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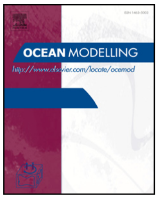

Downscaling biogeochemistry in the Benguela eastern boundary current

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ABSTRACT

Dynamical downscaling is developed to better predict the regional impact of global changes in the framework of scenarios. As an intermediary step towards this objective we used the Regional Ocean Modeling System (ROMS) to downscale a low resolution coupled atmosphere–ocean global circulation model (AOGCM; IPSL-CM4) for simulating the recent-past dynamics and biogeochemistry of the Benguela eastern boundary current. Both physical and biogeochemical improvements are discussed over the present climate scenario (1980–1999) under the light of downscaling.

Despite biases introduced through boundary conditions (atmospheric and oceanic), the physical and biogeochemical processes in the Benguela Upwelling System (BUS) have been improved by the ROMS model, relative to the IPSL-CM4 simulation. Nevertheless, using coarse-resolution AOGCM daily atmospheric forcing interpolated on ROMS grids resulted in a shifted SST seasonality in the southern BUS, a deterioration of the northern Benguela region and a very shallow mixed layer depth over the whole regional domain. We then investigated the effect of wind downscaling on ROMS solution. Together with a finer resolution of dynamical processes and of bathymetric features (continental shelf and Walvis Ridge), wind downscaling allowed correction of the seasonality, the mixed layer depth, and provided a better circulation over the domain and substantial modifications of subsurface biogeochemical properties. It has also changed the structure of the lower trophic levels by shifting large offshore areas from autotrophic to heterotrophic regimes with potential important consequences on ecosystem functioning. The regional downscaling also improved the phytoplankton distribution and the southward extension of low oxygen waters in the Northern Benguela. It allowed simulating low oxygen events in the northern BUS and highlighted a potential upscaling effect related to the nitrogen irrigation from the productive BUS towards the tropical/subtropical South Atlantic basin. This study shows that forcing a downscaled ocean model with higher resolution winds than those issued from an AOGCM, results in improved representation of physical and biogeochemical processes.

1. Introduction

The BUS is one of the four major eastern boundary upwelling systems of the globe and its circulation is dominated by a coastal upwelling induced by winds that are controlled by the anti-cyclonic motion around South Africa high pressure system, the seasonal low pressure field over the subcontinent and by east moving cyclones which cross the southern part of the continent (Shannon and Nelson, 1996). The prevailing southerly winds imply Ekman divergence and pumping which bring subsurface water rich in nutrients to the surface layers where primary production occurs, the BUS being potentially the most productive of the four systems (Carr, 2002). Since this production sustains important marine resources (e.g. Hutchings et al. (2009)), it is essential, from social and economic points of view, to evaluate the impact of future climate change on the regional oceanic circulation and biogeochemistry.

1.1. *Modeling oceanic regional circulation in a "scenario" framework*

Understanding the regional climate change and its impacts in the Benguela Upwelling System (BUS) requires a reliable tool to represent key features of the regional circulation. Dynamical

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downscaling is the process of deriving regional information based on large-scale climate conditions using higher resolution regional circulation models (RCMs). Oceanic RCMs require information at their lateral and surface boundaries which can be derived from observational data or basin-scale and global circulation models (GCM). Numerous studies have demonstrated the ability of the Regional Oceanic Modeling System (ROMS; Shchepetkin and McWilliams, 2005) to provide realistic circulations of eastern boundary currents. Based on similar physics as GCMs, ROMS improves the representation of the dynamics in upwelling regions (weak in GCMs) partly thanks to much higher resolution but also to an adequate representation of processes which are locally important but not necessarily taken into account in GCMs (e.g. Allen et al. (2010)).

Besides their proper ability to represent key regional processes and interactions, the realism of the RCMs in simulating regional circulation depends strongly on their boundary conditions. Many papers focusing on modeling eastern boundary currents have been dedicated to process studies using climatological forcing from oceanic databases which are supposed to provide the most realistic boundary conditions (e.g. Marchesiello et al. (2003), Penven et al. (2006), Echevin et al. (2008), Veitch et al. (2009), Mason et al. (2011)). It has been shown that atmospheric interannual forcing derived from model re-analyses can alter ROMS solution obtained using climatological forcing (Veneziani et al., 2009). Large scale oceanic boundary provided by GCMs may also strongly impact the regional solutions. Echevin et al. (2011) tested the impact of remotely forced coastal waves in the Humboldt Current System by using three distinct Ocean General Circulation Models (OGCMs) for the initial and boundary conditions of their regional climatological experiments. They demonstrated that the different stratifications and equatorial circulations of these OGCMs affect differently the seasonal variations of the eddy kinetic energy inside their domain. Similarly, based on climatological simulations in the Humboldt Current System, Montes et al. (2014) showed the sensitivity of the simulated oxygen minimum zone extent to the conditions of the tropical oceanic circulation off the Humboldt Current System.

In the framework of climate scenarios at regional scale, as far as we are aware, only few studies have been carried out in eastern boundary currents. To investigate the impact of climate warming in the Humboldt Current System, Echevin et al. (2012) used ROMS to downscale two contrasted scenarios, the so-called preindustrial and quadrupling CO_2, simulated by a global climate model (IPSL-CM4). In upwelling systems, the uncertainties related to the wind forcing (particularly the wind stress curl) has often been put forward to explain biased solutions (e.g. Capet et al. (2004), Miranda et al. (2012)). To overcome this problem Echevin et al. (2012) have used a statistical method proposed in Goubanova et al. (2011) to downscale the winds forcing over their domain from coarse-resolution IPSL-CM4 atmospheric outputs. The study focused on the comparison of the physics of two contrasted scenarios but has not discussed the local solution obtained by imposing $2^\circ \times 1^\circ$ model outputs as open boundary conditions for a $1/6^\circ \times 1/6^\circ$ RCM resolution. Recently, Miranda et al. (2012) have attempted to project the evolution of the circulation in the Iberian Upwelling System at the end of the current century under a specific climate change scenario (SRES A2 emission scenario; Nakicenvoic et al., 2000). They used atmospheric forcing from a scenario simulated by a regional atmospheric climate model (RACMO) and oceanic boundary conditions from ocean climatological data because of “the unavailability of ocean boundary conditions from the global ocean model” hence preventing them from studying the regional impact of remote signals induced by large scale oceanic variability.

1.2. Main climatic drivers of the Benguela Upwelling System

The major features affecting the BUS have been reviewed in Hutchings et al. (2009) who published one of the last of numerous disciplinary reviews of the Benguela region. The Benguela is very unique as an eastern boundary current since it is bordered both north and south by warm waters.

As an extension of the south equatorial counter-current, the Angola Current flows southward along the shelf of Angola and interacts with the wind-driven upwelling system to form a very dynamic but relatively shallow front called the Angola–Benguela Frontal Zone (ABFZ) located between 15° and 17°S (Veitch et al., 2006). The front is aligned normal to the coast and its seaward extension varies at interannual and seasonal time scales and can reach 600 km. Salinity data suggest that the front may extend to a depth of at least 200 m but it is particularly marked in the upper 50 m (e.g. Shannon et al. (1987)). The south-flowing Angola Current, which is of mixed tropical/equatorial origin, is warmer, saltier and poorer in nutrients than the north-flowing Benguela Current. Controlled by the pattern of the wind stress curl distribution, tropical water from the cyclonic gyre in the area of the Angola Dome leaks southward through the Angola–Benguela front as a poleward current along the continental shelf in the Northern Benguela (Lass et al., 2000; Veitch et al., 2009). Colberg and Reason (2007) studied the low-frequency variability of the South Atlantic and found that the tropical Atlantic presented mainly interannual fluctuations. Compared to the tropics, northeastern subtropics are characterized by stronger variations at interannual to decadal scale (Colberg and Reason, 2007) superimposed on a seasonal variability which increases southward. Blanke et al. (2002) showed that the shelf of the west African coast extending 400 km north of Cape Columbine (southern tip of the BUS) is equally sensitive to local fluctuations of the forcing and open-sea wind fluctuations.

The southern boundary of the BUS is formed by the Agulhas Current (AC) system. Among the 60–80 Sv of the AC transport which flows along the Agulhas Bank on the south coast of South Africa, most of it retroflects back into the south Indian ocean but some of the warm saline water flows northward into the eastern south Atlantic ocean as jets, filaments and large anticyclonic rings (e.g. Hutchings et al. (2009)). The region of the retroflection which takes place south of Africa is a very complex and energetic region where the AC interacts with the Subtropical and Subantarctic Fronts. Blanke et al. (2005) emphasized the connections between the southern BUS and the large scale circulation in relation with the Agulhas Current retroflection and associated ring shedding for driving its variability.

Garzoli and Gordon (1996) estimated a transport at 30°S for the upper 1000 m of the Benguela Current of about 13 Sv northward, 50% being derived from the central Atlantic (mainly South Atlantic water), 25% coming from the Indian Ocean (Agulhas water), and the remaining 25% may be a blend of Agulhas and tropical Atlantic waters. The mean Benguela Current transport does not change interannually more than 20%.

Demarcq (2009) showed that a warming trend is observed in satellite SST over the last 20 years in the southern BUS. This trend could be interpreted as the result of an increase of the Agulhas leakage to the Southeast Atlantic subtropical basin (Rouault et al., 2009; Biastoch et al., 2009).

Along with their impact on physical parameters the remote drivers described hereabove, i.e. Angola dome and current and AC, control also the variability of biogeochemical variables in the northern and southern BUS, although the regional knowledge of these variables is rather limited. Tropical Atlantic thermocline waters of low oxygen content are advected southward along the continental