Harmful Algae 11 (2011) 23–32

Contents lists available at ScienceDirect

Harmful Algae

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

Anoxia in southern Benguela during the autumn of 2009 and its linkage to a bloom of the dinoflagellate *Ceratium balechii*

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ARTICLE INFO

Article history:
Received 23 March 2011
Received in revised form 2 July 2011
Accepted 2 July 2011
Available online 12 July 2011

Keywords:
Upwelling
Anoxia
Red tide
Ceratium balechii
Southern Benguela

ABSTRACT

Oxygen deficiency in the southern Benguela has a pronounced negative impact on living marine resources and within the greater St Helena Bay anoxia is the cause of large episodic mortalities of the rock lobster *Jasus lalandii*. These impacts have motivated further investigation, specifically of the role of high biomass dinoflagellate blooms, commonly known as red tides, in the development of anoxic conditions. A high resolution time series of dissolved oxygen concentrations obtained from a bottom mooring off Elands Bay, located within the greater St Helena Bay region, is examined in relation to the development of an exceptional bloom of the dinoflagellate *Ceratium balechii* and an anoxia-induced mass mortality. A clear seasonal trend is evident in bottom dissolved oxygen concentrations, initiated in spring by upwelling events that advect low oxygen waters across the shelf. Increased deposition of organic carbon derived from primary production maxima in summer and autumn, together with the development of an increasingly stratified environment exacerbate dissolved oxygen deficits leading to a progressive decline in dissolved oxygen concentrations in the cold bottom layer. Within this seasonal timeframe episodic anoxia may occur throughout the water column of shallow inshore regions following the decay of red tides accumulated within these environments under conditions of persistent downwelling. Anoxia within these shallow non-stratified nearshore regions is dependent on exceptional organic loading of the water column as afforded by the decay of red tide and to the absence of wind-induced mixing or wave action. These requirements contribute to the local and transient character of these events of anoxia. With the onset of winter strong mixing results in reduced primary production and increased ventilation of bottom waters causing an increase in dissolved oxygen concentrations.

1. Introduction

Oxygen deficit in the oceans is a critical determinant of biological and ecological processes and the expansion of hypoxia and anoxia represent major perturbations to the diversity, structure and functioning of coastal marine ecosystems (Rosenberg et al., 1991; Wu, 2002; Chan et al., 2008; Vaquer-Sunyer and Duarte, 2008). Furthermore, the onset of hypoxia or anoxia is often associated with increases in sulfide concentrations which are severely toxic to most aerobic organisms (Conley et al., 2009; Vaquer-Sunyer and Duarte, 2010). Dissolved oxygen is now recognized as a property of the ocean that has changed dramatically over a short period of time (Diaz and Rosenberg, 1995; Diaz, 2001), with oxygen deficiencies having increased in frequency, duration, and severity during recent decades (Diaz and Rosenberg, 2008). Rates of oxygen decline are considered to be greatest in coastal regions (Gilbert et al., 2010) and evidence for eutrophication as an important causal factor is increasing (Conley et al., 2009). Temperature also interacts through a multitude of processes to control the extent of oxygen depletion, and projected increases in warming associated with climate change show an increase in susceptibility of coastal marine ecosystems to hypoxia and/or anoxia (Conley et al., 2009).

Eastern boundary upwelling systems are among the most productive large marine ecosystems in the world contributing a large portion to the global fishery yield. While upwelling determines the productivity of these systems it also transports oxygen-poor waters onto the continental shelf, where degradation of organic matter can further reduce water column dissolved oxygen content and thus subject these coastal ecosystems to the risk of hypoxia or anoxia (Chan et al., 2008). Because upwelling transports waters that can be both dissolved-oxygen deficient and nutrient-rich onto productive continental-shelf systems, hypoxia and/or anoxia may represent a general and critical link between

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doi:10.1016/j.hal.2011.07.001

climatic variability, shifts in ocean circulation and marine ecological change (Grantham et al., 2004).

Of the world's four major eastern boundary current systems, water column shelf anoxia is best known in the Humbolt and Benguela Currents (Levin et al., 2009; Monteiro et al., 2011). However, the intensification of severe inner-shelf hypoxia and anoxia has recently been reported in the California Current large marine ecosystem and is considered to reflect a basin-wide reduction in dissolved oxygen (Grantham et al., 2004; Bograd et al., 2008; Chan et al., 2008). The novel rise of shelf anoxia in this system demonstrates the potential for rapid reorganization in the distribution of anoxia and the sensitivity of the shelf environment of upwelling systems to discontinuous ecosystem change. Of particular concern is the possibility that changes in low oxygen waters and related physical and biogeochemical processes may be linked to global change (Grantham et al., 2004). The emergence of severe shallow-water hypoxia in the California Current System therefore highlights the importance of ecological thresholds in mediating ecosystem sensitivity to climatic variability, and reinforces the fundamental need for ecosystem-based management of coastal fisheries and habitats (Grantham et al., 2004).

Low oxygen bottom water is an endemic characteristic of the Benguela system, forced by the interaction of both large-(basin) and local-(shelf) scale forcing, in that low oxygen variability is determined by the degree of oxygen depletion in waters advected onto the shelf, and by local oxygen demand driven by the sedimentation of upwelling-linked new production (Monteiro and van der Plas, 2006; Monteiro et al., 2006). In the southern Benguela the risk of hypoxia or anoxia is greatest within the greater St Helena Bay region (Fig. 1). Here seasonal stratification is maintained by the advection of cold upwelled water onto the shelf and by sun-warming of the surface layer, and functions together with the retentive properties of the Bay, resulting from cyclonic circulation within the lee of the Cape Columbine headland, to enhance productivity (Probyn et al., 2000; Weeks et al., 2006; Pitcher and Weeks, 2006). The resulting high rates of sedimentation of surface derived primary production (Bailey, 1991) and poor ventilation, lead to the formation of an oxygen depleted bottom layer, capped by well-oxygenated surface waters (Bailey and Chapman, 1991; Monteiro and van der Plas, 2006).

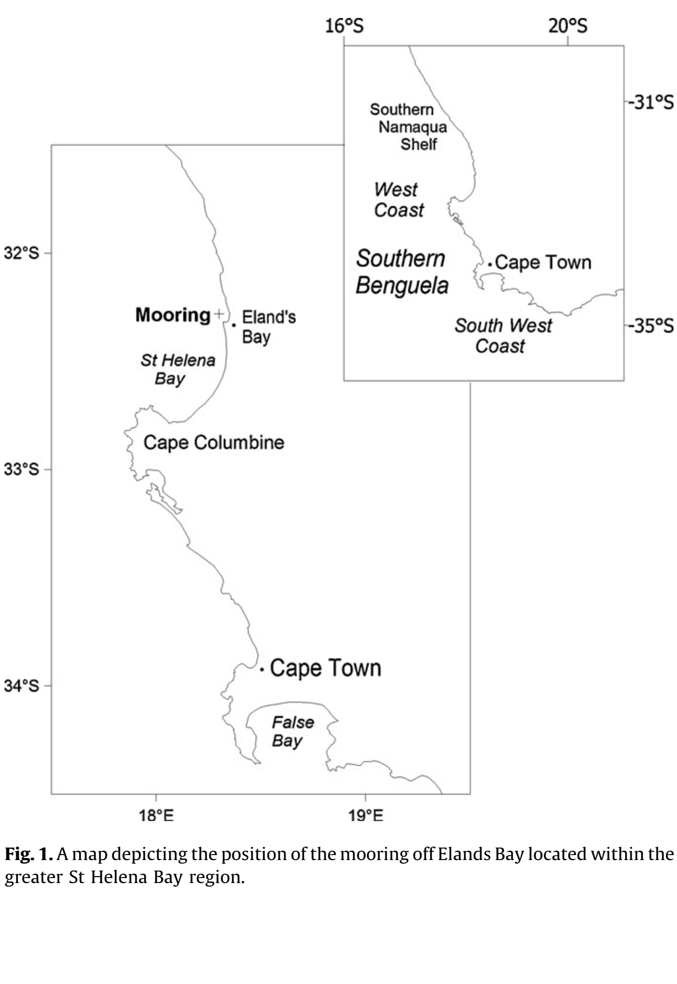

Fig. 1. A map depicting the position of the mooring off Elands Bay located within the greater St Helena Bay region.

Of all environmental properties, oxygen deficiency in the Benguela is considered to have the most pronounced negative impact on the living marine resources of the system (Monteiro and van der Plas, 2006; Van der Lingen et al., 2006). Low oxygen waters have in the recent past led to major mortalities and shifts in the distribution of economically important marine resources. In the southern Benguela this is particularly evident for the rock lobster *Jasus lalandii* which has been subject to spectacular mortalities during low oxygen events often attributed to the inshore accumulation and decay of high biomass dinoflagellate blooms referred to as red tides (Cockcroft, 2001). In the 1990s lobster fisheries in the greater St Helena Bay were severely affected by an increase in the frequency and severity of these lobster mortalities (Cockcroft, 2001), with landings reduced to $<10\%$ of their average catch during the 1980s (Cockcroft et al., 2008). These impacts have motivated further investigation of the incidence and causes of anoxia within the region, specifically of the relationships between red tides and anoxia, which remain poorly documented.

This study reports on the variability of dissolved oxygen concentrations on the inner shelf of the St Helena Bay region. Central to the study was a high resolution time series of oxygen concentrations obtained from a bottom mooring at 19 m depth off Elands Bay (Fig. 1). The oxygen regime was further examined in relation to the development of a high biomass bloom of the dinoflagellate *Ceratium balechii* and an anoxia-induced mass mortality occurring on the southern shores of St Helena Bay (Fig. 1). These data provided a unique opportunity to establish two categories of oxygen depleted waters in the nearshore environment of St Helena Bay: (1) a seasonal decline in bottom water dissolved oxygen corresponding to an increasingly stratified environment and to primary productivity maxima in summer and autumn, and (2) episodic events of anoxia occurring in shallow inshore environments following the decay of red tides.

2. Materials and methods

2.1. Elands Bay mooring

A mooring was maintained off Elands Bay (32 17.522N; 18 19.073E) in 19 m of water from 27 November 2008 to 9 October 2009 (Fig. 1). The mooring comprised a Starmon-mini temperature recorder and a Turner Designs SCUFA (Self-Contained Underwater Fluorescence Apparatus) deployed at 5 m depth, and a Wet Labs WQM (Water Quality Monitor) deployed on the seabed at 19 m depth. The estimates of temperature provided by the Starmon-mini at 5 m and the WQM at 19 m provided information relating to the physical status of the water column, including upwelling–downwelling and mixing events. The SCUFA allowed bloom development to be tracked through estimates of chlorophyll *a* (Chl *a*) at 5 m depth and the WQM provided estimates of bottom water dissolved oxygen.

The SCUFA has 3 sensitivity settings and automatic gain control is always active providing an estimate of *in vivo* Chl *a* concentrations. Default calibration settings as determined by the Turner Designs facility using primary standards of Chl *a* were employed.

The WQM combines the chlorophyll and fluorometer-turbidity sensors of WETLabs with the conductivity, temperature, and depth (CTD) and dissolved oxygen (DO) sensors of Sea-Bird Electronics.