Progress in Oceanography 153 (2017) 16–23

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Seasonality of coastal upwelling trends under future warming scenarios along the southern limit of the canary upwelling system

Magda Catarina Sousa [a,*], Ines Alvarez [a,b], Maite deCastro [b], Moncho Gomez-Gesteira [b], João Miguel Dias [a]

[a] CESAM, Departamento de Física, Universidade de Aveiro, 3810-193 Aveiro, Portugal
[b] EPhysLab (Environmental Physics Laboratory), Universidade de Vigo, Facultade de Ciencias, Ourense, Spain

ARTICLE INFO

Article history:
Received 26 July 2016
Received in revised form 17 January 2017
Accepted 4 April 2017
Available online 6 April 2017

Keywords:
Global warming
Upwelling
Sea surface temperature
Wind
CORDEX
CMIP5
Canary upwelling ecosystem

ABSTRACT

The Canary Upwelling Ecosystem (CUE) is one of the four most important upwelling sites around the world in terms of primary production, with coastal upwelling mostly a year-round phenomenon south of 30°N. Based on annual future projections, several previous studies indicated that global warming will intensify coastal upwelling in the northern region and will induce its weakening at the southernmost latitudes. However, analysis of historical data, showed that coastal upwelling depends on the length of the time series, the season, and even the database used. Thus, despite previous efforts, an overall detailed description of seasonal upwelling trends and their effects on sea surface temperature (SST) along the Canary coast over the 21st century remains unclear. To address this issue, several regional and global wind and SST climate models from CORDEX and CMIP5 projects for the period 1976–2099 were analyzed. This research provides new insights about coastal upwelling trends under future warming scenarios for the CUE, with results showing opposite patterns for upwelling index (UI) trends depending on the season. A weakening of the UI occurs from May to August all along the coast, whereas it increases from October to April. Analysis of SST trends reveals a general warming throughout the area, although the warming rate is considerably lower near the shore than at open ocean locations due to coastal upwelling effects. In addition, SST projections show higher warming rates from May to August than from October to April in response to the future decreasing trend in the UI during the summer months.

1. Introduction

Eastern Boundary Upwelling Systems (EBUS) are among the most productive of the world's ecosystems. They cover a small ocean area (<1%) but contribute 20% of the global fish catches (Pauly and Christensen, 1995) and thus are areas with high ecological and socio-economic impact.

The effects of climatic modulations on upwelling variability in marine ecosystems located in EBUS have been extensively studied in the past, mainly in terms of upwelling trends. In 1990, Bakun reported that for these coastal areas, the increase in the ocean-land thermal gradient due to greenhouse warming will result in stronger winds intensifying the upwelling of deeper water to the surface (Bakun, 1990). Subsequently, several authors analyzed the Bakun hypothesis using historical wind data. Contradictory results were obtained, as most studies were based on wind estimates from different databases and the periods evaluated were usually distinct (Bakun et al., 2015; Barton et al., 2013; Cropper et al., 2014; Gutierrez et al., 2011; Santos et al., 2016; Sydeman et al., 2014; Varela et al., 2015). Some of the disagreement among previous studies could be resolved by considering only the winds during the upwelling season, as annually averaged wind trends generally do not support intensification (Sydeman et al., 2014).

In other studies, future upwelling trends were analyzed along EBUS using projected changes provided by climate models. Wang et al. (2015) used wind data from several points located 100 km from the coast provided by RCP 8.5 simulations of 22 CMIP5 Global Circulation Models (GCMs) over the period 1950–2099. They found that coastal upwelling will intensify in three of the four EBUS (Canary, Benguela, and Humboldt). This projected intensification was found to occur at high but not low latitudes. These authors suggested a relationship between increasing land-sea temperature differences and intensified alongshore winds in most EBUS, supporting the Bakun proposition. Rykaczewski et al. (2015) also analyzed projected changes in wind intensity along the four most productive marine ecosystems using 22 CMIP5 GCMs over the period 1861–2100 for the summer season defined as June–August (January–March) in the Northern (Southern) Hemisphere. They

---

* Corresponding author at: CESAM, Departamento de Física, Universidade de Aveiro, 3810-193 Aveiro, Portugal.

E-mail address: mcsousa@ua.pt (M.C. Sousa).

http://dx.doi.org/10.1016/j.pocean.2017.04.002
0079-6611/© 2017 Elsevier Ltd. All rights reserved.

reported that summertime winds near poleward (equatorward) boundaries of upwelling zones are projected to intensify (weaken). These projected changes in wind intensity were found to be associated with poleward migration of major atmospheric high-pressure cells, rather than with the increase in land-sea temperature differences.

Results from previous studies of upwelling trends performed using historical wind data also revealed contradictory results for the Canary Upwelling Ecosystem (CUE) (Barton et al., 2013). On one hand, observations of wind time series over the last decades indicated a decreasing trend in upwelling intensity (Gómez-Gesteira et al., 2008; Pardo et al., 2011), which contradicted the Bakun hypothesis. On the other hand, upwelling intensification has been observed by several researchers over the last decades. These differences indicate that analysis based on annually averaged winds can produce different results from analysis based only on winds from the most favorable upwelling months (Cropper et al., 2014; McGregor et al., 2007; Narayan et al., 2010; Patti et al., 2010; Varela et al., 2015).

Wang et al. (2015) analyzed future wind projections along the CUE and found a general increase in upwelling intensity during the 21st century in the northern region (from 42°N to 25°N) and a weakening of upwelling intensity at the southernmost latitudes (from 25°N to 15°N). Rykaczewski et al. (2015) reported a similar pattern, indicating an intensification of upwelling favorable winds at the northern limit of the CUE and a decrease at the southern limit (from 30°N to 26°N). These two studies were conducted using GCMs with a spatial resolution on the order of 100–200 km. Today, the AFRICA-CORDEX initiative provides regional climate projections using GCMs from CMIP5. These projections offer higher spatial resolution data with grid sizes of about 50 km (0.44°). This resolution could help to better resolve nearshore coastal upwelling patterns in intense and localized upwelling zones such as the CUE. Therefore, the use of this new high resolution long-term dataset may provide new and detailed insights about the seasonality of CUE trends under future warming scenarios, especially along the Canary coast's southern limit, and it may clarify previous contradictory results.

Consequently, the goal of this study was to investigate seasonal upwelling trends along the southern limit of the CUE using high-resolution wind projections from several Regional Climate Models (RCMs) from the AFRICA-CORDEX project under a future warming scenario (RCP 8.5). Within this context, the influence of future seasonal upwelling trends on local SST patterns was also investigated.

2. Material and methods

Near surface monthly zonal (W_x) and meridional (W_y) wind components from 1976 to 2099 were obtained from 17 simulations carried out with RCMs available from the AFRICA-CORDEX initiative (http://www.cordex.org/index.php/community/domain-africa-cordex), which provides regional climate projections for the Africa coast with 0.44° (~50 km) resolution. The AFRICA-CORDEX simulations use the global climate simulations from the CMIP5 long-term experiments up to year 2100 (Taylor et al., 2012). These simulations were produced using five RCMs forced by nine different GCMs (Table 1). Near surface wind data used to analyze the past-present period (1976–2005) were extracted from the historical runs. Future wind data were obtained from future climate projections for the RCP 8.5 scenario over the period 2006–2099. This scenario correspond to stabilization of radiative forcing after the 21st century at 8.5 W m^{-2} (Moss et al., 2010).

Ocean Sea Surface Temperature (SST) data are not available from simulations carried out with RCMs obtained from the AFRICA-CORDEX initiative. Thus, SST data used in this study were derived from eight simulations carried out with GCMs for historical and climate periods (the first eight GCMs shown in Table 1). In the present study, the region 20°N–34°N and 5.5°W–22°W were analyzed from the global dataset from 1976 to 2099. GCMs have different horizontal resolutions from 100 to 210 km. Thus, SST data were interpolated on a common 1° × 1° grid using a nearest neighbor interpolation.

Table 1
AFRICA-CORDEX simulations.

GCM	RCM			
	CCLM4-8-17	RCA4	RACMO22T	HIRHAM5
CNRM-CM5	X	X		
CSIRO-Mk3-6-0		X		
EC-EARTH	X	X	X	X
HadGEM2-ES		X	X	
IPSL-CM5A-MR		X		
MIROC5		X		
MPI-ESM-LR	X	X		
NorESM1-M		X		X
GFDL-ESM2M		X		
CanESM2		X		

Offshore wind-driven Ekman transport (Q) and upwelling index (UI) were calculated following Gomez-Gesteira et al. (2006):

$$Q_x = \frac{\rho_a C_d}{\rho_w f}\left(W_x^2 + W_y^2\right)^{1/2} W_y \tag{1}$$

$$Q_y = -\frac{\rho_a C_d}{\rho_w f}\left(W_x^2 + W_y^2\right)^{1/2} W_x \tag{2}$$

$$UI = Q_\perp = -\sin\left(\theta - \frac{\pi}{2}\right)Q_x + \cos\left(\theta - \frac{\pi}{2}\right)Q_y \tag{3}$$

where Q_x and Q_y are the zonal and meridional Ekman transport respectively; ρ_w is the sea water density (1025 kg m^{-3}); C_d is a dimensionless drag coefficient (1.4×10^{-3}); ρ_a is the air density (1.22 kg m^{-3}); f is the Coriolis parameter and θ is the angle between the coastline and the equator (145°). Positive (negative) UI corresponds to upwelling favorable (unfavorable) conditions.

UI future trends were computed using 31 points distributed along the southern part of the CUE at approximately 50 km from the coastline (Fig. 1, grey dots).

A multimodel mean was used to minimize the individual model biases (Annan and Hargreaves, 2010; Raisanen and Palmer, 2001;

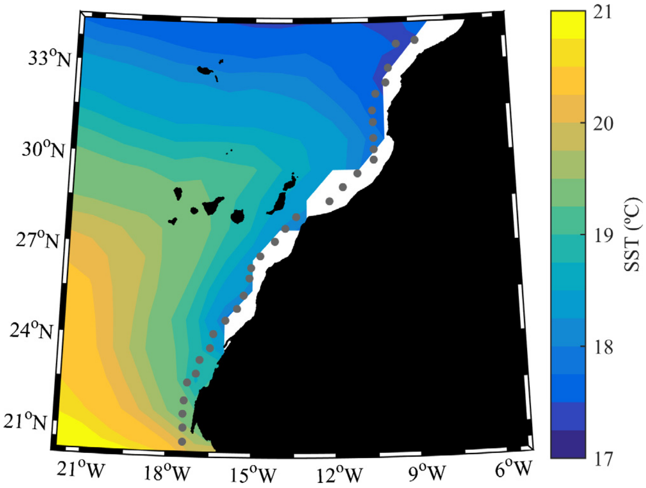

Fig. 1. Annual multimodel mean SST averaged from 1976 to 2005. Grey points represent the points where UI was calculated.