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Interannual hypoxia variability in a coastal upwelling system: Ocean–shelf exchange, climate and ecosystem-state implications

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Abstract

In this study we use multi-year time series to examine the dynamic characteristics of coupled physical–biogeochemical processes that modulate interannual coastal hypoxia in the Benguela upwelling system in the southeast Atlantic. The results confirmed earlier findings on the role of advection to explain much of the seasonal–decadal variability. These results challenge the predominantly biogeochemical basis, namely benthic–pelagic coupling, to understand the variability of hypoxia and its ecosystem implications. Unexpectedly, the results showed that the variability was insensitive to changes in the electron-donating capacity (carbon export fluxes) but strongly dependent on the advected oxygen fluxes. The dynamics of the interaction of equatorial and polar boundary conditions (ocean–shelf exchange) and seasonally phased shelf advection were the key forcing functions that explained hypoxia variability in seasonal–decadal time scales. The vulnerability of the system to climate change lies in the long-term response of the equatorial system that governs seasonal and interannual warming at the Angola–Benguela front as well as wind stress in the Luderitz southern boundary that governs ventilation. The proposed model was able to explain most of the decadal scale variability of two different ecosystem-state indicators. The model predicts a long-term decline of present ecosystem function with climate change.

Keywords: Oxygen; Hypoxia; Upwelling; Climate; Benguela; Ecosystem

1. Introduction

Natural shelf hypoxia has recently re-emerged as a major consideration in understanding the variability of fisheries ecosystems and ecological complexity (Diaz and Rosenberg, 1995; Levin and Gage, 1998; Rogers, 2000; Levin, 2003; Helly and Levin, 2004; Monteiro et al., 2006; Monteiro and Van der Plas, 2006). Coastal hypoxia research has had a historical emphasis on the biogeochemistry of anthropogenically driven systems (Diaz, 2001; Rabalais and Turner, 2001). Although natural marine hypoxia is spatially well characterised at a global scale, the dynamic considerations that govern its variability and its links to climate forcing are less well constrained (Chapman and Shannon, 1985; Lass et al., 2000; Lass and Mohrholz, 2005; Monteiro et al., 2006; Mohrholz et al., 2007). Much

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of the focus has been on the biogeochemical fluxes, microbiology and ecology that characterise benthic–pelagic coupling (Bremner, 1983; Bailey, 1991; Ferdelman et al., 1999; Schulz et al., 1999; Brüchert et al., 2000, 2003, 2006). This gap is particularly noticeable in instances where the dynamics are the result of the interaction of both remote oceanic and local shelf forcing (Grantham et al., 2004; Ho et al., 2004; Escribano et al., 2004; Monteiro et al., 2006) or large-scale biogeochemical changes in response to a re-organisation of circulation systems between the glacial and inter-glacial states (Sigman and Boyle, 2000; Reichart et al., 2002; Reuer et al., 2003).

The uncertainty in respect of the response of hypoxic coastal systems to climate forcing has stimulated a shift towards obtaining a better understanding of the scales that characterise the coupled interaction between physical and biogeochemical processes, especially across ocean–shelf boundaries. Initially dynamic considerations were limited largely to quantifying the variability in upwelling rates as the main flux of nutrients that governed the electron-donating capacity linked to the hypoxia (Morrison et al., 1999; Brüchert et al., 2000; Weeks et al., 2004; Müller-Karger et al., 2004) and the associated biogeochemical characteristics of the depositional zones (Brüchert et al., 2000, 2003; Emeis et al., 2004; Monteiro et al., 2005). However, once established hypoxia–anoxia variability is regulated by dynamics of the net fluxes of electron donors (POC) as well as electron acceptors (O_2, NO_3, SO_4) over a range of time scales (Ho et al., 2004; Monteiro et al., 2006; Whitney et al., 2007). The rates of vertical mixing of oxygen in shallow or weakly stratified systems are often adequate to oxidise the export production aerobically. However, the same does not hold for deeper or stratified shelf systems that are more sensitively dependent on advective scales to supply the required electron acceptors (Rabalais and Turner, 2001; Ho et al., 2004; Monteiro et al., 2006). For these systems, a focus on the longer-term (interannual and decadal) scales governing advection is necessary to understand not only contemporary ecological variability but also both past and future climate scale responses (Sigman and Boyle, 2000; Reichart et al., 2002).

The central Benguela upwelling system is characterised by hypoxia–anoxia variability driven by advection over a wide range of scales from event to interannual (Monteiro et al., 2006; Monteiro and Van der Plas, 2006; Mohrholz et al., 2007). Hence, it offers an opportunity to examine the generic question of how shelf hypoxia will respond to sustained global warming through a better understanding of the physical forcing scales. The Benguela upwelling system is an important part of the South Atlantic thermocline circulation system which provides ocean boundary conditions to the shelf from two biogeochemically different water types: the relatively fresh Cape Basin South Atlantic Central Water and the more saline and hypoxic Angola Basin Central Water (Duncombe Rae, 2005). The boundary between these two water types lies between the two major upwelling centres (Luderitz and Cape Frio) of the central Benguela (Fig. 1). These two thermocline water types form a biogeochemically distinct boundary on the slope but mix on the shelf after upwelling through Cape Frio and Luderitz, both being locations of maximum wind-stress curl and shelf narrowing (Monteiro et al., 2006) (Fig. 1a and b). Previous work showed that the seasonal modulation of hypoxia on the shelf is governed by the temporal phasing of meridional transport from Luderitz in the early upwelling season (August–November) and poleward from Cape Frio in the late upwelling season (January–May) (Monteiro et al., 2006). In this study, we examine the importance of interannual and decadal forcing in understanding the variability of natural coastal hypoxia. Here we present the hypothesis that, as was the case for the seasonal scales, interannual shelf hypoxia variability is modulated by the interaction on the shelf of variable forcing at the two main upwelling centres linked to two different oxygen boundary conditions through ocean–shelf exchange.

2. Methods

2.1. Oceanographic data sampling

The temperature, salinity and oxygen decadal time series were derived from a quasi-monthly cross-shelf sampling programme (MOM—Monthly Oceanographic Monitoring) run by the Ministry of Fisheries and Marine Resources along 23°S latitude over that period. A Seabird 911plus or Seabird 19plus CTD-O with rosette was lowered to within 5–10 m of the seabed at each station. Water samples were collected with 5-L PVC Niskin bottles for salinity and oxygen data calibration. The data were extracted from a depth of 100 m at a station located 40 nm offshore in a total depth of 140 m (Fig. 1a). The spatial salinity distribution (Fig. 6a and b) was