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Importance of winds, freshwater discharge and retention time in the space–time variability of phytoplankton biomass in a shallow microtidal estuary

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ABSTRACT

In the present study, we analyze the effects of the hydrodynamics induced by action of wind and river discharge on the space–time variability of chlorophyll *a* concentration in estuary of Patos Lagoon. The study was carried out through the analysis of time series of winds, currents, salinity and chlorophyll *a* concentration, all measured in the narrow channel that connects the lagoon to Atlantic Ocean. In addition, we also analyze spatial data collected during eight cruises performed in the estuarine area during 2012. Results reveal two patterns of maximum of chlorophyll *a* concentration in the time series. The most prominent peak, was related to microalgae resuspension due to strong inflow currents. The second pattern, indicated by a less intense peak that occurs after seaward flows, at time salinity starts to decrease. The analysis of longitudinal estuarine profiles suggests an increase in chlorophyll *a* after saltwater intrusion up to 50 km inside the estuary associated to vertical stabilization caused by freshwater input from the only nearby tributary. Results also indicate that the peaks of chlorophyll *a* are linked to longer retention time and the vertical salinity stratification of water column.

1. Introduction

Estuaries are one of the most productive marine ecosystems, since they usually contain high benthic algae, marine phanerogams and phytoplankton biomasses, supporting a large aquatic food chain with crustaceans, mollusks and fish, many of them of commercial importance (Adams et al., 2020; Perez-Ruzafa et al., 2020). The phytoplankton in these ecosystems are driven by same factors that control the microalgae in lakes, rivers and oceans, i.e., light, nutrients, predation and advection are important for the growth of these microorganisms (Cloern and Jassby, 2010; Abreu et al., 2010). However, estuarine regions are subjected to frequent and strong salinity changes, which represent a very stressful environment for several species to overcome and survive these conditions, even considering the nutrient availability (Muylaert et al., 2009). Although salinity and nutrients are limiting factors for phytoplankton growth, other driving forces like tides, currents, rainfall rates, freshwater input and winds also play an important role (Cloern and Jassby, 2010; Abreu et al., 2010).

Chocked coastal lagoons usually have particular circulation patterns due to their geomorphology. The narrow shape of their inlets often leads to great intensification of the streamflow and alter significantly the exchanges between the lagoon and the coastal region. The Patos Lagoon, located in Southern Brazil, (PL, 30–32°S and 50–52°W) (Fig. 1A) is one of the largest choked coastal lagoon in the world (Kjerfve, 1986). This long (250 km) and wide (40 km in average) water body is connected to the South Atlantic Ocean through a 20 km long and 2 km wide channel (14–18 m depth). The construction of two 4 km long jetties in beginning of last century altered morphology and plays a major role on the estuarine zone circulation (Möller and Fernandes, 2010), which comprehends the area from entrance (jetties) up to approximately 70 km inside the lagoon (Fig. 1B). Depths in Patos Lagoon Estuary (PLE; area of 1000 km^2) vary from 5 m at the inner portions of the estuary to 18 m in the main channel, and large shallow shoals (<1.5 m) prevail near the margins. PL drains the waters from a very large and important hydrographical basin (200.000 km^2) consisting of: drainage basin of Guaíba River (GR, Fig. 1A) that discharges in northern part of PL; Camaquã River (CR, Fig. 1A) discharging in central part of lagoon and; São Gonçalo

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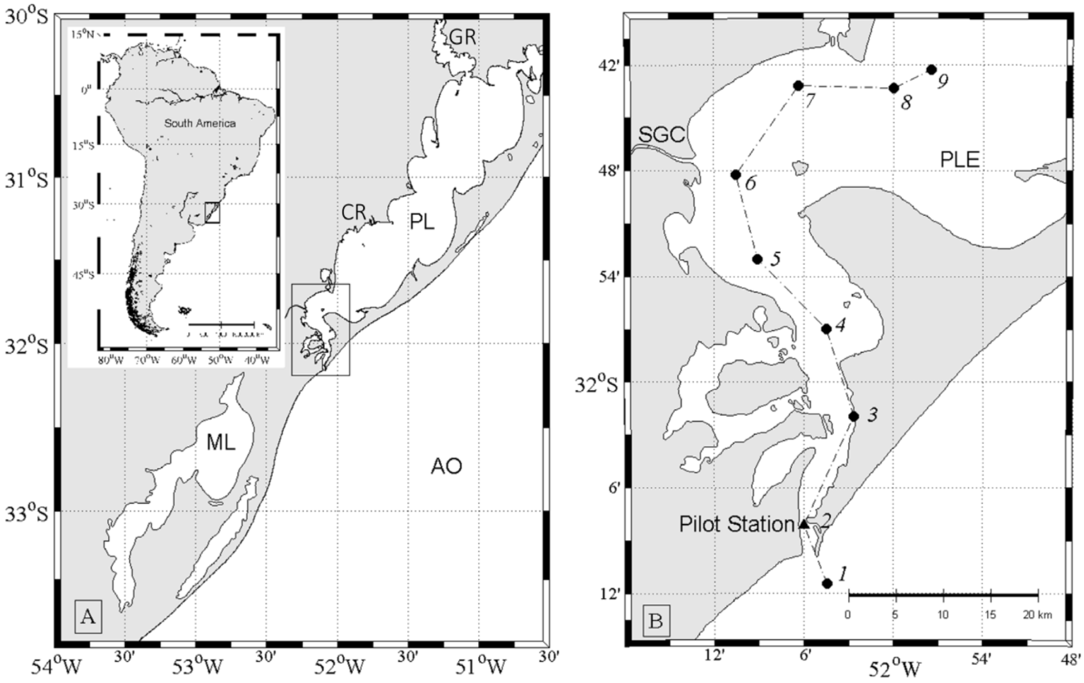

Fig. 1. Study area in southern Brazil, South America. (A) A general view of Patos (PL) and Mirim (ML) lagoons, Camaquã (CR) and Guaíba River (GR). (B) The estuarine area of Patos Lagoon Estuary (PLE), the São Gonçalo Channel (SGC) and the position of the 9 sampling stations (dots) and location of mooring system (triangle).

Channel (SGC, Fig. 1B) that drains the hydrographical basin of Mirim Lagoon (ML, Fig. 1A). The average annual river discharge of all hydrological basin is about 2400 $m^3\ s^{-1}$.

Due to proximity of an amphidromic point for M2 Tidal constituent (Möller et al., 2007) and reduced amplitude (0.5 m), tidal circulation is mostly weak in the PLE. Hydrodynamics is majorly controlled by the river discharge and wind and, according to Möller et al. (2001), the PLE is a system dominated by the freshwater runoff. At low and moderate discharges ($Q < 2400\ m^3\ s^{-1}$), mainly observed during summer and autumn, the combination of remote and local effects of wind cause inflow (winds SW) and outflow (NE winds), respectively. Significant saltwater intrusions are typically associated with the passage of atmospheric fronts lasting from 3 to 15 days. Strong southerly winds can persist for 2–4 days, retaining the water in PLE with increasing retention time consequently (Odebrecht et al., 2015). However, when discharge is high ($Q > 2400\ m^3\ s^{-1}$), in winter and spring, SW wind effect is reduced and inflow currents are only observed during events of very strong winds. In spring, seawater flow is enhanced by NE winds. Large interannual variability associated with ENSO events are also observed (Barros et al., 2002; Möller and Fernandes, 2010). Long periods of drought (La Niña events), leads to intense salinization that occasionally, can reach 150 km inside the lagoon (Möller and Castaing, 1999; Odebrecht et al., 2005). Moreover, during El Niño the lagoon can remain fresh for several months, usually in spring and part of summer (Fernandes et al., 1998).

Chlorophyll *a* (chl-*a*) variations in this environment at short time scales (24 h) have been related to effects of hydrologic and meteorological factors (Abreu et al., 2010). Considering the shallow water areas of PLE, Fujita and Odebrecht (2007) conducted a study that demonstrated that high-frequency variations in water circulation (out - inflows) controlled by wind, is in the same framework of cell division rates (1–2 days), being of great importance in phytoplankton ecology. Regarding larger time scales (annual), studies in PLE showed a clear seasonal pattern of this pigment, with higher concentrations between September and February (spring and summer), as a result of the periodic larger input of nitrogenous nutrients in the water column (Bergesch, 1990; Abreu et al., 2010). Other studies related to seasonal and interannual cycles (Abreu et al., 1994a; Persich et al., 1996; Bergesch and Odebrecht, 1997; Odebrecht et al., 2005) indicated the importance of rainfall in watershed of PL for accumulating phytoplankton biomass. According to Abreu et al. (2010), hydrology influenced variations in phytoplankton biomass, which is mostly affected by meteorological factors such as wind, precipitation and evaporation. Odebrecht et al. (2015) suggests the occurrence of phytoplankton blooms by the increase in water retention time in PLE. Although authors have statistically demonstrated the relationship between the increase in estuarine water retention time (salinity variation used as a proxy) and the occurrence of high values of chl-*a*, the mechanisms responsible for this are not completely elucidated.

The main objective of this study is to verify the residence time hypothesis using the same fluorescence data used in Odebrecht et al. (2015), with additional information from hydrodynamic/hydrologic data. In addition, the determination of biomass accumulation mechanisms was also sought, with data collected through cruises carried out during 2012.

2. Materials and methods

2.1. Time series data

Hourly data obtained from March 2010 to August 2011 was recorded by a moored system placed in the geographical position indicated by triangle in Fig. 1B. The time series consisted of: (a) wind velocity and direction, recorded by Rio Grande Pilot Station through an automatic wind gauge; (b) vertical profiles of current velocity measured by a SONTEK Acoustic Doppler Current Profiler (ADCP, 1.5 MHz) positioned near the center of entrance channel in front of Pilot Station at depth of 15 m; (c) salinity and temperature were recorded by two SBE 37 SM thermo-conductivimeters, one near the surface (1,5 m) and other near the bottom (10 m); (d) fluorescence from a Turner Cyclops fluorometer, equipped with salinity and temperature sensors, installed at 5 m depth. The instruments listed in items “c” and “d” were part of the same mooring, placed at the pier of the Rio Grande Naval Station (ENRG/MB). The distance between the ADCP, the wind station and the mooring was approximately 200 m. Additional data of river discharge from the main tributaries of PL was downloaded from the webpage of the Brazilian National Waters Agency (ANA, www.ana.gov.br) No exists river flow data for the SGC that connects Patos and Mirim lagoons. Wind and current velocity vectors were decomposed into along shelf and along channel components (Miranda et al., 2002), and filtered with a low-pass Lanczos-Cosine filter (Thompson, 1983), to remove high frequency.

In order to convert the voltage data recorded by the fluorometer in chl-*a*, 28 water samples were collected during maintenance visits and compared with fluorescence readings. The water samples were filtered (Whatman GF/F Ø47 mm), and chl-*a* was extracted in the dark and cold (−12 °C) using 90% v/v acetone, and its concentration was determined fluorometrically using a Turner TD-700 Fluorometer. The fluorescence data measurements were translated into chl-*a* concentration using a linear regression estimated from simultaneous observations of fluorescence and chl-*a*, with determination coefficient (r^2) calculated equal 0.48.

2.2. Cruise data

In order to analyze the longitudinal distribution of chl-*a* and environmental variables, 8 cruises, with 9 stations each (Fig. 1B, dots), were carried out from January to October of 2012 in the estuarine area. Each cruise consisted of samplings and measurements obtained at same positions in two consecutive days, like described in Ávila et al. (2014). Data consisted of: (a) vertical profiles of salinity and temperature measured with a SBE 37IS CTD; (b) current velocity and direction obtained by a (another) SONTEK ADCP, 1.5 MHz, with Bottom Tracking; (c) water samples collected by Niskin bottles in surface, middle and near bottom to determine chl-*a* concentrations; (d) Secchi disk depth. Water samples were filtering on board, sun exposition was avoided and filters were immediately frozen. Chl-*a* measurements were performed in laboratory using same procedures for moored fluorometer. Station positions were set with a Garmin GPS coupled with the ADCP.

3. Results

3.1. Temporal variability of chlorophyll a

Fig. 2 presents the main time series (hourly recorded) used in this analysis. Fluorescence and salinity (Fig. 2a–b), both 5 m depth, gaps along time series were caused by technical problems. From April 2011 onwards there were many gaps along time, thus, it was decided not to present this gaps in the figure. Therefore, only continuous data set (marked by dashed boxes) were analyzed together with longitudinal current velocity vertically integrated (Fig. 2c) and the wind component parallel to the coastline (not shown) covering two periods of 2010: April–June (austral autumn) and October–December (austral spring).

For period ranging from April–June 2010 (Fig. 3), a correlation between along shelf winds and depth-averaged currents (Fig. 3a), both tidally filtered, is observed with a determination coefficient of 0.6. SW winds (positive values) caused landward flow and NE winds (negative) caused the opposite situation. Salinity follows the velocity variation (Fig. 3b), with $r^2 = 0.5$. No significant correlation was found between current and chl-*a* (Fig. 3c), and salinity and chl-*a* (Fig. 3d). However, some peaks of this pigment followed those of salinity (Fig. 3d) and two distinct type of peaks can be depicted:

1. Coincident chl-*a* and salinity peaks with no lag (marked by the gray arrows in Fig. 3d).
2. Chl-*a* peak occurring during seaward flows and decrease in salinity (black arrows, Fig. 3d).

A similar pattern and correlation coefficients for time series recorded in autumn (Fig. 3a–d), was observed on spring 2010 (Fig. 4a–d).

3.2. Flushing time and chlorophyll a concentration

The results presented in the previous section suggests that most of peaks of chl-*a* are derived from wind generated fluxes. The question that arises is about the intensity and duration of these features. Are they, in any sense tied with residence or flushing time? It is important to mention that the definition of residence or flushing time takes into account the ratio between estuarine volume and freshwater input. Increased freshwater discharge will decrease flushing time. Using this argument, a single plot (Fig. 5) of chl-*a* concentration obtained by the moored fluorometer was compared with the freshwater discharge from principal's tributaries (GR and CR, Fig. 1) of PL. In general, it can be noticed that as freshwater increases the concentration of chl-*a* decreases. It becomes more important for river flows above 2400 $m^3\ s^{-1}$, the mean annual river discharge (Vaz et al., 2006), when the points become more aligned with the discharge curve. For lower freshwater input there is a large scatter of chl-*a* concentration points indicating that for lower river inputs, chl-*a* concentration will depend on the residence time provided by combination of river discharge and wind effects. In this case, the dispersion of chl-*a* concentration is large and varies from 3 to 30 mg m^{-3}.

Then, it is possible to separate the wind and river discharge effects. River discharge values above 2400 $m^3\ s^{-1}$ dominate hydrodynamics forcing seaward flows and reduce the flushing time. In this conditions the most of these microalgae are exported to coastal zone. On the other hand, for lower freshwater discharge values (Fig. 5, dashed box) the dispersion of points is an indication that flushing time will vary according to wind stress.

3.3. Spatial variability of chlorophyll-a

Fig. 6 represents the most observed conditions during the cruises: a salt wedge estuary (Fig. 6a) with chl-*a* concentration increasing towards the bottom (Fig. 6b), which suggests the resuspension of benthic algae occurring in seaward portion of the estuary. The type 2 peak mentioned in the time series appeared in two different occasions. The first was observed on May 23 and 24, 2012, as shown in Figs. 6 and 7, where the landward flow was induced by southwesterly winds (SW). In Fig. 6, apart from the maximum due to resuspension near the entrance (stations 1 and 2) a second chl-*a* peak appears near station 6 and is clearly associated to stratification in the inner tip of salt wedge. A two-layer current profile was observed along most of the entire longitudinal section (Fig. 6c). Secchi disk depth was about 2 m in practically all stations, except in 6, where it reached 2.5 m (SGC). Similar conditions were observed during another cruise carried out in July 10th.

As the landward flow continued on the second day of the cruise (Fig. 7c), saltwater was displaced to the inner portions of the estuary (Fig. 7a). However, as stratification persisted the chl-*a* concentration increased (Fig. 7b) both in concentration and in attained area. At station 7 Secchi disk reached 3 m.

The second situation where this maximum chl-*a* is observed is due to vertical stratification, but in this case, caused by freshwater input from the SGC, which can be seen in Fig. 8 on the cruise carried out in October 4. A salt wedge was observed at the estuary entrance with no chl-*a* resuspension (Fig. 8a, b). Fig. 8b also

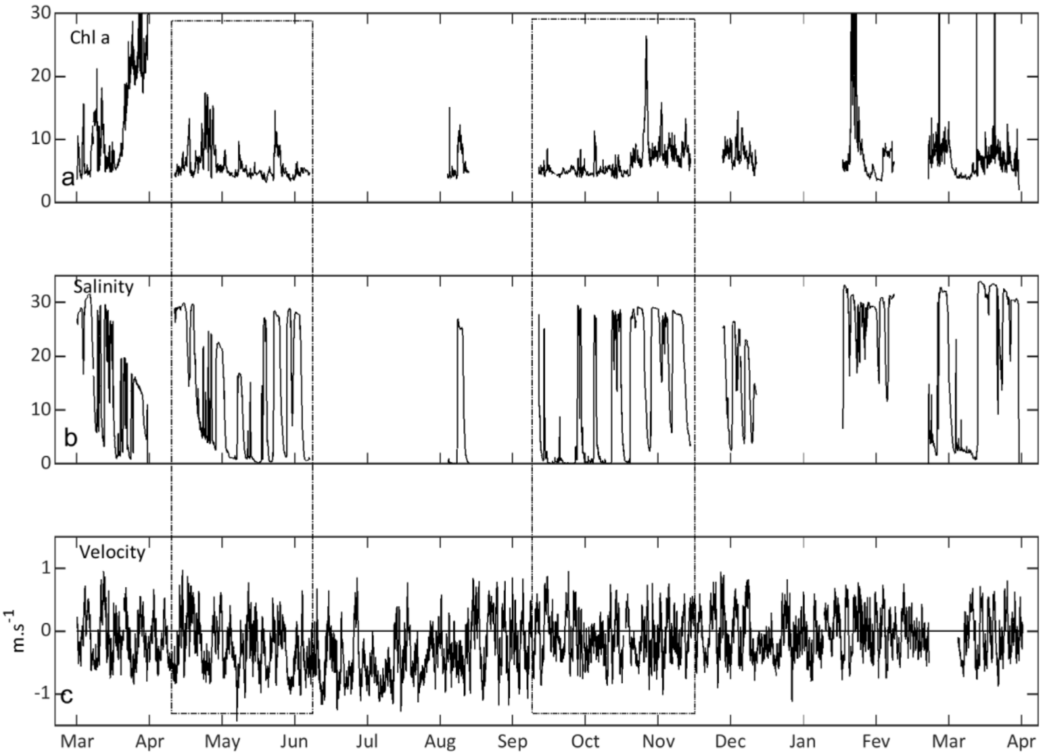

Fig. 2. Time series of (a) Chlorophyll *a* (mg m^{-3}); (b) Salinity and (c) depth-integrated current velocity where negative values indicate outflow. The dashed boxes are the periods chosen for analysis from April–June (autumn), October–November (spring) of 2010.

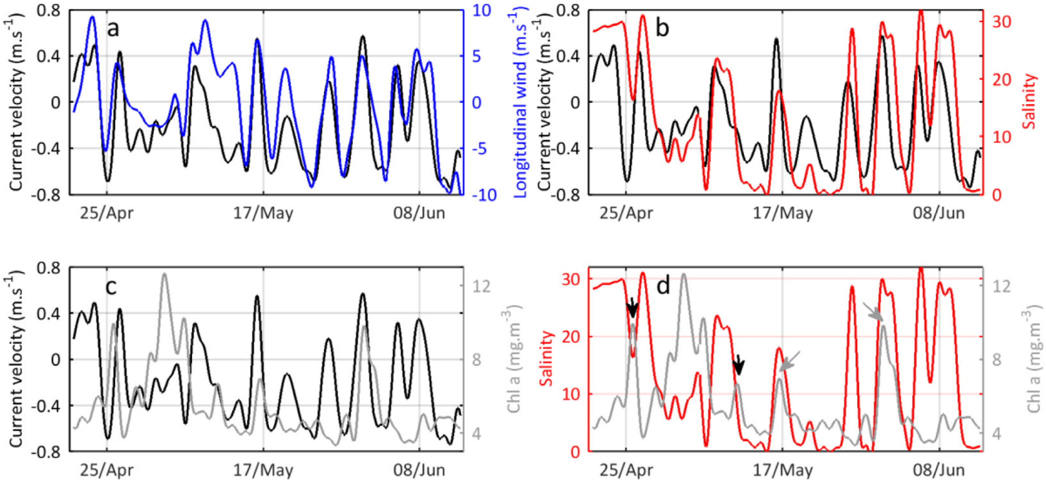

Fig. 3. Time series from April–June 2010. (a) Along shelf wind (blue, negative values indicate NE winds) and along channel current (black, negative values indicate seaward flows); (b) Along channel current (black) and salinity (red); (c) along channel current (black) and chl-*a* (gray); (d) Salinity (red) and chl-*a* (gray line). Gray and black arrows represents chl-*a* peaks types 1 and 2, respectively. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shows a very strong peak (>8.0 mg m^{-3}) of chl-*a* concentration registered around station 6, near the mouth of SGC. This is related to vertical salinity stratification yielded by the freshwater input in this location. During the following day, the structure was no more observed (Fig. 9), because strong winds and seaward fluxes may have dispersed it. The same pattern with the maximum chl-*a* at the same place was observed during the cruise carried out in August 31 (not shown). The maximum surface values of chl-*a* observed during the cruises of May and October when displaced seaward can account for type 2 peak observed in time series. Both of them are formed in areas of low salinity as those registered by the moored fluorometer.

4. Discussion

As a very large chocked coastal water body that presents an exponential reduction of cross sectional area towards the entrance, the PL has its circulation mainly driven by local and remote winds and freshwater discharge (Möller et al., 2001). The reduction of cross sectional area plays an important role by filtering tidal effects (Möller et al., 2007) and enhancing landward and seaward flows. During the seasonal flood period or in El Niño years, this type of morphology can contribute to form a hydraulic barrier that avoids the entrance of shrimp larvae affecting the fisheries of this species in the following year (Möller et al., 2009).

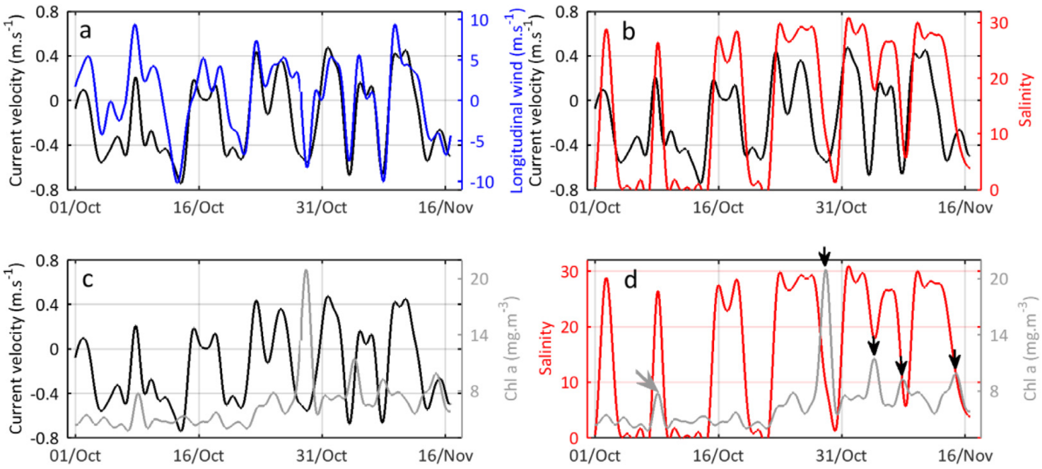

Fig. 4. Time series from period October–November 2010. (a) Along shelf wind (blue, negative values indicate NE winds) and along channel current (black, negative values indicate seaward flows); (b) Along channel current (black) and salinity (red); (c) along channel current (black) and chl-*a* (gray); (d) Salinity (red) and chl-*a* (gray). Gray and black arrows represents chl-*a* peaks types 1 and 2, respectively. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

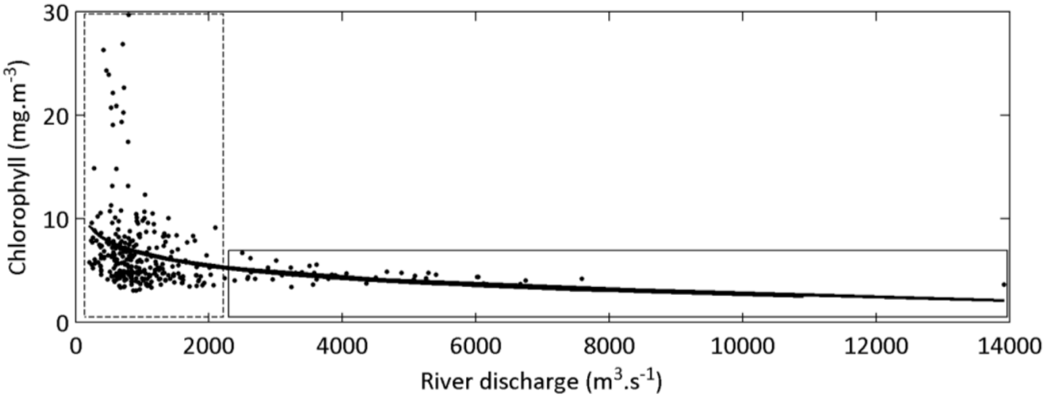

Fig. 5. Daily river discharge (principal tributaries) and daily average concentration of chl-*a*, for the analyzed period of mooring data. Dashed box represents river discharge values below 2400 m^3 s^{-1} and solid box represents values above 2400 m^3 s^{-1}.

In this type of situation, nutrients and biological compounds are rapidly flushed out of the lagoon and can contribute to enrich the coastal zone (Ciotti et al., 1995).

Several studies that describe the dynamics of the phytoplankton in the PLE have identified that factors such light (Abreu et al., 1994a), nitrogen nutrients (Proença et al., 1994; Bergesch and Odebrecht, 1997) and zooplankton predation (Abreu et al., 1994b) are determinant in the phytoplankton variability in this ecosystem. However, the influence of winds, rainfall and evaporation on estuarine hydrology, are also extremely important factors controlling the short- and large-scale time scale of phytoplankton variability in the PLE (Fujita and Odebrecht, 2007; Abreu et al., 2010). By analyzing a time series of continuous fluorescence measurements using statistical methods, Odebrecht et al. (2015) observed a significant increase of chl-*a* relative to linear mixing especially in brackish water outflow. Moreover, the authors observed that the level of chl-*a* was proportional to the duration of previous coastal water inflow, corroborating the hypothesis that higher water residence time leads to the accumulation of phytoplankton biomass. Although the authors have demonstrated the effect of increasing residence time on generation of phytoplankton blooms, the mechanisms that generate high microalgae biomass were not thoroughly described.

In the present study, it was demonstrated that fresh and saltwater flows play a very important role in the chl-*a* concentration variability in the PLE. It not only alters the residence time, which affects the chl-*a* concentration, but also yields vertical stratification through the lateral freshwater input from the SGC. This process causes a water column stabilization that keep phytoplankton cells within the euphotic layer in this light limiting environment, favoring an increase in the concentration of chl-*a*.

Regarding the residence time, the results agree with those of Odebrecht et al. (2015), but also bring a more detailed insight about the related processes. However, it was observed that for river flows above 2400 m^3 s^{-1} (SGC flow is not considered) the concentration decreases rapidly as the flow increases. It indicates that all these organisms are being flushed out to the coastal zone and biogeochemical processes will take place there. A similar scenario was described by Lane et al. (2007) for the Mississippi River estuary, where high river discharge reduce residence time by carrying phytoplankton biomass off the estuary. For lower freshwater discharge values, i.e. low flushing times the phytoplankton biomass is distributed in an interval ranging from 3 to 30 mg m^{-3}. The flushing time is reduced as river runoff increases, but the large dispersion of phytoplankton concentration indicate that other processes are interfering in the flushing time, such as the duration and intensity of winds before and after passage of meteorological front.

The landward saltwater input due to SW winds cause two effects: (a) resuspension of phytoplankton in the entrance channel, that may have important consequences for the environment

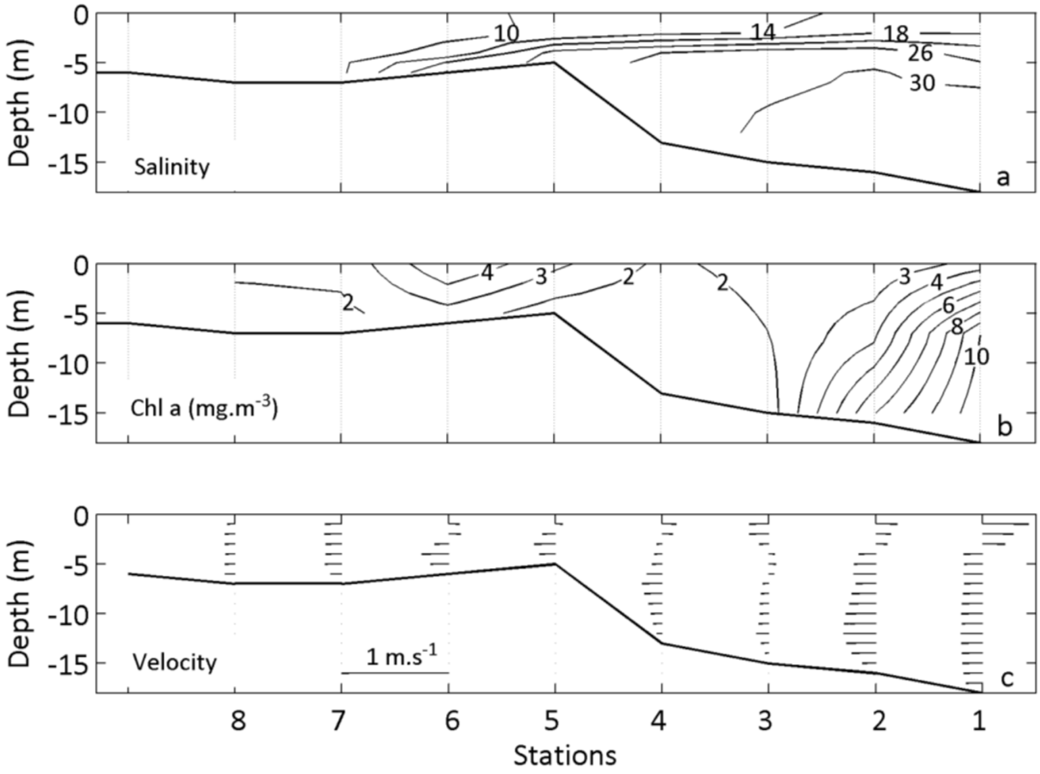

Fig. 6. Longitudinal distribution of: (a) salinity; (b) chl-*a* concentration and (c) current velocity for the May 23, 2012 cruise.

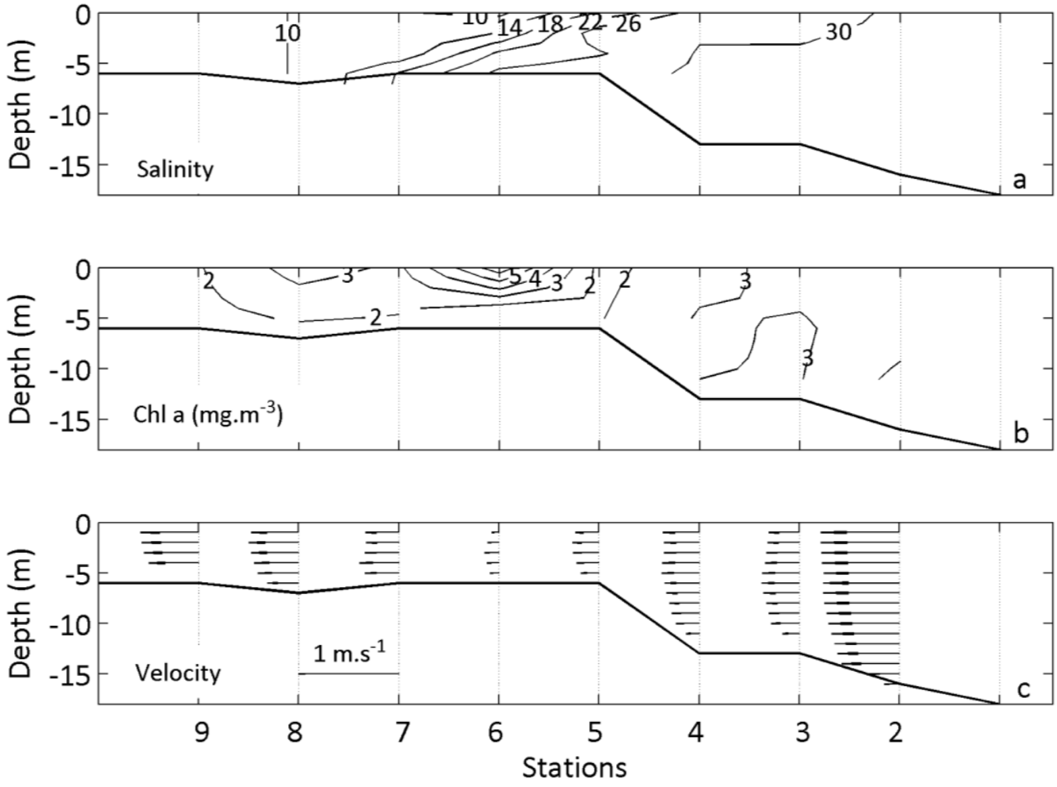

Fig. 7. Longitudinal distribution of: (a) salinity; (b) chl-*a* concentration and (c) current velocity for the May 24, 2012 cruise.

as observed for Formosa lagoon (Brito et al., 2012) but still undetermined for the estuarine area of Patos Lagoon ecosystem; (b) shallow vertical stratification in the water column provided at the tip of the salt wedge that keeps phytoplankton within the euphotic zone. The first observed pattern (type 1) was the generation of peaks that occurs simultaneously to increase in salinity (Figs. 3d and 4d, gray arrows). Some studies suggested that resuspension mechanism of benthic microalgae in channel

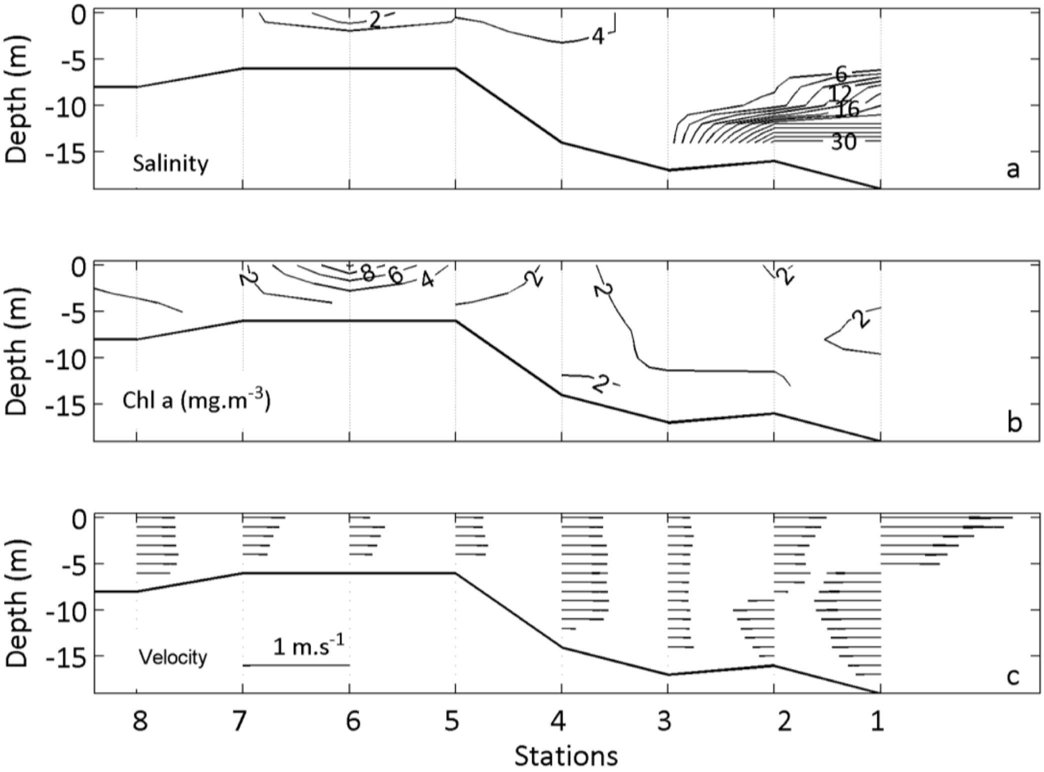

Fig. 8. Longitudinal distribution of: (a) salinity; (b) chl-*a* concentration and (c) current velocity for the October 4, 2012 cruise.

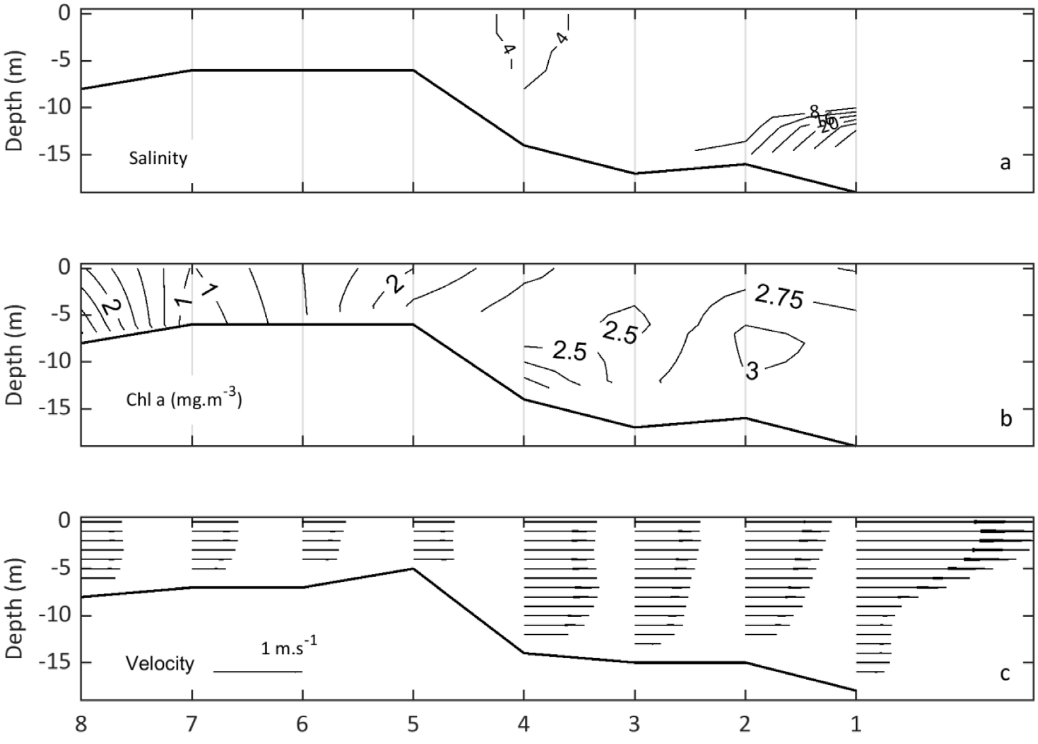

Fig. 9. Longitudinal distribution of: (a) salinity; (b) chl-*a* concentration and (c) current velocity for the October 5, 2012 cruise.

area is responsible for high levels of chl-*a* (Abreu et al., 1995, 2010). The observed increase of chl-*a* towards the bottom (see Fig. 6b for reference) was observed in some cruises, confirming the hypothesis of benthic microalgae resuspension. The resuspension is usually caused by action of waves, as in the case of the tidal flats of the Ems-Dollard estuary (De Jonge and van Beusekon, 1995; Lucas, 2003). In Caeté estuary (Amazonian, Brazil), the strong local tidal currents and shallow depths of the estuary were responsible by the re-suspension of sediments and the appearance of benthic species the microphytoplankton community (Matos et al., 2011). Tidal movements, wind action and coastal marine currents were suggested as factors that conditioned the dynamics of some microalgae populations, considered very frequent and abundant in a coastal area close to Canela Island (North of Brazil) (Sousa et al., 2008). However, in case of the deep entrance channel of PL (16 m depth), this process will be forced by the strength of wind-generated currents and also on the amount of available fluid mud containing the microscopic algae deposited during the previous slack conditions, or benthic species that reside in this environment. The other pattern of maximum chl-*a* (type 2) occurs during outflow and is associated to decreased in salinity. The results obtained in cruises in October 4 and 5 showed the stratification/de-stratification conditions in station 6 near SGC (Fig. 8), where a plume of low salinity and high concentration of chl-*a* was found, which maintain the organisms in the most enlightened layer. On next day, this high biomass was dissipated, following the outflow, being advected toward the channel area. This result shows a second component in temporal and spatial variation of chl-*a* concentration. In all cases in which this maximum chl-*a* was observed, it was associated with a vertical stratification of salinity. It is important to note that the SGC can also input high concentrations of nutrients and suspended particulate matter in the PLE (Fia et al., 2009; Hartmann and Harcot, 1990), which may make this area light-reduced. It should be noted that, the PLE is not a nutrient-limited environment, as described in previous works (Almeida et al., 1993; Niencheski and Windom, 1994; Abreu et al., 1995; Seeliger and Odebrecht, 2010).

The stratification/de-stratification of water column is likely to be the main mechanism of phytoplankton bloom leading to the accumulation of high biomass due to the increment of water residence time. However, this mechanism is highly dependent on the wind magnitude. Thus, Southern winds lead to the input of coastal water, increase the water residence time and favor the water column stabilization. On the other hand, an increase in speed of Southern winds could destabilize the water column though vertical mixing. The stabilization of water column is likely to be the main mechanism of phytoplankton bloom in this light limited environment even in this very shallow ecosystem (Odebrecht et al., 2005). It leads to the accumulation of high biomass due to the increment of water residence time in the euphotic zone. Tremblay et al. (1997) found similar results for the lower Saint Lawrence estuary. However, strong winds can rapidly disintegrated phytoplankton patches, decreasing the mean chl-*a* in the water column.

5. Conclusions

The influence of hydrodynamics over the space–time variability of chl-*a* peaks in the PLE was determined. Two patterns of maximum chl-*a* concentration were depicted. One maximum occurs simultaneously to increase in salinity and suggests that resuspension due to strong inflow currents and benthic microalgae in channel area is responsible for this high levels of chl-*a*. The other maximum shows an increase in chl-*a* after seaward flows when salinity starts to decrease. It is associated with a vertical stratification/de-stratification of salinity and is likely to be the main mechanism of phytoplankton bloom leading to accumulation of high biomass due to the increment of water residence time. The water column stabilization occurs by introduction of freshwater derived from the only tributary that drain directly in this region and by a stratification in the inner tip of salt wedge. Our next step is to improve our findings related to residence and flushing times and the effect of vertical stability on phytoplankton size variability and distribution.

CRediT authorship contribution statement

Mauro Michelena Andrade: Planning and execution of the field trips, Discussion of the results, Writing of this article. **Paulo Cesar Abreu:** Planning and execution of the field trips, Discussion of the results, Writing of this article. **Rafael André Ávila:** Planning and execution of the field trips, Discussion of the results, Writing of this article. **Osmar Olinto Möller Junior:** Planning and execution of the field trips, Discussion of the results, Writing of this article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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