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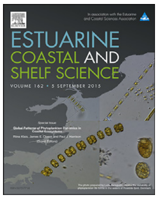

Retention time generates short-term phytoplankton blooms in a shallow microtidal subtropical estuary

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A B S T R A C T

In this study it was hypothesised that increasing water retention time promotes phytoplankton blooms in the shallow microtidal Patos Lagoon estuary (PLE). This hypothesis was tested using salinity variation as a proxy of water retention time and chlorophyll *a* for phytoplankton biomass. Submersible sensors fixed at 5 m depth near the mouth of PLE continuously measured water temperature, salinity and pigments fluorescence (calibrated to chlorophyll *a*) between March 2010 and 12th of December 2011, with some gaps. Salinity variations were used to separate alternating patterns of outflow of lagoon water (salinity <8; 46% of the time) and inflow of marine water (salinity >24; 35% of the time). The two transition phases represented a rapid change from lagoon water outflow to marine water inflow and a more gradually declining salinity between the dominating inflow and outflow conditions. During the latter of these, a significant chlorophyll *a* increase relative to that expected from a linear mixing relationship was observed at intermediate salinities (10–20). The increase in chlorophyll *a* was positively related to the duration of the prior coastal water inflow in the PLE. Moreover, chlorophyll *a* increase was significantly higher during austral spring-summer than autumn-winter, probably due to higher light and nutrient availability in the former. Moreover, the retention time process operating on time scales of days influences the long-term phytoplankton variability in this ecosystem. Comparing these results with monthly data from a nearby long-term water quality monitoring station (1993–2011) support the hypothesis that chlorophyll *a* accumulations occur after marine inflow events, whereas phytoplankton does not accumulate during high water outflow, when the water residence time is short. These results suggest that changing hydrological pattern is the most important mechanism underlying phytoplankton blooms in the PLE.

1. Introduction

Phytoplankton variability in coastal ecosystems is determined by diverse range of factors and complex interacting site-specific processes (Cloern, 2001; Cloern and Jassby, 2010; Gallegos et al., in this issue). Differences among ecosystems may result from physical, geomorphological and hydrodynamic characteristics, but also nutrient enrichment, climatology and human disturbances. In many estuaries and coastal lagoons, phytoplankton biomass and species composition variability are strongly associated with hydrodynamics, when basic growth requirements (light and nutrients) are plenty (Peierls et al., 2012; Thompson et al., in this issue).

Coastal lagoons are shallow, dynamic and highly productive ecosystems separated from the ocean by a sand barrier that is penetrated by one or several channels allowing water exchange with the ocean. Coastal lagoons are classified as choked, restricted or leaky according to their degree of water exchange with the ocean (Kjerfve, 1986). Due to the restricted water exchange, choked lagoons have comparatively long water retention time and high phytoplankton biomass (Knoppers et al., 1991; Roselli et al., 2013).

The Patos Lagoon in Southern Brazil (Fig. 1), is the largest (10,360 km^2) choked coastal lagoon in the world (Kjerfve, 1986). The connection with the coastal ocean in the southern area of the Patos Lagoon has typical estuarine conditions, which influence the growth and distribution of all biota from primary producers to fishes (Seeliger et al., 1997; Odebrecht et al., 2010). In the Patos

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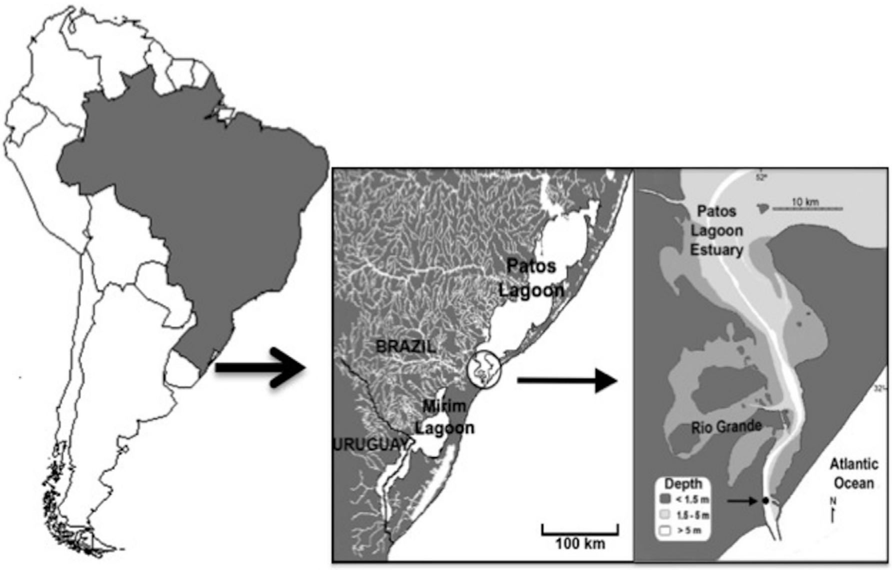

Fig. 1. Geographical location showing the watershed of the lagoons Patos and Mirim in the Southwest Atlantic Ocean and the sampling station located at the mouth of the Patos Lagoon Estuary near the city of Rio Grande.

Lagoon Estuary (PLE), phytoplankton growth and dynamics are strongly light-limited and only partially influenced by nutrients (Abreu et al., 1994a, 1995; Haraguchi et al., in this issue) and grazing (Abreu et al., 1994b). However, hydrology is considered the key forcing function of phytoplankton variability at both shorter and longer time scales (Abreu et al., 2010).

This strong connection to the hydrodynamics in the PLE makes phytoplankton variability in this estuary highly unpredictable on shorter time scales. However, peaks of chlorophyll *a* were frequently observed in oligohaline-mesohaline waters leaving the estuary after a certain period of coastal water entering the lagoon (Fujita and Odebrecht, 2007; Abreu et al., 2010), and these authors suggested that elevated chlorophyll *a* concentrations in this salinity range were likely the result of phytoplankton accumulation as a response to increasing water retention time.

In this study it is hypothesised that the occurrence of short-term phytoplankton blooms in the shallow microtidal PLE are linked to the increasing water retention time. To test this hypothesis a statistical approach was applied to identify such periods with enhanced retention time from continuous time series of salinity and chlorophyll *a* monitored in the main navigation channel of the PLE for almost two years. In this study a phytoplankton bloom is defined as a significant increment of chlorophyll *a* measured in the short time scale (hours – days), hypothesised to result from phytoplankton biomass accumulation generated by increasing estuarine water retention time. The duration of coastal water intrusion into the PLE, characterised by high salinity in the navigation channel, was used as a proxy of water residence time. The aim of the study was to investigate if the magnitude of the phytoplankton bloom increased with the duration of coastal water inflow. This relatively short-term, although high-resolution, investigation was compared with data from a long-term (21 years) monitoring program to assess the general applicability of the results.

2. Study area

The Patos Lagoon is a choked and shallow system (average depth 5 m) with a watershed of approximately 200,000 km^2 extending 250 km along the microtidal coastline of the southern Brazilian plain (10,360 km^2; 30°12′- 32°12′S; 50°40′- 52°15′W) (Fig. 1). The Patos Lagoon is mainly oligohaline, whereas large salinity variability characterises the Patos Lagoon Estuary (PLE; about 1000 km^2). In 1998, the PLE became a monitoring site of the Brazilian Long-Term Ecological Research Program (BR-PELD), and water quality and phytoplankton have been continuously sampled since 1993 (Abreu et al., 2010; Odebrecht et al., 2010).

The hydrology of this ecosystem is mainly driven by wind strength and direction, rainfall and evaporation (annual water surplus 200–300 mm, Klein, 1997), whereas tides are negligible. The PLE exchanges water with the Atlantic Ocean through a narrow inlet (0.5–1.0 km wide; 14–18 m depth) that is frequently dredged for shipping purposes. In general, southerly winds push the coastal water into the PLE, whereas the dominant winds from the north (mainly NE), acting along the main axis, forces the water from the lagoon through the PLE to the coastal region (Möller et al., 2001). During flood periods the seaward flow through the PLE, driven by large river discharge, is only reversed by strong south to westerly winds. Larger saltwater intrusions are typically associated with the passage of atmospheric fronts lasting from 6 to 10 days. Strong southerly winds can persist for 2–4 days, retaining the water in the PLE with increasing retention time as a consequence.

Owing to changing winds and freshwater discharge, large short-term salinity oscillations occur in the PLE, on the time scale of hours to days, alternating between fresh-oligohaline, over mesohaline to truly marine water; these strong variations influence the phytoplankton composition and abundance (Fujita and Odebrecht, 2007; Abreu et al., 2010). Except during drought periods, phytoplankton primary production in the Patos Lagoon is largely light limited, due high turbidity resulting from high seston input from land and sediment resuspension (Odebrecht et al., 2005). Depths in the PLE are less than 5 m, except for the main channel, and large shallow shoals (<1.5 m) prevail near the margins. However, even in these shoals, light limitation in the water column prevails from May to August, and sometimes also in austral spring/summer months (Abreu et al., 1994a).

3. Material and methods

Submersible sensors for *in situ* continuous monitoring of water temperature and salinity (RBR Ltd.) were deployed at 5 m depth at