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Characterisation of the suspended particulate matter in a stratified estuarine environment employing complementary techniques

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ABSTRACT

The ability to predict the sediment and nutrient circulation within estuarine waters is of significant economic and ecological importance. In these complex systems, flocculation is a dynamically active process that is directly affected by the prevalent environmental conditions. Consequently, the floc properties continuously change, which greatly complicates the characterisation of the suspended particle matter (SPM). In the present study, three different techniques are combined in a stratified estuary under quiet weather conditions and with a low river discharge to search for a solution to this problem. The challenge is to obtain the concentration, size and flux of suspended elements through selected cross-sections using the method based on the simultaneous backscatter records of 1200 and 600 kHz ADCPs, isokinetic sampling data and LISST-25X measurements. The two-ADCP method is highly effective for determining the SPM size distributions in a non-intrusive way. The isokinetic sampling and the LISST-25X diffractometer offer point measurements at specific depths, which are especially useful for calibrating the ADCP backscatter intensity as a function of the SPM concentration and size, and providing complementary information on the sites where acoustic records are not available. Limitations and potentials of the techniques applied are discussed.

1. Introduction

Estuarine systems are complex environments that show seasonal and spatial variations in water temperature and salinity, as well as in concentrations and sizes of suspended particulate matter (SPM). In brackish waters, suspended particles rarely exist in their primary state; instead, they are typically found as aggregated and heterogeneous assemblages of mineral and organic material. The texture, size and density of the particles are largely controlled by flocculation, which acts as one of the principal factors determining the transport and deposition of suspended matter in estuaries (Chen et al., 2005). Therefore, the flocculation mechanisms control the fate of SPM and of all contaminants associated with the particulate phase, including bacteria, viruses and chemical and metallic contaminants (Verney et al., 2009). The high spatial and temporal variability of suspended sediment and its associated components, in conjunction with the typically low flow velocities, generate different engineering and environmental challenges in these particular systems. Consequently, since measurements of SPM concentration and size are needed to study the distribution patterns and the associated deposition-erosion processes, interest has increased in the characterisation and quantification of the estuarine transport of SPM. The main challenge is to select, a priori, the appropriate method before determining the suspended matter characteristics.

Common measurement techniques include gravimetric analysis, the use of optical instruments (Downing, 2006) and acoustic sensing (Thorne and Hanes, 2002), or a combination thereof. The gravimetric technique involves the direct measurement of the particle concentration; however, all sampling procedures are usually time-consuming, expensive and intrusive, have limited spatial and temporal resolution and require considerable training and practice. Of greater concern in estuaries, the handling and analysis of samples may alter the flocs. Therefore, the characterisation of SPM that is prone to form flocs essentially requires in situ measurements, so methodologies based on samplings and laboratory analysis (such as those usual in fluvial environments) are not appropriate. In the last decades, indirect sampling methods have been developed to provide size and concentration of the SPM. These methods are based on turbidity (bulk optics), acoustic backscatter principles, laser diffraction, pressure differences, and digital imaging and holography (Gray and Gartner, 2009; Anderson et al., 2010; Gray and Landers, 2013; Talapatra et al., 2013; Agrawal and

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Hanes, 2015).

Acoustic Doppler current profilers (ADCPs) are increasingly being used to provide water velocity distribution (Szupiany et al., 2012) and bathymetry (Duncker et al., 2015), but they are also appreciated as tools for the indirect determination of the distribution of the SPM concentration using the strength of the backscattered acoustic signal (Deines, 1999; Moore et al., 2013; Latosinski et al., 2014; Venditti et al., 2016, among others). The usefulness of this application arises from its practicality for acquiring high spatial-temporal resolution information in a non-intrusive, continuous and simultaneous manner through the whole water column. This method typically relies on taking a large number of water samples and building an empirical relationship between the mass concentration of SPM and the acoustic backscatter intensity, and it entails different assumptions regarding sediment heterogeneity in the ensonified volume (e.g., particle-size distribution and spatial concentration gradient) (Guerrero et al., 2016). However, this approach provides little or no information about the degree of sediment flocculation (MacDonald et al., 2013; Vincent and MacDonald, 2015). Another disadvantage is that the intensity of the backscatter signal depends on the characteristics of the instrument and the suspended elements (e.g. concentration, size and type of particles; content of organic matter; dissolved solids) present in the water column (Guerrero et al., 2011). This condition is a problem in estuarine systems where flocculation processes are intense and control the SPM dynamics (e.g. size and density spectra), as these are key information for the inversion of the backscatter signal and the ultimate SPM concentration calculation.

The most advanced multi-frequency technique incorporates the effect of grain size on the scattering process and provides both the concentration distribution of the suspended elements and the grain size profiles. This acoustic method has been successfully employed in regions predominantly composed of non-cohesive sandy and fine-grained sediments (Guerrero and Lamberti, 2011; Guerrero et al., 2013, 2016). However, if the process of flocculation occurs, interpretation of the acoustic observations remains uncertain.

Field-deployable laser-diffraction instruments have been used in several investigations in marine and estuarine waters (e.g. Fugate and Friederichs, 2002; Chang et al., 2006; Curran et al., 2007), and have provided direct high temporal resolution measurements of suspended sediment volume concentration and particle-size in fluvial environments (e.g. Williams et al., 2007; Guo and He, 2011; Czuba et al., 2014; Haun et al., 2015). The instruments available for field particle measurements include the laser in-situ scattering and transmissometry (LISST) sensor series (Sequoia Scientific Inc.). These devices require only a simple specific calibration; however, only point measurements are possible and these are time consuming when an anchored vessel is used.

The present study aims to assess the results obtained using three methods in terms of the characterisation (i.e. size, concentration and net flow) of SPM in a challenging stratified estuary where flocculation processes occur. Comparison of the performance of the two-ADCP method, the LISST-25X measurements and the physical sampling analysis provides the limitations and potentials of the techniques employed. The method based on the simultaneous backscatter records of 1200 and 600 kHz ADCPs employed by Guerrero et al. (2013) in rivers, where the sediment mainly consists of sand, was used here to determine the size of flocs in brackish and salt water. To our knowledge, the findings verify this technique as a novel and promising one. It can be implemented by using the provided relationships between the strength of the backscattered acoustic signal of each ADCP and the SPM size obtained using a LISST-25X diffractometer or sampling the water column in selected locations of an estuary.

2. Measuring instruments and methods

Measurements were performed in the Quequén Grande river estuary (QGRE), located in southeastern Buenos Aires province in Argentina. The QGRE is a microtidal coastal plain primary system between 150 and 200 m wide. The mean river discharges range from 6 to 10 m^3/s, with occasional maxima of about 170 m^3/s, while the tide has a mean amplitude of 1.03 m, with a maximum of 1.85 m during the spring tides. The minor falls located at 13.7 km from the mouth mark the head of the estuary. The saline wedge intrudes about 10 km from the sea. The Quequén Harbour is located in the last 2 km of the estuary and its 12–14 m depth is maintained by regular dredging. Further upstream, the thalweg is 3–4 m deep, with an irregular topography exhibiting small canals, 5–7 m deep. Consequently, an artificial abrupt depth step that separates the estuary into two parts is created. Typically, the river discharge slightly mixed with salt water crosses the harbour zone in a 1–3 m surface layer with a halocline below with salinities reaching over 30 practical salinity units (PSU), being homogeneous down to the bottom. Two jetties prevent the entry of sand from the sea, except during severe storms. Granulometric analysis indicated that nearly 50% of the bottom sediments have a diameter between 30 μm and 300 μm, also with a most probable size in the range of 90–100 μm, and a significant silt content with a maximum in the range of 10–15 μm (Pereyra et al., 2014).

Data for analysis were obtained in two surveys conducted between 19 and 21 November 2013, during complete tidal cycles close to spring-tide, and on 28 March 2015. Three measurement stations were set at 1.3 (S1), 1.9 (S2) and 9.8 km (S3) from the estuary mouth, with the local depth at each location being 12.0, 4.5 and 5.0 m, respectively. A *SonTek CastAway* conductivity, temperature and depth (CTD) instrument was employed to obtain salinity profiles at all the stations with uncertainty of 0.1 PSU. The prevailing quiet meteorological conditions in the days prior to the surveys meant that the estuarine system was stratified and under analogous hydrodynamic conditions (see details in Table 1) when the field studies took place. On both occasions, the local meteorological records confirmed that the measurements were conducted in seasons of scarce rains and low river flow (Thomas and Marino, 2016), and the wind did not significantly affect the estuarine flows.

2.1. Physical isokinetic sampling

The SPM mass concentration, M, was determined in the first survey by collecting 0.5 l water samples using a P-61 isokinetic sampler in all measurement stations at depths of about 1.1, 1.5, 2.5, 3.0, 5.5 and 7.0 m. The samples were preserved in a 4% aqueous solution of formalin for future laboratory analysis, and left at rest for at least seven days. For each sample, the value of total dissolved solids (TDS) was determined by drying the supernatant by evaporation in a water bath at 105 °C, and by weighing the solids. Meanwhile, the settled solid matter was filtered, dried at 105 °C and weighed to obtain an estimate of total solids (TS). Total suspended solid (TSS) was determined by subtracting TDS from TS. Then, M was obtained by dividing TSS by the total volume of the sample. The Standard Methods 2540 criteria (SMWW, 1998) were followed.

Table 1
Hydrodynamic conditions in the Quequén Grande river estuary during the measurement days.

		2013 19–21 Nov	2015 28 March
Mean River flow		7.0–7.5 m^3/s	5.0–5.5 m^3/s
Tidal level variation		1.7 m	1.2 m
Number of days since last rain		5	11
Flood-Tide:	Mean maximum flow	90 m^3/s	80 m^3/s
	Mean maximum speed	0.5 m/s	0.4 m/s
Ebb-tide:	Mean maximum flow	100 m^3/s	90 m^3/s
	Mean maximum speed	0.6 m/s	0.5 m/s

After filtering, drying and weighing the settled solids, the organic matter content was determined by ignition in a furnace at 450 °C (i.e. the "loss-on-ignition" method) by computing the difference in weight before and after ignition. In addition, the granulometric analysis of the suspended solids, performed on some samples, was conducted with a *Mastersizer 2000* particle analyser (*Malvern Instruments*) that employs laser diffraction to measure the relative concentration of particles between 1 and 1000 µm with a precision of 1%. Each sample was homogenised for 1 min with a turbine and sonicated for 5 min to disrupt the existing aggregations; the measurements were repeated twice more.

Prior to the drying of the samples in the oven, the sizes of the suspended particles were determined from the images obtained with an optical ×40 microscope (*Endosa*) only for visual confirmation. Flocs with sizes between 40 and 400 µm were found.

2.2. Laser diffraction: LISST-25X

In the second survey, the volume concentrations and particle sizes were measured with the LISST-25X diffractometer for samples from the same stations and depths as in the previous survey. The LISST sensors make possible the in situ size characterisation of suspended material despite the formation or presence of flocs. The low velocities of the current ensured limited flow perturbation by the instrument, and avoidance of aggregate breakage. This characteristic represents a valuable advantage over physical sampling methods. This diffractometer provides the Total Sauter Mean Diameter of the complete sample (SMD_t) between 2.50 µm and 500 µm, and the Sauter Mean Diameter of the coarse fraction (SMD_g) between 63 µm and 500 µm. It also determines the total and coarse suspended matter volume concentration, the optical transmission level (*OT*) and the instrument operating depth. The Sauter Mean Diameter of the fine fraction (SMD_f) was calculated in the range of 10–63 µm using the algorithm proposed by Filippa et al. (2012).

The data were discarded when the levels of optical transmission fell outside the optimum range of 30–98%. For an optical path length of 2.50 cm, this range corresponds to concentrations between 7 mg/l (at 10 µm) and 8524 mg/l (at 200 µm). In this study, the reported concentration measurements are within these limits. Note that the LISST-25X instrument measures volume concentration (µl/l), whereas the classic method described above gives the weight concentration per unit volume (mg/l). The ratio of these two values gives the effective density ρ_{floc} of the suspended elements (mg/µl), which is usually difficult to measure in the presence of aggregations of sediment particles and biological matter. The average of the data obtained every 5 min at each depth level and the respective standard deviations were computed. The values of SMD_f and SMD_g were related to the mean sizes of the original particulates and flocs, respectively.

2.3. Acoustic backscatter: Simultaneous measuring of two ADCPs

In each survey, two *Workhorse Río Grande* ADCPs of 600 and 1200 kHz (*Teledyne RD Instruments*) and a global positioning system were employed to obtain simultaneous information about the velocity and backscatter intensity of the suspended matter and its location, respectively. Based on the existing hydraulic conditions and the characteristics of the instruments, Mode 1 was chosen to operate the 600 kHz ADCP and Mode 12 to operate the 1200 kHz ADCP. Both instruments were placed on the same side of a small boat for simultaneous measurement of the water column. Sailing transversally to the main current (back and forth, twice), the velocity distribution was averaged with the *VMT* software (Parsons et al., 2013). The backscatter signals (in counts) measured with each ADCP were averaged during the time when the samples were collected in the first survey, and the LISST-25X measurements were performed in the second one. These average values were corrected by considering the attenuation of the sound waves due to beam spreading, the absorption due to the water viscosity and the presence of sediments (Latosinski et al., 2014). The results were then correlated separately with the SPM concentration obtained from the analysis of the water samples and from the LISST-25X measurements, at the corresponding depth, to derive the calibration curves for each ADCP. The following paragraphs revisit the basics of the analysis and the adaptations made to the case of our interest.

The sonar equation models the interaction between a sonar and the acoustic targets. In logarithmic form, the volume scattering strength S_v (in dB) can be expressed as:

$$RL = EL + S_V - 2TL, \tag{1}$$

where $RL = K_c(E\text{-}E_r)$ is the reverberation level (measured backscatter intensity) of the received signal with *EL*, the ADCP-measured echo intensity in counts, and E_r is the undesired portion of the received signal caused by instrumental and environmental noises. The conversion factors K_c from counts to dB were obtained by laboratory testing using a hydrophone. The emitted signal *EL* (in dB) is a function of the transmitted pulse length *L*, the transmitted power P_w and the instrument-dependent constant *C*, which are related to the transducer's geometry and efficiency (Deines, 1999). *L* and P_w were obtained from the data provided by the PD0 files and were the same for both surveys.

The transmission losses, *TL,* produced by the beam spreading and the absorption of the medium may be expressed as (see, e.g. Latosinski et al., 2014):

$$2TL = 10\ \log_{10} \psi^2 (T + 273.16)\, r^2 + 2\alpha_f r + 2\alpha_s r. \tag{2}$$

The variables *T*, *r* and ψ are the temperature (in °C), the acoustic beam range or the radial distance from the transducer to the ensonified volume (in m) and the correction coefficient for the transducer in the near field, respectively; α_f is the fluid absorption coefficient (in dB/m) (Shulkin and Marsh, 1962) and α_s is the attenuation of the sound due to the suspended particles. Salinity profiles determined with the CTD were employed to estimate the sound attenuation due to water salinity. The average salinity was sufficient to give a good estimate of α_f. If *L, C,* P_w and E_r are constant, it follows from Eq. (1) that:

$$S_V = (RL + 2TL) + b, \tag{3}$$

where $b = -EL$ is a constant.

Considering that the backscatter is produced by *n* acoustic targets per unit volume, with mean radius a_s and density ρ_s, the intensity of the backscatter signal is (Thorne and Hanes, 2002):

$$S_V = 10\ \log_{10}\left(\frac{C_V\, f_s^2}{8\pi^2 a_s}\right), \tag{4}$$

where f_s is a form function that describes the scattering properties of the suspended elements, and C_V is the volume concentration:

$$C_V = n\frac{4}{3}\pi\ a_s^3. \tag{5}$$

Separating the contribution of C_V from the characteristics of the targets, Eq. (4) can be rewritten as follows:

$$S_v = 10\ \log_{10} C_V + 10\ \log_{10}\left(\frac{f_s^2}{8\pi^2 a_s}\right). \tag{6}$$

Substituting Eq. (3) into Eq. (6), gives:

$$RL + 2TL = 10\ \log_{10}(C_V) - b + e, \tag{7}$$

with

$$e = 10\ \log_{10}\left(\frac{f_s^2}{8\pi^2 a_s}\right). \tag{8}$$

If the mass $M = \rho_s C_V$ of the suspended targets per unit volume of water is provided, C_V must be changed by *M* in Eq. (7) and ρ_s must be included in the denominator of Eq. (8). Since $f_s = f_s(2\pi a_s/\lambda)$ where λ is the acoustic wave length, only the constant e changes for different frequencies. When the same suspended elements are registered simultaneously with two instruments operating with frequencies ν_1 and ν_2, the subtraction of the respective Eq. (7) leads to:

$$(RL + 2TL)_{\nu_1} - (RL + 2TL)_{\nu_2} + G = 10 \log_{10}\left(\frac{f_1}{f_2}\right)^2 \tag{9}$$

where $G = -b_1 + b_2$ is an empirical constant that considers the responses of both ADCPs.

Therefore, the ratio of the two form functions can be calculated by subtracting the ADCP signals (Eq. (9)), and the mean grain size $2a_s$ can then be estimated independent of the concentration by using the relationship $\frac{f_1}{f_2}(2\pi a_s/\lambda)$ provided by Thorne and Hanes (2002). Note that G is the only constant of interest, and not the values of P_w, L, E_r and b, among others, separately.

3. Results

3.1. Calibration curves

The values of $RL+2TL$ as a function of the concentration determined from the water samples analysis (first survey) and measured in situ with the LISST-25X (second survey), are shown in Figs. 1 and 2, respectively, and the corresponding best fit lines are presented. The error bars in Fig. 1 represent the measurement uncertainties, and those in Fig. 2 indicate the standard deviations (or root mean square errors) of the set of values, which are greater than the instrument uncertainty, obtained during the measuring interval. As expected, the intensity of the backscatter signal for both ADCPs is linearly correlated with the concentration of the suspended matter. In Fig. 1, the results obtained with the 1200 kHz ADCP are well represented by a straight line with the same slope as in Eq. (7), but those provided by the 600 kHz ADCP show a slight dispersion of the points. Note that the backscatter generated by the flocs is compared here with the mass concentrations of the organic and inorganic matter. Therefore, the (RL + 2TL)-intercept (i.e. the coefficient e in Eq. (2)) should be related to the floc size rather than to the silt and clay particle sizes. By contrast, the agreement of the results in Fig. 2 with the theoretical solution is not very good. Therefore, the uncertainty is smaller for concentrations obtained by weighing the content of the solids in the samples under laboratory controlled conditions than for those measured in situ with the LISST-25X. The random variability of the measurements performed with this instrument is most likely caused by the temporal and spatial variations in the size and composition of the aggregations and by other environmental factors

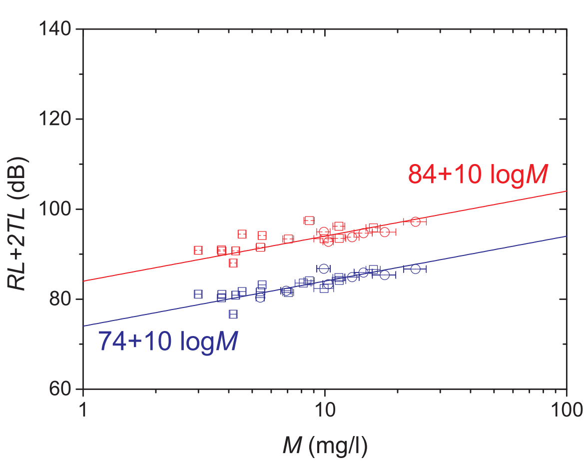

Fig. 1. Intensity of the backscatter signal as a function of the mass concentration obtained by analysing the water samples collected at S1 (circles) and S2 (squares) in the 2013 survey. The symbols represent the measurements provided by the 1200 (blue) and 600 (red) kHz ADCPs at depths greater than 1.2 m and 2 m, respectively.

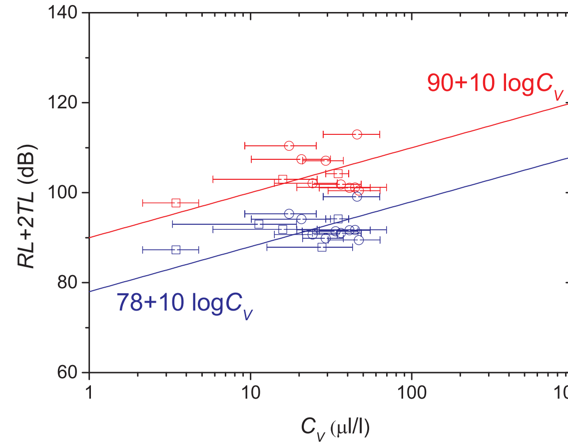

Fig. 2. Intensity of the backscatter signal as a function of the volume concentration measured with LISST-25X at S1 (circles) and S2 (squares) in the 2015 survey. The symbols represent the measurements provided by the 1200 (blue) and 600 (red) kHz ADCPs at depths greater than 1.2 m and 2 m, respectively.

that are difficult to control during the surveys.

The information contained in Figs. 1 and 2 can be integrated to obtain the mean density of the aggregations, $\rho_{floc} = M/C_V$. The measurements performed with ADCPs and the LISST-25X are consistent with $\rho_{floc} = (1.7 \pm 0.5)$ g/ml, which is less than the density of the sediment (2.65 g/ml). The ρ_{floc} values correspond to a percentage of organic matter (with density $\rho \approx 1$ g/ml) between 28% and 88%, in the range of the values obtained with the loss-on-ignition method accounted for 75–85% of the total.

Then, the backscatter intensity of any ADCP is transformed, cell by cell, into concentration. The total SPM flow crossing a given cross-section is obtained by multiplying the concentration by the velocity and area in each cell and by integrating the whole cross-section. Thus, a suspended matter flow of about 5 kg/s is found for the flood tide and about 6 kg/s for the ebb tide. The similarity in the suspended matter flows between the flood and ebb tides implies that the wash load (in this case, in the form of flocs) dominates and that no noticeable sedimentation occurs during a tidal cycle.

3.2. Determination of SPM size

The SPM mean size of about 300 µm determined by microscopic observation agrees with that obtained in situ by the LISST-25X. The granulometric analysis performed with the particle analyser revealed that the inorganic suspended matter consists of medium to fine-grained silt (4–32 µm), with a small clay content (< 4 µm). Subtracting the backscatter signals of both ADCPs and applying Eq. (9), it follows that $6 < f_1/f_2 < 16$ for both surveys; the smallest value corresponds to a particle size of 350 µm, consistent with the maximum size of the flocs that compose the samples observed under the microscope. The G value is found by minimizing the difference between the particle sizes obtained with the two-frequency method and the diffractometer. Fig. 3 shows the result of the G fitting process, which gives $G \approx 22$. The concentration of fine sediments, that attenuates the sound waves, was used to estimate α_f in Eq. (2).

Several typical vertical profiles of size obtained from the difference in the backscatter signals of both ADCPs are shown in Fig. 4. Every size profile obtained with the two-ADCP method (black lines) corresponds to a 5 min time interval during which the measurements with the LISST-25X were performed to determine the time variations. Significant differences in the size profiles indicate an important change in the characteristics of the flow. The mean sizes derived from LISST-25X measurements are based on data with considerable fluctuation, as indicated by the error bars in Fig. 4. The measurements that generate the diffractometer results represented in Fig. 4(a) are shown in Fig. 4(b) for

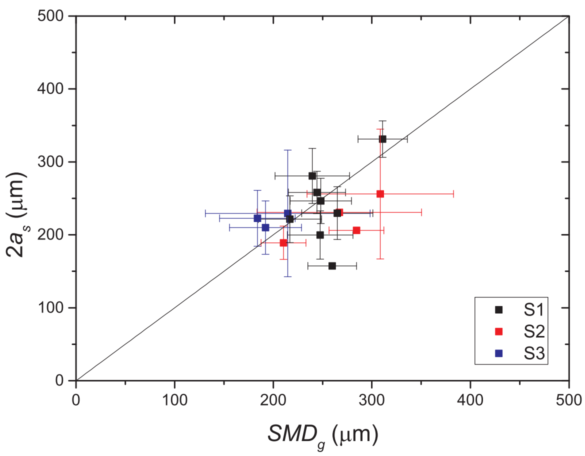

Fig. 3. Aggregate sizes determined using the two-ADCP method as function of the measurements performed with the LISST-25X. The horizontal bars correspond to the standard deviation of the measured values, while the vertical bars indicate the uncertainties caused by the approximations used in the calculation.

different depths. SMD_f is in the range of 8–15 µm in all cases.

4. Discussion

The results shown in Figs. 3 and 4 indicate that both techniques, the two-ADCP method and the LISST-25X measurements, are equally effective in determining the floc sizes in the QGRE. The employment of ADCPs has the advantage of simultaneously obtaining the distributions of the $2a_s$ size and concentration of the SPM throughout an estuary cross-section by means of the calibration of the backscatter distribution. The estimate based on the ADCP records uses the backscattering-attenuation model that is valid when suspended sand is acoustically dominant (Guerrero et al., 2013). When this model is applied in a different environment where flocs of different sizes are acoustically dominant, the measured strength of the backscattered signal correlates empirically quite well with the suspended matter concentration obtained either directly or indirectly (Figs. 1 and 2, respectively). The reason for this finding probably lies in the dominant size of the flocs, which range between 200 and 400 µm (Fig. 3). These particles generate most of the backscatter, similar to sand under other conditions.

With the choice of appropriate working frequencies, the benefit of using two ADCPs simultaneously lies in the ability to subtract the respective backscatter signals (Eq. (9)) to determine the size of the acoustically dominant suspended elements. For the ADCPs employed, the methodology is useful when particles are greater than 50 µm (Guerrero et al., 2012), since $f_1/f_2 \approx 16$ and the SPM size is undetermined for particles of sizes smaller than that limit. This allows us to use only limited SMD_g values of particles larger than 63 µm obtained with the LISST-25X to calibrate and calculate particle size. The SMD_f values are also useful for estimating the attenuation (α_f in Eq. (2)) due to the presence of fine sediments that are considered in the acoustic model. Here, note that two sizes are compared: the diameters in the sonar equation are the mean size associated with the number distribution (see, e.g. Thorne and Hanes, 2002), while the LISST-25X measures the volume distribution. In any case, the use of the semi-empirical constant G in Eq. (9) enables the adjustment of the sizes estimated with the ADCPs to those obtained with the LISST-25X, or to any other reference measurement (e.g. the floc sizes provided by the water samplings analysis).

One disadvantage of the two-ADCP method is the need to determine the backscatter signal strength without the perturbation generated by the source. Therefore, a minimum measurement depth of 1.2 m is required for the 1200 kHz ADCP and 2.0 m for the 600 kHz ADCP. Thus, reliable values of the size of the acoustic targets using these ADCPs are obtained only from 2 m below the surface, and the measurements in the surface layer, where the greater floc concentrations and sizes are found in the QGRE, are left out. Even though no information is available on the flocs in the surface layer, the size of the flocs at greater depths are in the same range in both surveys, thus implying that the ADCP backscattered signals are alike in intensity. Therefore, the calibration determined in each survey may be used interchangeably in the data processing.

The use of acoustical technology to determine SPM concentration and size is advantageous when unsteady flows are present, since measurements are possible throughout the water column in a short time, and velocity distributions are obtainable in estuary sections perpendicular to the streamflow with high temporal and spatial resolutions. Small values of SPM concentration (e.g. those found in this study) can be determined by the transverse averaging of the backscatter strength recorded in several courses at a given estuarine cross-section. In this way, the noise and other random variations become negligible, and the quantification of the mean particle diameter is possible. The size of the backscatter cell (= 0.50/0.25 m^3 for the 600/1200 kHz ADCP) is large enough to obtain the mean size of a number of particles, and thus fluctuations from one cell to another and in time are avoided, as observed in Fig. 4. In addition, slight variations in size caused by changes in the matter transported by the currents are revealed as the differences among the profiles (black lines in Fig. 4a).

The LISST-25X diffractometer simultaneously provides the SPM concentration and size at depths where ADCPs do not offer reliable information. However, note that volume concentration is measured and that density is required to provide the mass concentration for comparison with other methodologies. This condition becomes inconvenient, especially when flocs of variable composition are present. In addition, when flows are unsteady, the number of measurements must be limited and performed in periods when the flow does not significantly change. Another limitation of the LISST-25X arises due to the small size of the tested volume, as the concentration and size distributions may vary for greater tested volumes. In this case, the measurements notoriously fluctuate according to the suspended elements passing through the measuring head (Fig. 4b). This problem is partly solved by measuring over a longer duration until the variations of the averages and the standard deviation are acceptable.

Another issue to consider is that the values provided by the LISST-25X are discrete. For this study, measurements were obtained along the central line of several estuary cross-sections at specific depths. However, the transverse distributions of velocity and concentration in the QGRE are asymmetric because of the presence of meanders that cause the maximum velocity and concentration to occur mainly close to one of the banks. This effect can be partially corrected by repeating the measurements performed with LISST-25X at many positions throughout an estuarine cross-section, but doing so has the disadvantage of being time consuming. Moreover, the LISST-25X was designed to measure in stationary flows; in the case of variable flows, such as those that prevail in estuaries, the tested volume passing through the measuring head may not contain the same particle concentration and size found in the flow outside. However, the error derived from this non-isokinetic sampling is expected to be less important when the particles are flocs than in the case of sand (frequently analysed) because of the smaller density of flocs. The measurements reported here were conducted during different tidal phases and, consequently, with different current velocities, and this condition is probably why Figs. 2 and 3 present a non-negligible dispersion.

5. Conclusions

The concentration and size of the suspended elements were measured by combining the information provided by different (acoustic, diffractive-optic and physical sampling) techniques in a stratified estuary under quiet weather conditions and with low river discharge. The

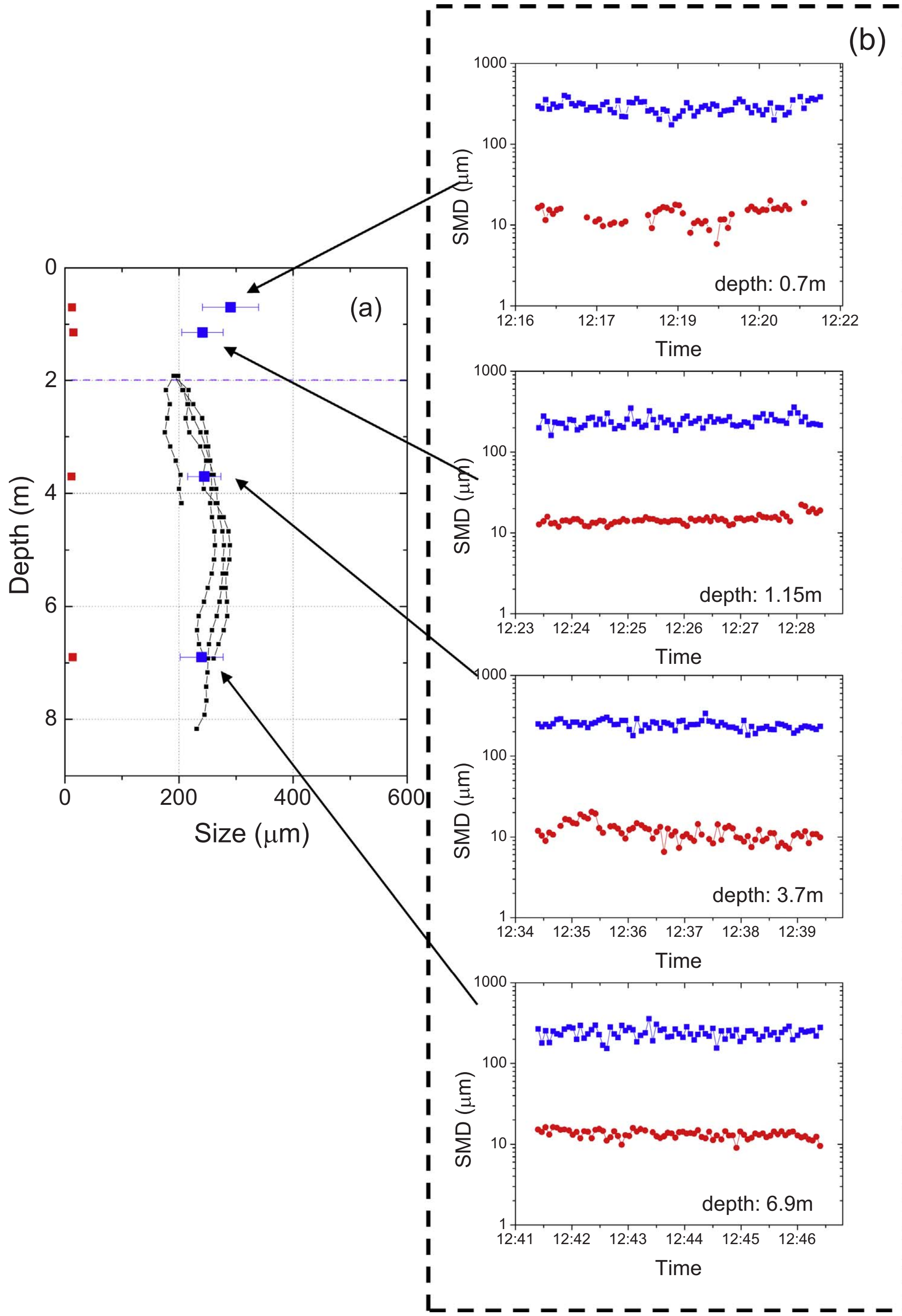

Fig. 4. (a) Typical size profiles determined by the two-ADCP method (black lines), and values of SMD_f (red symbols) and SMD_g (blue symbols) obtained with LISST-25X as indicated in (b) at S1. The violet horizontal dashed line marks the depth from which Eq. (9) is valid.

environment where the testing was conducted is not highly dynamic, and flocs have a high organic content. These circumstances make the comparison specific to regions where no discrete sand particles are suspended.

The use of the 1200 and 600 kHz ADCP backscatter records is highly effective for determining the SPM concentration and size distributions in a non-intrusive way throughout estuary cross-sections, as well as the SPM flux. The presence of flocs as acoustic targets, which are greater in size than discrete organic and inorganic particles, is an additional advantage, since flocs cause more intense backscatter intensity. The speed at which measurements can be made enables the detection of spatial and temporal variations due to changes in the local current velocity. The main disadvantage of this technique is the impossibility of obtaining measurements in the ≈ 2 m-thick surface layer, where complementary techniques must be deployed. In the stratified QGRE, where most of the suspended elements concentrate precisely in that layer, the estimate of the SPM flow may have an error of 100% if only the results obtained at greater depths are considered.

The application of the two-ADCP method is the first attempt to obtain mean size distributions with high spatial-temporal resolution in an estuarine environment and the results are promising. The isokinetic samplings and LISST-25X measurements are useful for calibrating the ADCP backscatter intensity as a function of the SPM concentration and size. The samplings are convenient for finding the concentration of a relatively large volume (e.g. 0.5 l) unlike the small test volume of the LISST-25X ($\approx$ 0.1 ml). A larger volume gives better averages and greater confidence for determining calibration curves. The LISST-25X is also an effective tool for measuring in situ the size of the suspended particles, because it provides the mean values and their variations (i.e. the standard deviation) at any depth and does not need calibration.

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