6.3. RECENT CHANGES AND TRENDS OF THE UPWELLING INTENSITY IN THE CANARY CURRENT LARGE MARINE ECOSYSTEM

Aïssa BENAZZOUZ[1], Hervé DEMARCQ[2] and Gonzalo GONZÁLEZ-NUEVO[3]

[1] Institut National de Recherche Halieutique. Morocco

[2] Institut de Recherche pour le Développement. France

[3] Centro Oceanográfico de Vigo, Instituto Español de Oceanografía. Spain

6.3.1. INTRODUCTION

The Canary Current Upwelling System (CCUS), which extends from the Iberian Peninsula (IP) (43°N) to the south of Guinea-Bissau (8°N) (Fig. 6.3.1), and includes the Canary Current Large Marine Ecosystem (CCLME), one of the world's four major Eastern boundary upwelling ecosystems (EBUEs). The seasonal variability of the trade winds between winter and summer induces pronounced coastal sea surface temperature (SST) anomalies with a high seasonal contrast, mainly in the southern part of the system (Arístegui et al., 2009a; Barton et al., 2013).

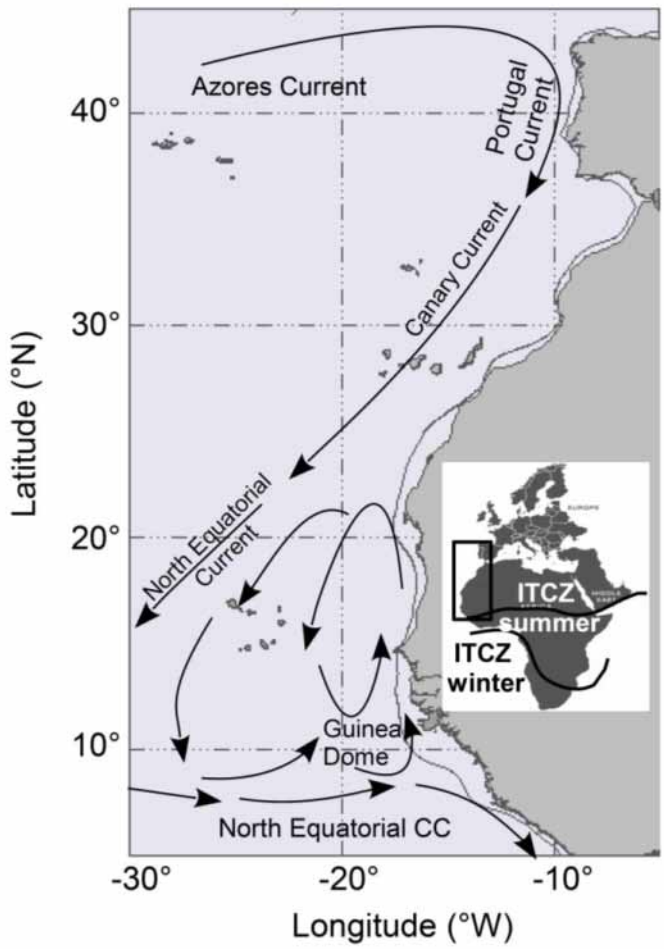


Figure 6.3.1. Study area of the CCLME region with the main surface currents: Azores, Portugal, Canary, North Equatorial current and North Equatorial counter-current. The 200 m isobath is superimposed.

In 1990, Bakun observed a general trend of the upwelling intensification related to the wind intensity increase. Later on, Bakun et al. (2010) hypothesized that in the context of the climatic change due to the global warming, a higher thermal gradient between the land and water masses intensify the alongshore upwelling favorable wind stress that consequently intensify the upwelling process.

This effect has been strongly supported by several authors (García-Reyes and Largier, 2010; McGregor et al., 2007; Narayan et al., 2010). However, contrary to this study, several recent trends in wind and temperature suggest a reduction of upwelling in the Northwest Africa (NWA) and Iberian coast (Alvarez et al., 2008; Lemos and Pires, 2004). In addition, Pardo et al. (2011) have examined the long term variation in the Canaries and other upwelling zones, finding a ‘‘weakening of the upwelling intensity in the Iberian/Canary and NWA regions”. Barton et al. (2013) and Cropper et al. (2014) have found no coherence between wind intensification and coastal SST cooling.

In the context of these conflicting results, our overriding aim is to test the Bakun hypothesis related to the upwelling intensification.

6.3.2. DATASETS

We use two homogeneous datasets from spatial observation: a 30 years SST series from the AVHRR (Advanced Very High Resolution Radiometer) version 5.2 day-time for the time period September 1981 to December 2011 (http://www.nodc.noaa.gov/sog/pathfinder at 4 km resolution, accessed on 15 October 2014), and the global wind CCMP (Cross-Calibrated Multi-Platform) from July 1987 until 2010 funded under the United States National Aeronautics and Space Administration (NASA) Earth Science Enterprise (Atlas et al., 2010).

6.3.3. REGIONAL UPWELLING INDEX DATASET

Our analysis focuses on the coastal-upwelling areas off NWA. The NWA coast is the core area of the eastern North Atlantic upwelling system with the northeast extension covered by the IP.

The definitions of the environmental indices and their regular availability in time are of key importance in the management of coastal upwelling systems. Such indices are derived from physical parameters (wind and SST) and computed on a regular basis, to describe and follow the state of the environment as well as to estimate possible trends.

To quantify upwelling at synoptic time-scales, we have used two different indices that are based on the two different characteristics of the upwelling process. The first index quantifies the physical forcing, the Cross-Shore Ekman Transport (hereafter noted CSET) (Bakun, 1973; Ekman, 1905), the second one considers the physical response of upwelling through the SST (Benazzouz et al., 2014a; Van Camp et al., 1991) and the surface layer during upwelling events (hereafter noted CUI). Statistical analyses have been done on two periods according to the available time series datasets.

The trend is calculated using yearly averaged data. The linear regression is applied for the whole time series, with a least squares (LS) fit used as a linear adjustment.

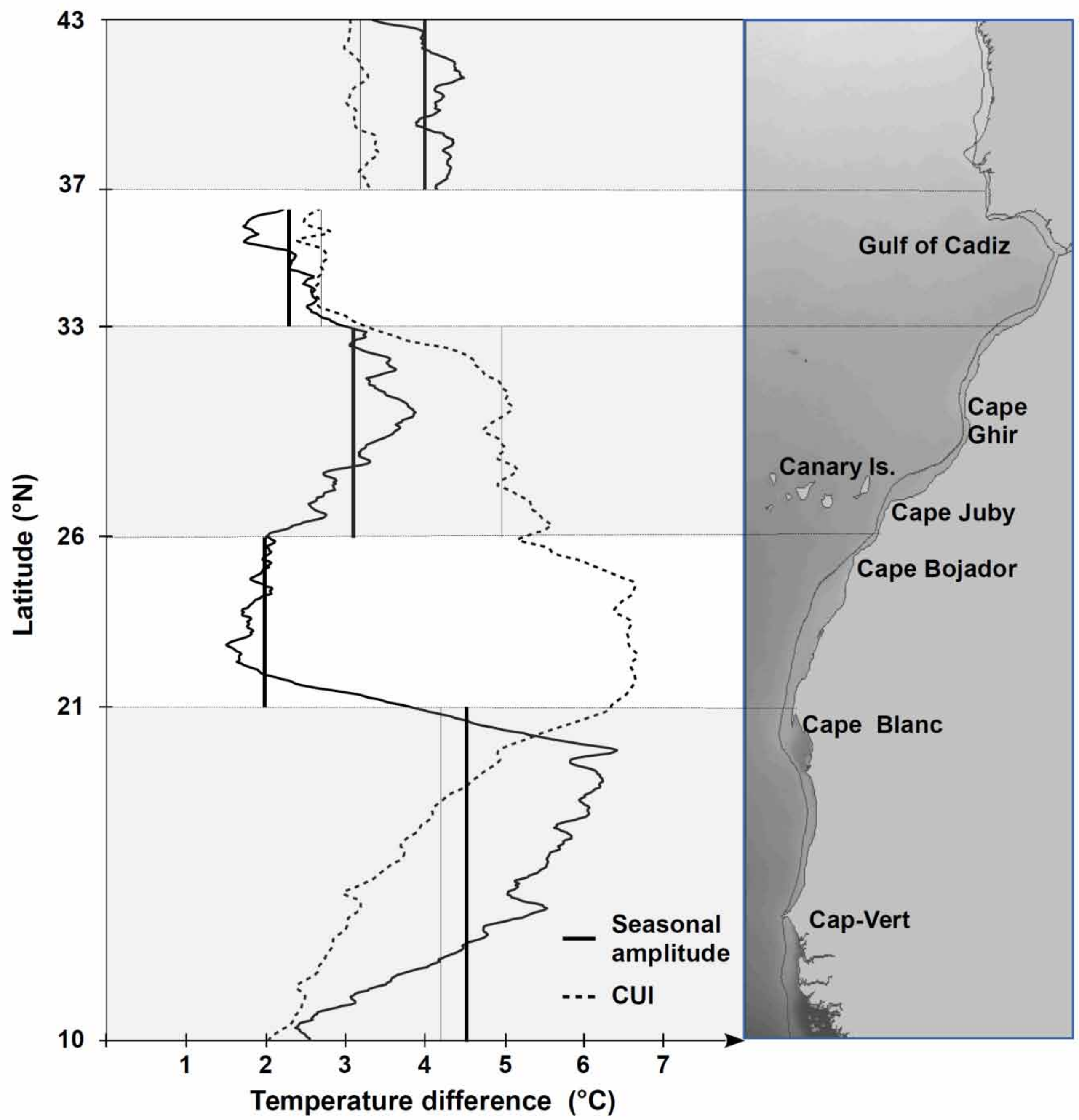


Figure 6.3.2. Latitudinal partition of the study area in five upwelling areas, based on the average value of their thermal zonal difference (CUI) and their seasonal amplitude, both expressed in °C. The vertical bars help to visualize the average values of the parameters.

6.3.4. RESULTS

6.3.4.1. Partitioning of the study area according to average intensity and seasonality

In order to simplify the following results, we use the CUI to define distinct latitudinal regions by combining the intensity of the CUI and its seasonal amplitude. A partition into five regions, from north to south is presented in Figure 6.3.2: the Portuguese coast (37°N-43°N) characterized by a high and stable seasonality; the 33°N–36°N area characterized by a low seasonality and upwelling index; the 26°N–33°N area with a progressively higher index and seasonality; the region between 21°N–26°N with a high index and a very low seasonality; and the 10°N–21°N region, with a very high but decreasing seasonality associated to regularly decreasing upwelling indices.

6.3.4.2. Interannual variability of the Cross-Shore Ekman Transport

The interannual variability of the CSET showed oscillations that depended on latitude (Fig. 6.3.3).

The five regions previously defined are still very distinct, with the greatest intensity occurring in the coastal strip from 21°N to 26°N, where upwelling is quasi permanent, followed by the strip 26°N–33°N in summer, and south of Cape Blanc in winter.

Particularly, the CSET was very high in the last decade, with the highest values observed in 1999, 2002, 2004, 2007, 2008, 2009 and 2010. The lowest CSET is observed north of Cape Bojador in 1996 and for the whole CCLME region in 1997.

From this figure (Fig. 6.3.3) we can appreciate the acceleration of the trade winds within the study area. This seems to be linked to a general increase in the equatorward winds in the tropical belt worldwide (Demarcq, 2009). This trend is also consistent with the measurements of local coastal wind worldwide, as synthesized by Bakun (1990) who demonstrated a general alongshore wind increased in EBUEs in 1950–1985. Nevertheless, this increase is not uniform in the whole area: the wind is stronger north of Cape Blanc and decreases towards the Cap-Vert region.

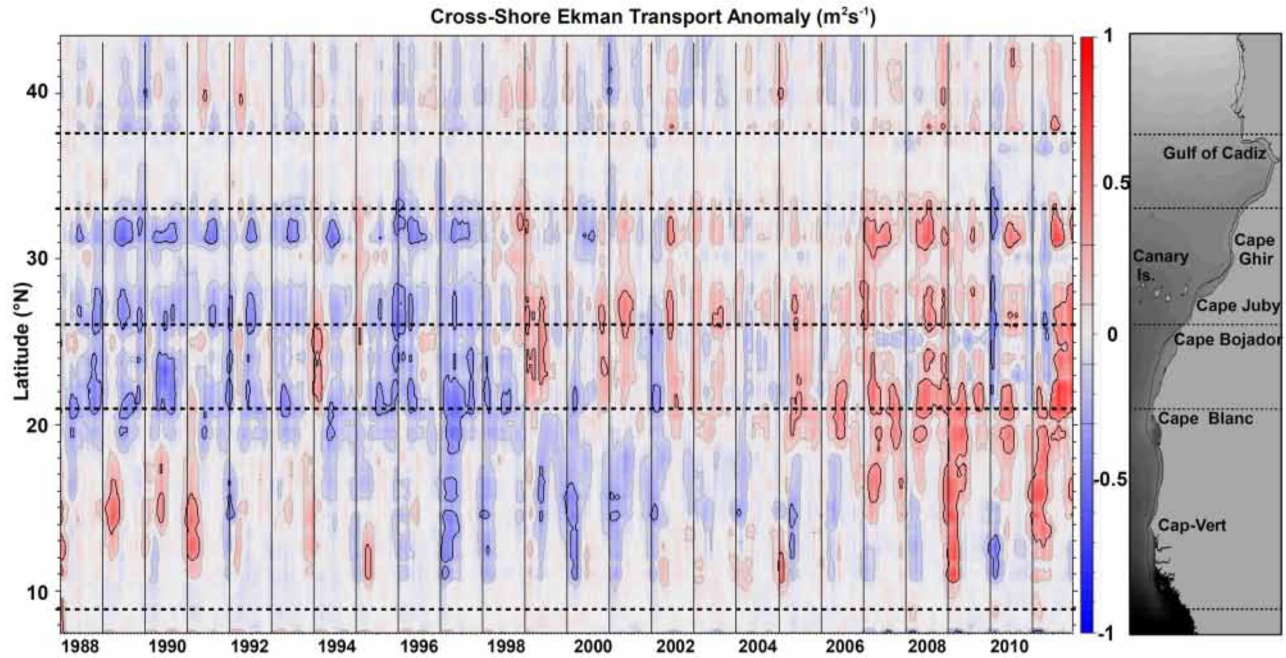


Figure 6.3.3. Space-time Hovmöller plot, illustrating the seasonal and interannual variability of the CSET anomaly from January 1988 to December 2011.

6.3.4.3. Interannual variability of the thermal coastal upwelling indices (CUI)

The space-time diagram of the coastal SST-based upwelling index (CUI), as computed from the 8-day SST (Fig. 6.3.4), shows the seasonal and interannual variations of the upwellings for the period from July 1981 to December 2011 (30 years). It highlights the latitudinal variations in upwelling intensity and seasonality, as well as in terms of spatio-temporal extent.

The interannual variability is more pronounced in the central and northern part of the system, with well-defined continuous latitudinal anomalies.

The whole time period was characterized as having considerable year-to-year variability and oscillations between periods of strong (1982, 1984, 1991, 1993, 1996, 1998, 1999, 2002 and 2005) and anomalously weak upwelling (1983, 1987, 1989, 1990, 1994, 1995, 1997, 1998, 2001, 2005, 2006 and 2009). Nevertheless, only a few years present clear anomalies for the whole system, as 1998–1999 or 2008–2009, where a north to south propagation of the high upwelling intensity is visible. Alternatively, several exceptional upwelling seasons were found to occur in only one portion of the system, for example a very weak upwelling is observed from the end of 1995 to 1997 in the 26°N-33°N area (Fig. 6.3.4), related to an exceptional relaxation of the trade winds (Fig. 6.3.3). These strong anomalies have been associated to a quasi-absence of juveniles in 1996 and 1998, and the collapse of the regional sardine stock between 1996 and 1997 (Machu et al., 2009). On the contrary, some years are associated to strong upwelling seasons only in the southern part of the system, as in 1986, 1996, 1999, 2005, 2009 and 2011.

In general, the interannual variability of the CSET and CUI show a similar pattern: high CSET intensity coincides with positive CUI anomaly in 1999, 2001, 2002, 2007 and 2008; and vice versa, low CSET intensity coincides with negative CUI anomaly in 1995-1998. This last anomalous period (1995-1998) is considered as a Pacific El Niño years, where the zonal wind anomalies act as a bridge linking the two ocean basins (Pacific and Atlantic), and in turn reinforce the inter-basin SST gradient through the atmospheric Walker circulation and associated oceanic processes (Wang et al., 2009).

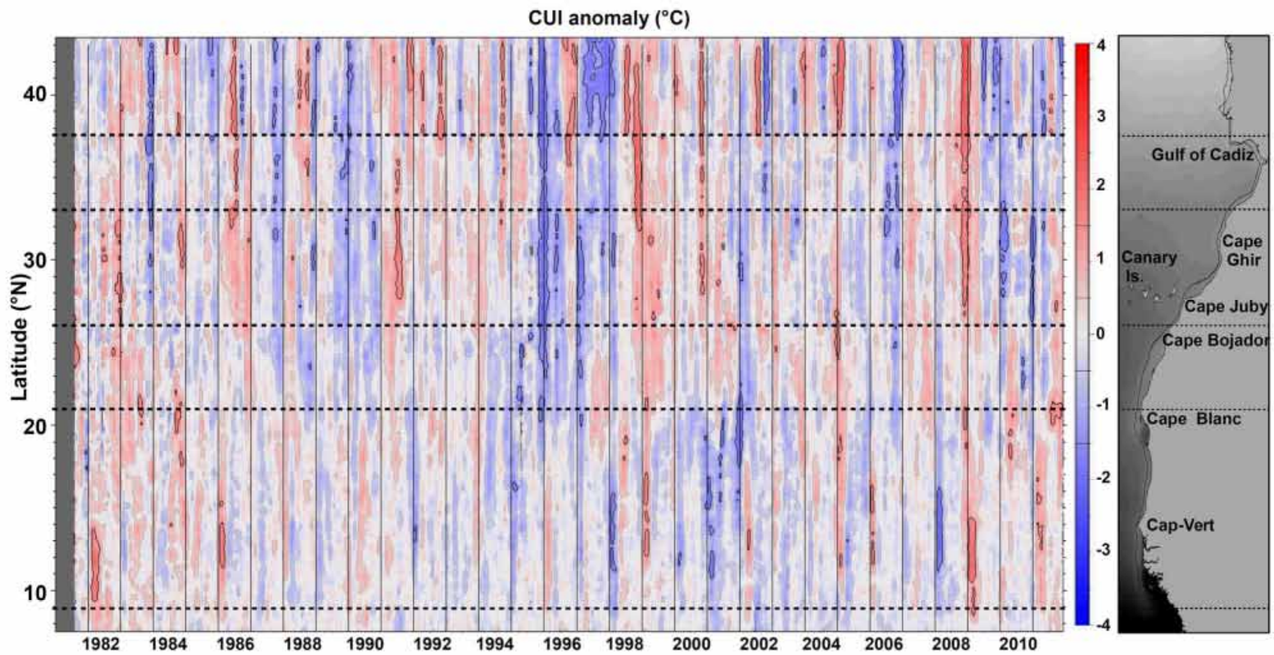


Figure 6.3.4. Space-time Hovmöller plot, illustrating the seasonal and interannual variability of the CUI anomaly from September 1982 to December 2011.

6.3.4.4. Determining the temporal trends in the upwelling time series

Temporal wind trend

The linear trend of the CSET for each upwelling area is documented in Figure 6.3.5a.

The long-term trend of the CSET shows high temporal and regional variability, with a general strengthening of the Ekman transport throughout the whole area. Nevertheless, the order of magnitude off the trend slope varies significantly between areas.

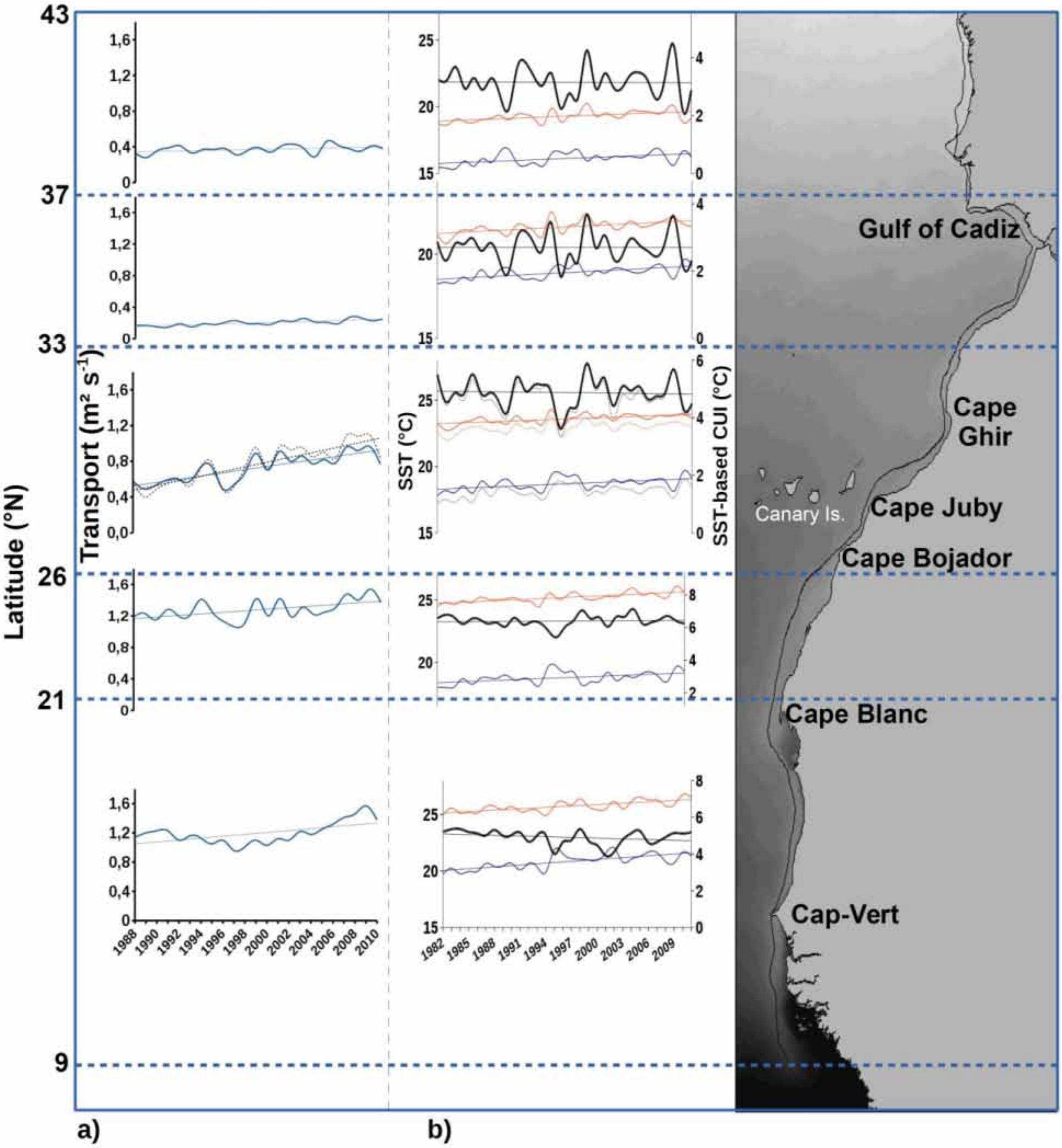


Figure 6.3.5. Linear trends for a) the annual-mean Ekman Transport (m^2 s^{-1}) during 1988-2011 for the five regions of upwelling regimes previously defined, and b) the annual-mean SST during 1982-2011 for SST_{max} (red line), SST_{min} (blue line) and CUI (thick black line).The Cape Ghir trends (dashed lines) are superimposed on the plot for the 26°N-33°N area.

The trends in the CSET are reported in the Table 6.3.1.

The upwelling areas show uniformly significant positive values. An exceptional insignificant trend is observed over the IP, in the northern zone (37°N-43°N).

Table 6.3.1. Linear decadal slopes, associated significance levels, and relative (%) decadal change, computed for the period 1981–2011 for the CSET and for the CUI and its SST components (SST_{min} and SST_{max}) during 1988-2011.

	CSET (m^2s^{-1})		CUI (°C)		SST_{max} (°C)	SST_{min} (°C)
	Slope	Decadal change (%)	Slope	Decadal change (%)	Slope	Slope
37°N-43°N	0.037	16.164	0.007	0.231	0.293**	0.283**
26°N-33°N	0.170**	32.070**	-0.001	-0.015	0.272**	0.275**
21°N-26°N	0.095**	7.825**	0.060	0.945	1.362**	0.265**
17°N-21°N	0.136**	14.242**	-0.134	-2.622	0.428***	0.571**
Cape Ghir	0.252***	52.895***	0.038	0.874	0.260**	0.227**

*Significance level: '***' 0.001 '**' 0.01*

This first result shows, indeed, that there is a trend of the wind generating upwelling. However, this trend is not uniform for the whole area.

The most intense CSET trend is observed in the 26°N-33°N area, which includes the permanent Cape Ghir filament (31.5°N) with a positive slope of 0.170°C $decade^{-1}$. This result is statistically significant at p-value <0.001 and corresponds to an increase of about 32% $decade^{-1}$.

This result corroborates the Bakun hypothesis, stipulating the upwelling-favorable wind intensification. Contradictory to the Bakun's hypothesis, the Iberian system exhibits no positive trend.

The second part of the Bakun hypothesis, which examines the strengthening of cooling as consequence of the wind intensification, is the purpose of the following section.

SST and the CUI trends

The long-term linear trend of the thermal fields is computed for the thermal coastal upwelling index, based on the coastal SST_{min} and offshore $SST_{max,}$ according to the same methodology adopted for the wind.

The annual averaged linear trends are shown in the Figure 6.3.5.

The annual means computed for the 1981-2011 period, both for SST_{min} and SST_{max} (Figure 6.3.5b) show very distinct warming trends over the whole studied area. This result implies that the CCLME is largely affected by global warming.

The warming illustrated by these curves refers to both the coastal upwelling and oceanic waters; this explains that the Atlantic Ocean subtropical basin is warmed in its eastern part, as shown in Demarcq (2009).

In general, both terms (SST_{min} and SST_{max}) evolve in the same way and show significant trends of the annual-mean value in the five regions (Table 6.3.1). In fact, SST_{max} is located mostly at 3000 km offshore, practically in the mid-Atlantic Ocean. Therefore, if both terms (SST_{min} and SST_{max}) are warming simultaneously, they affect the whole eastern part of the Atlantic Ocean interdependently of the upwelling itself which is supposed to be more intense, as a cooling response to the favorable wind strengthening. Nevertheless, the thermal CUI, derived from SST_{max} and SST_{min}, displays an ambiguous trend and is statistically insignificant (Fig. 6.3.5 and Table 6.3.1).

In the light of those results, it should be noted that the linear trend of the thermal fields, as computed from LS, reveals that the whole area is subject to very distinct warming trends, both in its coastal and oceanic parts.

This result can also be considered as contrary to the Bakun hypothesis that stipulates a more intense cooling in response to the wind strengthening.

6.3.5. DISCUSSION

The annual time series highlight the interannual variability as well as the potential existence of the long term trend. Table 6.3.1 summarizes the long term linear trend of the thermal and wind-based indices.

The temporal trend of the CSET shows a statistically significant positive strengthening trend between 17°N and 33°N. The meridional wind has intensified over the whole Moroccan area, with a mean value of 0.3 m s^{-1} $decade^{-1}$ and about 0.8 m s^{-1} $decade^{-1}$ in front of Cape Ghir (results not shown). Between 17°N and 21°N (upwelling seasonal part), the wind speed has increased only about 0.24 m s^{-1} $decade^{-1}$. This weak intensification is of the same order as the magnitude near the IP (0.29 m s^{-1} $decade^{-1}$).

We can conclude that the long term trends resemble those obtained by Bakun, which predicted an increase of the wind stress on the coastal upwelling systems.

However, the results reveal that most of the CCLME has significantly and considerably warmed. This warming concerns the offshore oceanic water as well as the coastal upwelling waters. During the last three decades, the SST_{min} and SST_{max} have increased respectively by 0.28°C $decade^{-1}$ and 0.29°C $decade^{-1}$ in the IP, while in the Senegalese-Mauritanian region the SST_{min} and SST_{max} have increased respectively about 1.71°C (0.57°C $decade^{-1}$) and 1.28°C (0.44°C $decade^{-1}$).

The resulting linear trend of the thermal fields sustain the projection of the Intergovernmental Panel on Climate Change (IPCC, 2013) of a significant increased trend in global SST during the last 100 years, especially the most recent 30 years (Trenberth, 2010).

Furthermore, the coastal upwelling water warming is in contradiction with Bakun hypothesis, which predicts more upwelling water and cooling in response to the strengthening of the upwelling-favorable wind.

In fact, the wind has intensified but this relative strengthening is not accompanied by a significant cooling, instead it displays a clear warming.

The analysis of the CUI variability characterizes in a complementary way the information from the CSET by revealing that:

- The linear trend of the upwelling activity is increasing south of Cape Juby, particularly in the (21°N-26°N) area, while it is visually decreasing south of Cape Blanc (17°N-21°N) and experiences no changes in the rest of the ecosystem.

- According to the CUI index, no trend is statistically significant.

The observed increase over time in the magnitude of the upwelling-favorable wind in the NWA and IP coast is consistent with a recently documented increase of annual-mean upwelling off California, Portugal, Morocco and Peru throughout the 1945-1985 period (Bakun, 1990).

Our results are partially consistent with Bakun's (1990) upwelling intensification hypothesis, which predicts that increased greenhouse gas emissions lead to a stronger thermal gradient between the relatively warm land mass and cool coastal ocean, thereby driving more persistent upwelling-favorable winds in coastal upwelling systems worldwide (Bakun, 1990; Bakun et al., 2010; McGregor et al., 2007; Mendelssohn and Schwing, 2002).However, we predict that these trends would instead be accompanied by coastal warming rather than cooling.

These can be explained in two different ways:

1. - The actual wind could not have sufficient energy to upward the cold water, found at deeper layers. Additionally, it is possible that an increase in wind intensity is constrained by an increasingly stratified water column which would restrict upwelling.

2. - Physical constraints set by the topographic steering and coast line geometry, the width of the continental shelf and the depth of the mixed-layer can potentially alter the long-term variability in a coastal upwelling system.

6.3.6. CONCLUSIONS

In this work we have studied the changes expected on the upwelling trend at the NWA and the IP coast. Studies have been done using different datasets on SST and wind, and the derived indexes. After the study of the behavior of the upwelling in the last three decades, the conclusion is that the wind is actually intensifying. However the temperature at the sea surface is increasing. Also, no trends are observed by the thermal upwelling index in any case: neither in the north, nor in the south.

The general trend of the temperature anomaly during the upwelling season showed an increase of about 0.71°C from 1982 to 2011 (Fig. 6.3.5b). This general trend does not agree with the hypothesis that the strength of upwelling increases due to the global warming signal.

Indeed, the CUI, used as an indicator to quantify the upwelling intensity, shows ambiguous results with quasi absence of a statistically significant trend. Additionally, the surfacing thermal signal which is the oceanic response to the physical forcing process, displays positive warming rates both in the coastal area and in the offshore water. This result corroborates Barton et al. (2013) conclusion, but contrasts with McGregor et al. (2007) who reported an acceleration of a cooling trend in front of Cape Ghir region during last century.

Nevertheless, the trend of the thermal gradient is quasi null except in front of the Mauritanian region where the thermal difference between the offshore and the inshore is more less decreasing, whatever statistically insignificant. In fact, this visually decreasing trend is due to the increase of the SST_{min} more than SST_{max} (about 1.75°C and 1.28°C, respectively) during the last three decades.

The CUI has been considered to be a complex index, based on a precise spatial analysis of the upwelling structure and its thermal characteristics, granting it a proven robustness. However, we have shown that the surfacing thermal structures on the coastal band are affected by the upwelling process, therefore giving a signal that could be altered by different factors. For example, the reduction of the mixed layer can affect the temperature of the upwelled water and hence the thermal gradient. Equally, storms can drag down the mixed layer and consequently, the wind intensification cannot compensate the stratification or this sinking by the vertical transport. In the Barton et al. (2013) paper, it is mentioned that the analyses at depths of 50 m and 100 m, based on the World Ocean Database 2005 (Boyer et al., 2006) at 50 m and 100 m, show relatively uniform behavior in the sub-tropical North Atlantic, with statistically significant warming across the basin between 15°N and 50°N (Harrison and Carson, 2007). Warming rates approached 0.2°C decade^{-1} in the NWA region at both depths. This result is coherent with what we have found at the sea surface from satellite-based data.

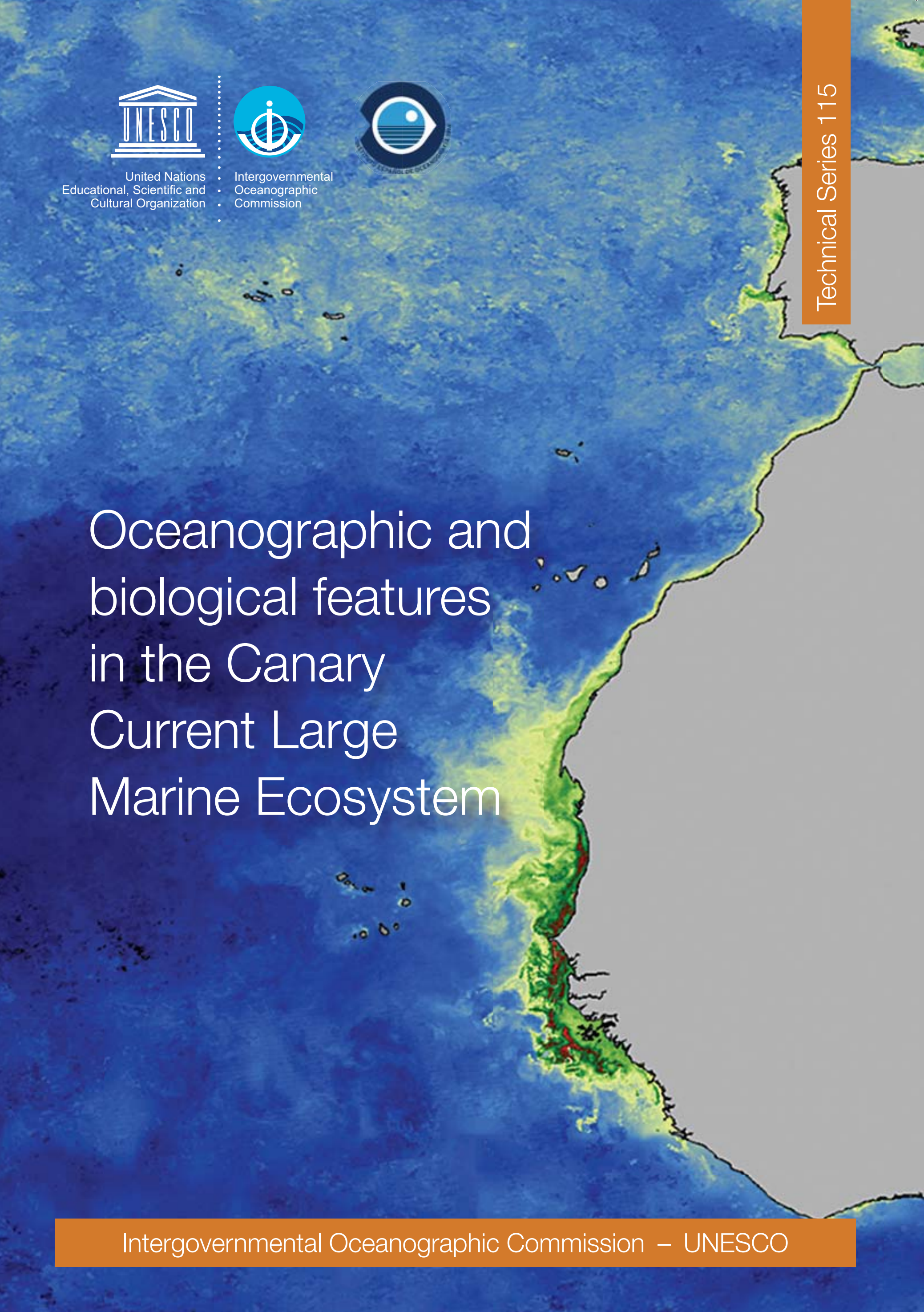
According to these results we can hypothesis that, in the context of the climatic warming, the wind will indeed intensify but the warming of the upwelled water may not take place.

Acknowledgments

The SST data were provided by GHRSST and the US National Oceanographic Data Center, in a project partly supported by a grant from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Record (CDR). CCMP global wind data were obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory.

We are also grateful to the EPURE project (ANR-11-CEPL-005 EPURE) founded by the French National Research Agency that has supported partially this work.

We are grateful to Itahisa Déniz González and Josep Lluis Pelegrí for their helpful comments that substantially improved the manuscript.



United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

Technical Series 115

Oceanographic and biological features in the Canary Current Large Marine Ecosystem

Intergovernmental Oceanographic Commission – UNESCO

Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO)

UNESCO's Intergovernmental Oceanographic Commission (IOC), established in 1960, promotes international cooperation and coordinates programmes in marine research, services, observation systems, hazard mitigation, and capacity development in order to understand and effectively manage the resources of the ocean and coastal areas. By applying this knowledge, the Commission aims to improve the governance, management, institutional capacity, and decision-making processes of its 147 Member States with respect to marine resources and climate variability and to foster sustainable development of the marine environment, in particular in developing countries. The Commission responds, as a competent international organisation, to the requirements deriving from the United Nations Convention on the Law of the Sea (UNCLOS), the United Nations Conference on Environment and Development (UNCED), and other international instruments relevant to marine scientific research, related services and capacity-building.

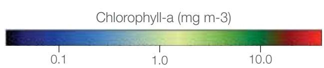
Instituto Español de Oceanografía (IEO)

The Spanish Institute of Oceanography (IEO), founded in 1914, is a public research body attached to the Ministry of Economy and Competitiveness. The IEO is dedicated to marine science research, especially in relation to scientific knowledge of the ocean, sustainable marine living resources and fisheries, aquaculture and the marine environment. The IEO is committed to addressing the challenges facing the ocean for the benefit of society and is also an advisory institution on oceanographic research, ocean health and conservation and fish stock management for the Spanish government. The IEO networks with the Spanish scientific community, as well as partner organizations in many countries; it also fosters a long-standing commitment to international cooperation with developing countries aimed to ensure the sustainable use of marine resources and the oceanographic research. The IEO represents Spain in most intergovernmental science and technology forums related to the ocean and its resources such as the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), the International Council for the Exploration of the Sea (ICES), the Mediterranean Science Commission (CIESM), and the Committee for the Eastern Central Atlantic Fisheries (CECAF) among others.

Spanish Agency for International Development Cooperation (AECID)

AECID, the Spanish Agency for International Cooperation for Development, is a public entity under the Ministry of Foreign Affairs and Cooperation, in charge of the coordination of the Spanish policy on international cooperation for development, aimed to the reduction of poverty and the achievement of sustainable human development. Since its foundation in 1988, the Agency has established international alliances and strengthened Spain's relations with other countries and multilateral institutions such as the United Nations agencies. This work has contributed to the recognition of Spain as a reliable partner in the field of international cooperation, promotion of equitable and sustainable societies and respect for human dignity. It is also an AECID primary objective to promote and encourage the presence of Spanish experts in international organizations devoted to international cooperation such as UNESCO and other agencies in the United Nations.

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



Intergovernmental Oceanographic Commission

Technical Series 115

Oceanographic and biological features in the Canary Current Large Marine Ecosystem

Editors:
Luis Valdés
Itahisa Déniz-González

With the support of the Spanish Agency for International Development Cooperation (AECID)

UNESCO 2015

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)