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Abstract

Estuarine boundary layer and water column \textit{in situ} measurements of hydrodynamics, sediment resuspension and sediment particle size distribution are presented for a macrotidal environment in SE China. Vertical and tidal variability of sediment size and its relation to turbulence and hydrodynamic forcing are examined using time-series from two week long experiments after they are phase-averaged to reconstruct typical neap and spring tidal cycles. \textit{In situ} particle size distributions obtained using laser diffraction show clear evidence of flocculation processes that change dynamically during the tidal cycle. Mean particle size of particles in suspension is found to be one order of magnitude larger than the primary size of the sediment. The coarser particles in suspension were present in the upper water column while the finer particles were confined predominantly within the bottom boundary layer. Correlation analysis indicated that aggregate size appears to be controlled by turbulence more than any other parameters with floc size being inversely related to turbulence dissipation, while settling velocity of aggregates being proportional (on a log scale) to turbulence dissipation. Simple statistic and dynamic models incorporating the turbulence parameter are adopted and compared with previously developed models; the comparative study using our data sets shows that the dynamic model of Winterwerp [1998] as modified by Law et al. [2013] to include advection qualitative captures both the tidal and vertical variability of aggregate size.

Keywords:
Suspended particulate matter (SPM), Turbulence dissipation, Floc size, Flocculation/aggregation, Settling velocity, Macrotidal estuary.

1 Introduction

Estuaries are important coastal systems that constitute the interface between terrestrial, riverine and marine environments. They are temporal sedimentary sinks of riverine material, predominantly in the vicinity of the estuarine turbidity maximum area [Liu et al., 2011; Uncles and Stephens, 2010; Woodruff et al., 2001; Xu et al., 2010], a salient estuarine feature. This material may be resuspended and subsequently exported to the coastal ocean during periods of high river discharge known as freshets [Geyer et al., 2001]. The fine sedimentary particles found in estuarine waters are in either individual or aggregated (flocculated) form; they provide the surface area for the absorption of heavy metals and other pollutants as well as nutrients. The transport and fate of these particles and the material attached to them varies as a function of the state they exist (i.e., aggregated or non-aggregated). During periods of intense sedimentation, the particles can be trapped into the seabed through sediment burial and the attached material may be modified by a number of complicated physical and/or bio-chemical processes [Sholkovitz, 1976; Wang, 2002; Zhang, 1999] that affect the biogeochemical cycle. Subsequent resuspension events contribute to the release of the particle
attached material and potentially secondary pollution can occur [Calvo et al., 1991; Manning et al., 2010b]. Therefore, an improved understanding of the physical processes of the sedimentation - resuspension cycle is of great importance for accurately predicting the sedimentation processes and the associated biogeochemical cycle taking place within an estuary.

Flocculation represents a very important process within the sedimentation cycle as it can alter particle settling velocities and change the mode of sediment transport. Floc generation, size of flocculated particles and associated settling velocities are essential information required for accurate simulation and prediction of sedimentation processes and sediment transport rates. The latter are very important as their gradients control the morphological evolution of the estuarine environment and affect the long-term evolution of the ecosystem. Given their importance, significant efforts have been placed on understanding flocculation processes and developing predictive capabilities to be included in numerical models. To-date we know that flocculation is affected by both physical hydrodynamic forcing and biological activity. Brownian motion, differential settling and turbulence (i.e., fluid shear) have been shown to both promote aggregation by enhancing particle collision rates and limit the maximum size of a floc [Eisma, 1986; Eisma, 1991; Guo and He, 2011; Winterwerp, 2002]. Electrochemical processes also affect aggregation of clay-size particles, which occurs at certain salinity and turbulence intensity levels. On the other hand, biological processes, including algae growth and organic gelling, play an important role. Eisma [1986] found that mucopolysaccharides, which are produced by bacteria, algae and higher plants and are mobilized from the suspended matter at low salinity levels, are important in gelling particles together and contributing to floc formation.

In this study we focus mainly on the physical forcings that affect flocculation processes. We present experimental data of hydrodynamics and sedimentary particle characteristics from a macrotidal estuarine environment in SE China. Our objective is to accurately describe the resuspension cycle (i.e., resuspension, flocculation/de-aggregation, and settling) of estuarine sediments. Particular emphasis is placed on the process of aggregate formation and destruction as a function of tidally varying hydrodynamic and turbulence levels and the results are compared with existing models describing these processes. In the remaining of the paper we describe the study site and its environmental setting (Section 2) and the methods and techniques used for data collection (Section 3). This is followed by a presentation of the data processing and analysis (Section 4) while the results are presented in Section 5. A discussion of our findings can be found in Section 6 with the final conclusions presented in Section 7.

2 Study Area

The area under investigation is the Jiulong River estuary near Xiamen (Fujian Province, China), located on the western side of the Taiwan Strait, along the southeast coast of China’s mainland (Figure 1). The estuary is a semi-enclosed water body with a number of islands being located on its seaward side providing protection from oceanic wave activity. The winds are mainly from the NE and NNE and contribute to the generation of local waves with a maximum significant wave height of 1.8 m [Lin et al., 2009]. The mean tidal range is 3.9 m with a maximum range of 6.4 m [Ji, 2006; Jiang and Wai, 2005]. The water depth within the estuary is generally less than 15 m (at lowest low water datum), while there are extensive intertidal mudflats surrounding the main channel and along the coastline (see regions at above the 0 m bathymetric contour in Figure 1). The seabed material consists of sediments with sizes ranging from 10 μm to 700 μm.

Jiulong River is the second longest river in the province, with a total length of approximate 1,148 km, and a drainage basin area of 11,909 km² [Zhang et al., 2002]. The mean annual air temperature is about 20.9°C while the precipitation is 1,772 mm yr⁻¹. The mean annual water discharge is 1.2x10¹⁰ m³, about 70% occurring during April to September (i.e., the wet season) when typhoons
and tropical storms are frequent. During November to February (dry season) the river discharge is approximately 15-20% smaller than the mean annual discharge [Liu et al., 1994]. The annual sediment discharge is approximately 2.5×10⁹ kg, with the majority of it occurring during June to September. The catchment is heavily affected by agriculture and in particular by activities associated with intensive use of fertilizer (a mean value of 690 kg N ha⁻¹ yr⁻¹, commonly applied on the soil surface). Approximately 75% of the annual nitrogen export occurs during the wet season as storm runoff [Cao et al., 2005; Chen and Hong, 2011].

3 Data Collection

An instrumented bottom mounted tripod was deployed during the periods March 23-29 and April 2-9, 2010. The deployment site was located at a mean water depth of 8.7 m (see Figure 1) and the data collected corresponded to tidal conditions that changed from neap to spring and spring to neap for the March and April deployments, respectively.

The tripod was equipped with three acoustic Doppler velocimeters (ADV, 6MHz Nortek Vector) measuring 3-D current velocities at 0.2, 0.6 and 1.0 m above the bed. In addition, three electromagnetic current meters (EMCM, Alec Compact) were installed at elevations of 0.4, 0.8 and 1.3 m above the bed measuring the 2 horizontal components of the flow. Both types of sensors were collecting data in burst mode at 20 min intervals. The ADV burst duration was 2.13 min and the sampling frequency within each burst was 16 Hz (i.e., 2,048 data points per burst), while the EMCM bursts were 2 min long with a sampling rate of 1 Hz (i.e., 120 data points per burst). Due to instrument malfunction no data were retrieved from the ADV installed at 0.6 m elevation. Additionally, time-series of turbidity, temperature and salinity were obtained at 4 elevations (0.2, 0.6, 1.0, and 1.3 m) above the bed using four nephelometers (OBS-3A, D&A Instrument Co.), while a pressure transducer (Seabird SBE26) fixed at 1.8 m above the bed recorded time-series of mean water level and wave statistics.

The near bed tripod measurements were augmented with hydrodynamic and sedimentary data collected throughout the water column from a boat anchored some 50 – 75 m away from the tripod deployment locations. Velocity profiles were obtained using a downward looking acoustic Doppler current profiler (ADCP, 1,200 kHz) every 2 s. The profile range extended from 0.8 m below the
mean sea surface (after accounting for ADCP transducer location and blanking distance in front of it) to near the bed with a vertical resolution (bin size) of 0.15 m.

Hydrographic and in situ particle size data were also collected throughout the water column hourly using a profiling system consisting of a LISST-100X (Seabird Scientific) and a CTD (Seabird SBE25). These profiling data were augmented with water samples (approximately 2 L) collected hourly from 3 to 4 layers (from surface to bottom) within the water column. Water sampling was carried out only during day time, for a period of 13 hours, and on the days of March 23, 24, 25, 27, and 29, 2010. These samples were used to derive suspended particulate matter (SPM) concentrations through filtration (using 0.45 μm filters); the concentrations were subsequently utilized to calibrate the ADCP acoustic signal for sediment concentration. Water samples of larger volumes (~2 L) were collected on April 3, 5 and 7, 2010, which were used subsequently for estimating SPM concentration estimates and for laboratory grain size analysis. The latter was aimed to identify the size and distribution of the disaggregated primary particles that made up the floculates present in the estuary. A laser Malvern Mastersizer 2000 granulometer (range 0.02 - 2,000 μm with a duplicate measurement error <3%) was utilized for these measurements. Finally a water sample of 50 L was collected from the lower water layer, which was then used to calibrate the OBS sensors installed on the tripod. The sampling scheme was completed with the collection of surficial bed sediment samples (using a grab) during the same period as the profiling and with a frequency of a sample every 3 to 4 hours.

4 Data Processing and Analysis

The mean hydrodynamic flow conditions were determined from the velocity sensors (ADV and EMCM) installed on the tripod and the ADCP profile data after averaging over a common period of 2 min. In addition the ADV-collected instantaneous velocity time series were analyzed in order to produce estimates of turbulence kinetic energy dissipation and mean bottom shear velocity that are used to characterize near bed turbulence throughout the experimental period. Similarly, estimates of mean sediment concentration and particle settling velocity of the sediment in suspension were produced. The details of these analyses are described below.

4.1 Bottom Shear Velocity Estimates

Bottom shear velocities can be estimated using three independent methods: (i) the law of the wall, (ii) the Reynolds stress method, and (iii) the inertial dissipation method [Sherwood et al., 2006]. However, the law of the wall method is very sensitive to the elevation above the bed and it is not easily applicable at low velocity speeds (i.e., slack water) when the signal to noise ratio is high. Hence, in this study we restricted our analysis to the remainder two techniques. Prior to any analysis for the extraction of turbulence statistics, an inter-comparison of mean flows and their variances as produced from the different sensors was carried out as this allowed us to examine for influence of the tripod’s structure elements on the flow. Data from sensors that indicated unusual velocity defects when compared with neighboring sensors were excluded from further analysis. During this stage, ADV data from the sensor installed at 0.2 m during the March 23-29, 2010, deployment were found to be contaminated by vortex shading from the tripod’s support leg and as such they were not used for any of the analyses presented below.

The instantaneous velocity data recorded within each burst of the ADV sensors were used to estimate the Reynolds stress. Assuming that near the bed production of turbulence is balanced by dissipation, the bottom shear velocity \( u_s \) can be estimated by:

\[
  u_s = \left(-\langle u'w' \rangle \right)^{1/3},
\]

Wang et al., 2013: Sediment resuspension, flocculation and settling in a macrotidal estuary, JGR
where \( u' \) and \( w' \) are the instantaneous turbulent components of the downstream \( (u) \) and vertical \( (w) \) velocity components, respectively; the brackets indicate time-averaging over the burst period.

The inertial dissipation method was applied to the vertical component of the flow collected by the ADV sensor. According to this method, the Kolmogorov’s turbulent spectra model [Tennekes and Lumley, 1972]

\[
E_{ww}(k) = \frac{4}{3} \frac{9}{55} \alpha \cdot \varepsilon^{2/3} \cdot k_u^{-5/3}
\]

is fitted to the vertical velocity turbulent kinetic energy spectra \( (E_{ww}) \) estimated from the ADV data assuming \( \alpha=1.5 \). \( k_u \) is the downstream wavenumber estimated from the spectral frequency and the mean downstream current speed applying Taylor’s frozen turbulence assumption [Sherwood et al., 2006; Voulgaris and Trowbridge, 1998]. The fitting processes was applied to the inertial subrange \((k_u \cdot \kappa \cdot z > 1.8)\) of the spectrum and the turbulent kinetic energy dissipation rate \( (\varepsilon) \) was estimated.

Assuming that the turbulence spectrum is measured within the constant stress layer, shear velocity can be derived from the turbulent kinetic energy dissipation rate \( (\varepsilon) \) using:

\[
\varepsilon = \frac{\mu^3}{\kappa z},
\]

where \( \kappa \) is the von Karman constant and \( z \) is the elevation of the measurement sample volume above the sea bed.

### 4.2 SPM Concentration Estimates

Studies have shown that the acoustic returns from the ADCP can be used to measure the vertical variability of SPM concentrations after proper calibration [Hoitink and Hoekstra, 2005; Moura et al., 2011; Wang et al., 2000]. A calibration equation was established by fitting the in situ SPM mass concentration \((C \text{ in mg L}^{-1})\) into the range corrected ADCP acoustic backscatter intensity \((I_{adcp} \text{ in dB})\) using:

\[
\log_{10}(C) = \alpha \cdot I_{adcp} + K,
\]

where \( K \) and \( \alpha \) were determined by linear regression analysis, as shown in Figure 2a, for the two deployment periods.

The recorded signal from the OBS-3A sensors was converted to SPM mass concentration using the laboratory derived calibration curve that utilized the in situ water samples. Subsequently, the relation between OBS derived turbidity and corresponding ADV acoustic intensity was established for the two ADV sensors installed at 0.2 m and 1.0 m above the seabed (Figures 2b and c) as in Voulgaris and Meyers [2004] and Fugate and Friedrichs [2002]. The calibration coefficients for converting the acoustic signal to sediment concentration were found to be almost identical between the two different ADV sensors for the same deployment periods. However, the calibration coefficient values slightly varied from deployment to deployment (0.069 vs. 0.067 for the March and 0.091 vs. 0.086 for the April deployment, see Figures 2b and c, respectively) probably due to different sediment characteristics that can affect the response of either the OBS, the ADV or both sensors [Voulgaris and Meyers, 2004] or experimental setup (e.g., battery voltage) that might alter the response of the sensors.

The LISST data were converted to volumetric particle size distributions (32 classes, logarithmically spaced between 2.5 to 500 \( \mu \text{m} \)) using the manufacturer’s instructions and accounting for the presence of random shaped particles as described in Agrawal et al. [2008].

Wang et al., 2013: Sediment resuspension, flocculation and settling in a macrotidal estuary, JGR
distributions were used to estimate the mean ($M_z$), median ($M_d$) and 95th percentile ($D_{95}$) sizes of the sediment in suspension.

Figure 2. Calibration curves for the conversion of acoustic signal ($I$ in dB) to suspended sediment concentration ($C$ in mg L$^{-1}$) for: (a) the ADCP acoustic intensity; (b) the ADV sensors during the March 23-30, 2010 data collection and (c) the ADV sensors during the April 2-9, 2010 data collection period. Note that for each experimental period two ADV calibration curves are shown corresponding to the two sensors installed at 0.2 and 1.0 m above the bed. $N$ denotes the number of data pairs and $R$ the correlation coefficient.

4.3 Sediment Settling Velocity and Effective Density Estimates

Sediment settling velocities were estimated using the method of balancing the vertical flux of sediment as initially proposed by Fugate and Friedrichs [2002]. According to this method, instantaneous vertical velocity values and sediment concentrations from the calibrated signal of the ADV sensor can be used to estimate the vertical flux of sediment. In the absence of significant horizontal sediment advection should be balanced by the product of mean concentration ($\bar{C}$) and settling velocity ($w_s$) as follows:

$$w_s \cdot \bar{C} = \langle w' C' \rangle ,$$

(5)

where $C'$ and $w'$ are the instantaneous concentration and vertical velocity fluctuation values obtained from the ADV. It should be noted that Fugate and Friedrichs [2002] only calculated the tidally averaged settling velocity for tidal cycles using all estimated values of mean SPM concentration and vertical SPM turbulent fluxes. However, Voulgaris and Meyers [2004] applied this method to resolve the tidal variability of settling velocity in a tidal creek environment and this is the method adopted in this study.

The particle effective density, $\Delta \rho$ (in kg m$^{-3}$) defined as the difference between the particle and water densities, was calculated using [Mikkelsen and Pejrup, 2001]:

$$\Delta \rho = \frac{C}{VC} ,$$

(6)

where $C$ is the SPM mass concentration (in mg L$^{-1}$) estimated from the acoustic inversion of the ADCP acoustic signal (see equation 4) and VC is the volume concentration (in $\mu$l L$^{-1}$) obtained from the LISST data.
5 Results

5.1 Temporal Variability of Hydrodynamics and Sediment Characteristics

The mean current data obtained from the ADCP were combined with those from the EMCM and ADV to extend close to the bed the description of the vertical variability of flow throughout the water column. The resulting vertical distribution of mean current speed is shown in Figures 3a and 4a, for the March (year days 82 - 89) and April (year days 92 - 99) data collection periods, respectively. A phase difference between current speed and water level is observed where minimum flow (i.e., slack water) occurs approximately 30 min after high or low water level. The maximum surface current speed measured was approximately 0.9 m s\(^{-1}\) and 1.1 m s\(^{-1}\) for the neap and spring tides respectively, which correspond to tidal ranges of 4.0 and 5.6 m. Within the bottom boundary layer, the velocities are slightly reduced to 0.7 m s\(^{-1}\) at 1.0 m above the seabed (e.g., year day 87.6). It is also worth noting that close to bed the flow appears to be flood dominant. Higher in the water column, the flow is flood dominant only during spring tides (see Figure 4a, days 92.5 - 94.0), while during neap tides, there are occasions when the flow is ebb dominant (e.g., see Figure 4a, days 98 - 99) mainly due to the effect of river discharge.

Time series of the vertical distribution of salinity, as measured by the CTD profiling and the OBS associated with the tripod, are shown in Figures 3b and 4b for the two deployment periods. The tidal variability is clearly exhibited in the salinity signal. The contrast of salinity distribution indicates slightly to well mixed conditions during high water and stratified conditions during low water and flood stages, due to tidal straining. Salinity values exceed 29 psu within the whole water column during the spring period (e.g., year days 92.5 - 92.6, Figure 4b) while during periods with smaller tidal range, the high salinity values are constrained in the bottom and mid water levels. During low water, a salinity gradient develops with the lowest salinity (13 psu) occurring the surface layer and the highest (25 - 29 psu) near the seabed.

Similarly to the flow measurements, the ADCP derived SPM concentrations, were combined with the OBS-derived ones to obtain a water column concentration profile (Figures 3c and 4c). SPM concentrations are relatively low (< 20 mg L\(^{-1}\)) for the majority of the time, except during the spring tide periods at the end of March (year day 87.4 - 87.5, see Figure 3c) and beginning of April (year day 92.5 - 92.6 in Figure 4c). During these periods much larger concentrations were observed, especially close to the sea bed (i.e., 1 m above the bed), reaching values up to 300 - 400 mg L\(^{-1}\). Furthermore, the high SPM concentrations observed near the sea bed exhibit an asymmetry similar to that of the mean current speed as they are higher during the flood stage of the tide. This correlation of near bed flow intensity and vertical gradient of SPM concentration suggests that sediment resuspension is a local process with little effect of advection.

The temporal variability of the vertical distribution of the measured mean particle size, as extracted from the LISST data, shows an overall composite pattern suggesting two different processes operating at different time-scales. At longer time scales a trend of decreasing overall mean size from neap to spring tidal periods (days 82.5 - 88.8, see Figure 3d) is observed which is followed up by an increasing mean size from spring to neap (days 92.4 - 99.0, see Figure 4d). At shorter, tidal time scales the overall pattern is coarser particles being present during ebb and finer particles during flood. Given the stratified environment in the study site, light scattering caused by density differences can cause multiple scattering (i.e., Schlieren effect, see Mikkelsen et al. [2008]) that can affect the performance of the LISST readings (i.e., apparent decrease in particle size derived from the LISST). However, as per Mikkelsen et al. [2008], this effect is mainly concentrated in the region of the pycnocline and does not extend over large areas of the water column. The calculated buoyancy frequency (see Figures 3e and 4e) and the pycnocline (see dot-lines in Figures 3e and 4e) do not seem to correlate with abrupt, localised changes in the LISST derived sizes (see Figures 3d
and 4d). We interpret this as insignificant to minimal affect of stratification to the LISST derived data.

Figure 3. Vertical and temporal variability of (a) current speed (m s$^{-1}$), (b) salinity (psu), (c) SPM concentration (mg L$^{-1}$), (d) in situ mean particle size (µm) and (e) buoyancy frequency (s$^{-1}$) as measured from the anchored boat during the period March 23-30, 2010. The line in panel (d) shows the temporal variation of depth averaged mean particle size while the horizontal solid and dashed lines in panel (a) denote neap and spring tidal conditions, respectively; the dot-line in panel (e) denote the location of the pycnocline defined as the location of the maximum value of buoyancy flux.
Figure 4. Vertical and temporal variability of (a) current speed (m s\(^{-1}\)), (b) salinity (psu), (c) SPM concentration (mg L\(^{-1}\)), (d) in situ mean particle size (µm) and (e) buoyancy frequency (s\(^{-1}\)) as measured from the anchored boat during the period April 2-9, 2010. The line in panel (d) shows the temporal variation of depth averaged mean particle size while the horizontal solid and dashed lines in panel (a) denote neap and spring tidal conditions, respectively; the dot-line in panel (e) denote the location of the pycnocline defined as the location of the maximum value of buoyancy flux.

5.2 Averaged Tidal Conditions

As shown in the previous section, neap and spring tidal conditions differ by over 1.5 m in terms of tidal range and over 0.5 m s\(^{-1}\) in terms of maximum current speed. In addition, flood dominance is more prominent during spring tides. These observations exemplify the different processes that occur between spring and neap tides. In an attempt to explore further these differences, and to obtain insights on flocculation processes for different tidal conditions, the time-series shown in Figures 3a and 4a are segregated by tidal range to those corresponding to spring and neap conditions, respectively. This segregation was based on maximum tidal range for each 24 hours tidal cycle. Data collected during 24 hour periods with a maximum tidal range less than 4.5 m were assumed to representat neap tidal conditions, while data collected during periods with maximum ranges greater...
than 4.5 m were assumed to be representative of spring tide conditions. Subsequently, all data from
the same category (neap or spring) of tidal conditions were phase-averaged as in *Murphy and
Voulgaris* [2006] and *Voulgaris and Meyers* [2004], and representative mean spring and neap 24-
hour tidal cycles were calculated. The selection of two tidal cycles (24 hrs) for tidally averaging was
based partially on our attempt to capture the small inequality of the 2 successive tidal cycles (see
Figures 3 and 4) but more importantly on the fact that this method allows for a better visualization
of the processes during low water. Selecting only one tidal cycle makes this harder due to
discontinuity at the beginning and end of the averaged tidal cycle. Furthermore, using two tidal
cycles provides some additional statistical confidence in the results by examining the repeatability of
the process under examination. The vertical distribution of mean flow, salinity, SPM concentration
and mean size of sediment in suspension for each of these averaged tidal cycles are shown in Figure
5.

Figure 5. Phase averaged tidal and vertical variability of (a)/(h) current speed (m s$^{-1}$), (b)/(i) salinity (psu) and averaged
location of pycnocline (dashed line), (c)/(j) SPM concentration (mg L$^{-1}$), (d)/(k) *in situ* mean particle size ($\mu$m), (e)/(l)
difference between mean particle and median particle size (i.e., $M_p - M_z$), (f)/(m) effective density (in kg m$^{-3}$) of sediment
in suspension estimated using equation (6), and (g)/(n) turbulence dissipation parameter ($G$ in s$^{-1}$). Panels on the left
represent neap conditions while those on the right represent spring tidal conditions.
The phase-averaged data (Figure 5) present a clear picture of the temporal and vertical variability of the the flow throughout the tidal cycle. Surface current velocities are much higher during the spring periods (>1 m s\(^{-1}\)) near the sea surface while during both neap and spring periods current speed is reduced close to the sea bed due to friction (see Figures 5a and h). The phase-averaged salinity plots (Figures 5b and i) show stratification during low water and at the early stages of flood for the neap tidal cycle, but mixed conditions during spring tides mainly due to the higher kinetic energy of the flow, despite the higher salinity levels observed near the bed at high water.

The phase-averaged neap and spring tidal cycle SPM concentration time series represent a case in which high concentrations are present near the sea bed with the spring near bed concentration being almost an order of magnitude larger than that observed under neap conditions (see Figures 5c and j). For both neap and spring conditions, peak SPM concentrations occur mainly during the flood and ebb maxima of the tide in response of the stronger current speeds at these times. However, during spring tides and at the first tidal cycle (see Figure 5j, hours -8 to -6) higher concentrations are found during high water. This is attributed to higher current speeds occurring at this composite tidal cycle (see Figure 5h) even during high water; this might allow for advection and settling of material that was resuspended during the previous flood stage of the tide. This is not the case for the subsequent tidal cycle where the flows are weaker and a clear drop in current speed is found at slack water. In this latter case the SPM exhibits two maxima, a main one coinciding with the flood period of the flow, and a weaker one at the ebb stage of the flow similarly to the pattern for the neap tidal conditions.

The mean particle size data obtained in situ using the LISST in a profiling mode show increase in mean particle size from the bed toward the sea surface which is much more profound during neap conditions (Figure 5d). During spring tides (Figure 5k) the coarsening with elevation above the sea bed is still observable but certainly less profound than that shown during the neap tidal cycle. In both cases the coarser sizes are found during low water slack conditions with the particles at neap tide being larger (~200 µm) than those found during spring conditions (~60 µm). The difference between median and mean size \((M_d - M_z)\) provides a proxy for the size uniformity of the population of sediment in suspension; the smaller this value the more uniform the distribution of sizes in suspension in the water column. During neap conditions (Figure 5e) this difference is between 50 to 100 µm for the majority of the water column, with the exception of the lowest 2 m above the sea bed and for periods of strong current flows. During spring tides (Figure 5l) these values of \(M_d - M_z\) are found only near the sea surface (up to 3m below the sea surface) waters and also during low water slack conditions. The effective density estimated using the SPM concentrations from the ADCP and the volume concentrations from the LISST (see equation 6) shows a general pattern of decreasing value with increasing elevation above the seabed (see Figures 5f and m). The particles with small effective density are usually observed in the upper layers of the water column which are also the areas where high values of mean particle size \((M_z)\) are found. During spring tides (Figure 5m), intensified mixing due to stronger flows allows particles with relatively high effective density to disperse higher in the water column.

5.3 Turbulence and Shear Velocity Estimates within the Bottom Boundary Layer

The current speed measured at 1.0 m above the bed is used as a representative parameter to describe nearbed flow variability within a tidal cycle (see Figure 6a). The time series of this current speed show a flood dominance during neap conditions (Figure 6a) when the current speed reaches a peak of approximately 0.55 m s\(^{-1}\), whilst the maximum ebb current speed at 1 m above the bed is between 0.30 and 0.40 m s\(^{-1}\). During the spring tidal cycle (Figure 6f), the flow exhibits a weak ebb dominance with a maximum speed of 0.65 m s\(^{-1}\) at 1 m above the bed; the maximum flood current is 0.61 m s\(^{-1}\). A weather station located some 150 km upstream the study site recorded a rain storm (with rainfall of more than 50 mm per day) in early March and heavy precipitation (rainfall more...
than 25 mm per day) in late March. Although these events may be responsible for enhancement of the ebb flow due to increased river discharge, no river discharge data are available to verify this. A comparison of the shear velocity values, obtained by the two different methods (see Section 4.1) shows agreement in both absolute value and tidal variability pattern (see Figures 6b and g, respectively). Thus, a mean value of the two shear velocity estimates per ADV sensor/elevation was calculated so two estimates (one per elevation) were obtained. A comparison of the mean shear velocities estimated at 1.0 m above the seabed with those derived from the sensors located at 0.2 m above bed is shown in Figures 6c and h. The good agreement of the two estimates confirms the assumption that our measurements were carried out within the constant stress layer. In order to increase the significance of the estimates, the shear velocities from the two elevations were further averaged to produce a single mean shear velocity value that is deemed representative of the tidal variation and it is used to describe the flow in the subsequent analyses.

Figure 6. Phase averaged tidal variability of (a)/(f) water level (m) and near bed current speed (m s⁻¹), (b)/(g) mean shear velocity (m s⁻¹) calculated using the Reynolds stress (u*²S) and inertial dissipation (u*²d) methods at the elevations of ADV sensor installation (1.0 and 0.2 m above the bed), (c)/(h) averaged mean shear velocity (m s⁻¹) by method and for each elevation, (d)/(i) suspended sediment concentration (mg L⁻¹) and its vertical gradient dC/dz (estimated from the 0.2 - 1.3 m above the seabed region), and (e)/(j) sediment settling velocity Wₛ,ADV estimated from the ADV signal using the sediment vertical flux method at the 2 ADV sensor levels (0.2 and 1.0 m above the bed). Panels on the left (a to e) represent neap conditions while those on the right (f to j) represent spring tidal conditions.

5.4 Sediment Resuspension

Similarly to the analysis of the mean current speed and shear velocity, the tidal variability of SPM was estimated for each averaged tidal period using the calibrated ADCP signal. The time-series from a single elevation (1 m above the sea bed) are shown in Figure 6 for the neap (Figure 6d) and spring (Figure 6i) tidal periods, respectively. In addition, the mean vertical gradient in mass concentration (dC/dz) was estimated from the same data and for the same elevation and it is shown on the same figure panels. The data reveal a tidal variability of SPM concentration that resembles those of the current and shear stress velocities, suggesting that local resuspension is the main controlling factor for the SPM concentration variations within the bottom boundary layer.

Following slack water at either low or high water the current speed gradually increases, reaching a maximum some 2 hours later (Figures 6a and f). The SPM concentration increases in a similar
pattern, though it attains its maximum value some 1 to 2 hours after the maximum current speed is reached. This could be explained by the mechanism of sediment movement lag or “diffusion/settling lag” as discussed by Yu et al. [2011]. Especially during flood, the high SPM concentration can persist all the way to high water level. A sharp decrease in SPM concentration occurs during high water (6 hours before or after the middle low water level) presumably due to particle settling which is associated with a period of high vertical gradient \(dC/dz\) in SPM concentration. A minimum SPM concentration (<10 mg L\(^{-1}\)) is found during low water and lasts for approximately 2 hours; this minimum SPM is associated with a low vertical gradient in mass concentration which corresponds to periods of low bed shear velocity (see Figures 6c and h).

In general, SPM concentration values are low (<50 mg L\(^{-1}\)) on neaps while they increase almost by an order of magnitude, reaching up to 300 - 400 mg L\(^{-1}\), on springs. The data suggest that bottom shear velocity values of 0.015 m s\(^{-1}\) and 0.02 m s\(^{-1}\) (i.e., corresponding to shear stress values of 0.23 N m\(^{-2}\) and 0.41 N m\(^{-2}\), respectively) might represent the critical values for maintaining resuspension with high SPM concentrations >10-30 mg L\(^{-1}\) and >100 mg L\(^{-1}\) during the neap and spring tides, respectively (Figures 6d, i). Nevertheless, the persistent occurrence of high shear stress over a longer period of time can contribute to higher SPM concentrations during the spring period through a continuous entrainment of sediment into the water column that can explain the higher SPM values found during spring than neap periods. The total periods when mean shear velocity exceeds the critical value of 0.02 m s\(^{-1}\) are between 13 to 15 hours on springs (Figure 6h), and 9 to 12 hours on neap tides (Figures 6c). In addition, the maximum/mean shear velocities are much higher (0.044 / 0.025 m s\(^{-1}\)) during the spring than during neap (0.035 / 0.019 m s\(^{-1}\)).

5.5 Settling Velocity Estimates

The estimation of the settling velocity using the ADV signal assumes that gravitational settling is balanced by upward motions due to turbulence. This assumption requires the effect of local and advective accelerations to be negligible [Fugate and Friedrichs, 2002; Voulgaris and Meyers, 2004]. In this study, estimations of the local acceleration term \(\partial C/\partial t\) verified that its value is 2 to 3 orders smaller than the settling term \(w_\ast \partial C/\partial z\). Unfortunately, no information exists on the horizontal gradient of sediment concentration, and as such no estimates of the advection term \((u\partial C/\partial x+C\partial u/\partial x)\) can be produced. The Fugate and Friedrichs [2002] study was carried out in a estuarine environment and they found that advection was not a significant issue although the hydrodynamics were slightly different than ours. In here, we use the relationship between SPM concentration and bottom shear stress as a proxy to evaluate the effect of advection. This is shown in Figure 7 for neap and spring conditions for both ADV elevations above the seabed. These scatter plots indicate relatively close correlations between the two variables especially for neap conditions, independently of elevation above the bed, with the ebb correlation providing higher correlations with shear stress than during the flood (Figures 7a and c). During spring conditions the correlation is lower especially at 1.0 m above the bed (Figure 7d) suggesting more influence of advection. So although we are not able to quantify the effect of advection the correlations presented earlier suggest small influence during the neap conditions and higher effect during spring conditions especially higher in the water column. As such the ADV derived estimates of settling velocity might be contaminated by advection during spring tides and this should be taken into consideration during data interpretation.

The settling velocities derived by both ADVs (see equation 5) are shown in Figures 6e and j, after being phased-averaged to reproduce the neap and spring tidal cycles. They vary between 0.1 mm s\(^{-1}\) at slack water and 5.0 mm s\(^{-1}\) mainly during the flood and ebb stages of the tidal cycle.
Figure 7. Scatter plots between shear stress ($\tau$, m s$^{-1}$) and suspended sediment concentration (C, mg L$^{-1}$) measured at (a)/(b) 0.2 m and (c)/(d) 1.0 m above the bed. Panels on the left (a and c) represent neap tides while those on the right (b and d) represent spring tidal conditions.

6 Discussion

6.1 Flocculation Processes

Overall the data collected and presented in this study are indicative of a tidally variable sediment resuspension process that is also modulated by the neap-spring cycle. The variability in mean size shown in Figures 5d and k suggests that flocculation processes are active. The $M_s$ values (see Figures 5d and k) estimated with the LISST are more than 10 times larger than that values estimated in the laboratory from the dispersed sediment found in the water samples (see Table 1). The latter was found to be consistently around 10 $\mu$m throughout the water column. The mean size from the in situ LISST measurement, on the other hand, varies from 18 $\mu$m to 350 $\mu$m (see Figure 5d). This difference in mean particle size between in situ and water sample (i.e., dispersed) derived sediment sizes is indicative of flocculation processes operating in the estuary with the particles measured by the LISST being mainly flocculates consisting of a primary population of sediment with a mean size of 10 $\mu$m as derived in the laboratory.

Table 1 Mean grain size ($M_s$) and its corresponding 95% confidence interval for sediment found in suspension. The results were derived from the analysis of dispersed sediment obtained from 139 water samples collected on April 3, 5, and 7, 2010 and remotely from in situ measurements using LISST (statistics in 95% confidence interval). The results from the dispersed samples represent the primary sedimentary particles, while the in situ values represent the flocculated particles.

<table>
<thead>
<tr>
<th>Water column</th>
<th>Neap Tide</th>
<th>Spring Tide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dispersed</td>
<td>$M_s$ (µm)</td>
</tr>
<tr>
<td></td>
<td>$M_d$ (µm)</td>
<td>$M_t$ (µm)</td>
</tr>
<tr>
<td>Upper</td>
<td>10.6±0.2</td>
<td>12.8±0.6</td>
</tr>
<tr>
<td>Middle</td>
<td>8.7±0.4</td>
<td>10.2±0.3</td>
</tr>
<tr>
<td>Lower</td>
<td>9.6±0.0</td>
<td>10.6±0.0</td>
</tr>
<tr>
<td>Mean Values</td>
<td>9.6</td>
<td>11.2</td>
</tr>
</tbody>
</table>
The in situ sizes are mostly larger during the neap period (>128 µm) while during spring tide the sizes observed are mainly smaller than 128 µm in diameter (see Figures 5d and k). Within a tidal cycle, the floc size is larger at low water and decreases at mid-flood and ebb stages. A prominent emerging pattern is that macroflocs (> 128 µm) develop mainly near the surface while microflocs (< 128 µm) are found mainly close to seabed. Furthermore, the macrofloc sizes seem to extend throughout the water column during low water (slack conditions, see year day 96.5 in Figure 4d) and middle low water level (see Figure 5d). This pattern of vertically varying floc size under energetic flow conditions suggests that turbulence, as it varies within elevation above the sea bed, might be the controlling factor. This is further supported by the fact that floc sizes are roughly uniformly distributed in the water column at less energetic flow conditions, when turbulence levels are reduced.

Figure 8. Histograms for neap (black bars) and spring (shaded bars) tidal conditions showing: (a)/(d) primary grain size distribution of sediment in suspension as derived from the analysis of dispersed sediment obtained from water samples collected in the middle of the water column; (b)/(e) in situ particle size distribution of sediment in suspension using the LISST-100X; and (c)/(f) seabed sediment grain size distribution. The analysis of the sediment from the water samples (a)/(d) and the seabed was carried out in the laboratory using a Malvern Mastersizer 2000 instrument. The left panel represents the tidal phase of low water and the right middle flood, respectively.

The laboratory analysis of the dispersed water column sediments, showed a unimodal primary particle size distribution with a mean size of approximately 10 µm (cf. Table 1). Similar results were obtained from sediment samples for neap and spring tides (see Figures 8a and d) which are typical for all the analyses of dispersed sediment we carried out. On the other hand, the LISST derived sediment particle size distribution recorded in the middle part of the water column revealed a mostly bimodal distribution, as shown in Figures 8b and e for two discrete times during the data collection period corresponding to flood and low water conditions, respectively. The peaks of this bimodal distribution correspond to particle diameters of approximately 20 µm and 250 µm. The shift of the peaks between the primary and in situ sizes is indicative again of aggregation being operational in this natural estuarine environment. In addition, the coarser component has been more prominent during neap and low water than during spring and middle flood (Figures 8b and e) with the former conditions being representative of less energetic flow conditions. The analysis of one of the bed sediment samples showed a distinct bimodal distribution during low water (Figure 8c) with the peak
corresponding to the finer sizes being around 9 μm, similar to the diameter of dispersed SPM.

However, the in situ distribution of the suspended sediment (Figure 8b) resembles that of the bed sediment but with the finer sediment mode being slightly coarser than the corresponding mode on the seabed. The coarser size modes of the SPM, at mid-water and bottom sediments appear to be identical in size (Figures 8b and c). Since these samples correspond to slack water conditions, when no significant flow and/or turbulence exists, the mode of sediment with the larger size cannot originate from the sea bed; most likely is the result of sediment aggregation due to flocculation of the primary sediment. This occurs in the water column in response to higher turbulent levels that were present at preceding times; the aggregated sediment was subsequently settled onto the sea bed.

In addition, the fine component can be entrained into the water column by energetic flows during middle flood, and then only few of the fine particles would remain on the sea bed, especially during spring tides (Figure 8f).

6.2 The Effect of Turbulence

In order to examine the interplay between turbulence and particle size we utilize the concept of the Kolmogorov microscale which represents the maximum size of turbulent eddies present in a turbulent environment [Tennekes and Lumley, 1972]. These eddies control the maximum size of flocs present in a turbulent environment as any floc with a size greater than this parameter will be sheared off by the eddies while smaller in size flocs can be enclosed within the eddy and as such remain unaffected [van Leussen, 1997; Verney et al., 2011]. The Kolmogorov microscale can be estimated from the turbulence dissipation rate (ε) obtained using the inertial dissipation method as [Tennekes and Lumley, 1972]:

\[
\eta = \left( \frac{\nu}{\epsilon} \right)^{\frac{1}{3}},
\]

where \( \nu \) is the molecular viscosity. This correlation indicates that variations in floc size are limited by the turbulent eddy evolution during a tidal cycle. Another similar parameter usually used in the study of turbulence effects on floc creation is the dissipation parameter \( G \) [van Leussen and Cornelisse, 1993] which again is a function of the turbulence dissipation rate (ε) and defined as:

\[
G = \left( \frac{\epsilon}{\nu} \right)^{\frac{1}{5}}.
\]

The in situ particle sizes measured by the LISST are plotted against the associated turbulence parameters, defined above in Figure 9a. A significant negative relationship is found between in situ floc mean size and the turbulence dissipation parameter (G) which suggests that reduction in size is due to high turbulent shear that tends to destroy aggregates. The tidal variability of the dissipation parameter \( G \) is shown in Figures 5g and n for neap and spring tides, respectively; \( G \) takes high values during periods of strong flow at mid-flood and -ebb stages, especially close to the seabed (see Figures 5g and n). This pattern is similar to that of floc distribution within the water column (e.g., Figures 5d and e) which suggests a flocculation mechanism similar to that identified by Manning and Dyer [1999]. In their study it was shown that floc mean size (\( M_c \)) is proportional to \( G^{-m} \), where the exponent \( m \) varied between 0.47 and 1.29 for 80 and 200 mg L\(^{-1}\) concentrations, respectively. A similar trend is obtained with our data with the exponent \( m \) taking a value of 0.43 (see Figure 9a). In our analysis we were not able to identify a correlation of the exponent \( m \) with mass concentration as in Manning and Dyer [1999], however replacing the parameter \( G \) with the product of mass concentration and \( G \), (i.e., \( C \cdot G \)), we were able to significantly improve the correlation with \( M_c \) from -0.59 to -0.83 using the relationship (Figure 9b):
The above equation implies that floc size decreases both with concentration and turbulence although it should be noted that the two parameters are not independent from each other, as high turbulence allows for higher quantities of sediment being present in the water column.

Effective density ($\Delta \rho$) and mean floc size ($M_z$) appear to be negatively correlated with a slope of -0.84 (see Figure 9c), which is between the slope of -0.46 for flocs on the Californian Shelf found by Sternberg et al. [1999] using video techniques and a value of -1.084 for the Tamar Estuary by Fennessy et al. [1994]. This lends credibility to the method used to obtain $\Delta \rho$ in the present study, where LISST estimates of VC were coupled with SPM data. The scatter in the data set could be due to operational constraints or simply to natural variability.

More complicated models for the quantification of the dependence of mean particle size of flocculated particles to turbulence include that of Manning and Dyer [1999] which relates mean floc size ($M_z$) to dissipation parameter ($G$), sediment concentration ($C$) and aggregate settling velocity ($W_s$). Following their approach and using a multiple regression analysis we were able to increase the correlation ($R=0.87$, $N=26$) between measured and predicted mean floc sizes using the following equation:

$$M_z = 200(C \cdot G)^{-0.25}.$$  \tag{9}
In addition to the relationship shown above, Winterwerp [1998] has developed a dynamical model that describes flocculation and change of mean floc size as a function of time. This model was recently extended by Law et al. [2013] to account for sediment advection. This more advanced dynamical model relates changes in aggregate representative size \( D \) to the initial size of the aggregate, the size of the primary particle \( (D_p) \), sediment mass concentration \( (C) \) and turbulence conditions represented by the dissipation parameter \( (G) \) and by advection [Law et al., 2013]:

\[
\frac{dD}{dt} = k_A CGD^2 - k_B G^{3/2} D^2 (D - D_p) - (u - u_m) \alpha_D,
\]

where \( D \) is a representative particle size which can be the median or the mean, \( k_A \) is an aggregation parameter with units of \((m^2 \text{kg}^{-1})\), \( k_B \) is a floc breakup parameter with units of \((s^{3/2} \text{m}^{-2})\), \( C \) is the mass concentration of the sediment in suspension \((\text{in kg m}^{-3})\), \( G \) is the dissipation parameter \((s^{-1})\) and \( D_p \) is the representative size of the primary particles, the last term in the equation represents advection with \( \alpha_D \) being the longitudinal gradient in flocculated size, \( u \) the tidal flow and \( u_m \) the tidally averaged mean flow.

In here we use the mean floc size \( (M_f) \) as representative diameter \( D \), and mean size of dispersed sediment as representative size of the primary particles \( D_p \) (see Table 1). Using the flow, SPM concentration and turbulence information obtained at 1.0 m above the seabed (cf. Figure 6), equation (11) was fitted to the data for both neap and spring tides. The least square fitting \((R=0.65, N=26)\) resulted in estimating an aggregation parameter \( (k_A) \) of \(7.84 \times 10^{-7} \text{ m}^2 \text{kg}^{-1}\) and a floc breakup parameter \( (k_B) \) of \(2.54 \times 10^{-10} s^{3/2} \text{m}^{-2}\), and a longitudinal gradient of flocculated size \( (\alpha_D) \) of \(7.2 \times 10^{-3} \mu \text{m m}^{-1}\) which suggests that the effect of advection on the spatial floc size is \(7.2 \mu \text{m km}^{-1}\) along the estuary.

An inter-comparison of the performance of the three models presented above is shown in Figures 10a and b for the neap and spring tidal cycles where the model predictions are plotted as a time-series with the measurements superimposed. In Table 2, the RMS errors between model predicted and observed values are listed for each model. The error analysis shows the Dyer and Manning [1999] model of equation (10) producing the least error overall error, while the most overall error is produced by the Winterwerp [1998] model as has been modified by Law et al. [2013] to account for advection (see equation 11). The simple model of equation (9) that describes mean size as being proportional of the product of mean mass concentration and turbulence has an error of 28 \( \mu \text{m} \), which statistically is not different than that of Dyer and Manning [1999] which had an error of 22 \( \mu \text{m} \).

![Figure 10](image)

Figure 10. Comparison of observed (dots) and predicted (lines) tidal variability of floc mean size and sediment settling velocity: (a, b) observations (dots) and predicted (lines) floc mean size \( (M_f, \mu \text{m}) \); (c, d) observations (dots) and predicted (lines) sediment settling velocity \( (W_s, \text{mm s}^{-1}) \), for tidally averaged neap and spring conditions, respectively, at 1.0 m above the seabed.

*Wang et al., 2013: Sediment resuspension, flocculation and settling in a macrotidal estuary, JGR*
distribution is not
significant amount of organic
This is

W Stokes

\[ gM \rho - \Delta \mu \]

The existence of significant amount of organic

\[ W_{s-Stokes} = \frac{\Delta \rho g M_{z}^2}{18\mu} \]

where \( \mu \) is the water viscosity. Despite the Stoke’s law, when we plot the estimated settling velocity against the product \( (\Delta \rho \cdot M_{z})^2 \) we still see a negative relationship (Figure 11b) which is due to the fact that our data have shown that effective density reduces with increasing floc size (see Figure 9c).

This discrepancy can only be explained by inaccurate estimates of effective density. This is plausible and can be the result of (i) erroneous estimates of volumetric concentration from LISST; (ii) erroneous mass concentration values obtained from the calibrated ADCP data; and (iii) a combination of both of the above. For example, the existence of significant amount of organic detritus material will appear as a large volume in measurements based on optics, but might be transparent in acoustic measurements. This could create discrepancies like the ones we see in here, especially during this period as it coincided with the storm associated river discharge we mentioned earlier that occurred in the March experiment of 2010.

Table 2 Root mean square (RMS) errors of flocculation and settling model results comparison with measured at 1.0 m above the bed.

<table>
<thead>
<tr>
<th>Mean Floc Diameter, ( M_z (\mu \text{m}) )</th>
<th>Settling Velocity, ( W_z (\text{mm s}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{Eq.9}</td>
<td>\textit{Eq.10}</td>
</tr>
<tr>
<td>Neap</td>
<td>30±11</td>
</tr>
<tr>
<td>Spring</td>
<td>26±9</td>
</tr>
<tr>
<td>Mean</td>
<td>28±7</td>
</tr>
</tbody>
</table>

6.3 Settling Velocity of Aggregates

A number of earlier studies have attempted to relate the settling velocity of aggregates with their diameter and SPM concentration using Stoke’s law (e.g., Mikkelsen and Pejrup [2001]; Winterwerp [2002]). In addition, empirical formulae have been used to establish a relationship between settling velocities and mean size of aggregates [Voulgaris and Meyers, 2004]. Despite the uncertainty regarding the influence of advection in our estimation of settling velocity values, similar correlations have been attempted in here and the results are shown in Figure 11a together with the empirical relationships from other investigators. Our data fail to reveal a correlation between settling velocity and either floc size and/or SPM concentration. However, a weak correlation emerges when the tidally averaged data sets are separated by tidal type (i.e., neap vs. spring). Surprisingly, the \( W_z \) vs. \( M_z \) relationship (Figure 11a) derived in here are much different than that from the previous studies [Mikkelsen and Pejrup, 2001; Sternberg et al., 1999; Voulgaris and Meyers, 2004] as it suggests a decrease of settling velocity with increasing floc size.

According to Stokes’ law, the settling velocity of a flocculated particle should depend on its size and its effective density, this is something that has been successfully applied to flocculated particles elsewhere [Manning and Dyer, 1999; Mikkelsen and Pejrup, 2001; Winterwerp, 1998]:

\[ W_{s-Stokes} = \frac{\Delta \rho g M_{z}^2}{18\mu} \]
Figure 11. Scatter plots of sediment settling velocity ($W_s$, mm s$^{-1}$) values obtained using the ADV and (a) in situ floc mean size ($M_z$, µm); (b) the product of sediment effective density and floc mean size ($\Delta \rho M_z^2$); (c) turbulence dissipation parameter ($G$, s$^{-1}$); and (d) the product of mean floc size and turbulence dissipation parameter ($M_z G$) as measured at 1.0 m above the seabed. $N$ denotes the number of data in each plot and $R$ is the correlation coefficient. The dashed and solid lines shown in panel (a) represent the least square fit regression lines for the tidally averaged data obtained during neap and spring, respectively.

A notable relationship between settling velocity and turbulence dissipation parameter (see Figure 11c), as also suggested by Manning et al. [2011] and Spearman et al. [2011] is found in the data. This relationship indicates that settling velocities increase with increasing turbulent dissipation as follows (Figure 11c):

$$W_s = 0.20G^{1.22},$$

(13)

with a correlation coefficient ($R$) value of 0.82 ($N=26$). In addition, the product of mean floc size and turbulent dissipation parameter ($M_z G$, in mm s$^{-1}$) was found to be significantly positive related to settling velocity ($W_s$) (Figure 11d):

$$W_s = 3.28(M_z G) + 0.19,$$

(14)

with a correlation coefficient ($R$) value of 0.53 ($N=26$) significant at the 95% confidence interval. Also, it should be noted that a correlation between settling velocity and mean size, turbulence and floc size can also be extracted from equation (10) presented earlier.

A comparison of the performance of the settling velocity models presented above is shown in Figures 10c and d with the RMS error between predicted and observed values listed in Table 2 for each model. From this analysis the empirical exponential model of equation (13) produces the least error of 0.76 mm s$^{-1}$, and a slightly larger but not significantly different error of 0.90 mm s$^{-1}$ is found when using equation (14). Solving the multiple regression model of equation (10) for settling velocity provided the largest error of 3.86 mm s$^{-1}$, which is of the same magnitude as that of settling velocity itself.

6.4 Application of the Empirical Models to the Present Data Set

Although the mean floc size and settling velocity correlations presented in the previous section where based on near bed conditions, in here a qualitative evaluation is carried out by extending them throughout the water column. This is done after applying the appropriate scaling to the turbulence parameters with elevation above the seabed, while mean flow and suspended sediment mass values are obtained from the measured data (see Figures 5a-h, c-j, and g-n). The predicted mean floc size...
temporal and vertical distribution from equations (9), (10) and (11) are shown in Figures 12a-b, c-d and e-f, respectively. As expected all models capture the tidal variability. Equations (9) and (10) seem to either under- or over-estimate the size of the flocs (Figures 12a-b and c-d). However, qualitatively we argue that they reproduce the observed pattern of tidally variations (see Figures 5d and k) where macroflocs are present in the upper water column while microfloc are found closer to the sea bed in the lower parts of the water column. It is important to note that the dynamic model of Law et al. [2013] (equation 11) manages to reproduce not only the correct pattern but also the correct floc size values (see Figures 12e, f versus Figures 5d, k).

Figure 12. Tidal and vertical variability of mean floc size and floc settling velocity as they are predicted by the various regressions established in this study (see text for details). Panels on the left represent neap tidal conditions while panels on the right correspond to spring tidal conditions.

Settling velocities estimated using equation (13) show a pattern of high velocity values during periods of strong currents (i.e., at flood and ebb stages of the tidal cycle) which means that both strong resuspension and rapid settling occurs simultaneously (Figures 12g and h). In addition, the larger flocs located in the upper layer have a relatively small settling velocity, which in turn explains their longer residence in that part of the water column as confirmed by Manning et al. [2010a] who reported a similar case of smaller settling velocities for macrofloc than for microfloc. The flocs with settling velocity > 5 mm s\(^{-1}\) are confined within the bottom layer, e.g. 0-2 m above the seabed.

7 Conclusions

Hydrodynamic and sediment size measurements from an estuarine environment were presented in this study. Detailed analysis of the data showed that flocculation responds to local turbulence during both neap and spring tidal cycles. A significant negative relationship was found between floc mean size and turbulence dissipation parameter (see Figure 9a), which is further increased using the product of SPM concentration and turbulence dissipation parameter (see equation 9 and Figure 9b). This dependence of aggregate size to turbulence intensity explains the observations that revealed coarser particles within the upper water column with finer particles being confined mainly within the bottom boundary layer a region of higher turbulence intensity.

The statistics based, exponential-type model of equation (9) although agrees with the data near the bed (e.g., 1.0 m above the seabed) its performance deteriorates when applied throughout the water column. However, the model of Winterwerp [1998] as further developed by Law et al. [2013] to include advection appears to be able to reproduce the correct temporal and spatial distributions of
floc size throughout the water column. This model appears promising for simulating flocculation in coastal waters assuming that SPM concentration and turbulence are known or accurately estimated by other models, although more verification from different environments is recommended.

Aggregate settling velocity estimates did not show the same dependence on aggregate size that has been shown in other investigations, though it revealed a close correlation with shear (see equation 13).

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