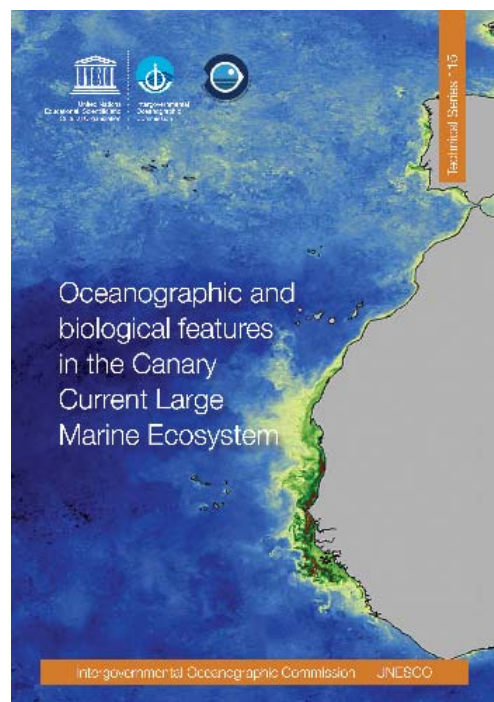


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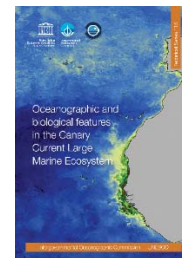
The report *Oceanographic and biological features in the Canary Current Large Marine Ecosystem* and its separate parts are available on-line at: <http://www.unesco.org/new/en/ioc/ts115>.

The bibliography of the entire publication is listed in alphabetical order in pages 351-379. The bibliography cited in this article was extracted and listed in alphabetical order at the end of this separate part, in unnumbered pages.

## **ABSTRACT**

The Sea Surface Temperature in the Canary Current Large Marine Ecosystem (CCLME) for the 32 years in the period 1982-2013 shows a mean warming trend of  $0.28^{\circ}\text{C decade}^{-1}$ . However, this overall warming trend shows significant changes due to the influence of the different dynamical regimes that coexist in the CCLME. Near the coast, in the area under the influence of the upwelling, between Cape Blanc and Cape Beddouza, the warming trend is not statistically different from zero. Near the coast, but in the waters under the influence of downwelling, between Cape Verde and Cape Blanc, the warming trend is higher ( $>0.5^{\circ}\text{C decade}^{-1}$ ), and statistically significant. In the oceanic regions, there is a statistically significant trend of  $0.25^{\circ}\text{C decade}^{-1}$ , a trend that is also observed in waters shallower than the permanent thermocline (200-600 dbar). This warming rate is density compensate, with an increase in salinity of  $0.02 \text{ decade}^{-1}$ . Neither the intermediate waters nor the upper deep waters show any statistically significant trend. The deep waters (2600-3600 dbar) in the oceanic waters north of the Canary Islands, show a warming rate of  $-0.01^{\circ}\text{C decade}^{-1}$  and a freshening of  $-0.002 \text{ decade}^{-1}$ .

*Keywords: Sea surface temperature, Upwelling, Downwelling, Warming, Thermocline, Canary Current Large Marine Ecosystem, Northwest Africa*



## OPEN OCEAN TEMPERATURE AND SALINITY TRENDS IN THE CANARY CURRENT LARGE MARINE ECOSYSTEM

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### 6.1.1. INTRODUCTION

The Canary Current Large Marine Ecosystem (CCLME) in the Northwest African (NWA) coast is a high productive ecosystem with strong socio-economic impact since it supports a vast and diverse marine population. The high productivity of the CCLME is mainly driven by the trade winds that flows alongshore, parallel to the NWA coastline, and therefore the actual global warming scenario may affect the CCLME by warming the upper ocean waters, but also, as suggested by Bakun (1990), by intensifying the upwelling and therefore cooling the upper ocean waters. Bakun's hypothesis suggested that the increase in greenhouse gases will lead to an increase in the temperature gradient between land and ocean, which would intensify the continental–oceanic pressure gradient, and therefore increase the alongshore wind stress that forces the coastal upwelling. Upwelling favorable wind intensification could benefit marine populating by increasing the nutrient supply to the euphotic layer, however, it could affect also in a negative way by transporting plankton out of the shelf or disrupting trophic interactions.

Although there is not doubt about the increase in global temperatures, the impact on the upwelling ecosystem is controversial. Pardo et al. (2011) estimated the upwelling intensity in the CCLME, using data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project, and found a general sea-surface warming and weakening of the upwelling intensity between 1970–2010. Using Sea Surface Temperature (SST) images for the period 1987–2006 and remote sensing wind stress Marcello et al. (2011) found intensification of the upwelling system in that period, while the alongshore wind stress remained stable. These authors also found that in the period 1987–2006 upwelled waters off Cape Blanc have increased their offshore spreading. Using different estimates of wind observations, including coastal meteorological stations, Barton et al. (2013) did not found evidences of intensification in upwelling favorable winds, moreover they found a significant increase in sea surface temperature at all latitudes in the CCLME region. Based on that, these authors concluded that there was no evidence for a general increase in the upwelling intensity in the CCLME. Sydeman et al. (2014) carried out a meta-analysis of all the literature focused in understanding the impact of the climate change in the wind intensification of coastal upwelling, and concluded that most of the literature, although subtle and spatially variable, support Bakun's hypothesis. In the case of the CCLME, the authors indicated that wind changes were ambiguous, with warm-season winds as likely to be intensifying as not. These authors found that in the CCLME, studies based on direct observations were significantly more likely to detect intensifying than weakening, while model/data reanalysis products were more likely to detect

weakening winds. Contrarily, Cropper et al. (2014), using a variety of upwelling indices for the period 1981–2010 concluded that there was compelling evidence in favor of the Bakun's hypothesis, with an increase in upwelling-favorable winds north of 20°N, and an increase in downwelling favorable winds south of 20°N.

Estimating upwelling trends from wind data is difficult due to the limited number of observations that can be used to represent ocean winds and that are not under the influence of topographic features, particularly from meteorological stations on the NWA coast. In the case of the California Current Large Marine Ecosystem, the amount of well-measured records was the reason given by Sydeman et al. (2014) to explain the exceptionally coherence between the model-data reanalyzes and the observations, both data types supporting Bakun's hypothesis. Moreover, recently Benazzouz et al. (2014b) have questioned the appropriateness of local indices, based on instantaneous wind forcing, to predict the upwelling due to the long temporal memory of the upwelling system.

Given this controversial about the upwelling intensifying, in this article we have focused in the actual impact of the global warming in the temperature and salinity of the CCLME region. Trends in the surface have been estimated using satellite SST measurements for the whole CCLME, while in the water column data from the only long-term time series available in the area has been used to estimate the impact of the current global warming scenario in the different waters masses.

### 6.1.2. DATA

SST data was obtained from the National Oceanic and Atmospheric Administration (NOAA) high-resolution blended analysis of Advanced Very High Resolution Radiometer (AVHRR). Daily SST were retrieved, with a spatial resolution of 1/4°, from 1982 to 2013. From the daily data, monthly means were calculated, and the trends were computed using monthly values.

Since 1996, the Centro Oceanográfico de Canarias (COC) of the Instituto Español de Oceanografía (IEO) in collaboration with the Instituto de Oceanografía y Cambio Global (IOGAG) of the Universidad de Las Palmas de Gran Canaria (ULPGC), has been carrying out the Radial Profunda de Canarias project (RAPROCAN, Vélez-Belchí et al., 2014) to study the water masses and circulation around the Canary Islands. With a yearly or twice a year frequency, 50 stations are carried out around the Canary Island archipelago. In each of the stations a Conductivity–Temperature–Pressure (CTD) SeaBird 911+ probe is used from the surface down to 5-10 m above the bottom of the ocean. The station separation is about 30 km in the oceanic waters and 5-10 km for the shelf/coastal stations. The SeaBird 911+ probe is equipped with a redundant temperature and salinity sensor for inter-comparison, and the salinity data is calibrated, following the World Ocean Circulation Experiment (WOCE) requirements, with precise measurements from a guildline-8400B autosal salinometer

The trends were computed using a robust multi-linear regression, which incorporates iteratively reweighted least squares with a bi-square weighting function. This method is insensitive to outliers, but the results are very close to the standard linear least squares trends. The confidence intervals for the slopes were calculated using Student's t test.

### 6.1.3. RESULTS

#### 6.1.3.1. Surface waters

Overall, the CCLME region shows a warming trend in the yearly averaged SST (Figure 6.1.1b). The mean value for the period 1982-2013 in the region is  $0.28^{\circ}\text{C decade}^{-1}$ , although the mode is  $0.25^{\circ}\text{C decade}^{-1}$ . The minimum values, around  $0.02^{\circ}\text{C decade}^{-1}$  are located west of Cape Beddouza in the weak permanent annual upwelling zone (Cropper et al., 2014), and south of Cape Bojador in the permanent annual upwelling zone. The spatial scale of these minimum values, as can be observed between Cape Juby and then Canary islands, is approximately 30 nm, more than half a degree in longitude at this latitude. The maximum warming trend in the yearly SST,  $0.65^{\circ}\text{C decade}^{-1}$ , is located west of Cape Timiris in the Mauritania-Senegalese upwelling zone. The patterns in the distribution of the warming trends correspond to the dynamical regimes of the region.

Using the mean SST distribution as a proxy that characterized the different dynamical regimes in the region, it is observed (Figure 6.1.1a) that near the coast the minimum values are enclosed by the  $20^{\circ}\text{C}$  isotherm, that characterizes the upwelling regime, except in the area between Cape Ghir and Cape Draa, where the warming is higher than  $0.25^{\circ}\text{C}$ . In this area the coastline is not parallel to the trade winds, and therefore there is weakening in the upwelling. The maximum trend values are between the  $24^{\circ}\text{C}$  and  $22^{\circ}\text{C}$  isotherms, where, in annual average, the influence of the upwelling is weaker than the influence of the downwelling favorable winds during the summer. In the oceanic waters, the area of high warming trends ( $>0.35^{\circ}\text{C decade}^{-1}$ ), is within the limits of the Mauritania-Senegalese upwelling zone where Cropper et al. (2014) reported an intensification of the downwelling favorable winds and it is the area where the Canary Current separates from the coast to become the westward flowing North Equatorial Current (Hernández-Guerra et al., 2005). North and south of this area, the warming trends are weaker ( $<0.25^{\circ}\text{C decade}^{-1}$ ), except of the oceanic waters north of  $32^{\circ}\text{N}$  that are characterized by the Azores Current (Comas-Rodríguez et al., 2011; Pérez-Hernández et al., 2013).

The distribution of the summer (July, August and September) warming trend, confirms the results observed with the yearly data, with a mean summer trend in the region of  $0.21^{\circ}\text{C decade}^{-1}$ . The minimum values are lower than using the yearly data, as expected due to the increase of the upwelling during the summer, and reach  $-0.14^{\circ}\text{C decade}^{-1}$  west of Cape Beddouza and south of Cape Bojador in the permanent annual upwelling zone, except in the area between Cape Ghir and Cape Draa, where the warming is higher than  $0.25^{\circ}\text{C}$ . The maximum values are also higher than using the yearly data, as expected due to the increase of the downwelling during the summer, up to  $0.90^{\circ}\text{C decade}^{-1}$  west of Cape Timiris. The distribution of the warming trends during summer also corresponds to the dynamical regimes of the region. Near the coast, the lower, and negative values, are enclosed by the  $22^{\circ}\text{C}$  isotherm, and correspond to the areas with strong upwelling during the summer, while the maximum values are found where the isotherms are perpendicular to the coast, in the area where the downwelling is stronger in summer. As in the annual trends, north of the Azores current region, the warming rates are higher than south of it.

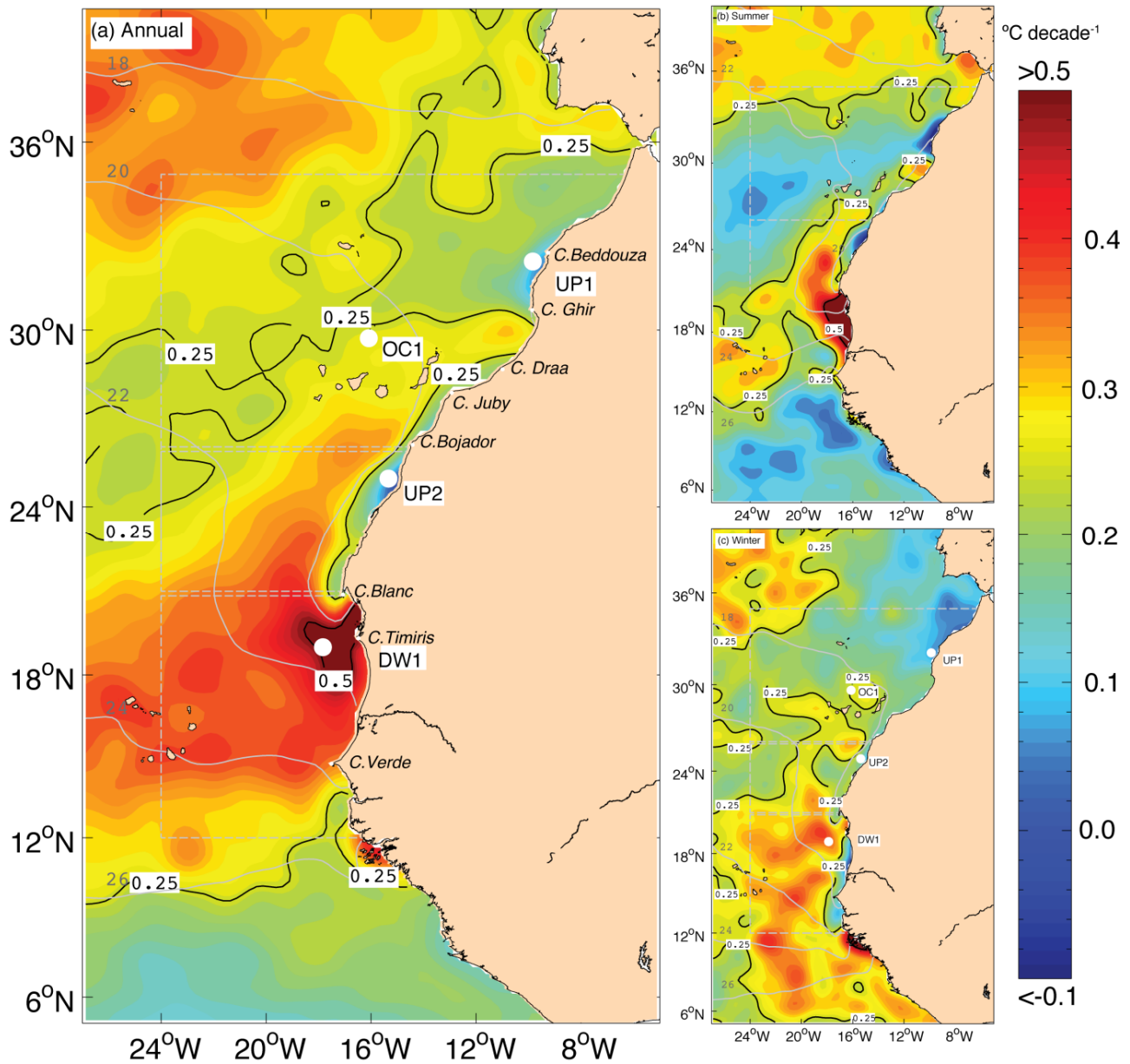


Figure 6.1.1. (a) Sea surface trends ( $^{\circ}\text{C decade}^{-1}$ ) computed from NOAA high-resolution ( $1/4^{\circ}$ ) blended analysis of Daily SST for the 1982–2013 period. (b) as (a) but for the summer (June, July and August, JJA) months, (c) as (a) but for the winter (January, February and March, JFM). The white dots are the location of the time series of Figure 6.1.2. The dashed grey line denote the three upwelling areas as defined by Cropper et al. (2014): the weak annual upwelling zone ( $26^{\circ}\text{N}$ - $35^{\circ}\text{N}$ ), the permanent annual upwelling zone ( $21^{\circ}\text{N}$ - $26^{\circ}\text{N}$ ) and the Mauritania-Senegalese upwelling zone ( $12^{\circ}\text{N}$  - $20^{\circ}\text{N}$ ). The thin solid grey lines correspond to the isotherms ( $18^{\circ}\text{C}$ ,  $20^{\circ}\text{C}$ ,  $22^{\circ}\text{C}$ ,  $24^{\circ}\text{C}$  and  $26^{\circ}\text{C}$ ) of the mean field for each season. Note that the color scale is the same for the three figures, although the range is different, as describe in the text.

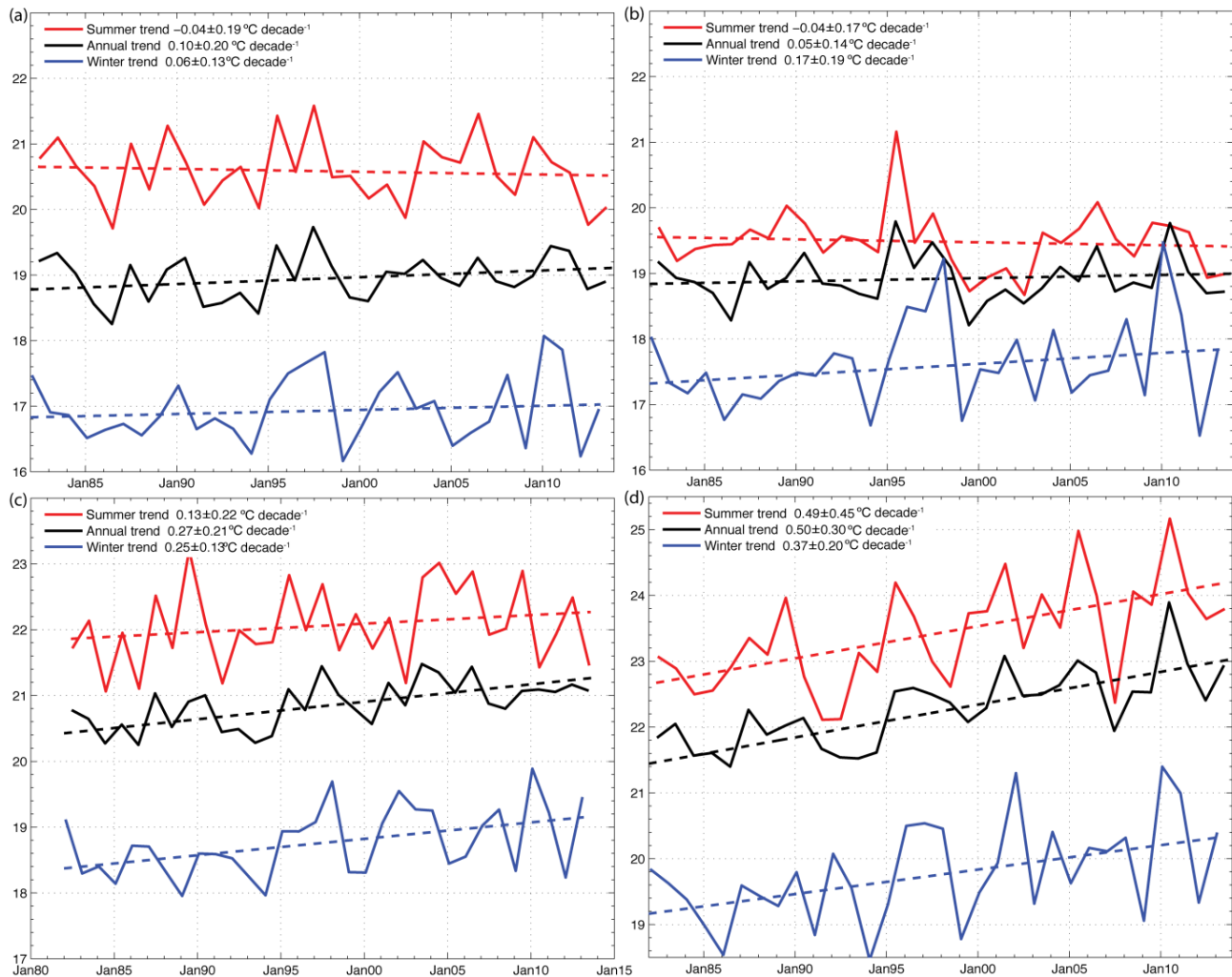


Figure 6.1.2. Yearly values of the SST for the four locations describe in the text and represented in Figure 6.1.1. (a) UP1, west of Cape Beddouza in the weak permanent annual upwelling zone (b) UP2, south of Cape Bojador in the permanent annual upwelling zone (c) OC1, in the oceanic waters north of the Canary Islands, and (d) DW1, west of Cape Timiris, in the Mauritania-Senegalese upwelling zone. In each of the figures, the red line is for the summer mean, the blue for the winter, and the black for the annual average. Trend values (dashed line in  $^\circ\text{C decade}^{-1}$ ), and statistical significant range at the 95% confidence level are indicated in the legend for each one of the locations.

During the winter (January, February and March), warming trends are also coherent with the dynamical regime in the region, with a mean trend winter value in the region of  $0.24^\circ\text{C decade}^{-1}$ . The minimum values are found near the coast, north of Cape Beddouza, and in the coast of the Iberian peninsula, in the area, where the upwelling is stronger during the winter, but with trends lower than  $0.1^\circ\text{C decade}^{-1}$ . Overall, near the coast, both in the weak permanent annual upwelling zone and in the permanent annual upwelling zones, there are low warming rates, statically not different from zero. Near the coast, in the Mauritania-Senegalese upwelling zone, the trends are lower than during the summer, as low as  $0.10^\circ\text{C decade}^{-1}$ , coherent with the fact that during winter there are not downwelling favorable winds in the area. The spatial scale of these patterns of minimum values is approximately 30 nm, more than half a degree in longitude at this latitude.

To confirm the distribution of the observed trends, four locations, representatives of the different dynamical regimes explained before, were selected. The two locations (Figure 6.1.2 a, b) in the weak permanent annual upwelling zone (UP1) and in the permanent annual upwelling zone (UP2) shows trends not statistically different from zero for the yearly averages ( $0.1 \pm 0.20^{\circ}\text{C decade}^{-1}$  for UP1 and  $0.05 \pm 0.14^{\circ}\text{C decade}^{-1}$  for UP2), with negatives values for the summer months ( $-0.04 \pm 0.19^{\circ}\text{C decade}^{-1}$  for UP1 and  $-0.04 \pm 0.17^{\circ}\text{C decade}^{-1}$  for UP2), when the upwelling is stronger, and non statistically significant warming trends for the winter months ( $0.06 \pm 0.13^{\circ}\text{C decade}^{-1}$  for UP1 and  $-0.17 \pm 0.19^{\circ}\text{C decade}^{-1}$  for UP2). The correlation between the yearly values of the two locations is high, 0.77 ( $p < 0.01$ ) for the annually averaged SST and 0.88 ( $p < 0.01$ ) for the winter trend, as expected since the two locations are in the same dynamical regime. The location in oceanic waters (OC1, Figure 6.1.2c) shows warming trends statistically significant of  $0.27 \pm 0.21^{\circ}\text{C decade}^{-1}$  for the annual and strongly correlated with the locations in the upwelling regime (0.80,  $p < 0.01$ ) and in the downwelling regime (0.77,  $p < 0.01$ ). The location in the Mauritania-Senegalese upwelling zone (DW1) shows warming trends statistically significant during winter and summer with an annual value of  $0.5 \pm 0.3^{\circ}\text{C decade}^{-1}$ . This high warming has been related, by some authors as Cropper et al. (2014), to the recovery of the African monsoon, and the downwelling favorable winds.

### 6.1.3.2. Water column

Figure 6.1.3a shows the current distribution of hydrographic stations carried out in the framework of the RAPROCAN project, one of the few, if not the only one, long term time series in the Coastal Transition Zone (CTZ) of the Canary Current Large marine ecosystem. Stations from 5 to the 24 have been sampled since 1997.

The area is characterized by four waters masses (Figure 6.1.3b), the North Atlantic Central Waters (NACW), roughly between 200 dbar and 600 dbar and lighter than the  $27.25 \text{ kg m}^{-3}$  isopycnal; the intermediate waters, mainly Mediterranean (MW) and Antarctic Intermediate Waters (AAIW), between 600 dbar and 1600 dbar, and lighter than the  $27.85 \text{ kg m}^{-3}$  isopycnal; and the North Atlantic Deep Waters (NADW), deeper than 2600 dbar and heavier than the  $27.85 \text{ kg m}^{-3}$  isopycnal (Vélez-Belchí et al., 2014).

The trends in temperature and salinity, for the oceanic area (stations 11-24, Figure 6.1.4) and the area in the Lanzarote Passage (LP, stations 5-10, Figure 6.1.5), closer to the upwelling region, were estimated in four different depth stratum, to characterize the trend of the water masses in the area. For the depth stratum (200-600 dbar) that characterize the NACW waters, both the oceanic area and the LP area shows a statistically significant warming trend,  $0.20 \pm 0.11^{\circ}\text{C decade}^{-1}$  for the oceanic area and  $0.20 \pm 0.25^{\circ}\text{C decade}^{-1}$  for the LP. The variability in the LP is higher due to the proximity of the upwelling region, and the frequent intrusions of upwelling filaments (Hernández-Guerra et al., 2003), and therefore the uncertain is higher in the trend estimations. Similarly, the analysis shows an increase in salinity of  $0.03 \pm 0.023 \text{ decade}^{-1}$  for the oceanic area and of  $0.028 \pm 0.038 \text{ decade}^{-1}$  for the LP. These changes are similar to those found in the subtropical Atlantic at  $24^{\circ}\text{N}$  by Vargas-Yáñez et al. (2002), Vélez-Belchí et al. (2010) and Benítez-Barrios et al. (2008) in the Canary basin. The strong inter-annual variability was also pointed out by Vélez-Belchí et al. (2010). The increase in temperature and salinity almost compensate in density, corroborating that the observed trends are due to deepening of the isoneutral surfaces rather than changes along the isoneutral (Vélez-Belchí et al., 2010).

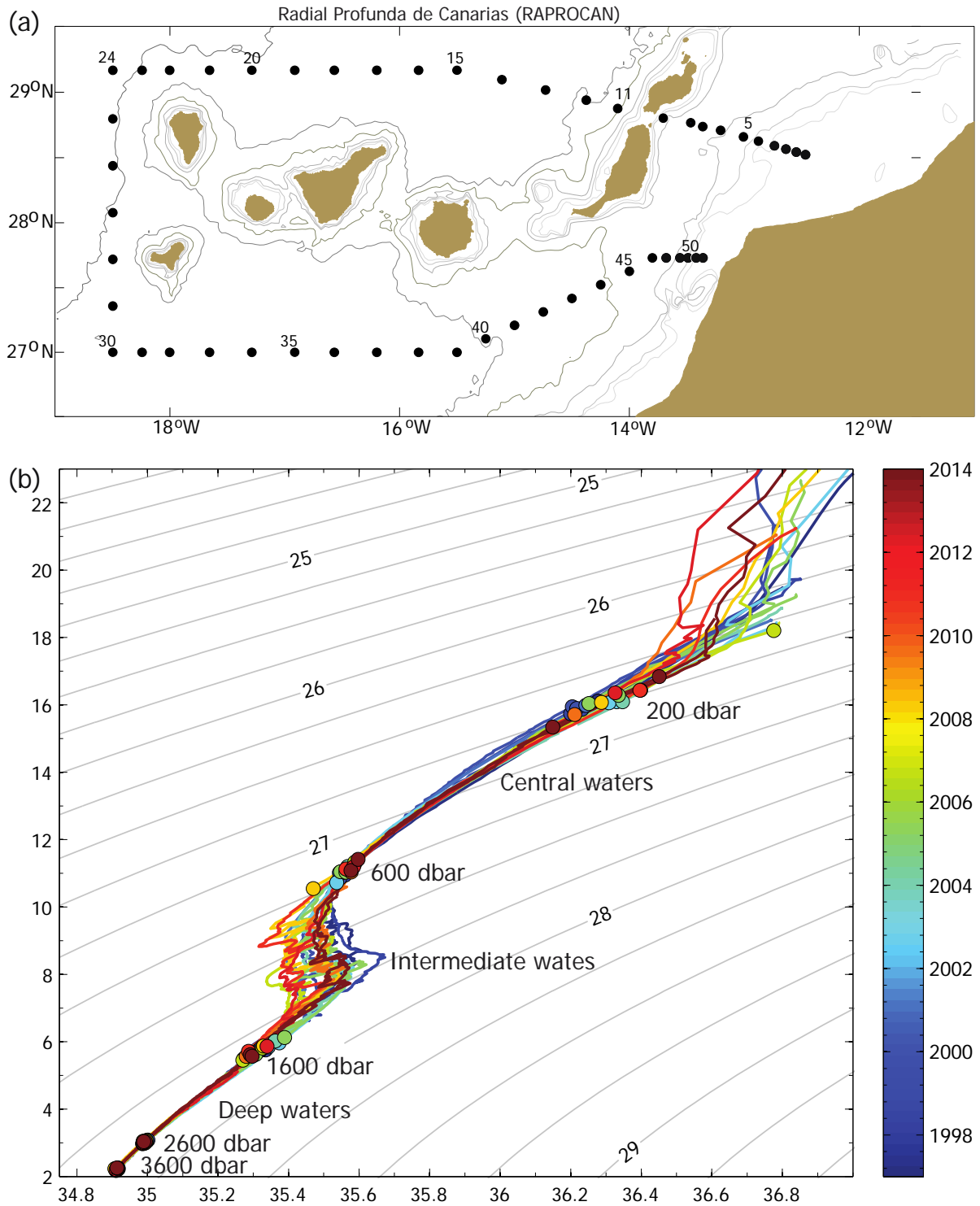


Figure 6.1.3. (a) Localization of the CTD stations currently carried out during the RAPROCAN cruises. (b) Potential temperature/salinity diagram for station 15 (European Station for Time Series in the Ocean, ESTOC), representative of the area. The colors indicated the year of the CTD cast, and the dots are located at 200 dbar, 600 dbar, 1600 dbar, 2600 dbar and 3600 dbar, approximately delimitating the thermocline waters; the central waters (mainly NACW); the intermediate waters (mainly MW and AAIW); and the deep waters (mainly NADW).



The observed trends in temperature in the central waters are very similar to those found using the SST as previously described. The trend in the location OC1 (Figure 6.1.2c), that roughly correspond to station 15, and gave a trend of  $0.27 \pm 0.21^{\circ}\text{C decade}^{-1}$ , was reduced to  $0.22 \pm 0.11^{\circ}\text{C decade}^{-1}$  when only the time series since 1997 was considered.

In the intermediate waters, the trends for temperature and salinity were not statistically significant, neither in the oceanic region nor in the LP. Both time series (Figure 6.1.4b and 6.1.5b) show high variability due to fact that, as pointed out before, two very different intermediate water masses converge in the region.

For the deep layers, two depth stratums were analyzed. In the shallower one (1700-2600 dbar), corresponding to the upper NADW, there were weak warming and increase in salinity statistically non different from zero. However, in the deeper depth stratums (2600-3600 dbar), where mainly NADW is found, a marginally statistical significant cooling ( $-0.01 \pm 0.01^{\circ}\text{C decade}^{-1}$ ) and freshening ( $-0.002 \pm 0.002^{\circ}\text{C decade}^{-1}$ ) is observed. This freshening corresponds to the reported freshening of the sub-polar North Atlantic since the 1970s (Curry et al., 2003; Curry and Mauritzen, 2005; Dickson et al., 2002).

#### 6.1.4. CONCLUSIONS

Trends in the open ocean temperature and salinity in the CCLME have been analyzed using satellite high resolution SST that covers the whole region, water column CTD data in the Canary basin and the CTZ with a long-term time series, that goes back to 1997.

The SST for the 32 years in the period 1982-2013, shows a warming trend in the CCLME, with a mean value of  $0.28^{\circ}\text{C decade}^{-1}$ . However, the warming trend shows significant changes linked to the different dynamical regimes that coexist in the CCLME. Near the coast, in the area closed linked to the upwelling, between Cape Blanc and Cape Beddouza, the warming trend is not statistically different from zero, and during the stronger upwelling months, the summer, there is a cooling trend neither statistically different from zero. The spatial scale of some of these patterns is smaller than one degree, and therefore could only be observed using high resolution SST. Near the coast and in the oceanic waters under the influence of downwelling, between Cape Verde and Cape Blanc, the warming trend is higher ( $>0.5^{\circ}\text{C decade}^{-1}$ ), and statistically significant, but decreasing towards the west. In the oceanic regions, there is a statistically significant trend of  $0.25^{\circ}\text{C decade}^{-1}$ .

The trends in SST are also observed in waters over the permanent thermocline (200-600 dbar) with a slight weaker statistically significant rate, up to  $0.25^{\circ}\text{C decade}^{-1}$ , that is density compensate with an increase in salinity of  $0.02 \text{ decade}^{-1}$ . Neither the intermediate waters nor the upper deep waters shows any statistically significant trend, however the deep waters (2600-3600 dbar) in the oceanic waters north of the Canary Islands, shows a warming rate of  $-0.01^{\circ}\text{C decade}^{-1}$  and a freshening of  $-0.002 \text{ decade}^{-1}$ .

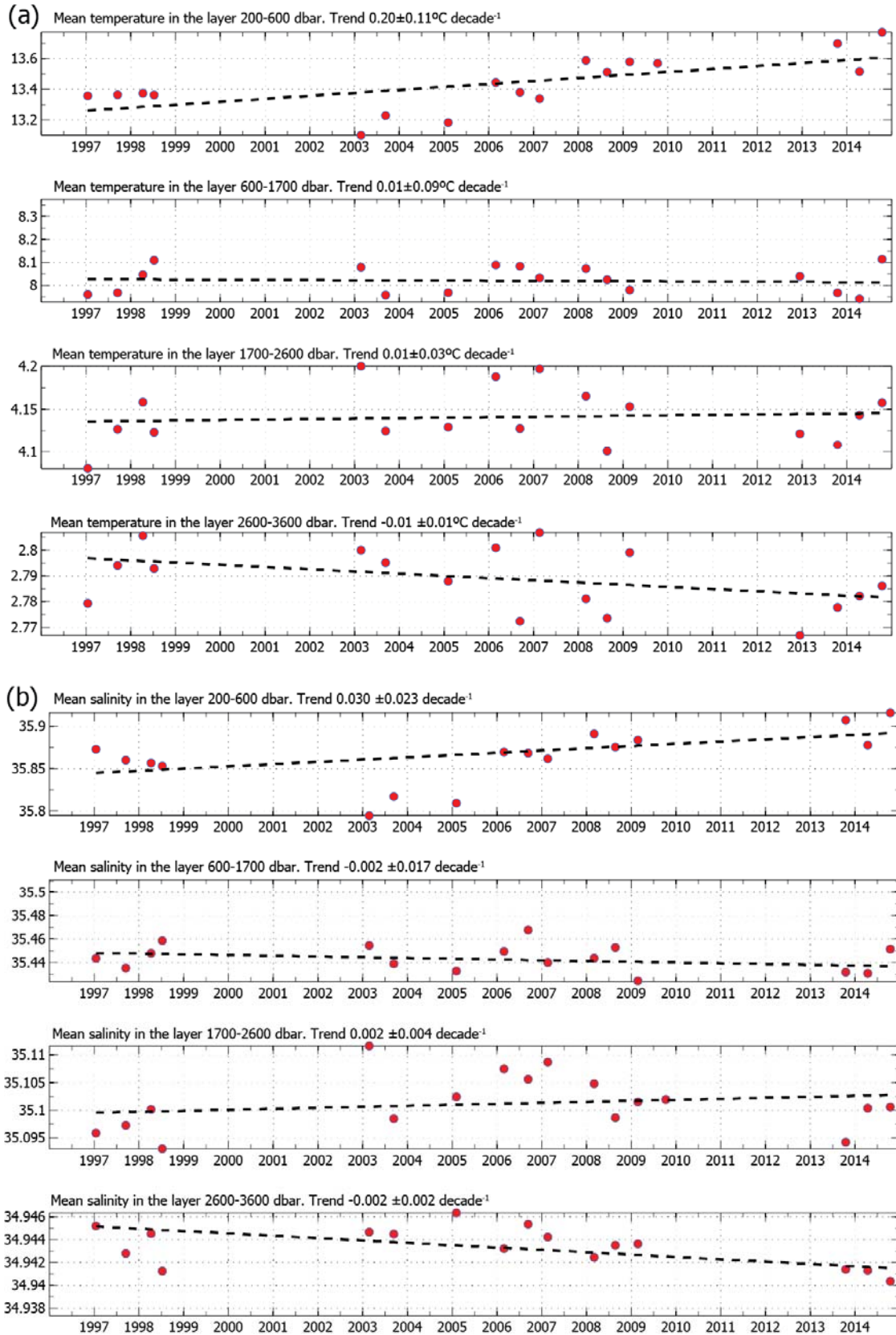


Figure 6.1.4. Time series of (a) mean temperature (°C) and (b) mean salinity between stations 11-24 for four different vertical strata, representative of the central waters (200-600 dbar), intermediate waters (600-1700 dbar), and deep waters (2600-3600 dbar). Trend (dashed line) and trend values, and statistical significant range at the 95% confidence level are indicated for each depth stratum.

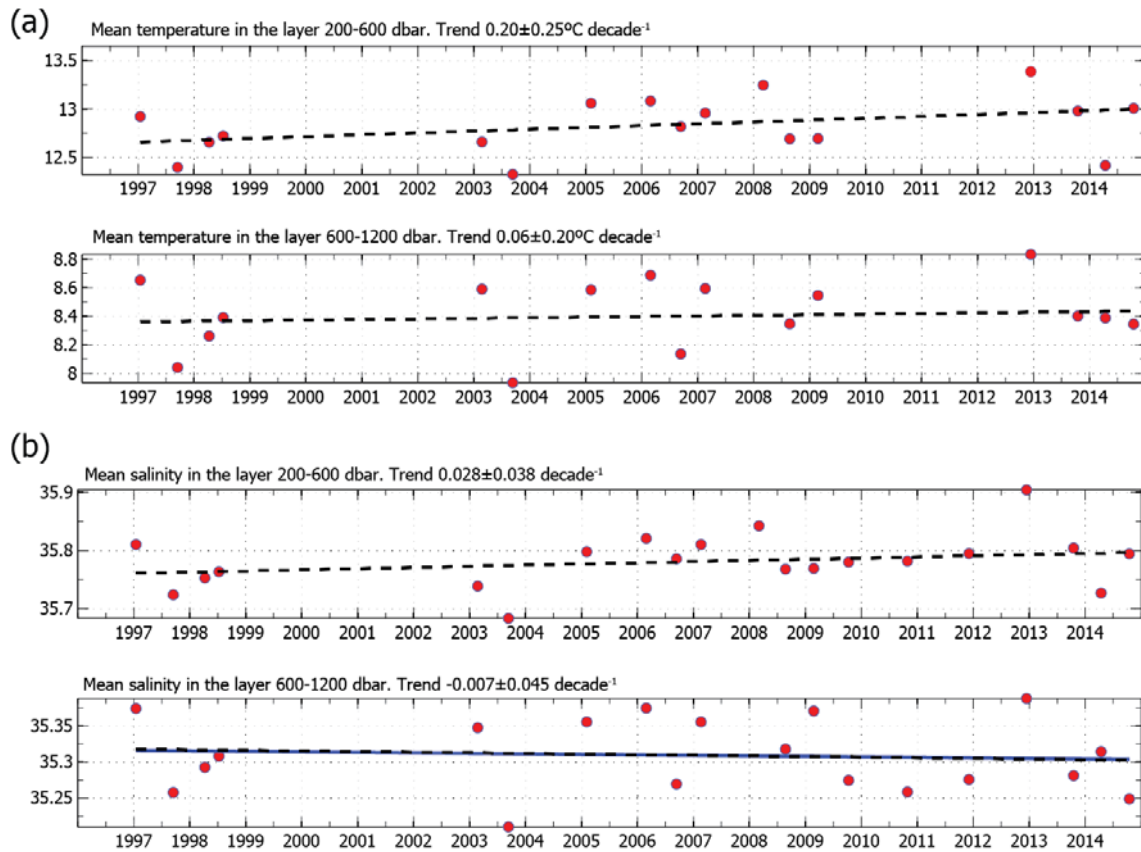


Figure 6.1.5. Same as Figure 6.1.4, but two different vertical stratums, representative of the central waters (200-600 dbar) and intermediate waters (600 dbar-bottom, 1300 m is the maximum depth in the Lanzarote passage).

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## BIBLIOGRAPHY

- Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science*, Vol. 247 (4939), pp. 198-201. doi:10.1126/science.247.4939.198.
- Barton, E. D., Field, D. B. and Roy, C. 2013. Canary current upwelling: More or less? *Progress in Oceanography*, Vol. 116, pp. 167-178. doi:10.1016/j.pocean.2013.07.007.
- Benazzouz, A., Pelegrí, J. L., Demarcq, H., Machín, F., Mason, E., Orbi, A., Peña-Izquierdo, J. and Soumia, M. 2014b. On the temporal memory of coastal upwelling off NW Africa. *Journal of Geophysical Research: Oceans*, Vol. 119, pp. 6356-6380. doi:10.1002/2013JC009559.
- Comas-Rodríguez, I., Hernández-Guerra, A., Fraile-Nuez, E., Martínez-Marrero, A., Benítez-Barrios, V. M., Pérez-Hernández, M. D. and Vélez-Belchí, P. 2011. The Azores Current System from a meridional section at 24.5 degrees W. *Journal of Geophysical Research: Ocean*, Vol. 116. doi:10.1029/2011JC007129.
- Cropper, T. E., Hanna, E. and Bigg, G. R. 2014. Spatial and temporal seasonal trends in coastal upwelling off Northwest Africa, 1981–2012. *Deep-Sea Research Part I: Oceanographic Research Papers*, Vol. 86, pp. 94–111. doi:10.1016/j.dsr.2014.01.007.
- Curry, R., Dickson, B. and Yashayaev, I. 2003. A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, Vol. 426, pp. 826–829. doi:10.1038/nature02206.
- Curry, R. and Mauritzen, C. 2005. Dilution of the Northern North Atlantic Ocean in Recent Decades. *Science*, Vol. 308, pp. 1772–1774. doi:10.1126/science.1109477.
- Dickson, B., Yashayaev, I., Meincke, J., Turrell, B., Dye, S. and Holfort, J. 2002. Rapid freshening of the deep North Atlantic Ocean over the past four decades. *Nature*, Vol. 416, pp. 832–837. doi:10.1038/416832a.
- Hernández-Guerra, A., Fraile-Nuez, E., Borges, R., López-Laatzén, F., Vélez-Belchí, P., Parrilla, G. and Muller, T. 2003. Transport variability in the Lanzarote passage (eastern boundary current of the North Atlantic subtropical Gyre). *Deep-Sea Research Part I: Oceanographic Research Papers*, Vol. 50 (2), pp. 189–200. doi:10.1016/S0967-0637(02)00163-2.
- Hernández-Guerra, A., Fraile-Nuez, E., López-Laatzén, F., Martínez, A., Parrilla, G. and Vélez-Belchí, P. 2005. Canary Current and North Equatorial Current from an inverse box model. *Journal of Geophysical Research: Oceans*, Vol. 110, C12019. doi:10.1029/2005JC003032.
- Marcello, J., Hernández-Guerra, A., Eugenio, F. and Fonte, A. 2011. Seasonal and temporal study of the northwest African upwelling system. *International Journal of Remote Sensing*, Vol. 32, pp. 1843–1859. doi:10.1080/01431161003631576.
- Pardo, P. C., Padín, X. A., Gilcoto, M., Farina-Busto, L. and Pérez, F. F. 2011. Evolution of upwelling systems coupled to the long-term variability in sea surface temperature and Ekman transport. *Climate Research*, Vol. 48 (2), 231–246. doi:10.3354/cr00989.
- Pérez-Hernández, M. D., Hernández-Guerra, A., Fraile-Nuez, E., Comas-Rodríguez, I., Benítez-Barrios, V. M., Domínguez-Yanes, J. F., Vélez-Belchí, P. and De Armas, D. 2013. The source of the Canary current in fall 2009. *Journal of Geophysical Research: Ocean*, Vol. 118, C12019. doi:10.1002/jgrc.20227.
- Sydeman, W. J., García-Reyes, M., Schoeman, D. S., Rykaczewski, R. R., Thompson, S. A., Black, B. A. and Bograd, S. J. 2014. Climate change and wind intensification in coastal upwelling ecosystems. *Science*, Vol. 345, pp. 77–80. doi:10.1126/science.1251635.
- Vargas-Yáñez, M., García Lafuente, J., Sarhan, T., Vargas, J. and Vélez-Belchí, P. 2002. About the seasonal variability of the Alboran Sea circulation. *Journal of Marine Systems*, Vol. 35, pp. 229–248.
- Vélez-Belchí, P., Hernández-Guerra, A., Fraile-Nuez, E. and Benítez-Barrios, V. 2010. Changes in Temperature and Salinity Tendencies of the Upper Subtropical North Atlantic Ocean at 24.5°N. *Journal of Physical Oceanography*, Vol. 40, pp. 2546–2555. doi:10.1175/2010JPO4410.1.
- Vélez-Belchí, P. et al. 2014. Monitoring the Oceanic Waters of the Canary Islands: the deep hydrographic section of the Canaries. *IV Congress of Marine Sciences*, Las Palmas de Gran Canaria, Spain, 11-13 June 2014.