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Deep chlorophyll maximum and plankton community response to oceanic bottom intrusions on the continental shelf in the South Brazilian Bight

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ABSTRACT

The continental shelf of the South Brazilian Bight (Lat 23–28.5°S) is subject to bottom intrusions of the oceanic and nutrient-rich South Atlantic Central Waters (SACW) in summer, to compensate for the Ekman transport of surface waters offshore by northeasterly winds. In winter, shelf waters tend to overturn vertically due to tidal circulation and Ekman convergence of outer-shelf waters driven by southerly winds. From 9 November 2005 to 22 June 2006 the shelf off Santa Catarina State was surveyed to investigate hydrographic conditions and the seasonal dynamics of the plankton cross-shelf distribution and community structure. A strong wind-driven onshore bottom intrusion of the SACW with the formation of two independent deep chlorophyll maximum (DCM) layers on the shelf was clear. Chlorophyll concentrations ranged from 0.07 to 6.2 mg m^{-3} and phytoplankton carbon biomass from 0.2 to 511 μgC L^{-1}, mostly as large centric diatoms and in spite of the numerical dominance of small pennates. The mid-shelf DCM was 12 m thick between 38 and 50 m (1–5% of irradiance) with mean chlorophyll concentrations up to 1.8 mg m^{-3}. The DCM on the outer shelf was formed between 60 and 70 m depth (1–0.01% surface light) by small pennate diatoms and small phytoflagellates, with chlorophyll concentrations of 0.5–0.7 mg m^{-3}. Both DCMs were maintained independently from January to April 2006, and dispersed in June due to water column turnover during cold seasons. In the mid-shelf, the DCM was geographically extended towards the inner shelf and became thicker compared to pre- and post-intrusion periods. The freshwater species *Aulacoseira granulata* and large centric diatoms including the invasive *Coscinodiscus wailesii* were frequent along the shelf throughout the sampling period. *Oncaea waldemari*, *Ctenocalanus vanus* and *Oithona plumifera* usually dominated the zooplankton, which ranged from 23 to 7970 individuals m^{-3}. Abundances were always higher on the inner shelf regardless of the season of the year. Abundance on the mid-shelf peaked following the onset of the intrusion of the nutrient-rich oceanic SACW in the lower euphotic zone and the enhancement of the DCM. A 6-step circulation model of diatoms coupled with shelf hydrodynamics is proposed as the main mechanism of retention of diatoms in the shelf system. The model suggests that diatoms resuspended in the nearshore are transported offshore by Ekman forces toward oligotrophic waters, where they sink faster due to poor nutrient conditions. Sinking cells find better nutrient conditions in the pycnocline/nutricline layers, become shade-adapted and increase their buoyancy, contributing to the formation of the DCM. Resting cells sinking out of the euphotic zone reach near-bottom layers or the sediments, from where they are carried back onshore by oceanic intrusions of the SACW. We suggest how this hydrodynamic circulation pattern of diatoms may take place in other subtropical shelf systems dominated by western boundary currents.

1. Introduction

The continental shelf of the South Brazilian Bight (23–28.5°S) is a part of the westernmost transitional zone between the subtropical and temperate domains of the western boundary current system (Lohrenz and Castro, 2005; Longhurst, 2006). Different water

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masses interact with hydrographic gradients, creating important ecotones of biological enhancement in the euphotic zone over the entire shelf (Castro et al., 2006). Away from continental runoff, phytoplankton production depends on inputs of nutrients to the euphotic zone by meso-scale physical processes, which are regulated by the seasonal pattern of the wind field and the dynamics of the Brazil Current flowing over the shelf break. In the summer, the northeast winds cause Ekman transport of surface waters offshore. This is balanced by onshore bottom intrusions of nutrient-rich South Atlantic Central Water (SACW), which may be enhanced by cyclonic eddies and meandering of the Brazil Current along the continental slope (Castro and Miranda, 1998; Campos et al., 2000). The nutricline over the outer shelf (> 100 m) is periodically displaced shoreward, spreading the subsurface chlorophyll-rich layer over the inner- and mid-shelf areas (Brandini, 1990; Brandini et al., 1989; Castro et al., 2006). Despite the numerical dominance of diatoms reported in earlier investigations (Brandini, 1988a; Brandini et al., 1989; Fernandes and Brandini, 1999, 2004), microflagellates concentrate at tidal fronts on the middle shelf, and pico-sized flagellates dominate the upper oligotrophic layers (Brandini et al., 1989). About 70% of the biomass of herbivorous mesozooplankton in the South Brazil Bight (SBB) is dominated by copepods (Lopes et al., 2006). Thus, a diatom-copepod dominated planktonic food web is enhanced in the shelf ecosystem of the SBB during summer periods from December to March where new production (*sensu* Dugdale and Goering, 1967) is concentrated at the deep chlorophyll maximum (DCM) along the nutricline. In winter periods (June–August), new production is limited by smaller contribution of nutrients (mostly phosphate and silicate) from the continental drainage of the La Plata plume (Braga et al., 2008) and benthic regeneration, compared to the higher nutrient inputs from the summer intrusions.

Despite the regularity with which the SACW intrusions enhance nutrient input to the euphotic layers over the mid-shelf during the summer seasons, its effects on the plankton community structure and dynamics over the continental shelf are still poorly understood. During the annual cycle, the hydrography along the cross-shelf off Santa Catarina State, as representative of the mid-portion of the SBB, was surveyed during five sampling cruises in order to follow the seasonal development of the DCM and its effect on the seasonal dynamics of the plankton assemblage. This study was carried out to address the following questions: (i) what is the spatial (horizontal and vertical) magnitude of the DCM in summer compared to periods when SACW intrusions are absent, (ii) which phytoplankton and zooplankton species dominate at the DCM layers during summer intrusions of the SACW, and (iii) how the abundance and cross-shelf distribution of plankton assemblages are regulated by the hydrographic regime over an annual cycle.

2. Material and methods

2.1. Field work

Five oceanographic cruises were conducted between November 2005 and June 2006 with the *RV* "*Soloncy Moura*" across the shelf off the Santa Catarina coast (26°45′S). On each cruise we sampled 15 stations from the isobaths of 20–140 m (Fig. 1). Vertical profiles of in situ photosynthetically available radiation (E_o) and natural fluorescence flux (F_f) were obtained with submarine PAR and natural fluorescence (PNF) sensors (Biospherical Instruments Profiling Natural Fluorometer model PNF-300). Chlorophyll concentrations (in mg m^{-3}) were calculated from the measurements of E_o, F_f and two constants of the software for the PNF-300, following the equation:

$$\mu g\ \text{Chlor}\ L^{-1} \frac{F_f}{{}^{o}a_{c(\text{PAR})}.\phi_f.E_o}$$

where F_f=natural fluorescence data; E_o=in situ photosynthetically available radiation; $^{\circ}a_c$ (PAR)=chlorophyll-specific absorption coefficient=0.04 m^2 mg^{-1}; ϕ_f=quantum yield of fluorescence=0.045.

Salinity and temperature data were obtained with an InterOcean CTD/S4. Factory laboratory calibration showed high precision of the measurements of pressure (± 0.1 decibar), temperature (± 0.02 °C) and salinity (± 0.02). Hydrographic properties (T, C and p) were converted to salinity (S) and sigma-t (σ_t) according to the Practical Salinity Scale (PSS-78) and the International Equation of State of Sea Water (IES-80). In November 2005 salinity was not measured due to technical failures of the equipment and the temperature was obtained from the PNF sensor.

Wind data were provided by the Centro de Informações Ambientais e de Hidrometeorologia de Santa Catarina (EPAGRI/CIRAM) located in Itajaí (Fig. 1). These data were confirmed by modeling winds (model NCEP/NCAR) at a fixed position (26°30′S; 48°30′W) near the sampling transect. The depth of the upper mixed layer (Z_m, i.e., the physically homogeneous upper layer above the pycnocline) was calculated according to Montégut et al. (2004), and the chlorophyll heterogeneity index (CHI) was calculated according to Richardson (2005).

2.1.1. Phytoplankton

Net samples were collected at all stations, with vertical trawls of a conical plankton net with 20 µm mesh and diameter of 30 cm, from the bottom of the DCM to the surface. Samples were fixed with 0.4% formaldehyde in 200-ml polyethylene bottles. Using a Hydro-Bios water sampler of 1.2 L volume, water samples were

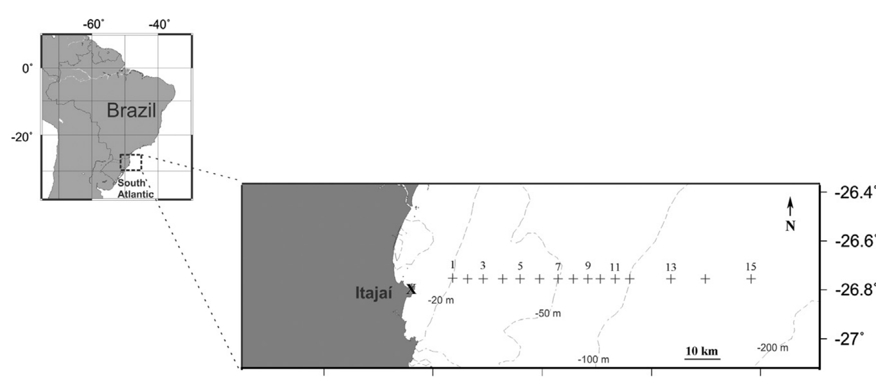

Fig. 1. Study transect off Santa Catarina, central South Brazilian Bight, with sampling stations (#1–15) visited between November 2005 and June 2006. The cross over Itajaí city indicates the position where wind data was obtained.