Relationships among estuarine floc size, optical properties, organic content, and settling velocity: insights gained from combining LISST and a particle imaging camera system

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Typical near-surface estuarine particles are not single solid particles, but clusters of inorganic and organic particles and water, called flocs. Floc properties that influence water clarity (such as size, composition, density and settling rate) are challenging to observe in-situ, so their influence on the optical properties of the system is not well understood. The objective of this project is to use a combination of optical instrumentation with transmissometers and irradiance meters to measure important floc properties, investigate the influence of organic particles and local hydrodynamics on those properties, and evaluate the influence of suspended flocs on light propagation in a partially mixed estuary. This project focuses on observations collected along the York River estuary, a major tidal tributary of the Chesapeake Bay, located in southeastern, VA, USA.

Observations of floc properties and optical attenuation were collected using the VIMS Coastal Hydrodynamics and Sediment Dynamics (CHSD) water column profiler (Cartwright et al., 2013) and additional optical profiling instruments. Mounted on the CHSD profiler is a Sequoia Scientific Laser In-Situ Scattering and Transmissometry instrument Type C (LISST), a high-definition particle imaging camera system (PICS) that includes an integrated settling tube, a YSI-EXO2 water quality sonde with sensors for turbidity, fluorescent dissolved organic matter (fDOM), chlorophyll, and conductivity-temperature-pressure, and a high-speed pump sampler with an intake hose at roughly the same height as the LISST and YSI-EXO2. During each cruise, 6 to 7 stations along the York were sampled once on the same day. The profiler was deployed off the VIMS R/V Ellis Olsson 1 to 3 meters below the surface. While at depth, water samples were collected with the pump sampler. Water samples were then taken back to the lab to be analyzed for total suspended particulate matter/solids (TSS) and for organic content as estimated by combustion. Before each profiler cast, profiles of downward irradiance (E_d) were measured using a LI-COR irradiance meter and/or a TRIOS RAMSES hyperspectral radiometer. The linear regression coefficient (i.e. slope) of the logarithm of E_d with respect to depth yields the vertical diffuse attenuation coefficient, K_d (Kirk, 1994). In addition to observations of K_d, LISST optical transmission was used to estimate the beam attenuation coefficient, c (Hill et al., 2011; Neukermans et al., 2012).

Key floc properties were observed in situ with the LISST and PICS. The LISST provided observations of particle size distributions from ~2.5-500 microns (Agrawal and Pottsmith, 2000). The PICS provided observations of particle size distributions from 30-1000 microns. It utilizes an automated particle-tracking feature (PTV/PIV) that corrects for fluid motion in the settling chamber to observe individual particle settling rate and density of particles with diameters >30 microns (Smith and Friedrichs, 2015). Volume distributions from the LISST were used to estimate projected area distributions. Assuming spherical geometry, area concentration per liter, AC_i, was calculated by dividing the volume concentrations, VC_i, at each specified size class range, D_i, by D_i (Bowers et al., 2011; Slade and Boss, 2011; Neukermans et al., 2012). The PICS particle tracking analysis determines particle projected area, A, based on measured major and minor axes lengths, and estimates an equivalent spherical diameter, $esd = \sqrt{\frac{4A}{\pi}}$. In order to capture a larger size range of particles and account for limitations associated with both instruments, area distributions measured by the LISST (2.5-500 microns) and PICS (range 30-1000 microns) were combined to create one distribution from ~2.5-1000 microns. By combining this full size distribution with pump samples for mass concentration, effective bulk density, ρ_a, was determined, and bulk settling velocity, w_s, was calculated via a Stokes approximation (Mikkelsen and Perjup, 2001; Bowers et al., 2009; Fettweis and Baeye, 2015).

Observations and preliminary analysis presented here suggest that floc size, density, and Stokes settling velocity in surface waters are strongly related to the relative concentrations of inorganic versus organic solids in suspension. In general, particle size increased with increased TSS (Figure 1A), and as particle size decreased density increased (Figure 1B). An increase in the relative fraction of organic matter resulted in a decrease in particle size (Figure C) and a decrease in settling velocity (Figure 1D). Our results suggest that the relative concentration of organic matter influences the concentration of these smaller, continually suspended, particles. Estuarine residual transport further segregates organic and inorganic matter along the length of the York, causing smaller, organic rich, slowly settling flocs to make up a larger fraction of SPM in the lower estuary while, flocs in the upper estuary are dominantly inorganic, and tend to be larger with larger settling velocities.

In terms of light propagation, observations indicate that total area concentration, AC_T, rather than TSS, is the dominant control on beam (c) and diffuse (K_d) attenuation (Figure 2). c and K_d increase proportionally to AC_T, but K_d is much noisier than c. c measured using the LISST is often considered a proxy for scattering by particles rather than absorption, while K_d captures the absorbance due to color dissolved matter (CDOM), water, particles, in addition to scattering by particles (Kirk, 1994; Hill et al., 2011; Slade et al., 2011; Neukermans et al., 2012). Consistent with observations from other systems, c (or scattering) is controlled by particle area while K_d (absorption+scattering), is influenced by area, as well as other particle and water properties, as evident by the increased scatter in Figure 2D (Bowers et al., 2011; Neukermans et al., 2012). Particle size distributions showed the majority of the AC_T are attributed to smaller particles, highlighting the importance of smaller flocs on light attenuation. Smaller particle sizes have larger surface area to volume ratios, increasing light scattering, thus increasing attenuation (Babin et al., 2003; Neukermans et al., 2012; Hill et al, 2013).

Results from this study highlight the influence of the relative fraction of organic matter on floc properties and the importance of these relatively small, organic rich particles on light attenuation. In response to estuarine eutrophication (i.e., an increase in the rate of supply of organic matter), floc size and settling velocity are likely to evolve differently in distinct sections of partially mixed estuaries, indicating the need for localized management strategies over system based strategies in the future. Further analysis is needed to refine along-estuary trends. The preliminary results presented here do not take into account temporal trends (seasonal or tidal), nor do they account for the spatial variability of the local hydrodynamics. Current velocities and turbulence observed by the ADVs on the CHSD profiler need to be analyzed. In addition, trends in particle settling velocity and density measured by the PICS and relative influence of colored dissolved organic matter (CDOM) need to be investigated.

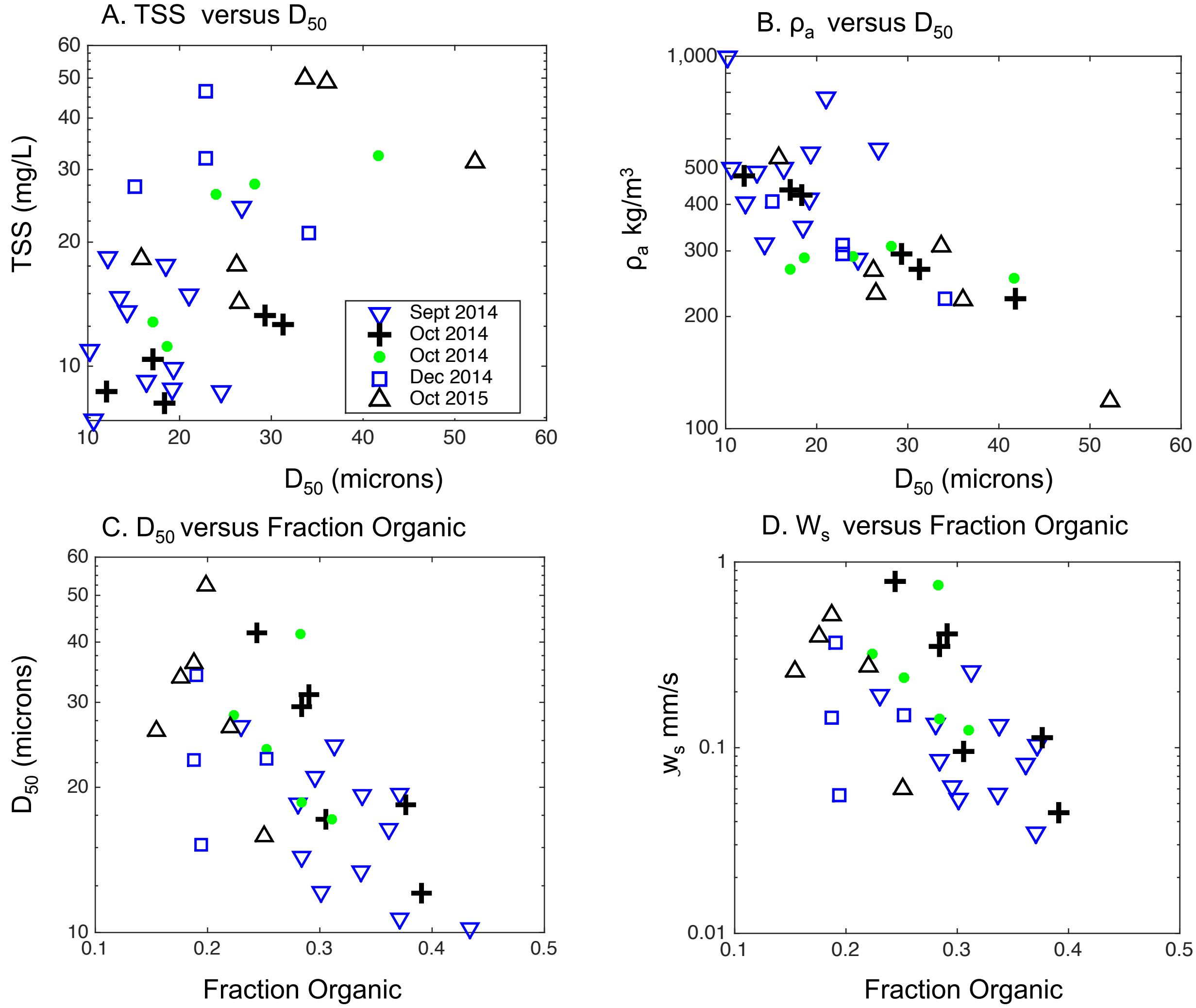

Figure 1: Relationship between median particle size (D_{50}) and total suspended solids, TSS (A), fraction of organic matter (B), apparent density, ρ_a (C), and Stokes settling velocity, w_s (D) in surface waters of the York River estuary.

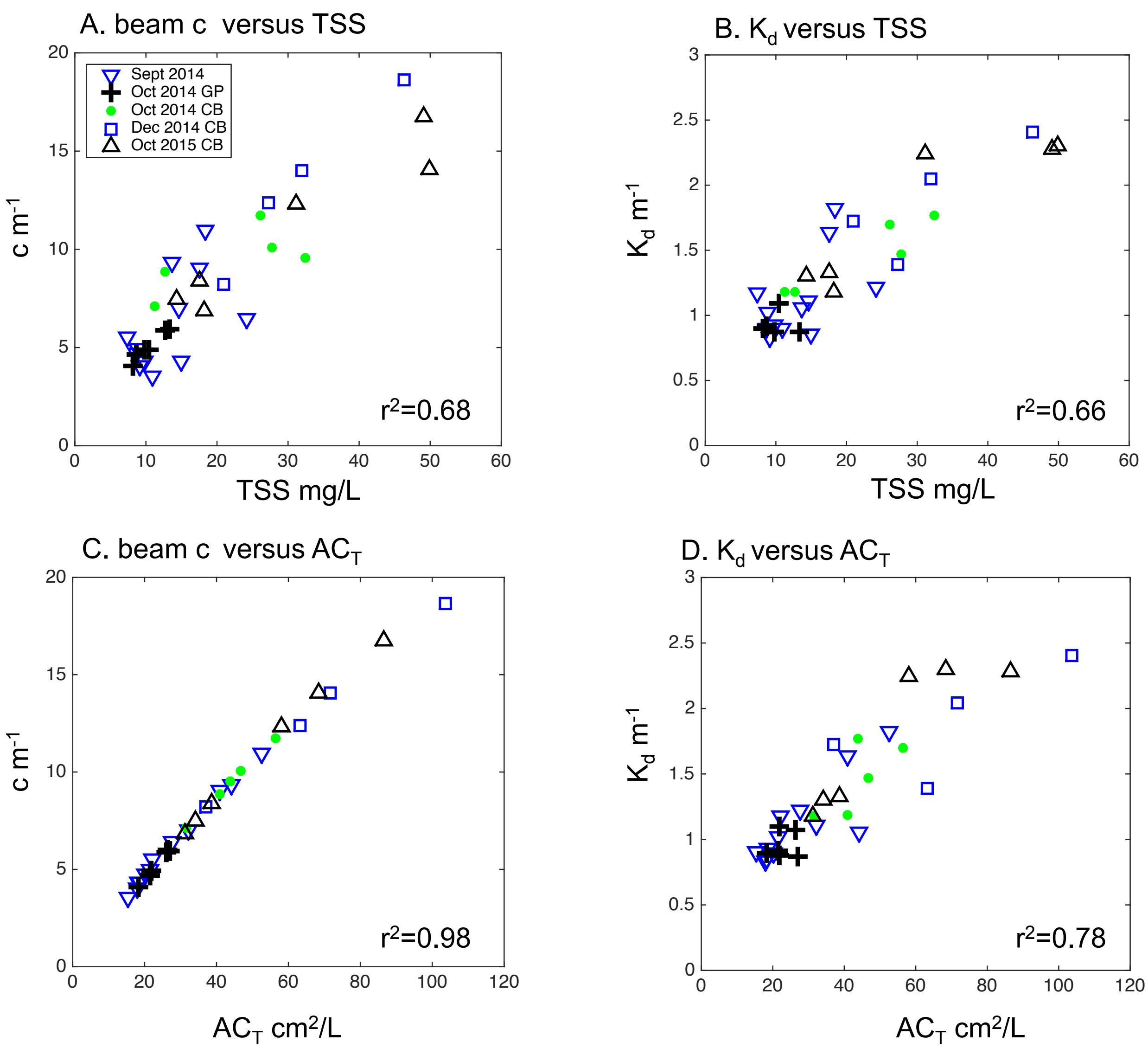

Figure 2: Relationships between optical attenuations, c (A,C) and K_d (B,D), and total suspended solids (TSS) and total area concentration AC_T in surface waters of the York River estuary.

References:

Agrawal, Y.C., Pottsmith, H.C., 2000. Instruments for particle size and settling velocity observations in sediment transport. Marine Geology 168: 89-114.

Babin, M., Morel, A., Fournier-Sicre, V., Fell, F., Stramski, D., 2003. Light scattering properties of marine particles in coastal and open ocean waters as related to the particle mass concentration. Limnology and Oceanography, 48, 843-859.

Bowers, D.G., Braithwaite, K.M., Nimmo-Smith, W.A.M., Graham, G.W., 2011. The optical efficiency of flocs in shelf seas and estuaries. Estuarine, Coastal, and Shelf Science, 91, 31-350.
Bowers, D.G., Braithwaite, K.M., Nimmo-Smith, W.A.M., Graham, G.W., 2009. Light scattering by particles suspended in the sea: The role of particle size and density. Continental Shelf Research, 29, 1748-1755.

Cartwright, G.M., Friedrichs, C.T., and Smith S.J., 2013. A test of the ADV-based Reynolds-flux method for in situ estimation of sediment settling velocity in a muddy estuary. Geo-Marine Letters, 33: 477-484. doi:10.1007/s00367-013-0340-4

Fettweis, M., Baeye, M., 2015. Seasonal variation in concentration, size, and settling velocity of muddy marine flocs in the benthic boundary layer. Journal of Geophysical Research: Oceans 120, 5648-5667, doi:10.1002/2014JC010644.

Hill, P. S., Bowers, D. G., & Braithwaite, K. M., 2013. The effect of suspended particle composition on particle area-to-mass ratios in coastal waters. Methods in Oceanography, 7, 95-109.

Hill, P.S., Boss, E., Newgard, J.P., Law, B.A., Milligan, T.G., 2011. Observations of the sensitivity of beam attenuation to particle size in a coastal bottom boundary layer. Journal of Geophysical Research, Vol. 116, doi: 10.1029/2010JC006539.

Kirk, J.T.O., 1994. Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, Cambridge.

Mikkelsen O.A., Pejrup, M., 2001. The use of a LISST-100 in-situ laser particle sizer for in situ estimates of floc size, density and settling velocity. Geo-Marine Letters, 20, 187–195

Neukermans, G., Loisel H., Mériaux X., Astoreca R., and McKee, D., 2012. In situ variability of mass-specific beam attenuation and backscattering of marine particles with respect to particle size, density, and composition. Limnology and Oceanography, 57.

Slade, W. H., Boss, E.S., Russo, C., 2011. Effects of particle aggregation and disaggregation on their inherent optical properties. Optics Express, Vol. 19, No. 9.

Smith, S. J., Friedrichs, C.T., 2015. Image processing methods for in situ estimations of cohesive sediment floc size, settling velocity, and density. Limnology and Oceanography Methods, Vol. 13 Issue 5, 250-264.