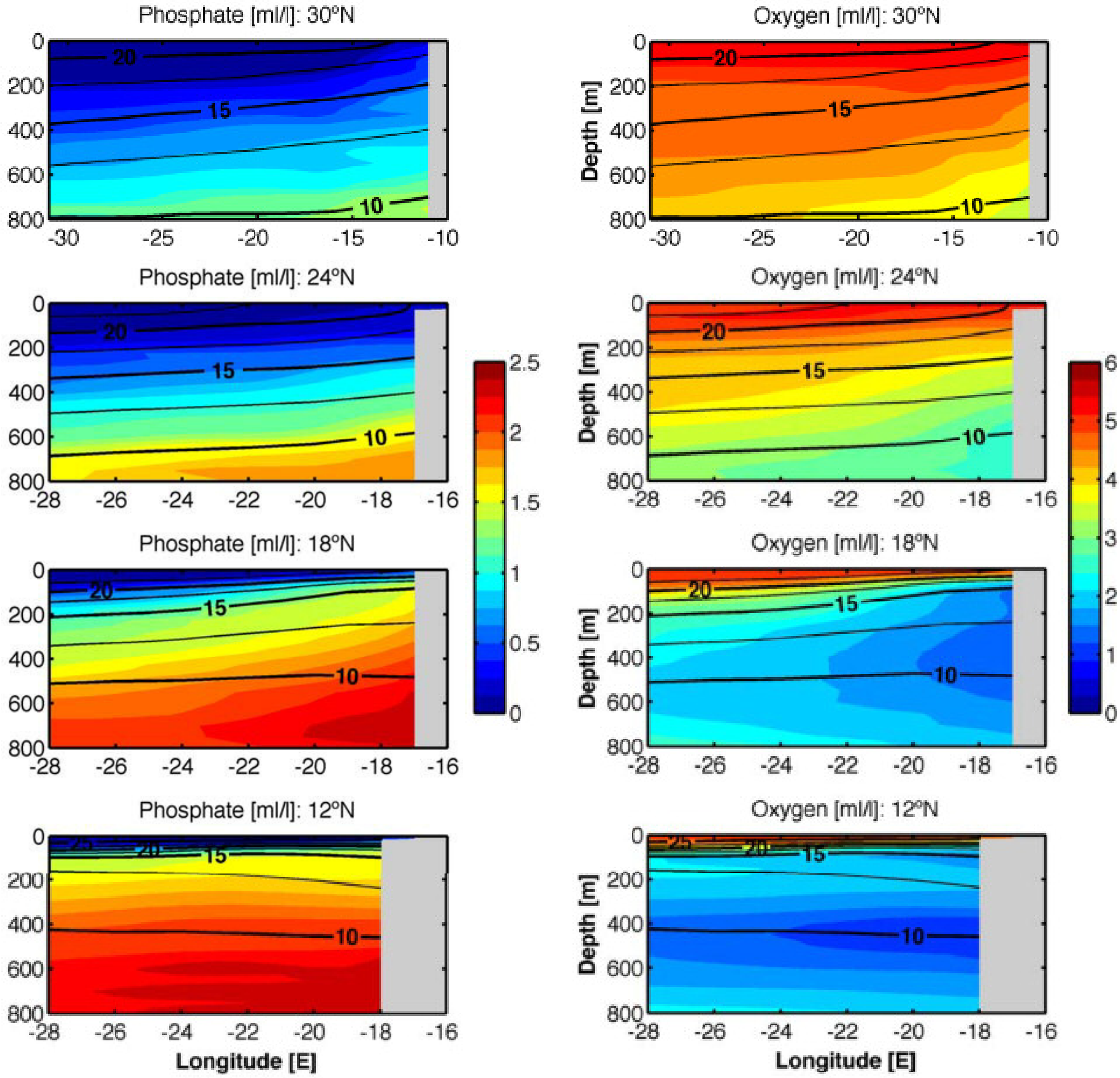


Figure 4.1.4. Annual-mean distributions of phosphate (left) and DO (right) concentrations (ml l^{-1}) along zonal sections (30°N, 24°N, 18°N, 12°N; from top to bottom), with temperature (°C) drawn as solid contours.

4.1.4. NUTRIENT AND OXYGEN RELATIONSHIPS

The differences in IN and DO between NACW and SACW can be identified using scatter plots (or property-property diagrams) (Figs. 4.1.5 and 4.1.6). The meridional transect along the continental slope sharply illustrates that SACW has higher IN and lower DO concentrations than NACW. This is true not only for any given depth but also for the whole water mass, as shown by the shift in data points representative of these two water masses (Fig. 4.1.5). The shift takes place rather abruptly across the CVF. Within the NATG there is a maximum in DO at 200-300 m (see also Fig. 4.1.3), which reflects enhanced ventilation of the upper thermocline by the along-slope PUC (Peña-Izquierdo et al., 2012, 2015).

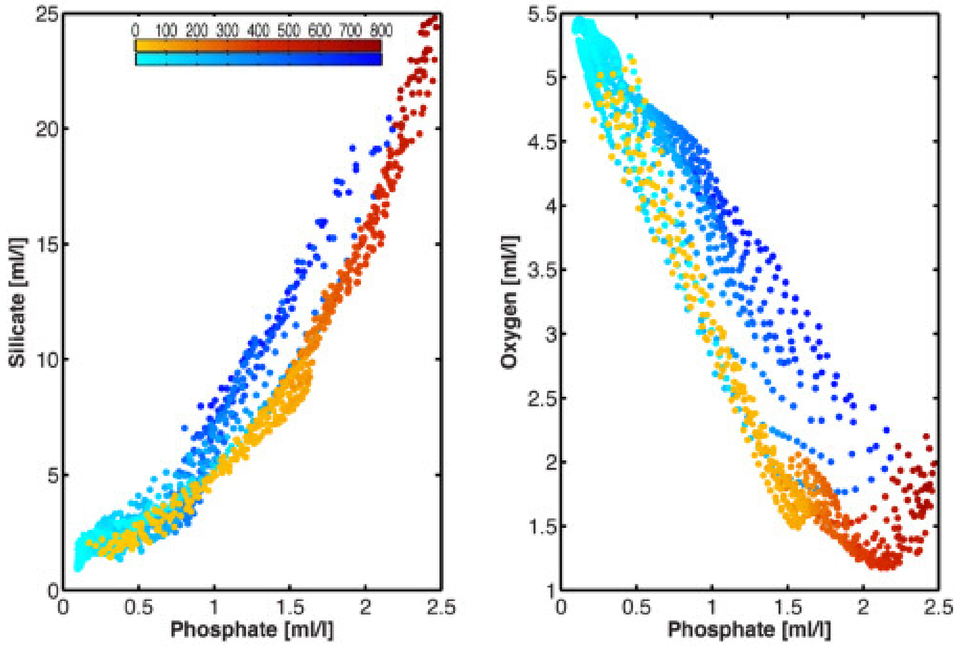


Figure 4.1.5. Scatter plots of silicate-phosphate (left) and DO-phosphate (right) (ml l^{-1}) along the meridional section depicted in the top-left panel of Fig. 4.1.2. The reddish/bluish colours correspond to data points at latitudes less/more than 20°N, with the colour code representing depth (m).

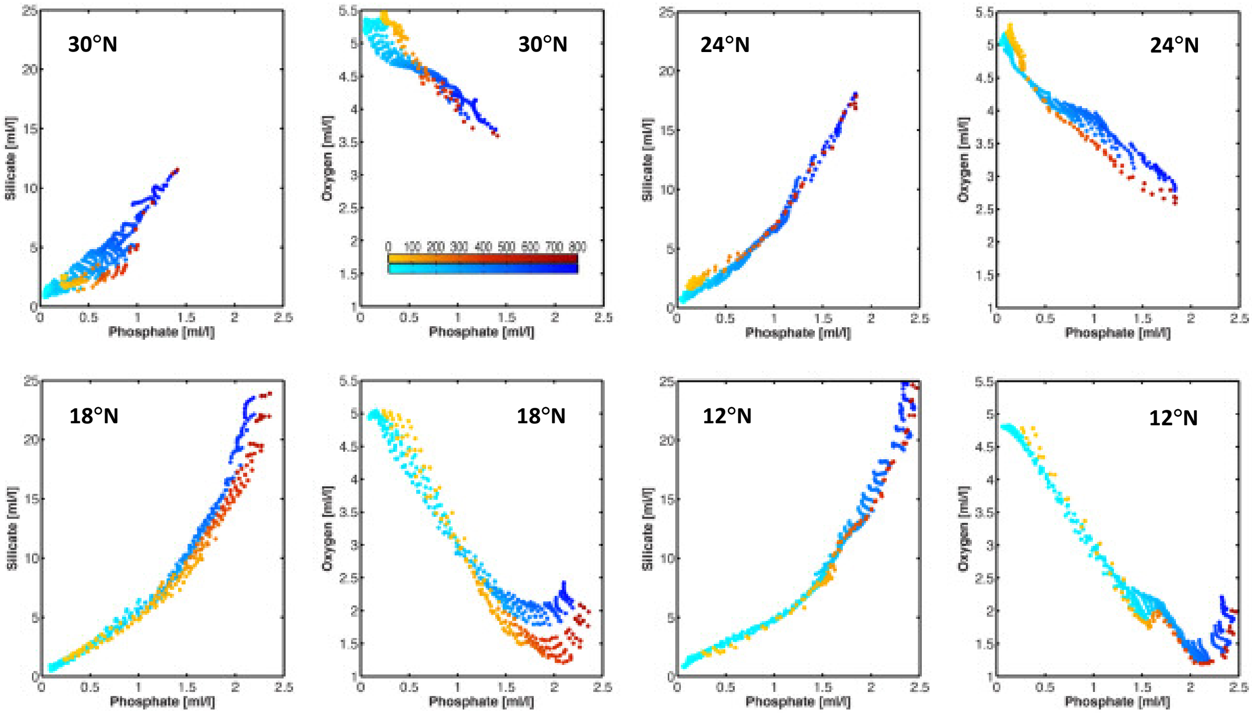


Figure 4.1.6. Scatter plots of silicate-phosphate (left) and DO-phosphate (right) (ml l^{-1}) along the zonal sections in Fig. 4.1.4. The reddish/bluish colours correspond to data points at longitudes east/west of 15°W (30°N), 22°W (24°N), 21°W (18°N), 21°W (12°N); the colour code represents depth (m).

The longitudinal changes at different latitudes show relatively minor differences, visible as small displacements in the scatter plots. The shoreward change in the depth of the isothermals (rising in the NASG and dropping for the NATG) affects the location of any particular set of IN-DO values but does not cause a large shift in the cloud of points. The most significant displacement for the NASG occurs in the DO-phosphate plot, where DO in the cold upwelled waters is relatively high compared with the warm and stratified offshore waters. Regarding the NATG, there is a general increase in DO when moving from 12°N to 18°N, resulting from the transfer of NACW through the CVF (Peña-Izquierdo et al., 2015); an exception occurs at depths between 200 m and 300 m, where the ventilation appears to be related to the northward PUC (Fig. 4.1.3; see Pelegrí and Peña-Izquierdo, 3.3 this book).

4.1.5. CONCLUSIONS

In this article we have described the annual-mean distributions of IN and DO within the surface layers and the permanent thermocline of the CCLME. We have neither discussed their temporal variability nor their relevance on ocean processes such as PP and biodiversity, as these topics are addressed in other articles. Instead, we have focused on those physical and biochemical processes that control the IN and DO distributions, as summarized below (see also Fig. 4.1.1).

4.1.5.1. Physical processes

The physical supply of water mass and associated properties includes both lateral and vertical transports. These arise from processes that range from the regional scale to the small-scale. Becasuse of their spatial and temporal scale, regional patterns are usually considered to be advective processes while mesoscale and small-scale phenomena are commonly thought in terms of mixing processes; the difference, however, resides solely in our skill, and interest, to study the variability acting at certain spatial and temporal scales.

Lateral advection by localized currents, for instance the CUC, leads to the appearance of convergent regions which may undergo water upwelling. One remarkable example is the confluence of the CUC and the Mauritanian Current at the CVF (Pelegrí and Peña-Izquierdo, 3.3 this book); as a result, high PP takes place in this region and surface waters, loaded with organic matter and IN, are exported to the NASG through the Cape Blanc giant filament (Pelegrí and Benazzouz, 3.4 this book). The fronts, however, act not only as a barrier to advection but also as a source of horizontal mixing through the generation of lateral instabilities. The CCLME has two distinctive fronts: the CVF, characterized by double-diffusive intrusions that enhance mixing between the nutrient-rich SACW and the nutrient-poor NACW (Pastor et al., 2008); and the coastal upwelling front, where upwelling filaments and mesoscale eddies lead to offshore transfer of inorganic and organic matter (García-Muñoz et al., 2005; Benítez-Barrios et al., 2011; Ruiz et al., 2014).

Vertical supply takes place as a result of both advection and mixing. Vertical mixing is induced through double diffusion, mainly within the NASG, and localized shear, associated with either frontal jets, mesoscale features or internal waves (Martínez-Marrero et al., 2008); however, the greater the vertical stratification, the greater the vertical shear required to induce mixing. Upward vertical advection, or upwelling, is a widespread and ubiquitous feature along NWA (until Cape Blanc, reaching as far south as Cape Vert only during boreal winter) (Benazzouz et al., 2014). Upwelling also takes place in the Dome of Guinea and within mesoscale features, such as eddies generated south of the Canary Islands or along the coastal upwelling front (Benítez-Barrios et al., 2011; Pastor et al., 2013).

4.1.5.2. Biogeochemical processes

The main biogeochemical supply of IN occurs in subsurface waters through the remineralization of organic matter in poorly ventilated areas, i.e. where waters have long residence times. Within the CCLME, this takes place in both the subtropical and tropical gyres but in very different ways. The upper-thermocline waters of the NASG originate at the high-latitude sea-surface, in regions of water subduction (Pelegrí and Peña-Izquierdo, 3.3 this book); these subducted waters carry relatively high DO concentrations (the higher the latitude the colder the water and the larger the DO concentration) and a high load of organic matter produced during the North Atlantic spring bloom. The path of these surface waters to the subsurface eastern boundary of the NASG is relatively short, so there is not enough time for the organic matter to be fully remineralized. As a consequence, these waters reach the CCLME with relatively high DO and moderate IN concentrations, with IN increasing and DO decreasing with depth within the permanent thermocline.

The waters arriving to the tropical ocean have high IN and low DO concentrations because of sustained remineralization on route from the South Atlantic (and even the Southern Ocean). These IN and DO concentrations are further increased or reduced as a result of low ventilation (equivalent to high residence times) and the local supply of organic matter (arising from enhanced upwelling and PP in the coastal band and the Dome of Guinea). The outcome is the OMZ, with the highest IN and lowest DO concentrations in the entire North Atlantic Ocean.

The sea surface is saturated in DO because of air-sea exchange; the partial pressure of oxygen within the water decreases with temperature, hence the concentration of sea-surface DO is larger in the coastal upwelling region off NWA than further offshore. This shows up not only at the sea surface but, as a result of intense vertical mixing within the coastal transition zone, also in the subsurface layers. Other IN sources (e.g. coastal, either natural or anthropogenic, or through atmospheric deposition of nitrogen) are generally much smaller and have been neglected (however, see Gelado-Caballero, 2.3 this book, on dust inputs).

4.1.5.3. A complex, hence difficult, forecast

The IN and DO distributions are the outcome of multiple drivers, with important feedbacks between different variables. For example, Stramma et al. (2009, 2012) have presented a scenario with worldwide expansion of the OMZs, possibly as a result of weakened tropical circulation and enhanced stratification (Matear and Hirst, 2003). However, Pastor et al. (2013) have shown that vertical supply in the CCLME is not dominated by vertical mixing but rather by upwelling in the coastal region and, particularly, in the Dome of Guinea. Hence, the warming of surface waters may not significantly reduce the ventilation of the upper-ocean layers. On the contrary, the changes in DO concentration are likely to depend on the long-term variability of the ventilation pathways (Peña-Izquierdo et al., 2015). The answer probably lies in the behaviour of the tropical system of zonal jets (Rosell-Fieschi et al., 2015) and the evolution of the surface winds and their effect on coastal and offshore upwelling (Benazzouz et al., 6.3 this book). A good example is the reported trend of increased trade winds that, non-intuitively, is accompanied by the warming of the coastal upwelled waters: the answer lies on the intensification of the upstream input of interior-ocean waters that have heated up as a result of climate change (Pelegrí and Benazzouz, 3.4.2 this book).

Also relevant is how remineralization may be influenced by climate change, with many possible feedbacks. For example, Llanillo et al. (2013) show that an increase in ventilation leads to a proportionally higher rate of respiration (for the OMZ in the South Pacific), causing a decrease in DO concentration; and Ridder and England (2014) propose that, as a result of global warming, nutrient supply and PP are reduced in the tropics, leading to a decrease in respiration and a contraction of the OMZ. Pelegrí et al. (2006) and Torres-

Valdés et al. (2009) have emphasized the important role of export of nutrients and organic matter from the eastern upwelling region in order to maintain the levels observed within the NASG. In particular, Torres-Valdés et al. (2009) observed significant differences in nitrate and phosphate within the NASG - the former is more abundant (above the Redfield ratio) possibly as a result of nitrogen fixation (Benavides et al., 2013) – probably causing phytoplankton to respire better dissolved organic phosphorus than nitrogen.

The relevance of the distributions of IN and DO on the trophic chain in the CCLME is unquestionable. The high complexity of the CCLME, i.e. variety of processes controlling the IN and DO distributions, may signify high resilience to anthropogenic perturbations (e.g. MacArthur, 1955); nevertheless, an improved understanding of the physical and biogeochemical processes, and their interactions, is still necessary for predicting how anthropogenic climate change will affect the CCLME future evolution.

Acknowledgements

This review has been supported by projects CANOA (CTM2005-00444/MAR), MOC2 (CTM2008-06438-C02-01) and TIC-MOC (CTM2011–28867), funded by the Spanish government. Jesús Peña-Izquierdo was funded by the Spanish government, through a FPI doctoral grant linked to project MOC2. We also wish to sincerely thank the many colleagues that have participated with us in these projects, for the hard work carried out together and the many enlightening and joyful conversations, particularly Javier Arístegui, Mikhail Emelianov, Alonso Hernández-Guerra, Irene Laiz, Francisco Machín, Ángeles Marrero-Díaz, María Pastor, Grant Pitcher, Ángel Rodríguez-Santana and Pablo Sangrà.

BIBLIOGRAPHY

Arístegui, J., Álvarez-Salgado, X. A., Barton, E. D., Figueiras, F. G., Hernández-León, S., Roy, C. and Santos, A. M. P. 2006. Oceanography and fisheries of the Canary Current/Iberian region of the Eastern North Atlantic (18a,E). In: *The Sea: The Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses*, Vol. 14B. Robinson, A. R. and Brink, K. H. (eds). Harvard University Press, pp. 877–931.

Barton, E. D. 1989. The poleward undercurrent on the eastern boundary of the Subtropical North Atlantic. In: *Poleward flows along Eastern Ocean Boundaries.* Neshyba, S., Smith, R. L. and Mooers, C. N. K. (eds). Springer-Verlag Lecture Note Series, pp. 82-95.

Barton, E. D. et al. 1998. The transition zone of the Canary Current upwelling region. *Progress in Oceanography*, Vol. 41, pp. 455– 504. doi:10.1016/S0079-6611(98)00023-8.

Benavides, M., Arístegui, J., Agawin, N. S. R., Álvarez-Salgado, X. A., Álvarez, M. and Troupin, C. 2013. Low contribution of N2 fixation to new production and excess nitrogen in the subtropical northeast Atlantic margin. *Deep-Sea Research Part I: Oceanographic Research Papers*, Vol. 81, pp. 36-48.

Benazzouz, A., Pelegrí, J. L., Demarcq, H., Machín, F., Mason, E., Orbi, A., Peña-Izquierdo, J. and Soumia, M. 2014. On the temporal memory of coastal upwelling off NW Africa. *Journal of Geophysical Research: Oceans*, Vol. 119, pp. 6356-6380. doi:10.1002/2013JC009559.

Benazzouz, A., Demarcq, H. and González-Nuevo, G. 2015. Recent changes and trends of the upwelling intensity in the Canary Current Large Marine Ecosystem. In: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. Valdés, L. and Déniz-González, I. (eds). IOC-UNESCO, Paris. IOC Technical Series, No. 115, pp. 321-330. URI: http://hdl.handle.net/1834/9198.

Benítez-Barrios, V. M., Pelegrí, J. L., Hernández-Guerra, A., Lwiza, K. M. M., Gomis, D., Vélez-Belchi, P. and Hernández-León, S. 2011. Three-dimensional circulation in the NW Africa coastal transition zone. *Progress in Oceanography*, Vol. 91, pp. 516-533.

Brandt, P., Hormann, V., Körtzinger, A., Visbeck, M., Krahmann, G., Stramma, L., Lumpkin, R. and Schmid, C. 2010. Changes in the Ventilation of the Oxygen Minimum Zone of the Tropical North Atlantic. *Journal of Physical Oceanography*, Vol. 40, pp. 1784–1801.

García-Muñoz, M., Arístegui, J., Pelegrí, J. L., Antoranz, A., Ojeda, A. and Torres, M. 2005. Exchange of carbon by an upwelling filament off Cape Ghir (NW Africa). *Journal of Marine Systems*, Vol. 54, pp. 83-95.

Gelado-Caballero, M. D. 2015. Saharan dust inputs to the Northeast Atlantic. In: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. Valdés, L. and Déniz-González, I. (eds). IOC-UNESCO, Paris. IOC Technical Series, No. 115, pp. 53-61. URI: http://hdl.handle.net/1834/9176.

Karstensen, J., Stramma, L. and Visbeck, M. 2008. Oxygen minimum zones in the eastern tropical Atlantic and Pacific oceans. *Progress in Oceanography*, Vol. 77, pp. 331–350.

Kawase, M. and Sarmiento, J. L. 1985. Nutrients in the Atlantic thermocline. *Journal of Geophysical Research*, Vol. 90, pp. 8961–8979.

Llanillo, P. J., Karstensen, J., Pelegrí, J. L. and Stramma, L. 2013. Physical and biogeochemical forcing of oxygen and nitrate changes during El Niño/El Viejo and La Niña/La Vieja upper-ocean phases in the tropical eastern South Pacific along 86°W: 1993 versus 2009. *Biogeosciences*, Vol. 10, pp. 6339-6355.

Luyten, J. R., Pedlosky, J. and Stommel, H. 1983. The ventilated thermocline. *Journal of Physical Oceanography*, Vol. 13, pp. 292–309.

MacArthur, R. H. 1955. Fluctuations of animal populations, and a measure of community stability. *Ecology*, Vol. 36, pp. 533-536.

Machín, F., Hernández-Guerra, A. and Pelegrí, J. L. 2006. Mass fluxes in the Canary Basin. *Progress in Oceanography,* Vol. 70, pp. 416-447.

Machín, F. and Pelegrí, J. L. 2009. Northward penetration of Antarctic Intermediate Water off northwest Africa. *Journal of Physical Oceanography*, Vol. 39, pp. 512-535.

Martínez-Marrero, A., Rodríguez-Santana, A., Hernández-Guerra, A., Fraile-Nuez, E., López-Laatzen, F., Vélez-Belchí, P. and Parrilla, G. 2008. Distribution of water masses and diapycnal mixing in the Cape Verde Frontal Zone. *Geophysical Research Letters*, Vol. 35 (7), L07609. doi: 10.1029/2008GL033229.

Matear, R. J. and Hirst, A. C. 2003. Long-term changes in dissolved oxygen concentrations in the ocean caused by protracted global warming. *Global Biogeochemical Cycles*, Vol. 17. doi:10.1029/2002GB001997.

Pastor, M. V., Pelegrí, J. L., Hernández-Guerra, A., Font, J., Salat, J. and Emelianov, M. 2008. Water and nutrient fluxes off Northwest Africa. *Continental Shelf Research*, Vol. 28 (7), pp. 915-936.

Pastor, M. V., Palter, J. B., Pelegrí, J. L. and Dunne J. P. 2013. Physical drivers of interannual chlorophyll variability in the eastern subtropical North Atlantic. *Journal of Geophysical Research: Oceans*, Vol. 118, pp. 3871-3886.

Pelegrí, J. L. et al. 2005. Coupling between the open ocean and the coastal upwelling region off Northwest Africa: Water recirculation and offshore pumping of organic matter. *Journal of Marine Systems*, Vol. 54, pp. 3-37.

Pelegrí, J. L., Marrero-Díaz, A. and Ratsimandresy, A. W. 2006. Nutrient irrigation of the North Atlantic. *Progress in Oceanography*, Vol. 70, pp. 366-406.

Pelegrí, J. L. and Peña-Izquierdo, J. 2015. Eastern boundary currents off North-West Africa. In: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. Valdés, L. and Déniz-González, I. (eds). IOC-UNESCO, Paris. IOC Technical Series, No. 115, pp. 81-92. URI: http://hdl.handle.net/1834/9179.

Pelegrí, J. L. and Benazzouz, A. 2015. Coastal upwelling off North-West Africa. In: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. Valdés, L. and Déniz-González, I. (eds). IOC-UNESCO, Paris. IOC Technical Series, No. 115, pp. 93-103. URI: http://hdl.handle.net/1834/9180.

Peña-Izquierdo, J., Pelegrí, J. L., Pastor, M. V., Castellanos, P., Emelianov, M., Gasser, M., Salvador, J. and Vázquez-Domínguez, E. 2012. The continental slope current system between Cape Verde and the Canary Islands. *Scientia Marina*, Vol. 76 (S1), pp. 65-78.

Peña-Izquierdo, J., Van Sebille, E., Pelegrí, J. L., Sprintall, J., Mason, E., Llanillo, P. and Machín, F. 2015. Water mass pathways to the North Atlantic Oxygen Minimum Zone. *Journal of Geophysical Research: Oceans*, Vol. 120, pp. 3350-3372. doi:10.1002/2014JC010557.

Ridder, N. N. and England, M. H. 2014. Sensitivity of ocean oxygenation to variations in tropical zonal wind stress magnitude. *Global Biogeochemical Cycles*, Vol. 28, pp. 909-926.

Rosell-Fieschi, M., Pelegrí, J. L. and Gourrion, J. 2015. Zonal jets in the equatorial Atlantic Ocean. *Progress in Oceanography*, Vol. 130, pp. 1-18.

Ruiz, S., Pelegrí. J. L., Emelianov, M., Pascual, A. and Mason, E. 2014. Geostrophic and ageostrophic circulation of a shallow anticyclonic eddy off Cape Bojador. *Journal of Geophysical Research: Oceans*, Vol. 119, pp. 1258-1270.

Sarmiento, J. L., Rooth, C. G. and Roether, W. 1982. The North Atlantic tritium distribution in 1972. *Journal of Geophysical Research*, Vol. 87, pp. 8047–8056.

Stommel, H. 1979. Determination of water mass properties of water pumped down from the Ekman layer to the geostrophic flow below. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 76, pp. 3051–3055.

Stramma, L., Brandt, P., Schafstall, J., Schott, F., Fischer, J. and Körtzinger, A. 2008. Oxygen minimum zone in the North Atlantic south and east of the Cape Verde Islands. *Journal of Geophysical Research*, Vol. 113 (C4), C04014.

Stramma, L., Visbeck, M., Brandt, P., Tanhua, T. and Wallace, D. 2009. Deoxygenation in the oxygen minimum zone of the eastern tropical North Atlantic. *Geophysical Research Letters*, Vol. 36 (20), L20607.

Stramma, L., Prince, E. D., Schmidtko, S., Luo, J., Hoolihan, J. P., Visbeck, M., Wallace, D. W. R., Brandt, P. and Körtzinger, A. 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, Vol. 2, pp. 33–37. doi:10.1038/nclimate1304.

Torres-Valdés, S. et al. 2009. Distribution of dissolved organic nutrients and their effect on export production over the Atlantic Ocean. *Global Biogeochemical Cycles*, Vol. 23 (4), GB4019.

Vaquer-Sunyer, R. and C. Duarte. 2008. Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 105, pp. 15452–15457.

WOA-13. 2013. World Ocean Atlas 2013. http://www.nodc.noaa.gov/OC5/woa13/ (Accessed December 2014).

Zenk, W., Klein, B. and Schröder, M. 1991. Cape Verde frontal zone. *Deep-Sea Research Part A. Oceanographic Research Papers*, Vol. 38 (S1), pp. S505–S530.