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Seasonal sources of carbon to the Brazilian upwelling system

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ABSTRACT

Environmental heterogeneity on coastal areas is an outcome of several hydrodynamic forces. Particularly, wind-driven upwelling is usually associated with alternating periods of water mixing and stratification. In addition, the effects of near shore oceanographic conditions may vary with coastline topography and anthropogenic impacts. Herein we evaluated the seasonal differences in the hydrodynamics of the Cabo Frio upwelling system (Brazil) in function of its local bay. Surface and deep water from 5 contrasting coastal areas were sampled 13 times during the spring/summer and in the fall/winter periods to use two-way Analysis of Variance comparing the measured variables in function of season and depth. Northeastern wind was predominant during both seasons but it was more intense during the spring/summer period when water temperature was colder and concentration of nutrients peaked. Southwestern wind was more common during the fall/winter period and was associated with cold fronts that decreased water salinity inner the bay. Consequently, the concentrations of nutrients, chlorophylls, prokaryotic secondary production (PSP) as well as fluorescent and non-fluorescent particles were significantly higher during the upwelling season while the concentration of particulate organic matter (POM) was highest during the non-upwelling season. Respectively, mean nitrate concentration varied from 2.2 to 0.9 μM, ammonium from 2.7 to 1.0 μM, chlorophyll *a* from 2.4 to 1.4 mg m^{-3}, PSP from 1.8 to 1.0 μgC.L^{-1} h^{-1} and POM from 2.6 to 6.4 mg L^{-1}. Contrasting surface and deep waters, mean nitrate concentration ranged from 0.9 to 2.2 μM, POM from 4.2 to 5.2 mg L^{-1} and PSP from 1.9 to 0.8 μgC.L^{-1} h^{-1}. Three scenarios were identified: water stratification, upwelling and water homogenization. The first two scenarios were more common outside the bay during the upwelling season. When upwelling was intense, deep water temperature in the bay dropped to less than 20 °C resulting in the stratification of water column in shallow sites. Water homogenization was common in the whole system through the non-upwelling season and was more pronounced during cold fronts. Our results evidenced a strong seasonal variation of carbon origin which was mainly associated with phytoplankton during the upwelling season and to POM during the non-upwelling season. The seasonal effect of upwelling and cold fronts on the hydrodynamics of the Cabo Frio upwelling system varied at a small spatial scale in function of site depth.

1. Introduction

Wind driven coastal upwelling systems are common in tropical, subtropical and temperate environments. However, there is a greater degree of knowledge in the main productive regions on the western coasts of the Americas and Africa being essential to study other systems since upwelling is expected to intensify under a global warming scenarios (Di Lorenzo, 2015). On the other hand, the current knowledge about the Eastern Boundary Upwelling Systems (EBUS) can help to understand other environments to verify the similarities and differences with EBUS patterns. For example, Su et al. (2013) showed the alongshore wind stress of a western boundary upwelling system had the same increasing trend in the last 20 years such as in EBUS. In the southern Brazilian coast,

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Venancio et al. (2016) observed intensification of the wind stress curl-driven upwelling more pronounced in the mid-shelf than in the outer shelf. Considering that upwelling can also enhance water column stratification into coastal embayment (e.g., Cheng et al., 2010) and that embayment facilitate plankton growth and production (Patti et al., 2008), it is essential to study the current pressure of upwelling in shallow systems to help future interpretations about the impact of climate change in these environments.

The principal upwelling area in the Brazilian coast (Cabo Frio region - 23°S, 42°W) follows many patterns from the main upwelling systems (EBUS) such as the seasonal features associated with upwelling intensity correlated to water stratification (Coelho-Souza et al., 2012). Coelho-Souza et al. (2013a) observed the entrance of cold waters in its embayment that could justify the high productivity in the bay. However, there are anthropogenic pressures inside the bay such as sewage emissions and port activities that also increase carbon production. In contrast, upwelling and cold fronts have greater impact outside the bay, mainly during the non-upwelling season. It is important to mention that cold fronts expand the heterotrophic food chain since they increase both vertical and horizontal mixing that improves primary and secondary production, as well as stimulating high abundance of plants and animals (Olson and Backus, 1985). Therefore, in the Cabo Frio region, it is expected to find hydrological heterogeneity in a small area in function of season and depth.

The aim of this research was to verify hydrological differences between the upwelling and non-upwelling seasons as well as between surface and deep waters in function of the coastline topography determined by the Cabo Frio bay. We did a series of samplings in five sites evaluating temperature, salinity and the concentrations of nutrients, fluorescent and non-fluorescent particles, chlorophylls and particulate organic matter (POM). Prokaryotic Secondary Production (PSP) was also measured since it indicates the degradation of particulate organic carbon and the conversion of dissolved organic carbon into the particulate pool, demonstrating both remineralisation of organic carbon and the trophic structure (Azam et al., 1983). The current knowledge about the functioning scenarios of the Cabo Frio region will help to interpret the impact of climate change in upwelling systems since both upwelling and cold fronts are expected to increase in the future.

2. Materials and methods

2.1. Study site

Brazilian upwelling occurs in the southeastern/southern coast and is more intense in the studied area of Arraial do Cabo (Cabo Frio region) (Fig. 1). Upwelling is characterized by the rising of the South Atlantic Central Water (SACW). North easterly winds prevailing in spring/summer (OND-JFM) cause coastal upwelling of SACW as indicated by a drop in sea surface temperature to values $\leq 20^{\circ}$ C (Valentin, 1984; Castro and Miranda, 1998). In contrast, sea surface temperature is usually higher than 22 °C during fall/winter (AMJ-JAS) when cold fronts are more common in function of south westerly winds (Pianca et al., 2010). The Arraial do Cabo area has the particularity to have benthic environments with tropical and subtropical features in a small scale. Inside the Cabo Frio bay predominates a rocky reef environment with epilithic algae matrix, the cnidarian *Palythoa* sp., corals, sponges and typical tropical reef fishes. Outside the bay, macroalgae are dominant (Coelho-Souza et al., 2012; Cordeiro et al., 2014). Anthropogenic impact is more evident inner the bay, mainly in function of sewage emissions (Coelho-Souza et al., 2013a) and port activities (Coelho-Souza et al., 2015) that intensifies sedimentation and change the structure of benthic community (Rogers et al., 2014).

2.2. Sampling and data analysis

The sampling design was based on the findings of a previous study (Coelho-Souza et al., 2013a) and considered the period between the end of October/2006 to beginning of March/2007 (10.10; 19.10; 31.10; 07.11; 13.11.06; 05.01; 12.01; 22.01; 05.02; 15.02;

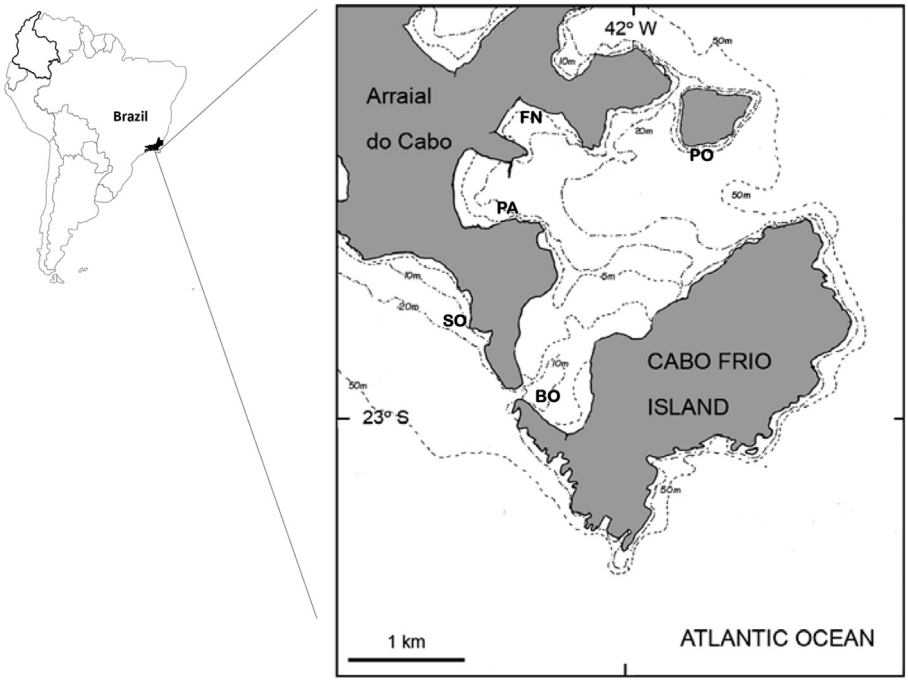

Fig. 1. Studied area and the sampling sites.