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Sensitivity of the simulated Oxygen Minimum Zone to biogeochemical processes at an oligotrophic site in the Arabian Sea

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ABSTRACT

Oxygen minimum zones (OMZs) are large, low-oxygen areas in the global oceans. Although OMZs represent a serious threat to ecosystem functioning and services, our capability of modelling the main biogeochemical processes driving OMZ dynamic are still limited. Here we performed a full sensitivity analysis of a complex ecosystem model to rank the most important biogeochemical parameters influencing the simulation of the OMZ at an oligotrophic site in the open Arabian Sea. We applied a one-dimensional configuration of the European Regional Seas Ecosystem Model (ERSEM) - here advanced by including denitrification - coupled with the General Ocean Turbulence Model (GOTM). The coupled model was skilled in simulating the vertical gradients of climatological data of oxygen and nutrients. The sensitivity analysis of the model was carried out in two steps: *i)* a preliminary Morris screening analysis of 207 ERSEM parameters, which selected the three most influential groups of parameters; and *ii)* a subsequent Monte Carlo sampling-based analysis for ranking the importance of the 38 parameters within the three selected groups. Overall, the four most important parameters for the simulation of the minimum oxygen concentration were found to be: 1) the cubic half saturation constant for oxygenic control of denitrification; 2) the parameter regulating the fraction of ingested matter excreted by heterotrophic nanoflagellates; 3) the bacterial efficiency at low oxygen levels; and 4) the specific rate of bacterial release of capsular material. Based on these findings, and assuming that the ranking of the model parameters reflects the relevance of the process they characterize, we present a conceptual model describing the most important biogeochemical processes affecting the OMZ at the study site. Our results suggest that including bacteria explicitly in ecosystem models is useful to simulate and predict OMZs, provided that efforts are invested in estimating parameters characterizing the microbial loop in marine ecosystems.

1. Introduction

Oxygen minimum zones (OMZs) are areas of the oceans characterized by low dissolved oxygen concentrations at intermediate depths (50–1000 m). Paulmier and Ruiz-Pino (2009) defined OMZs as regions where dissolved oxygen (DO) concentrations are less than 20 $\mu mol\,L^{-1}$, decreasing to 1 $\mu mol\,L^{-1}$ in the core of the OMZ. In the present ocean, OMZs are expanding as a consequence of eutrophication and climate change, representing a serious threat for ecosystem functioning and services such as fisheries (Oschlies et al., 2008; Stramma et al., 2008; Diaz and Rosenberg, 2008; Gilbert et al., 2010; Rabalais et al., 2014; Duarte et al., 2015, Breitburg et al., 2018).

The formation, maintenance and intensification of the OMZs are governed by the interaction of physical processes (oxygen solubility driven by temperature and salinity, presence of regions of low ventilation and subsurface currents of poorly oxygenated water) with biological processes (primary production, heterotrophic activities, bacterial respiration and remineralization of organic matter).

Physical processes influencing OMZs are linked to global patterns of temperature, salinity and circulation. For example, Bopp et al. (2002) used a coupled climate-ocean biogeochemistry model to predict the decrease in DO with climate change and the net outgassing of DO from the ocean. They argued that the physical processes driving the reduction in DO were: *i)* changes in surface water solubility due to temperature increase; and *ii)* changes in the ocean circulation pattern. Matear and Hirst (2003) used a climate model coupled with an oceanic

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biogeochemical model to investigate the multi-century impact of protracted global warming on the ocean biogeochemical cycles. Their model predicted a decline in the DO concentration through most of the subsurface ocean in the future years.

Marine biogeochemical processes are also crucial drivers of OMZs, and OMZs strongly impact global biogeochemical cycles. As a basic conceptual scheme of biogeochemical drivers of OMZs (see, e.g., Sarmiento and Gruber, 2006), waters at intermediate depth receive organic matter produced and sinking from the upper euphotic layers; aerobic bacteria feeding on this organic matter and respiration by zooplankton consume oxygen and lower its concentration within the OMZ. Diaz and Rosenberg (2008) showed that hypoxic areas in the coastal oceans increased since the 1960s because of the increase in primary production fueled by riverine runoff and eutrophication. Oschlies et al. (2008) showed that OMZs are particularly sensitive to changes in the marine biology, by predicting a 50% increase in the global suboxic water volume by 2100 in response to the respiration of excess organic carbon formed at higher atmospheric CO_2 levels. Increase in primary production leads to increase in accumulation of particulate organic matter that, in turn, increases microbial activity and consumption of oxygen in the waters below. However, other processes complicate this basic scheme of OMZs, such as the possible switch of the microbial community towards anaerobic bacteria, which can reduce nitrates to N_2 gas through denitrification, and can reduce sulfate to hydrogen sulfide when the OMZ reaches anoxic conditions (Richards, 1965; Sarmiento and Gruber, 2006). Large amounts of biologically reactive nitrogen are removed from the oceans by anaerobic denitrifying bacteria in OMZs, with crucial impact on the global cycle of nitrogen (Paulmier and Ruiz-Pino, 2009). While the above-mentioned studies have identified the different biogeochemical processes influencing the OMZ, an understanding of their comparative impacts has not yet been achieved.

The overall objective of this study is to contribute to fill this gap, by ranking the importance of the biogeochemical processes which need to be carefully described to understand, simulate and predict OMZ formation and evolution in the oceans. This was done by ranking the importance of biogeochemical parameters of a complex marine ecosystem model. This model is the European Regional Seas Ecosystem Model (ERSEM) (Butenschön et al., 2016), which includes most of the biogeochemical processes driving OMZ dynamics. New for this study is that we included denitrification in ERSEM, since this process is relevant in OMZ systems, but it was not represented in the pelagic component of the model (Butenschön et al., 2016). We ranked the importance of ERSEM parameters for OMZ simulation, by using in sequence the Morris screening technique, followed by a Monte Carlo sampling-based ranking. These techniques are already proven to be useful with other marine biogeochemical models (Pastres and Ciavatta, 2005; Cossarini and Solidoro, 2008) and a marine food-web model (Morris et al., 2014). This is the first systematic sensitivity analysis of ERSEM.

In the present study, the analysis was performed using a one-dimensional (1-D) implementation of ERSEM for an oligotrophic site in the open Arabian Sea (Fig. 1), advancing a comparable model configuration in this region by Blackford and Burkill (2002) and Blackford et al. (2004). The Arabian Sea is characterized by a vast OMZ with DO concentrations below 0.05 ml L^{-1}, at depths between 150 and 1250 m (Van Bennokom and Hiehle et al., 1994), and it is one of the three major denitrification sites in world oceans (Codispoti, 1989; Naqvi et al., 2006) with an annual denitrification rate of 10–30 Tg N yr^{-1} (Fauzi et al., 1993). At the present time, there is no consensus on which physical and biological processes maintain the spatial and seasonal pattern of the OMZ in the Arabian Sea (McCreary et al., 2013; Roullier et al., 2014), and hypotheses include high respiration related to monsoon-driven primary productivity, slow advection of intermediate waters, and influx of low oxygen waters from the South Indian Ocean (Swallow, 1984; Naqvi, 1987; Jayakumar et al., 2004; Wiggert et al., 2005). Results from both a box model (Sarma, 2002) and an eddy-resolving model (Resplandy et al., 2012) showed that horizontal oxygen transport is important for maintaining the OMZ. At the same time, ecosystem models of varying complexity, including the seminal NPZD model of McCreary et al. (1996) and the model by Ryabchenko et al. (1998) that resolved also the microbial-loop, were used to investigate the contribution of biological processes to the OMZ. The three-dimensional (3-D) coupled model by Anderson et al. (2007) confirmed the relevance of modelling bacteria to simulate the biogeochemical fluxes and demonstrated that vertical sinking of organic particles (in contrast to their horizontal transport) was a major driver of denitrification in the regional OMZ. For the first time, Blackford and Burkill (2002) and Blackford et al. (2004) applied the more complex ERSEM to this region, in a 1-D configuration with the physical model GOTM, and they found that vertical processes and microbial trophic dynamics were important drivers of biogeochemical variability in the Arabian Sea. This model added the representation of size classes of detritus and variable elemental ratios in the simulation of the Arabian Sea ecosystem –and these features were later recognized as essential ones to simulate OMZ in this region, as well as in the global ocean (Oschlies et al., 2008; McCreary et al., 2013).

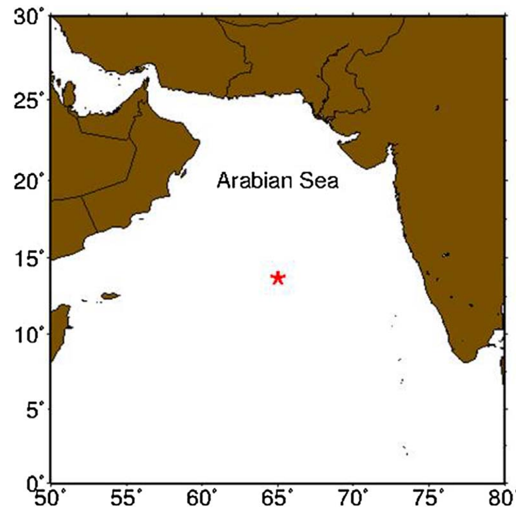

Fig. 1. Location of the study site in the Arabian Sea (65°E, 13°N).

However, the relative contribution of the different biogeochemical processes to the formation and evolution of the OMZ in the Arabian Sea remains uncertain, and further research has been invoked to improve their representation in mathematical models of this ecosystem (McCreary et al., 2013; Roullier et al., 2014). Therefore, we tested the sensitivity analysis methods in a case study that aims to rank the biogeochemical processes that determine the annual minimum value of oxygen concentration at the site in the open Arabian Sea in Fig. 1. Here, spatial-temporal biogeochemical variability is lower, and the OMZ thinner, than in the Northern Arabian Sea (Kao et al., 2015), arguably making acceptable the application of a 1-D model configuration to study the formation of the and maintenance of the upper oxycline at the study site.

The paper is structured as follows. Section 2 describes the coupled physical-biogeochemical model, the sensitivity methods and the set-up of the analysis. In Section 3, the results are presented: first the skill of the OMZ simulation is evaluated by comparing the results to climatological data, and then the results of the screening and Monte Carlo-based sensitivity analyses are synthetized. In Section 4 we discuss the results by presenting a conceptual model of the OMZ formation, and concluding remarks are pointed out in Section 5.

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