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Particulate suspended matter concentrations in the Bahía Blanca Estuary, Argentina: Implication for the development of phytoplankton blooms

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ABSTRACT

The inner zone of the Bahía Blanca Estuary is shallow, nutrient-rich and turbid. Tidal energy and water turbulence strongly affect the water column resulting in a well-mixed structure and high concentrations of suspended sediment. The phytoplankton community is mostly dominated by diatoms and the annual pattern has been characterized by a recurrent winter-early spring bloom. Here, we investigated to what extent the temporal variations of suspended particulate matter (SPM) regulate the phytoplankton blooms in the head of the estuary by light-limitation. Sampling was done on a fortnightly basis (weekly during the blooming season) at a fixed station in the inner zone of the estuary from January 2007 to February 2008. SPM concentrations and light extinction coefficients (k) in the water column were significantly correlated and showed relatively lower values during the phytoplankton maximal biomass levels. During winter, SPM and k reached values of 23.6 mg l⁻¹ and 0.17 m⁻¹ which were significantly lower than the annual means of 77.6 mg l⁻¹ and 2.94 m⁻¹, respectively. The particulate organic matter (POM) concentration was significantly correlated with the calculated phytoplankton biomass although the contribution of the latter to the total POM was rather low. Both, POM and biomass, had maximal values during winter (21.8 mg l⁻¹ and 393.5 μ g C l⁻¹) and mid summer (24.3 mg l⁻¹ and 407.0 μ g C l⁻¹), with cell densities up to 8×10^6 cells l⁻¹ and chlorophyll *a* up to 24.6 µg l⁻¹. Our results suggest that the decrease of SPM concentrations in the water column with a concomitant increase in the penetration of solar radiation seems to be one of the main causes for the development of the phytoplankton winter bloom in the Bahía Blanca Estuary.

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1. Introduction

In estuaries, sediments and seston are suspended in the water column either permanently or temporarily in a state of exchange with the bed sediment reservoir and the intertidal flats (de Jonge, 1995; de Jonge and van Beusekom, 1995). The origin of suspended matter and associated organic material in coastal environments could come from both internal and external sources (de Jonge, 2000). The former comprise autochthonous primary production of pelagic and benthic algae, erosion and sedimentation of channel beds, intertidal flats and salt marshes. In the latter, the particulate matter derives from freshwater runoff, water mass intrusion from the open sea and accumulation of mud from the coast (Postma, 1967; Hemminga et al., 1993; Velegrakis et al., 1997). The combination of shallow waters, strong

tidal currents and winds creates a complex pattern of suspended matter transport, deposition and resuspension dynamics as described in detail for the Ems estuary by de Jonge (1995) and de Jonge and van Beusekom (1995) and generalised in the diagrams of de Jonge (2000). The organic matter supply to estuaries is attributed to different sources such as microbial production (phytoplankton, bacteria and fauna), river discharge, domestic/industrial inputs, intertidal flats and salt marshes and their contribution differs among coastal systems (Hemminga et al., 1993; Goosen et al., 1999; Sobczak et al., 2002; Adolf et al., 2006). Estuarine phytoplankton development is often considered to be regulated by either light or nutrients, although both resources interact (Tilman, 1982; Grover, 1997; Huisman and Weissing, 1999, 2001; Roelke et al., 2003; Litchman et al., 2007). In shallow, turbid estuaries with elevated nutrients levels, the light availability is a key factor regulating the phytoplankton dynamics (Cloern et al., 1985; Cloern, 1987, 1996; Alpine and Cloern, 1988; Grobbelaar, 1990; Kocum et al., 2002). Suspended matter reduces the irradiance penetration in the water column. Turbidity thus directly affects the phytoplankton growth by modifying the light conditions (Colijn,

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1982). Because of variations in wind speed, diurnal tides and river flow, water turbidity vary throughout the year generating variable light exposures which consequently modify the timing of phytoplankton development. In temperate nutrient-rich and turbid estuaries, phytoplankton seasonality may be tightly controlled by fluctuations in the suspended matter concentration rather than the irradiance seasonal cycle (e.g. Kocum et al., 2002; Adolf et al., 2006). In these systems it is expected that light availability regulates not only the phytoplankton biomass maximum but also stimulates physiological adaptation to low light conditions (Falkowski and Owens, 1980; Richardson et al., 1983, 1986; Geider et al., 1997).

The inner zone of the Bahía Blanca Estuary is characterized by high turbidity with fine suspended sediments (i.e. silt and clay) and it has been regarded as eutrophic (Freije and Marcovecchio, 2004; Perillo et al., 2004; Popovich and Marcovecchio, 2008). The shallow and well-mixed water column is strongly influenced by tides and winds, and to a lesser extent by river inflow (Perillo and Piccolo, 1991). The phytoplankton has shown a marked recurrent pattern with a single winter-early spring diatom bloom (Gayoso, 1998, 1999; Popovich et al., 2008a,b), and the initiation of the bloom has been attributed to both high nutrients concentrations and a relaxation in grazing pressure due to the low water temperature (Pettigrosso et al., 1997; Popovich and Gayoso, 1999; Popovich and Marcovecchio, 2008; Popovich et al., 2008a). In addition, although light-limitation due to high water turbidity may represent a key factor for the winter bloom inception, so far simultaneous measurements of turbidity, light and phytoplankton dynamics have not been considered. The aim of this study was to determine the influence of turbidity as a function of suspended particulate matter (SPM) concentration on the phytoplankton seasonal pattern in the inner zone of the Bahía Blanca Estuary. We tested the hypothesis that light-limitation due to seston load is one of the main regulating factors of the development of the winter bloom. Although the phytoplankton cells may interact with the SPM (e.g. adhesion, aggregation, sedimentation; e.g. Kiørboe et al., 1990; Zimmermann, 1997) in this study we only considered the ecological role of SPM by: (1) determining the environmental factors responsible for the seasonal variability of the SPM and its influence on the light availability in the water column; (2) determining the amount of the suspended particulate organic matter (POM); (3) describing the phytoplankton annual pattern based on cells abundance, chlorophyll *a* concentration, species composition and biomass; and (4) identifying the potential relationships between the phytoplankton dynamics and the SPM concentration over an annual cycle.

1.1. Study area

Bahía Blanca is a shallow, mesotidal coastal plain estuary (38°45′ S: 62°22′ W) in the southwest of the Buenos Aires Province. Argentina (Fig. 1). For the last decades the estuary has undergone intense human-induced disturbances related to increased urban and industrial developments in the area (e.g. ships traffic, dredging and waste loads) (Freije and Marcovecchio, 2004). This temperate estuary extends over about 2300 km² and is formed by several tidal channels, islands, extensive tidal flats and marshes. The main channel, Canal Principal, has a total length of 60 km and varies in width from about 3–4 km at the mouth (22 m depth) to 200 m at the head (3 m depth). The channel has a funnel shape and is orientated in an NW-SE direction. The propagation of the tidal wave is affected by the geometry of the tidal channels resulting in a hypersynchronous estuary (Perillo and Piccolo, 1991). The mean tidal range increases from 2.2 m at the mouth to 4 m at the head. Two freshwater tributaries enter the estuary from the northern shore, the Sauce Chico River and the Napostá Grande Creek, with a mean annual runoff of 1.9 and 0.8 $m^3\,s^{-1}$, respectively. Freshwater inflow from other, smaller tributaries into the estuary is intermittent and only significant during periods of high local precipitation (Perillo and Piccolo, 1991). Puerto Cuatreros station, the fixed sampling site, is representative of the inner part of the estuary (Fig. 1). It is relatively shallow (mean depth of 7 m), well mixed and the mean tidal range is 3.6 m. The dominant winds are from NNW and generate local waves (Cuadrado et al., 2005). The salinity is rather high (17.3–41.9) and depends on tides, precipitation, runoff and evaporation (Freije and Marcovecchio, 2004).

2. Materials and methods

2.1. Field methods

Sampling was carried out in Puerto Cuatreros station during the period January 2007 to February 2008. The sampling frequency was fortnightly throughout the year and weekly during the winter bloom. Water sample collection and in situ measurements were taken from a pier at high tide. The in situ measurements consisted of surface water turbidity and dissolved oxygen and vertical profiles of temperature and conductivity (thereafter the conductivity was transformed into salinity and expressed in Practical Salinity Units, PSU) employing a digital multi-sensor Horiba U-10. Surface water samples were collected with a van Dorn bottle (2.5 l) to assess SPM and POM concentrations and phytoplankton abundance. The samples for the quantitative phytoplankton analysis were preserved with a few drops of acidified Lugol's solution. For species identification, samples were taken with a Nansen net (30 µm mesh) and fixed with a formaldehyde solution (final concentration: 0.4%). Vertical profiles of photosynthetically active radiation (PAR, μ E m⁻² s⁻¹) were obtained by measuring PAR at 10 cm intervals over the water column using a radiometer LI-COR model LI-192SB 2 π . Wind and precipitation were obtained from a meteorological station located in the sampling site.

2.2. Phytoplankton analysis

Chlorophyll *a* (chl *a*, μ g l⁻¹) was measured spectrophotometrically using the methods described in APHA (1998). Phytoplankton species identification was done using a Zeiss Standard R microscope and a Nikon Eclipse microscope with ×1000 magnification and phase contrast. Phytoplankton > 3 μ m was counted with a Sedgwick–Rafter chamber (1 ml) which was a suitable volume according to the amount of suspended solids. The entire chamber was examined at ×200 and each algal cell was counted as a unit according to McAlice (1971). The cell volumes were calculated assigning simple geometric shapes to the species (Hillebrand et al., 1999) and converted into carbon content (μ g Cl⁻¹) according to Menden-Deuer and Lessard (2000). Thereafter, the carbon/chlorophyll *a* ratios (C/chl *a*) were calculated.

2.3. SPM and POM determinations

SPM and POM (both in mg l⁻¹) were determined gravimetrically filtering 300–500 ml of water on pre-combusted and weighed GF/F filters (pore diameter = 0.7 μ m). Filters were then dried at 60 °C for 24 h and weighed for SPM estimation. Afterwards, they were combusted at 500 °C for 30 min and weighed again for POM determination as the difference between both weight values (Calliari et al., 2005). POM values were used to quantify the % organic matter in the SPM. The ratio between phytoplankton biomass (mg Cl⁻¹) and POM (mg l⁻¹) was determined to quantify the phytoplankton carbon percentage of the POM. It is worth noting that such comparison underestimate phytoplankton contribution



Fig. 1. Map of the inner area of the Bahía Blanca Estuary showing the location of Puerto Cuatreros station.

to POM since probably only 40–50% of phytoplankton dry weight may be made up of carbon.

2.4. Light availability

From vertical PAR profiles, light extinction coefficient (k, m^{-1}) in the water column was calculated considering that light was exponentially attenuated with depth. Besides, the mean light intensity in the mixed layer I_m was calculated with the equation (Riley, 1957): $I_m = I_0(1 - e^{(-kZ_m)}) (kZ_m)^{-1}$, where $I_0(\mu E m^{-2} s^{-1})$ is the light intensity received at the water surface and Z_m is the mixed zone (m) determined from the vertical profiles of water salinity and temperature. The depth of the euphotic zone (Z_{eu} , m) was estimated as the depth at which irradiance is 1% of the surface value, (i.e. $Z_{eu} = 4.6 k^{-1}$). Thereafter, we estimated the Z_{eu} to Z_m ratios (Z_{eu}/Z_m).

2.5. Statistical analysis

As the variables considered did not achieve the parametric assumptions, non-parametric tests were performed. Mann–Whitney tests were employed to compare SPM, turbidity and k values in winter with the rest of the year. Spearman correlations (r_S) were calculated among SPM, POM, *k* and phytoplankton biomass. Coefficients of variation (CV) were estimated to describe the temporal variability of different parameters. Principal components analysis (PCA) was conducted to examine the correlation among variables and their association with the sampling dates. We used the following data as inputs in the PCA: chl *a* (chlorophyll *a* concentrations, $\mu g l^{-1}$), BIOM (phytoplankton biomass, $\mu g C l^{-1}$) ABUND (phytoplankton abundance, cells l^{-1}), SPM and POM ($mg l^{-1}$), TURB (water turbidity, ntu), *k* (m^{-1}) and Z_{eu}/Z_m . The first two Principal Components (PC 1 and PC 2) were retained as they explained a meaningful part of the total variation according to

Kaiser–Guttman criterion (Legendre and Legendre, 1998). All the plotted variables present a percentage of reconstruction over 50% in the two-dimensional plot.

3. Results

3.1. Hydrography

Vertical profiles of salinity and temperature did not indicate stratification. Over the year the surface temperature varied between 4.6 and 24.2 °C (Fig. 2a) with a coefficient of variation (CV) of 43%. The mean temperature value in winter was 6.9 °C and in summer 21.8 °C. The annual variation in surface salinity was relatively small, CV = 10% and around a mean value of 32.7 (Fig. 2a). Dissolved oxygen (Fig. 2b) fluctuated between 4.2 and 12.1 mg l⁻¹ over the study period reaching maximal values in winter. The seasonal oxygen saturation varied from 53% to 150%. Turbidity was very variable, CV = 56%, fluctuating between 3 and 181 ntu (nephelometric turbidity units) with a mean value of 77 ntu (Fig. 2b). In winter there was a marked reduction in water turbidity since the mean winter value (32 ntu) was significantly lower than during the rest of the year (94 ntu) (Mann–Whitney test, *p* < 0.01).

3.2. Precipitation and wind

The precipitation in the inner zone of the estuary during the sampling period was relatively low (mean value in 2007: 392 mm) as compared to the characteristic annual mean of 614 mm (Campo and Capelli de Steffens, 2000). Minimal precipitation values (Fig. 3a) were registered between June and August, whereas the maximal values occurred in spring and summer. The wind velocities were generally low (mean annual value: 11.6 km h⁻¹) and relatively constant (Fig. 3b) throughout the year (CV = 21%). The wind intensity did not follow any seasonal variation. Northern



Fig. 2. Seasonal variability of surface (a) water temperature, salinity, (b) dissolved oxygen and water turbidity (nephelometric turbidity units, ntu) at Puerto Cuatreros station from January 2007 to February 2008.



Fig. 3. (a) Weekly means of precipitation and (b) wind direction and intensity (represented by the length of the arrows) in the inner zone of the Bahía Blanca Estuary from January 2007 to February 2008. Wind direction is indicated according to the meteorological convention (i.e. the direction from which the wind is blowing).

winds dominated throughout the year. However, this regime shifted in early autumn-late winter to a dominance of south-eastern winds (Fig. 3b).

3.3. Phytoplankton

Diatoms dominated the phytoplankton community all yearround. The annual dynamics showed several peaks over the annual means of chl *a* (6.5 μ g l⁻¹), cellular abundances (964 × 10³ cells l⁻¹) and calculated biomass $(92 \ \mu g \ C \ l^{-1})$ (Fig. 4). In winter, the dynamics of the phytoplankton described distinct accumulation episodes up to 8×10^6 cells l⁻¹, 24.5 µg l⁻¹ of chl *a* concentrations and biomass up to 393 µg C l⁻¹. The dominant species were *Chae*toceros sp., C. debilis, Thalassiosira sp., T. pacifica and T. curviseriata. The phytoplankton peak in mid summer 2007 was smaller in magnitude than the one in early summer 2008 (Fig. 4), but both peaks were composed of the same dominant diatom species, Thalassiosira minima. Other abundant species were the diatoms Guinardia delicatula and Skeletonema costatum, the Xantophyceae Ophiocytium sp. and small flagellates (3–14 µm). In summer 2008 the chlorophyll a was up to 11.5 μ g l⁻¹, biomass up to 407 μ g C l⁻¹ and cell abundance up to 5×10^6 cells l⁻¹. The C/chl *a* ratios remained rather low throughout the year; the mean annual value was 15.5 (Fig. 4b).

3.4. SPM and POM

The maximal SPM concentration was in spring, up to 277 mg l⁻¹, being almost 4-fold the annual mean of 77.6 mg l⁻¹ (Fig. 5a). The SPM decreased during winter (minimal value of 23.6 mg l⁻¹) and low levels persisted during the whole season, being significantly less (Mann–Whitney test, p < 0.01) than the annual mean. The POM concentration was significantly correlated with the phytoplankton biomass ($r_{\rm S} = 0.701$, p < 0.01), reaching maximal values during



Fig. 4. Seasonal variability of (a) phytoplankton cellular abundance and chlorophyll *a* concentration and (b) biomass at Puerto Cuatreros station from January 2007 to February 2008.



Fig. 5. Seasonal variation of (a) light extinction coefficient k, suspended particulate matter SPM and particulate organic matter POM concentration and (b) POM to SPM ratios expressed in % and phytoplankton biomass at Puerto Cuatreros station from January 2007 to February 2008.

winter (21.8 mg l⁻¹) and summer (24.3 mg l⁻¹) (Fig. 5a). The POM/ SPM ratios (Fig. 5b) reached a maximum of 57% in late autumn with relatively high values in winter and in summer 2008 (mean seasonal values of 37 and 24%, respectively). The rest of the year these ratios were below 15%. The phytoplankton biomass to POM ratios (biomass/POM) were generally low over the year reaching maximal values (up to 2.7%) during maximal phytoplankton biomass episodes in winter and summer.

3.5. Light availability

The light extinction coefficient *k* showed a yearly mean of 2.94 m⁻¹ (Fig. 5a) with a maximal in spring up to 7.8 m⁻¹. As *k* was highly correlated with the SPM concentration ($r_{\rm S} = 0.731$, p < 0.01) it also decreased in winter reaching a minimum of 0.17 m⁻¹. The *k* levels in winter (mean value of $1.5 \, {\rm m}^{-1}$) were significantly lower (Mann–Whitney test, both p < 0.01) than the respective annual mean. Water column was always vertically mixed as indicated by temperature and salinity profiles; hence water column depth at high tide was considered an indicator of mixed zone depth ($Z_{\rm m}$). The $Z_{\rm eu}/Z_{\rm m}$ ratios had a mean value of 0.36, with an euphotic depth varying between 0.6 and 4 m. The mean light intensity in the mixed layer ($I_{\rm m}$) was relatively low all year-round, it fluctuated between 22.8 and 355 $\mu {\rm E} \, {\rm m}^{-2} \, {\rm s}^{-1}$.

3.6. ACP

The Principal Components Analysis (Fig. 6) revealed significant correlations (Table 1) among the variables k, SPM and water



Fig. 6. Two-dimensional plots of principal component (PC 1 and PC 2) loadings of (a) phytoplankton and turbidity variables and (b) sampling months at Puerto Cuatreros station from January 2007 to February 2008.

turbidity. This group of variables ("turbidity group") was highly correlated with the positive axis of PC 1 (Fig. 6a). On the other hand, there were significant correlations (Table 1) among the phytoplankton biomass, cellular abundance, chlorophyll a concentrations, and POM; and these variables ("phytoplankton group") were strongly correlated with the negative axis of PC 1 (Fig. 6a). Based on this, these two groups of variables were strongly negatively correlated with each other considering their distribution on PC 1. In addition, Z_{eu}/Z_m ratios were negatively correlated (Table 1) with the variables of the turbidity group. The studied months were also clearly separated along PC 1 (Fig. 6b), since on the left (negative axis) the winter months appeared whereas on the right (positive axis) the late spring-summer months were plotted. Therefore, the phytoplankton group and the Z_{eu}/Z_m were associated with the winter months while the turbidity group was related to the late spring-summer months.

Table 1

Correlation matrix of the PCA. In bold letters, significant correlation values (p < 0.05).

	TURB	ABUND	BIOM	chl a	k	$Z_{eu}:Z_m$	SPM
TURB							
ABUND	-0.528						
BIOM	-0.294	0.604					
chl a	-0.191	0.470	0.508				
k	0.766	-0.357	-0.101	-0.187			
Z _{eu} :Z _m	-0.445	0.279	-0.100	0.059	-0.584		
SPM	0.825	-0.515	-0.255	-0.185	0.683	-0.556	
POM	-0.263	0.523	0.617	0.348	-0.310	-0.091	-0.130

4. Discussion

4.1. SPM and turbidity dynamics

In coastal ecosystems, the SPM dynamics is mainly driving by river discharges (Postma, 1967), waves and winds (de Jonge and van Beusekom, 1995), tides and residence time (de Jonge, 1995; Uncles et al., 2002), and the interactions among them (de Jonge, 1992; Velegrakis et al., 1997; May et al., 2003). In the Bahía Blanca Estuary, the freshwater inflow is generally low over the year, for which the river runoff is not considered an important source of suspended matter. A similar situation has been found in other estuaries like the Ems-Dollard, Schelde or Westerschelde, Humber and Thames where turbidity depends on tidal effects and residence time more than river sediment load (Uncles et al., 2002). Although in the present study the precipitation was rather low, it showed a marked seasonal variability with minimal values in winter coinciding with the SPM diminution in the water column. This suggests that the local precipitation might be one of the factors promoting water turbidity in the Bahía Blanca Estuary probably by bed remobilization and sediment transport from the surrounding tidal flats and islands. In addition, in meso and macrotidal estuaries the high turbidity commonly results from strong winds and tidal currents which induce sediment resuspension of fine particles from the tidal flats (de Jonge and van Beusekom, 1995; May et al., 2003). In the Bahía Blanca Estuary, winds and tides have been identified as the main inputs of energy (Perillo and Piccolo, 1991; Cuadrado et al., 2005), especially in the inner zone where the tidal height is maximal. Thus, turbidity might be generated by the combination of these two factors which promote strong internal sedimentation and erosion cycles. We have reduced the tidal effect by sampling at high tide, but even so, sediment resuspension and mixing/advection processes might affect the SPM concentration in slack tide.

In addition, the flat coastal topography allows the influence of winds in the study area (Cuadrado et al., 2005). In fact, the wind direction showed a marked shift during the late autumn-winter period coinciding with the diminution of the SPM concentration. This could be related with the fact that throughout the year the dominant wind direction was perpendicular to the main axis of the estuary producing local waves which in turn eroded the extensive continental plains, tidal flats and marshes that encompass important amounts of suspended matter. In contrast, during late autumn-winter period the dominant wind direction was parallel to the main axis of the estuary, contributing with low SPM from the sea zone due to fewer land/coastal/tidal flat erosion. Summarizing, the non-conservative behavior of turbidity in the annual cycle might be associated with intense turbulence and eroding processes produced by tides and winds and in a lesser extent by precipitations and river inflow. Fig. 8 gives a general overview of the relevance of the different factors that may regulate the SPM and POM concentrations in the inner zone of the Bahía Blanca Estuary.

4.2. SPM and light availability

The SPM concentration in turbid estuaries often exceeds 50 mg l⁻¹ (Cloern, 1987) and in these systems light is attenuated rapidly in the water column. Our results indicated that the Bahía Blanca Estuary is turbid (yearly average of 77 mg l⁻¹) and the light extinction coefficient *k* is tightly regulated by the amount of SPM. The *k* values were similar to those characteristic of turbid shallow estuaries such as the Ems–Dollard Estuary (Colijn, 1982), the San Francisco Bay (Alpine and Cloern, 1988), Great Ouse Estuary (Fichez et al., 1992), the Elbe, Westerschelde and Gironde estuaries (Kromkamp et al., 1995; Goosen et al., 1999), Colne Estuary (Kocum et al., 2002) and Río de La Plata Estuary (Calliari et al., 2005). The

interception of the regression between k and SPM (0.071 m⁻¹, Fig. 7) represents a mean value for the "background" extinction coefficient due to light attenuation by water, dissolved constituents and the seston uncorrelated with the SPM (e.g. phytoplankton). This value calculated in the Bahía Blanca Estuary was similar to the one estimated by Cloern (1987) (0.077 m⁻¹) in the San Francisco Bay. The slope of the linear function (0.027 $m^2 g^{-1}$, Fig. 7), however, is a measure of the specific attenuation coefficient (k's) of suspended sediments in the Bahía Blanca Estuary, and it is guite smaller than those observed for other turbid estuaries (Cloern, 1987). This implies that for the same SPM levels, the attenuation coefficient in the Bahía Blanca Estuary is lower than expected for similar turbid estuaries, since the magnitude of k's varies among water bodies depending on the nature of their suspensions. This may be indicative of inert sandy particles instead of other material since the ratio POM/SPM decreases at increasing SPM. As the depth of the euphotic zone Z_{eu} is an inverse function of k, the Z_{eu} in the sampling site was typically small and among the regular values measured in turbid coastal waters. Therefore, the Zeu/Zm ratios were relatively low (mean annual value of 0.36) being under the critical value of 0.16 (Alpine and Cloern, 1988) in spring. This critical Zeu/Zm ratio of 0.16 means that when the euphotic depth is less than approximately 16% of the mixed depth, total water column phytoplankton growth cannot be sustained. Except for some particular dates with extremely low ratios, we found that during the rest of the year our values exceeded the 0.20 critical value suggested by Cloern (1987). Moreover, in some occasions during winter the Z_{eu} was equal to the total mixed zone (Z_{eu}/Z_m ratios = 1) owing to the combination of a diminution of the SPM and a shallow water column.

4.3. Underwater light climate and phytoplankton

Diatoms are the microalgae best adapted to growth under low light conditions since they have low half-saturation constants for irradiance-dependent growth (Richardson et al., 1983). Moreover, they are better adapted to high nutrient and intense mixing conditions as they have low respiration to photosynthesis ratios and high growth rates, thus they can survive in weakly stratified waters (Cushing, 1989). In the Bahía Blanca Estuary, diatoms dominate the phytoplankton community all year-round, which denounces in advance the turbid, nutrient-rich and well-mixed characteristics of the water column. Experimental studies of blooming species isolated from the Bahía Blanca Estuary show that the phytoplankton community in the inner zone of the estuary is adapted to growth at relatively low light intensities i.e. growth became inhibited at ~150 μ E m⁻² s⁻¹ under laboratory conditions (Popovich and Gayoso, 1999). Our field study confirmed this observation since the underwater light climate was consistently



Fig. 7. Extinction coefficient as a function of SPM showing the regression line and equation.

low (I_m mean of 114 µE m⁻² s⁻¹) but even though phytoplankton blooms occurred. Moreover, although we did not conduct any experiment to measure physiological adaptation of the phytoplankton cells to light-limitation, the low carbon to chlorophyll *a* ratios suggested that the phytoplankton might be adapted to live under low light conditions as C/chl a values did not surpass 40 (Richardson et al., 1986) except for a unique measurement in summer. This approach is based on the concept that the increased cellular chlorophyll content results from a physiological adaptation to light attenuation that makes net phytoplankton growth possible in highly turbid environments (Richardson et al., 1983). In agreement with other researches in turbid and shallow coastal waters (e.g. Alpine and Cloern, 1988; Fichez et al., 1992; Kocum et al., 2002), we have shown that phytoplankton blooms occur even when a thin euphotic zone exists in a completely mixed water column. The explanation may be due to shallowness of the study area: the cells spend short time periods beyond the euphotic zone as they are continuously returned into the upper layer by vertical mixing processes. Thus, the phytoplankton cells undergo a mean light exposure that allows their survival. In the Bahía Blanca Estuary the Z_{eu}/Z_m ratio was generally above 0.16–0.2, which is the threshold to allow net primary production under light limiting conditions (Cloern, 1987; Alpine and Cloern, 1988; Grobbelaar, 1990).

Phytoplankton blooms result from the balance between production (growth, physical accumulation) and loss processes (grazing, sinking and advection). The approach used was to investigate how light variations mediated by water turbidity affect the development of the phytoplankton bloom focusing on phytoplankton biomass as an aggregated response variable. This indirect approach can be useful even if its explicative value is more limited. As it was mentioned in the introduction, the inception of the phytoplankton winter bloom in the inner zone of the Bahía Blanca Estuary has been attributed to the high nutrients concentrations in autumn (Popovich et al., 2008a,b) and to the low water temperature which may cause relaxation of grazing (Pettigrosso et al., 1997). On the other hand, the collapse of the bloom in August/September results from a combination of intensive copepod grazing and nutrient limitation, especially phosphate and nitrate (Popovich et al., 2008a). Regarding water turbidity, we found a strong negative relationship between the inception of the phytoplankton bloom and the SPM concentration. This suggests that an increase in water transparency and consequently more light penetration in the water column is one of the factors that indeed trigger the development of the winter bloom. Conversely, the end of the winter bloom seemed not to be a result of light-limitation by water turbidity since the collapse of the bloom occurred in August while the light attenuation level was at its lowest (0.17 m^{-1}) , much lower than the attenuation level when the bloom started in June (1.46 m^{-1}) . This suggest that light is not the only factor modulating the duration of the phytoplankton bloom and that nutrient limitation and zooplankton pressure in August may be involved in the drop of the bloom as was previously pointed out by Pettigrosso et al. (1997) and Popovich et al. (2008a). In addition, spatial and temporal studies carried out along the estuary by Popovich and Marcovecchio (2008) showed that water turbidity, chlorophyll *a* concentration, phytoplankton abundance, and nutrients decrease towards the mouth of the estuary. These gradients may be related with the hydrodynamic conditions (i.e. intensive tidal advection and resuspension, low river inflow, high residence time) that promote accumulation of phytoplankton biomass, nutrients and SPM in the inner zone (Fig. 8). Even when the head of the estuary has been described as the most turbid area, it has been considered the main source of primary production due to the occurrence of the winter diatom bloom (Popovich and Marcovecchio, 2008).

4.4. POM dynamics

Estuaries are perceived as highly productive ecosystems because they are often nutrient-rich and have several sources of organic matter to sustain populations of heterotrophs (Cloern, 1987). In the Bahía Blanca Estuary we measured high levels of POM (annual mean of 12.7 mg l^{-1}) compared with other turbid estuaries (e.g. Hemminga et al., 1993; Goosen et al., 1999). The maximal POM/ SPM ratio of 57% indicated that POM constitutes more than half of the total suspended matter concentrations in winter. However, it is worth noting that we measured the total POM, not only the particulate organic carbon (POC) as it is commonly measured in other estuaries; therefore, some discrepancies are expected. We followed the same methodology as in Calliari et al. (2005) to



Fig. 8. General diagrammatic representation of the main factors affecting the suspended particulate matter (SPM) and the particulate organic matter (POM) loads in the inner zone of the Bahía Blanca Estuary. The implicated physical processes are: direct loads (waste discharges, river inflow, dredging), erosion of the coast and tidal flats, resuspension, and advection by wind and tides. Accumulation of SPM and POM in the inner zone occurs due to the relatively high residence time.

estimate POM in the upper zone of Río de La Plata Estuary, and we obtained comparably high values.

The organic matter in estuaries may derive from multiple sources including riverine and waste inputs and autochthonous primary production by vascular plants, macro and microalgae (Cloern, 1987; Hemminga et al., 1993; Goosen et al., 1999; Calliari et al., 2005). Our results indicated that the calculated phytoplankton-derived organic matter constituted a small fraction of the total POM in the inner zone of the estuary. The phytoplankton biomass represented a minor source of POM (max. 2.7%) and they were significantly correlated. This correlation likely indicates that both POM and phytoplankton carbon were modulated by some common process that made them fluctuate in a coordinated fashion. The low percentage of phytoplankton biomass in the inner zone of the estuary raises the question of alternative sources to keep the high levels of organic matter. The main organic matter supply may derive from benthic microalgae and vascular plants, since the estuary is characterized by large areas of intertidal flats and marshes covered mostly by Spartina alterniflora mats (Fig. 8), so their contribution to primary production may be significant. In a mesotidal estuary, de Jonge and van Beusekom (1995) demonstrated that the effect of tides and winds are the principal forces promoting benthic microalgae resuspension which at the same time contribute with large amounts of organic matter to the plankton habitat (de Jonge, 1995) where the organic matter pool due to detritus is even many times larger. In addition, in the shallow inner zone of the Bahía Blanca Estuary, bottom resuspension may be considerable owing to the intense water turbulence induced by winds and tides. In addition, the retention time in the estuary may be a critical factor in the regulation of the amount of organic matter. The residence time is relatively high, close to 28 days. The fact that the organic matter was made up of refractory compounds (Hemminga et al., 1993) is less probable since low degradation rates are common in anoxic environments, and in the Bahía Blanca Estuary there was not oxygen depletion over the sampling period. This suggests that the rate of POM accumulation may be higher that the decomposition rate.

5. Conclusion

The fixed point sampling strategy employed in this study for the fortnightly survey in the inner zone of the Bahía Blanca Estuary provides detailed information on the temporal behavior of SPM and phytoplankton. This approach allows a simultaneous analysis of the dynamics of SPM, light availability and phytoplankton and a clear interpretation of the relation among them. Unlike other temperate coastal waters where the phytoplankton bloom is normally in spring owing to a reduction of the mixed zone as a consequence of stratification, in the Bahía Blanca Estuary the timing of the phytoplankton bloom is not regulated by the stability of the water column. In this well mixed, shallow, nutrient-rich and turbid estuary the bloom occurs in winter triggered by an increase in the light availability caused by a marked reduction in the SPM concentration. Besides high nutrient levels and low grazing pressure, light-limitation by SPM loads plays a major role in the initiation of the winter bloom. These results provide evidence that SPM dynamics must be considered in any phytoplankton study in turbid estuaries where light-limitation may strongly regulate primary production.

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