6.4. TRENDS IN PHYTOPLANKTON AND PRIMARY PRODUCTIVITY OFF NORTHWEST AFRICA

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6.4.1. INTRODUCTION

The Canary Current Upwelling System is one of the most productive coastal systems in the world, particularly in the subtropical latitudes. It sustains among the most productive monospecific small pelagic fisheries worldwide, mostly composed of clupeids. Catches that account for more than a quarter of the world's marine production (FAO, 2012), showed a strong increase from the 50s to the 90s, with a consistent decrease thereafter (about 15%) until 2011, a trend that explains the 'lose – lose' economic situation of the world's fisheries (Kelleher and Willmann, 2006).

In Northwest Africa (NWA), the contribution of fisheries to the gross domestic product (GDP) is between 2% and 4% for countries such as Senegal, Gambia and Cape Verde (de Graaf and Garibaldi, 2014). The recent trends for NWA countries show a slight but continuous increase in total catches, due primarily to an increase in fishing effort.

It is also well known that small pelagic species, because of their spawning strategy, are naturally very sensitive to environmental constraints (Cury and Roy, 1989; Meiners et al., 2010) and are responsible for most of the variability in the world's catches (Cury et al., 2008; Cury and Shannon, 2004). It is also recognized that regional primary productivity partly constraints natural levels of exploited stocks (Chassot et al., 2010).

The variability of marine primary productivity in the Canary Current Large Marine Ecosystem (CCLME) also plays an important role in the carbon cycle because oceans serve as a net sink of carbon dioxide (CO_2), by removing about 26% of anthropogenic emissions from the atmosphere (IPCC, 2013). It is estimated that this sink has increased only slightly over the last two decades (Sitch et al., 2015; Wanninkhof et al., 2013). The first factor partly controlling this trend is the reduced capability of the ocean to dissolve CO_2 because of continuous warming: the global mean surface temperature over the mean past 20 years (1993–2012) rose at a rate of 0.17°C decade^{-1} from 1979 to 2010 and at 0.24°C ± 0.06°C decade^{-1} from 1979 to 2010 in the northern hemisphere (Morice et al., 2012).

The observed surface warming of the tropical northern Atlantic, particularly for the CCLME region, is one of the highest over the last 30 years, with an average value of 0.30°C decade^{-1}, as computed from AVHRR (Advanced Very High Resolution Radiometer) satellite sea surface temperature (SST) from 1985 to 2007 (Demarcq, 2009; Good et al., 2007) or from more climate-oriented SST datasets (Cropper et al., 2014).

The global long-term warming trend, due to anthropogenic emissions of CO_2, remarkably anticipated by Broecker (1975), is also strongly altered by multidecadal variability (MDV ≈50–80 years). In the North Atlantic, Polyakov et al. (2009) show a general warming trend of 0.031 ± 0.006°C decade^{-1} in the upper 2000 m over the last 80 years of the 20th century, with periods of shorter duration strongly amplified by MDV. For example, MDV accounts for ≈60% of North Atlantic warming since 1970. The non linear and spatially heterogeneous nature of warming in the CCLME is well described from more than 30 years of satellite-based observations. It is also well established (Hansen et al., 2006) that global warming of more than 1°C (relative to 2000), will constitute a ‘‘dangerous’’ threshold with likely effects on species survival.

The second factor influencing the variability of the carbon cycle is of course the level of marine primary productivity. Likely due to an increase of ocean's stratification, that decreases the vertical exchanges and consequently the enrichment of the surface layer, a decreasing productivity trend has been observed in the world ocean (Behrenfeld et al., 2006; Polovina et al., 2008). In upwelling areas, these trends may be somewhat different as local winds are the major controlling factor in determining trends in productivity (Cropper et al., 2014; Demarcq, 2009).

The most in-depth attempt to compute long-term marine productivity trends from satellite chlorophyll-a data, a common proxy for phytoplankton biomass, was made by Antoine et al. (2005) from two temporally independent spatial missions, the Coastal Zone Color Scanner (CZCS; 1979–1986) and the Sea-viewing WIde Field-of-view Sensor (SeaWiFS, data from 1997–2002). They estimated an average 22% worldwide increase in productivity, mostly in the intertropical areas. It is interesting to note that within the CCLME region, a similar positive trend was observed between 15°N to 30°N for the period 1979-2002, the opposite to that found later in the same region by Demarcq (2009) and several other authors, synthesized by Gregg and Rousseaux (2014) from SeaWiFS data from 1998 to 2007.

Because they partly overlap in time, composite products have been created from SeaWiFS, MODerate resolution Imaging Spectroradiometer (MODIS) and MEdium Resolution Imaging Spectrometer (MERIS) ocean color (OC) data, with the help of a unique chlorophyll-a algorithm (Maritorena et al., 2010). Despite a great improvement in terms of data density and coverage, “clear differences” between sensors have been noted. These differences are explained by differences in calibration and atmospheric corrections, correction of sensor sensitivity drifts and various data processing constraints such as cloud masking and spatial variations in data density. It is therefore not surprising that the combination of all errors lead to significant differences in the retrieval of complex variables such as the chlorophyll-a concentration, in which algorithms differ in the number of sensors and characteristics (see for example Brewin et al., 2013). In the case of MODIS, Shang et al. (2014) noted important and seasonally varying differences between three different published chlorophyll-a algorithms, and *in situ* data. Gregg and Casey (2010) used the Empirical Satellite Radiance-In situ Data (ESRID) methodology (Gregg et al., 2009), an empirical method based on the *a posteriori* re-derivation of SeaWIFS and MODIS bio-optical algorithm coefficients from water-leaving reflectances adjusted from *in situ* data.

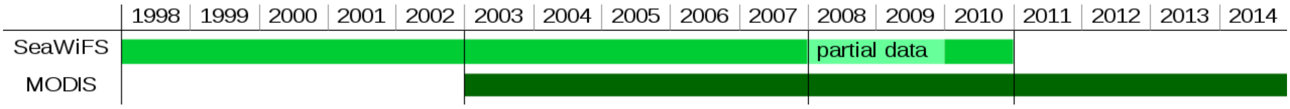
Recently, Gregg and Rousseaux (2014) used a new composite method with datasets from two sensors (SeaWiFS and MODIS) combined with the ESRID method, *in situ* data and their assimilation in global biogeochemical models to estimate global trends at the scale of oceanic basins.

The purpose in this work is to define an empirical seasonal bias correction model between the two concomitant chlorophyll-a time series of SeaWiFS and MODIS in complex coastal waters off NWA, in order to include MODIS data from 2008 to 2014 in the determination of trends in chlorophyll-a in the CCLME region. We explore how trends for the whole 17-year period from 2003 to 2014 have evolved in the region since the previous study of Demarcq (2009) for the period 1998-2007 as established from SeaWiFS data for the four major upwelling systems.

6.4.2. DATA AND METHODS

In order to reduce the above-mentioned constraints of using datasets from different sources, data from only SeaWiFS and MODIS-Aqua are used for the 17-year period, from 2003 to 2014. Monthly averages of chlorophyll-a data from the whole SeaWiFS mission from 1998 to 2010 (including major data gaps in 2008 and 2009) and the present MODIS period, from 2003 to 2014 (Table 6.4.1) are examined. Because spatial resolution is an important issue in coastal regions, 9-km monthly SeaWiFS data were downscaled to 4.5 km to match the resolution of level-3 MODIS data.

Table 6.4.1. Temporal coverage of the SeaWiFS and MODIS data used in this study.



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
SeaWiFS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	partial data		🟩				
MODIS						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

As of March 2015, the current standard OC products, distributed via the National Aeronautics and Space Administration (NASA) Ocean Biology Processing Group (OBPG) (http://oceancolor.gsfc.nasa.gov/cms/, accesed on 16 March 2015) are produced with the reprocessing versions R2010.0 for SeaWiFS and R2013.1 for MODIS-Aqua, and are intended to be equivalent in terms of quality. These versions are used is the present work, and are detailed in http://oceancolor.gsfc.nasa.gov/cms/reprocessing (accessed on 16 March 2015). The previous MODIS-Aqua reprocessing R2013.0 in particular has updated the instrument calibration to improve the late-mission temporal calibration, while the processing algorithms are identical with the previous versions (R2010.0 and R2012.0). The present chlorophyll-a standard algorithms are OC4v6 and OC3M, respectively for SeaWiFS and MODIS.

Ultimately, further data reprocessing (R2014.0) will be soon applied by the OC NASA/OBPG team to all OC missions. This reprocessing will include instrument calibration updates for all sensors to correct raw data for the latest known sensor degradations (such as a decrease in sensitivity over time). Significant changes are likely for some sensors, including SeaWiFS and MODIS-Terra (see http://oceancolor.gsfc.nasa.gov/cms/reprocessing/OCReproc20140.html - accessed 16 March 2015 - for details).

In the present work, special attention has been given to reconstruction of missing SeaWiFS data for the period 2008 to 2009 (2010 does not have full missing months). Fortunately, it has been possible to replace the missing days by the average for the same days of the two surrounding years, in order to minimize the impact of this reconstruction when computing trends.

Trends in primary productivity are derived from chlorophyll-a data. As previously shown (Demarcq, 2009), the results from a biomass-related index are very similar to those from a biomass-based production model such as the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski, 1997), as detailed in Demarcq (2009).

All trends are computed by splitting the time series into two parts. This procedure has been used for its robustness and conservative properties are compared to classic statistical methods (see Demarcq, 2009). In particular, the influence of the first and last years of the time series are greatly reduced in the case of extreme events.

Because of the naturally narrow distribution of the chlorophyll-a data, the adjustment has been made from the decimal logarithm of chlorophyll-a. The relative complexity of the observed biases between both datasets led to a two-step adjustment, utilizing a linear fit for chlorophyll values from 0.01 mg m^{-3} to 0.5 mg m^{-3} and a quadratic fit for higher values.

6.4.3. DIFFERENCES BETWEEN SENSORS

Because the above-mentioned differences between SeaWiFS and MODIS data, differences in chlorophyll-a have been computed separately for the 5-year period from 2003 to 2007 where both datasets are available (Figure 6.4.1). Within the CCLME, except for low chlorophyll-a concentrations, MODIS strongly overestimates measurements (Figure. 6.4.1a) compared to SeaWiFS (Figure 6.4.1b). The differences (Figure 6.4.1c) are high (> 3 mg m^{-3}) in the upwelling area, particularly over the continental shelf, where average concentrations of 10 mg m^{-3} are very common. In the coastal region (10°N-25°N / 15°W-18°W, red rectangle and inserted plot in Figure 6.4.1c), the time series shows a systematic difference of about 2 mg m^{-3} between the datasets. The average yearly difference in this coastal area is 42.5%, but only 32.4% for the greater region, from 15°W to 25°W.

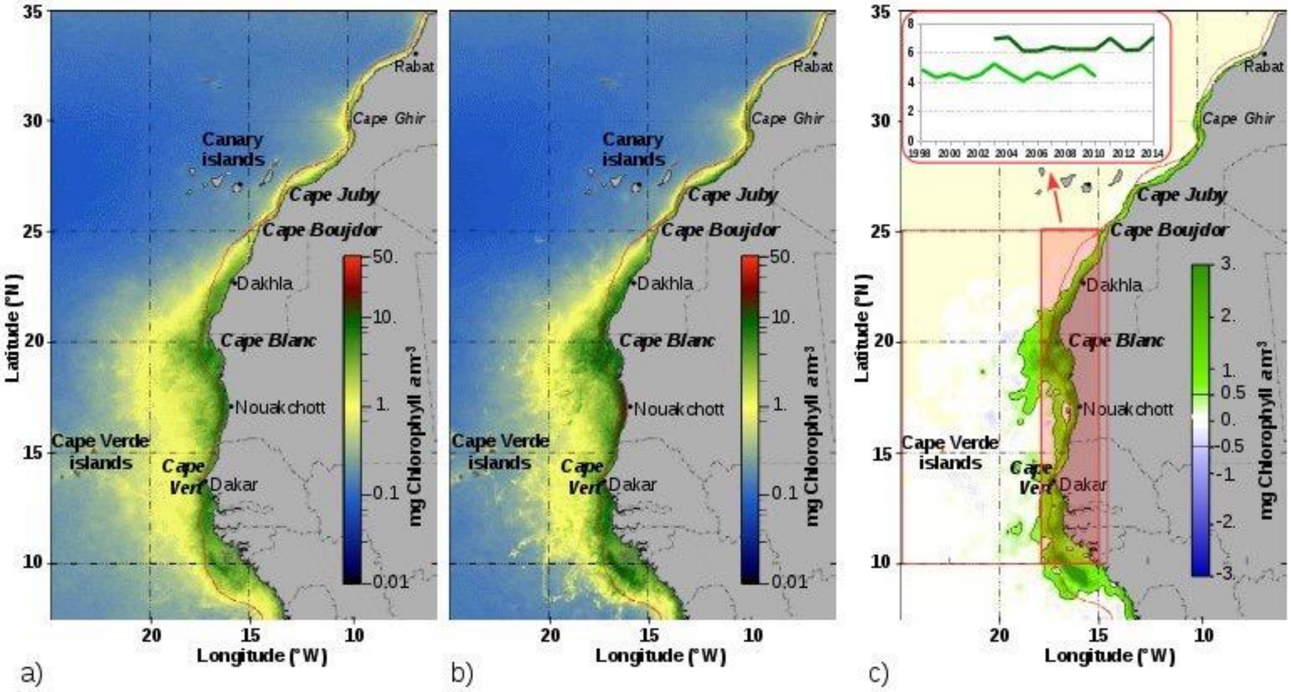


Figure 6.4.1. Average chlorophyll-a concentrations from a) SeaWiFS and b) MODIS data from 2003 to 2007 and c) the MODIS-SeaWiFS difference for the same period. The 200 m depth contour (red line) is superimposed. The insert in plot (c) shows the yearly averages of both sensors from 1998 to 2014 in the coastal area as defined by the red rectangle.

The relative stability of the differences over time shows that a systematic correction of the datasets is possible. The average difference between sensors does vary slightly according to season (not shown), probably because of differences in the atmosphere in this very seasonally variable region of the CCLME.

6.4.4. PARTIAL TRENDS DURING THE 1998-2014 PERIOD

In order to search for coherent temporal trends over the period 1998-2014, partial trends were computed separately for both the SeaWiFS and MODIS sensors for the Mauritanian and Senegalese regions of the CCLME (Figure 6.4.1), where trends were the strongest.

The SeaWiFS trend computed from 1998 to 2007 (Figure 6.4.2a) (Demarcq, 2009) shows mostly negative values with positive trends in the coastal regions of northern Mauritania and Guinea, in the vicinity of the shelf break. The trends computed from MODIS data from 2003 to 2014 (with a 5-year overlap with the previous one) show similar patterns (Figure 6.4.2b) with the dominance of positive trends. Because of the high bias between datasets, no common trend can be computed without preliminary correction.

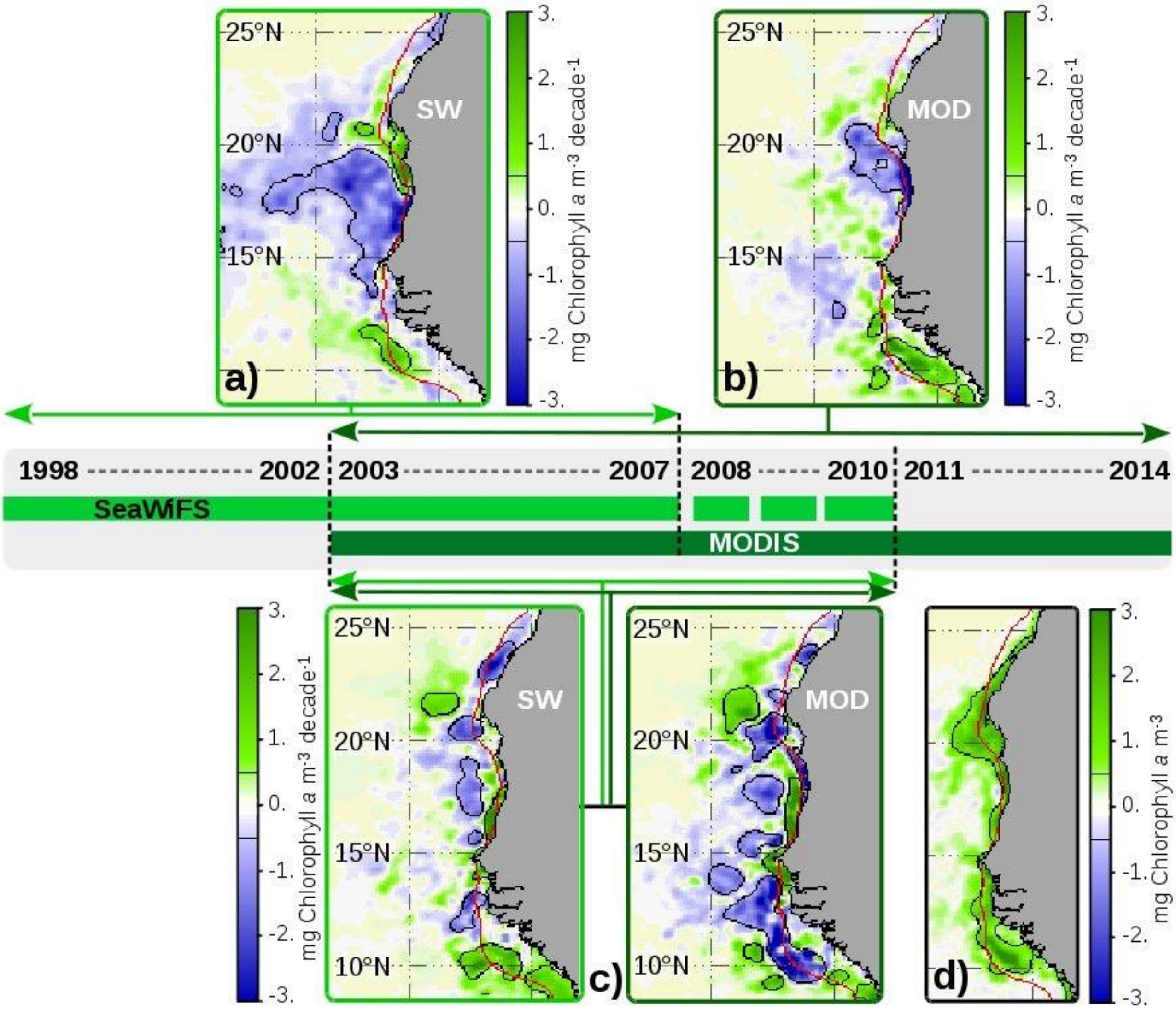


Figure 6.4.2. Partial trends computed for the region 8.5°N to 26°N from the longest homogeneous time series of a) SeaWiFS data from 1998 to 2007; b) MODIS uncorrected data from 2003 to 2014 and c) separately for the common period (2003 to 2010). All values are expressed in mg chlorophyll-a m^{-3} $decade^{-1}$. As a reference, the difference between MODIS and SeaWiFS data from 2003 to 2010 is shown (d). The 200 m isobath is superimposed.

The trends were then separately computed from 2003 to 2010 (Figure 6.4.2c) in order to test the spatial coherency between the datasets. The results show similar spatial patterns (although more contrasted from MODIS), with positive trends over the shelf and negative trends offshore between 14°N to 18°N. This spatial scheme is opposite north of 18°N. The only noticeable difference between both sensors is the large negative trend from MODIS (< -3 mg m^{-3}) over the shelf break between southern Senegal and Guinea (10°N-14°N). This difference is a likely consequence of known artifacts in the MODIS atmospheric correction that leads to incorrect values of chlorophyll-a in the most productive parts of the Senegalese upwelling region (see Figure 6.4.1a and b). Nevertheless, despite a large systematic positive bias in the MODIS data during this period (Figure 6.4.2d), the spatial coherency of these trends demonstrates the possible correction of MODIS data from a SeaWiFS referential for the computation of trends.

6.4.5. CORRECTION OF MODIS CHLOROPHYLL DATA

The monthly differences between SeaWiFS and MODIS chlorophyll-a are systematically examined for the averaged seasonal cycle of the 5-year period from 2003 to 2007 (Figure 6.4.3). It appears that the lower MODIS chlorophyll-a values (generally < 0.4 mg m^{-3}) are generally underestimated when compared to SeaWiFS, with minor seasonal differences. The negative bias of MODIS data is well known and noted by several authors (e.g. Gregg and Casey, 2010) who reported a worldwide difference between sensors of 12.2% during the 1988-2007 period. This difference produces a trend of -15%, instead of -2.6% with SeaWiFS data only.

On the contrary, high values (mostly > 1 mg m^{-3}) were systematically and substantially overestimated in the CCLME. As previously shown, this later part of the correction is of primary importance in upwelling regions where chlorophyll-a values are almost always higher than 1 mg m^{-3} (see Figure 6.4.1). The amplitude of the correction commonly reaches 80% to 120% for chlorophyll-a values higher than 10 mg m^{-3}, again with noticeable seasonal differences, probably caused of variations in the atmosphere and type of aerosols.

After application of the averaged monthly adjustments for the period 2003-2007, the global performance of the correction is estimated for the coastal region of the previous test area (5°N-25°N / 15°W-18°W), where all high chlorophyll-a values are found (see Figure 6.3.1c). The results, summarized in Table 6.4.2, show firstly that the average bias (last line of the table) of the corrected data is close to zero for the whole area and close to 0.01 mg m^{-3} for the coastal region, and secondly that these differences are relatively stable from year to year. The left part of the table shows the differences without MODIS adjustment for comparison.

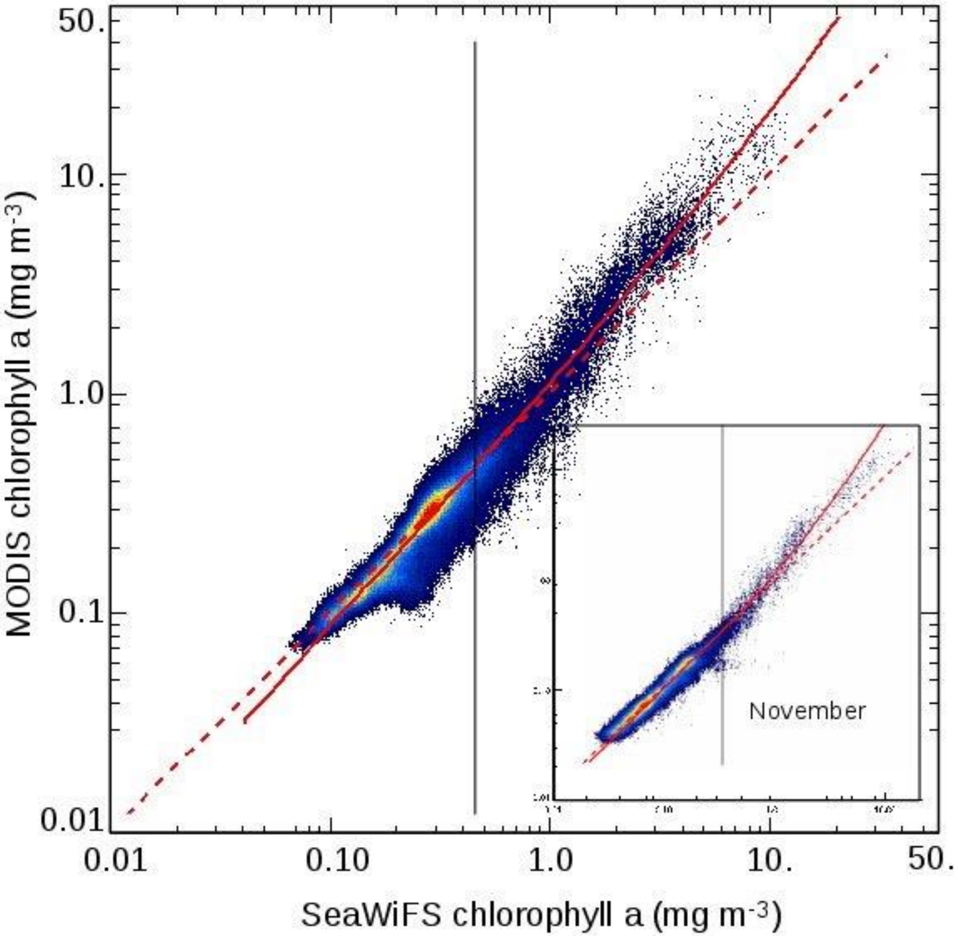


Figure 6.4.3. Example of bidimensional histogram of the MODIS and SeaWiFS chlorophyll-a data (2003-2007 average) including linear and quadratic fits (red lines, respectively for values <0.5 mg m^{-3} and above) for the month of March. The month of November (insert) is presented for comparison.

Table 6.4.2. Averaged biases in chlorophyll-a between MODIS and SeaWiFS data before (raw data) and after adjustment (corrected MODIS data) for the two areas of the Figure 6.4.1c for each year from 2003 to 2007.

Year	raw data		Corrected MODIS data	
	5-25°N	shelf only	5-25°N	shelf only
2003	0.157	0.696	-0.023	-0.027
2004	0.146	0.682	0.026	0.094
2005	0.132	0.800	-0.005	0.084
2006	0.140	0.585	-0.035	-0.246
2007	0.184	0.780	0.035	0.146
average	**0.152**	**0.709**	**-0.0004**	**0.0102**

Compared to the raw differences in chlorophyll-a between the SeaWiFS and MODIS data from 2003 to 2007 (Figure 6.4.4a), often higher than 3 mg m^{-3} (black areas on Figure 6.4.4a), the spatial structure of the residual (Figure 6.4.4b) shows only minor remaining differences of ± 0.5 mg m^{-3} and are mostly due to the spatial structure of the chlorophyll-a data rather than to the correction method itself.

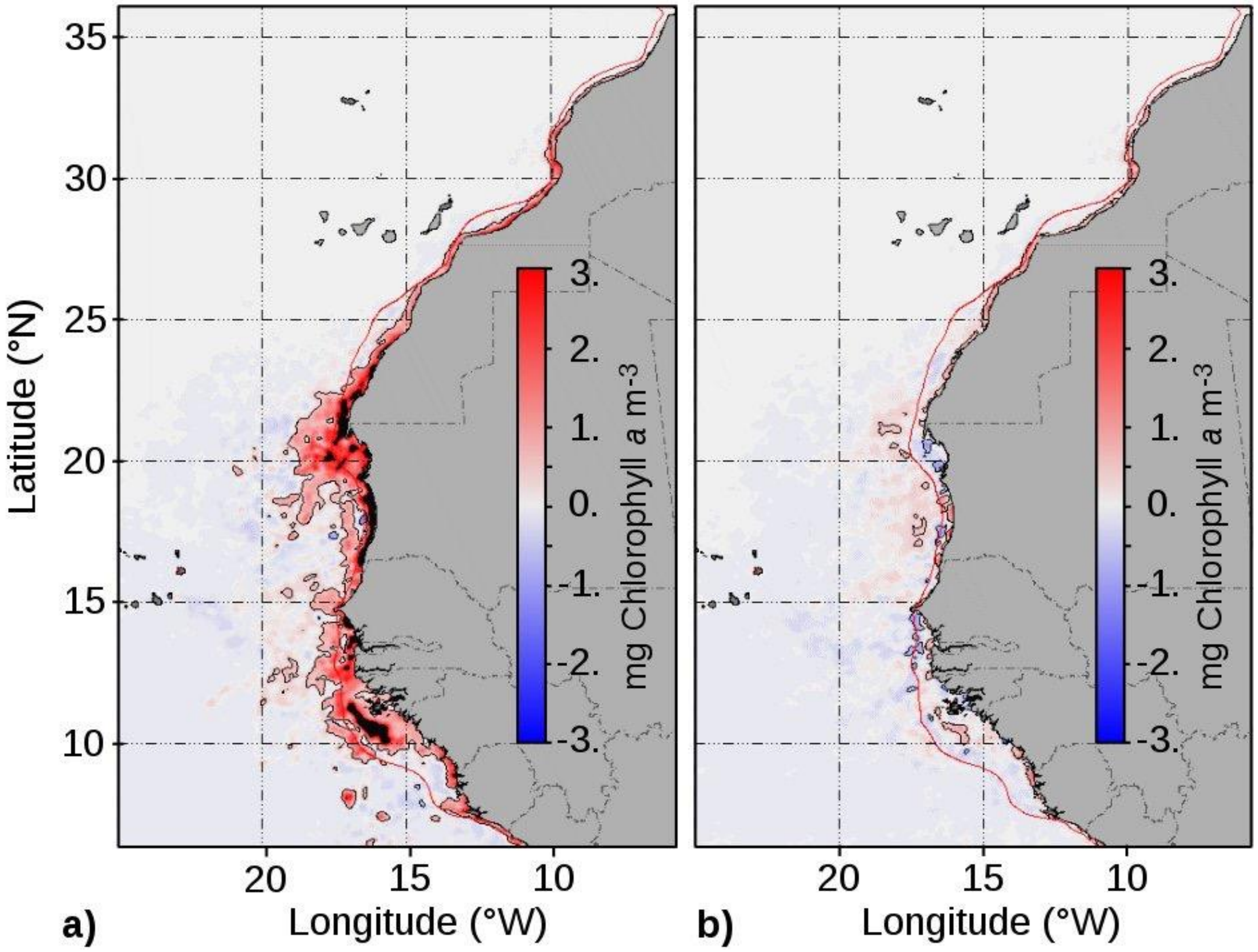


Figure 6.4.4. a) Initial differences between SeaWiFS and MODIS chlorophyll-a data for the period 2003 to 2007, b) same difference after MODIS data correction. The 200 m depth contour (red line) is superimposed.

6.4.6. RESULTING PRODUCTIVITY TRENDS FOR THE WHOLE PERIOD FROM 1998 TO 2014 AND DISCUSSION

It has been previously shown (Demarcq, 2009) that productivity in the CCLME region, computed from the 10-year time series of SeaWiFS data from 1998 to 2007 (Figure 6.4.5a) was clearly decreasing in the large central and southern parts of the system, from 12°N to 25°N, i.e. from the Canary Islands to the south of Senegal. All major anomalies (either negative or positive) were directly associated with the coastal upwelling signature, particularly over the continental shelf.

The few positive trends were mostly found between Cape Blanc (20°N) and central Mauritania (18°N, close to Nouakchott), and between 10°N and 12°N, at the southern tip of the upwelling system, an area where high values of productivity are found especially in June and July and from September to October.

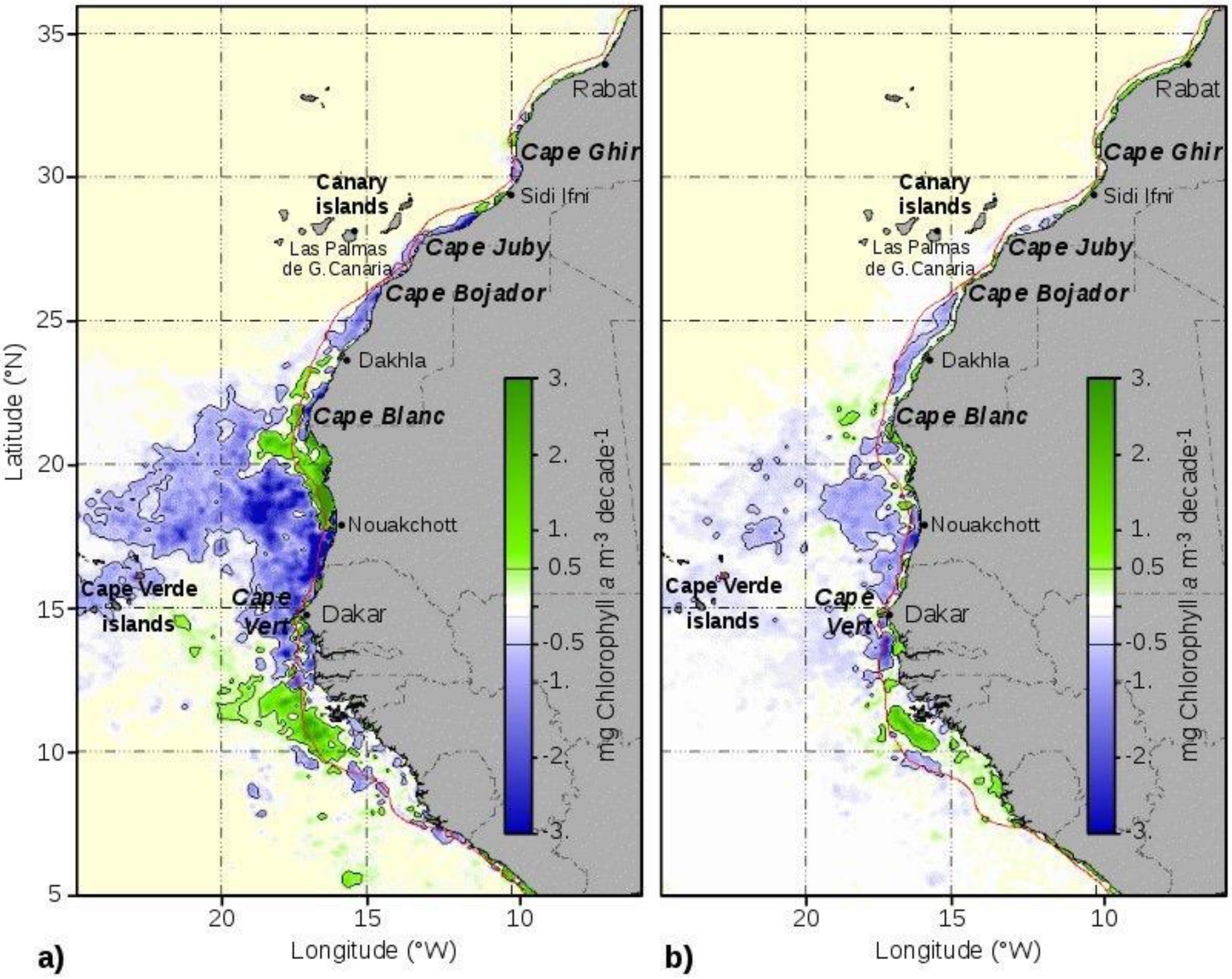


Figure 6.4.5. Trends in chlorophyll-a computed a) from SeaWiFS data from 1998 to 2003 and b) for the whole period 1998 to 2014 from the concatenation of SeaWiFS (up to 2007) and corrected MODIS data (from 2008), according to the method described in the text. Trends are expressed in mg chlorophyll-a m^{-3} decade^{-1}. The 200 m depth contour (red line) is superimposed.

The trends in productivity for the 17-year time series, from 1998 to 2014 (Figure 6.4.5b), have been computed from the suite of SeaWiFS data from 1998 to 2007 and MODIS data thereafter. It shows similar spatial patterns to that of the 1998-2007 period, though much less acute in the southern and seasonal part of the system, south of 22°N. The large negative trends previously found between 12°N and 25°N, are much less intense and more uniform in the coastal region, with a maximum signal over the continental shelf. The positive coastal trend found in northern Mauritania from 1998 to 2003 almost disappears, whereas the positive pattern in the extreme south still persists, with a weak extension up to Liberia. No significant trend is found between Cape Bojador and Cape Ghir (26°N-31°N) even close to the coast where upwelling occurs, except for a weak negative trend over the largest part of the continental shelf from 22°N to 26°N. On the contrary, the coastal area north of 28°N, where upwelling is at a maximum during summer, shows systematic positive trends, which progressively intensify to the north, up to the northern part of the Iberian Peninsula (not shown). It has been shown in this area that upwelling favorable winds are favored in summer because of the higher thermal contrast between sea and land (Bakun et al., 2010). The strongest continuous increase of upwelling-favorable wind in the CCLME has been observed between 26°N and 33°N (see

Benazzouz et al., 6.3 this book, Figure 6.3.3) from 1982 to 2011, and persists during the second half of this period, from 2007.

Further South, in the quasi-permanent upwelling region (21°N to 26°N), the trend or increasing winds is much weaker for the same period, except from 2006 (Benazzouz et al., 6.3 this book). This probably explains the weakening of the anomaly in this area compared to the 1998-2007 period, due to an increase in productivity during recent years. For comparison, an average increase of the productivity has been observed in all major upwelling systems from 2005 to 2007 (Demarcq, 2009), consistent with this observation in the CCLME.

The simultaneous increase in productivity extreme latitude within the CCLME (Iberian Peninsula and the region from Guinea to Sierra Leone), previously observed from 1998 to 2007, is still evident for the period 1998-2014 and reinforced in the Iberian Peninsula. This increase was attributed to a widening of the latitudinal Hadley atmospheric circulation cells, also predicted from circulation models (Kang and Lu, 2012; Seidel et al., 2008).

The same “back to normal” situation is also observed in the region of seasonal upwelling south of Cape Blanc, where winds increased again from 2005. This is likely related to the recovery of the productivity observed in this region, associated with the weaker negative trends previously observed.

A specific spatial pattern is observed off southern Senegal in the form of a marked negative anomaly south of Cap-Vert, where the coldest temperatures are recorded. This feature is either due to a local decrease in upwelling intensity or, more likely, to a change in the chlorophyll gradient between the SeaWiFS and MODIS chlorophyll-a products, due to known differences in atmospheric corrections that lead to more frequent erroneous reflectance values that confuse the chlorophyll-a algorithm.

It has also been shown that important dissimilarities exist between satellite-derived wind data series (Benazzouz et al., 2014a), leading to significant differences in upwelling indices and the computation of temporal trends. Such upwelling indices sometimes even disagree with SST-based indices in the CCLME region (see Benazzouz et al., 6.3 this book, Figure 6.3.5). For these reasons, the relationship between productivity and upwelling intensity must be considered with caution because of nonlinearities in the physical and biochemical processes involved.

6.4.7. CONCLUSION

Even if further efforts are required for algorithm development to ensure sensor compatibility over their entire ranges of sensitivity (and especially for high end values), empirical cross-correction of standard products, such as chlorophyll-a, is effective in the construction of longer time series of primary productivity in upwelling systems and in the CCLME in particular, in order to search for more reliable patterns of spatiotemporal variability.

The search for linear trends is always very challenging because of the temptation to systematically link them to global warming. In order to quantify temporal long terms changes, the mid-term oceanic variability associated with the Atlantic multidecadal oscillation (AMO) changes on a multi-decadal and basin scale modes should be considered as well as the North Atlantic oscillation (NAO) that controls the strength of the trade winds in the northern part of the CCLME. Consequently, the use of relatively short time series (less than 20 years) is potentially questionable.

The weakening of the trends related to primary productivity, previously observed in the CCLME region during a 10-year only period (Demarcq, 2009), is reassuring in this respect and is an important result of the present approach.

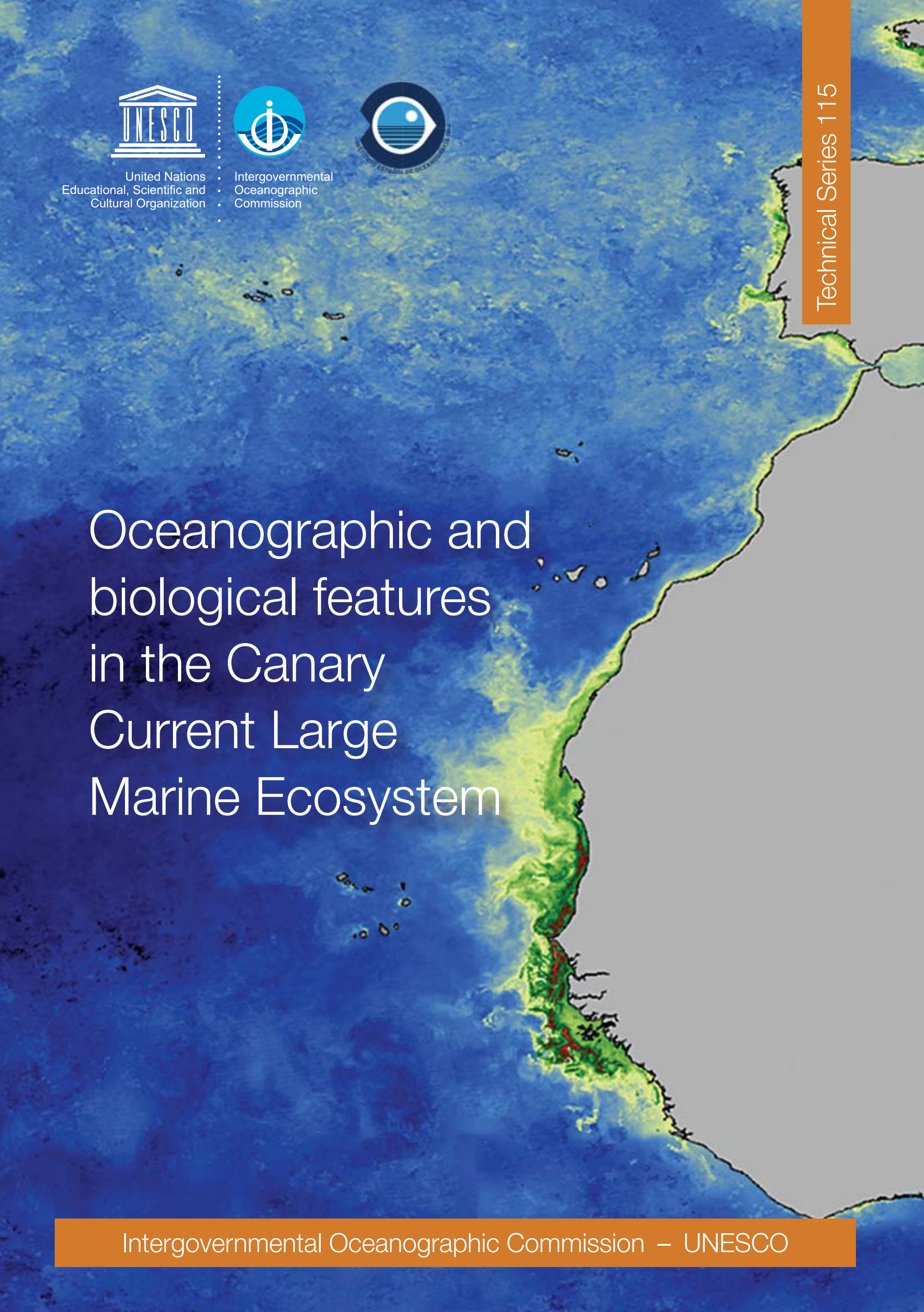
We show that the relative increase in wind from 1998 is probably responsible of the recent moderate increase in productivity in the CCLME, notwithstanding the fact that SST-based indices may contradict this conclusion.

During the last two decades, and despite global warming that has strongly affected the North-East tropical Atlantic, it is possible to state that the whole CCLME, especially the coastal upwelling region, is relatively stable in terms of primary productivity, more so than the oceanic basins, where a negative decrease if generally observed. Nevertheless, very little is known about the qualitative influences of climatic trends on the marine biodiversity of this diverse region, which is impacted more and more by pelagic fisheries.

It is therefore essential to make optimal use of the numerous time series of satellite-based observations made available over the past three decades in order to disentangle the different ways in which physical forcing influences the productivity of the different regions of the CCLME. Secondly, more effort needs to be directed at the integration of satellite data series in modeling in general, from biogeochemical to ecosystem approaches.

Acknowledgments

We are very grateful to the NASA/OBPG and their web data server (http://oceancolor.gsfc.nasa.gov/, accessed 16 May 2015) for providing the SeaWiFS and MODIS datasets used in this study.



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Technical Series 115

Oceanographic and biological features in the Canary Current Large Marine Ecosystem

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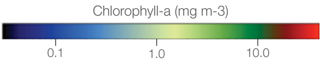
Cover photo: Phytoplanktonic blooms along the coast of Northwest Africa and Iberian Peninsula, as seen from the concentration of chlorophyll-a, in March 2013, deduced from the data of the MODIS sensor. Numerous mesoscale features such as fronts and filaments can be observed. Image by Hervé Demarcq, IRD



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For bibliographic purposes, this document should be cited as: Valdés, L.[1] and Déniz-González, I.[1] (eds). 2015. *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. IOC-UNESCO, Paris. IOC Technical Series, No. 115: 383 pp.

[1] Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), Paris, France

The publication *Oceanographic and biological features in the Canary Current Large Marine Ecosystem* is also available online at:

http://www.unesco.org/new/en/ioc/ts115

(IOC/2015/TS/115)