FINAL REPORT: Optics, Acoustics, and Stress in a Nearshore Bottom Nepheloid Layer

Paul S. Hill
Department of Oceanography
Dalhousie University
Halifax, Nova Scotia, CANADA B3H 4J1
phone: (902) 494-2266 fax: (902) 494-3877 email: paul.hill@dal.ca
http://www.phys.ocean.dal.ca/~phill
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LONG-TERM GOALS

The goal of this research was to develop greater understanding of the how the flocculation of fine-grained sediment responds to turbulent stresses and how this packaging of sediment affects optical and acoustical properties in the water column.

OBJECTIVES

1. Quantify the effects of aggregation dynamics on the size distribution of particles in the bottom boundary layer;
2. Quantify how changes in particle packaging affect the optical and acoustical properties of the water column.
3. Develop models describing the associations between particle aggregation, stress, and the acoustical and optical fields.

APPROACH

The approach was to obtain measurements that permitted comparisons of temporal evolution of bottom stress, suspended particle size, and optical and acoustical properties in the bottom boundary layer. The instrumentation was mounted on bottom tripods and an I-beam frame. The "OASIS" tripod included a 9-wavelength optical attenuation and absorption meter (WetLabs ae-9, with automated dissolved measurement for calibration-independent particulate measurements), LISST-100 (Type B) and LISST-Floc laser diffraction particle sizers (Agrawal & Pottsmith 2000), a digital floc camera (DFC) (Curran et al. 2002), a Tracor Acoustic Profiling System (TAPS), and an array of SonTek/YSI acoustic Doppler velocimeters (ADVs). Near-simultaneous ae-9 measurements with and without a filter assured high-quality particulate spectral absorption and attenuation measurements. The LISSTs and DFC together provided particle size distributions from 1.25 μm to 1 cm in diameter. The TAPS and ADVs obtained acoustical backscatter intensity over a wide range of frequencies that were used to generate particle size distributions (Holliday, 1987; Hay and Sheng, 1992). In 2006-2007 a new tripod was constructed and deployed. It is called the Modified In Situ Size and Settling Column Tripod (MINSSECT). It was developed to provide better constraint on conversions between optical signals, particle area, and particle mass. It carries a digital floc camera, a LISST-100 (Type B), a video settling column, and an automated water transfer system. The equipment on this tripod monitors in situ particle size distribution from 1.25 μm to 1 cm in diameter and size versus settling velocity for particles larger than approximately 100 μm. The water transfer system provides direct estimates of the mass in suspension that can be used to calibrate the beam attenuation coefficient to suspended mass. The I beam array consists of 4 of SonTek/YSI acoustic Doppler velocimeters (ADVs) mounted vertically ~ 0.25 m above the bottom.

The combined optical and acoustical measurements provided a comprehensive description of the suspended particles near the seabed. The velocity measurements obtained from the I-beam-mounted ADVs provided direct-covariance estimates of Reynolds stress and inertial-range estimates of the dissipation rate for turbulent kinetic energy.

Paul Hill and Tim Milligan collaborated closely on this project. Together they provided data and models on the flocculated size distribution of suspended sediment. Milligan and Hill had responsibility for the DFC on the OASIS tripod and for the entire MINSSECT. Brent Law (BIO), and John Newgard (Dal) provided support in the lab and field.

We also collaborated with Emmanuel Boss (UMaine) and John Trowbridge (WHOI) on this project. Boss was responsible for all optical and acoustical characterization of the water column. He has also conducted laboratory manipulations of the particle size distribution in order to explore the effect on optical attenuation. Boss and Hill have worked together on an optical model of marine aggregates. John Trowbridge was responsible for characterizing the stress in the bottom boundary layer during the deployments. We also collaborated with Oscar Schofield (Rutgers) who deployed gliders in the study area during our September 2007 deployment. A group from WetLabs deployed a profiling mooring during part of our September 2007 deployment. Yogi Agrawal (Sequoia Scientific) placed a prototype "LISST Back" on MINSSECT for part of our September 2007 deployment.

WORK COMPLETED

Work was completed in three areas. First, analysis of data from 2005, 2007, and 2009 deployments was completed. Papers on the effect of particle size on the mass normalized beam attenuation coefficient and on the effect of turbulence on particle size and extent of flocculation are in preparation. Second, we began development of a new simple model for floc fraction and began discussion with the Community Sediment Transport Model System (CSTMS) group on how to incorporate this model into CSTMS.

RESULTS

With our past OASIS support we have gathered three one-month-long time series of observations linking physical forcing, sediment concentration and size distribution, and optical properties. These data indicate that over a range of environmental conditions, the conversion from SPM to optical properties is more predictable than the theory that assumes constant-density particles suggests. The broad conclusion that can be drawn from our work is that particle and optical properties are easier to predict when the stress on the seabed is adequate to resuspend particles. When stresses are too low to resuspend sediment, biology and chemistry determine the concentration, composition, and size of particles in suspension, so biology and chemistry also determine optical properties. When stress grows large enough to resuspend particles, however, particle and optical properties are more closely linked to physical forcing, which is fundamentally more predictable. As well, the composition of particles becomes more uniform with increasing stress.

Time series from OASIS 2007 demonstrate the effect of stress on the predictability of optical properties. When stress is small, the mass-normalized particulate attenuation coefficient (*c_p:SPM*) is variable, but when stress is high, the value of the mass-normalized particulate attenuation coefficient stabilizes (Figure 1). Interestingly, this stabilization occurs despite considerable variation in particle size at high stress. Scatter plots of *c_p:SPM* versus shear velocity and versus median suspended particle diameter emphasize the relative uniformity of the mass-normalized particulate attenuation coefficient at higher stresses and its insensitivity to particle size when particles are large because of flocculation (Figure 2).

We have developed rigorous theoretical understanding of how flocculation significantly reduces the sensitivity of optical attenuation to in situ size distribution (Boss et al., 2009). Because of the fractal nature of flocs, particle cross-sectional area scales approximately as particle mass. It follows, therefore, that particulate attenuation scales approximately as suspended sediment mass and that particulate attenuation is much less sensitive to changes in the particle size distribution than it is for non-fractal particles.

Reduced sensitivity of the mass-normalized particulate attenuation coefficient at higher stresses is also linked to reduced variability in flocculated particle properties. Our OASIS data show that floc size and floc fraction are variable and difficult to predict at low stresses, but that these properties become more uniform and more predictable at higher stresses (Figure 3). In brief, floc size and floc fraction are variable when turbulence is weak to moderate. Eventually, however, increasing turbulence causes a systematic decrease in floc size and floc fraction.

We are now in a position to use these observations and their theoretical underpinnings to implement and test models that convert predictions of suspended particulate mass into predictions of the optical properties in bottom boundary layers. In December 2008, Milligan and Hill attended a CSTMS Workshop in Woods Hole to present a simple method for incorporating the key effects of flocculation and floc breakup into the model.

Our proposed modeling strategy works on three basic premises. First, CSTMS should treat small (< 16 μm) single grains as a single cohesive/aggregating pool. The single-grain population in this pool would have its own underlying, time-invariant size distribution, while flocs would add or subtract mass from this single-grain population. Flocs would be divided into a micro-floc pool that sinks at 0.1 mm/s and a macro-floc pool that sinks at 1 mm/s. Second, CSTMS should treat larger single grains as non-cohesive. And finally, because optical properties and sediment flux are more sensitive to floc fraction, which is the fraction of the total suspended mass contained within flocs, than to floc size, CSTMS should focus on modeling floc fraction rather than floc size.

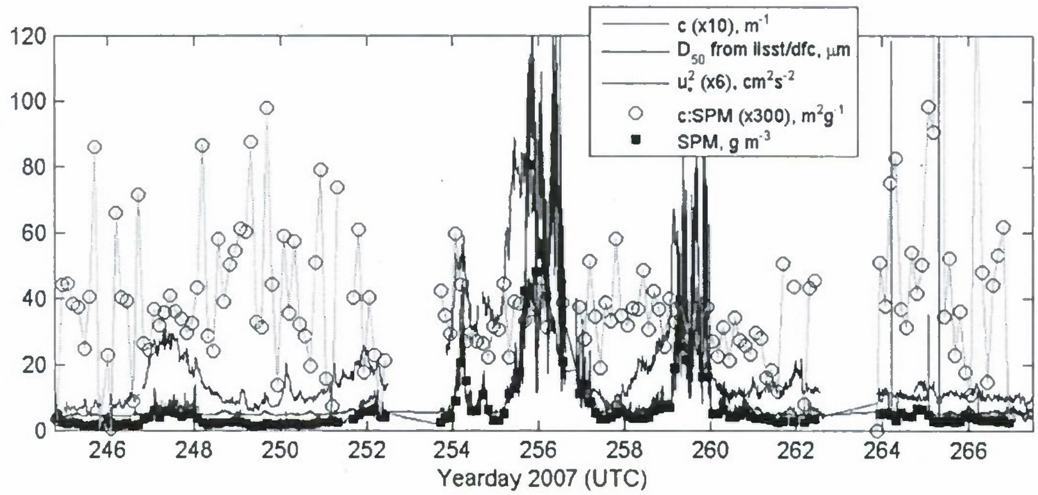

Figure 1. Time series of optical attenuation (c), median particle size (D50), the square of shear velocity (ustar^2), which is proportional to bottom stress, suspended particulate mass (SPM), and the mass normalized attenuation coefficient, which is the slope of the linear relationship between attenuation and SPM (c:SPM). When bottom stress is low, the mass normalized attenuation coefficient is variable, but when bottom stress is high, its value stabilizes, despite variability in particle size.

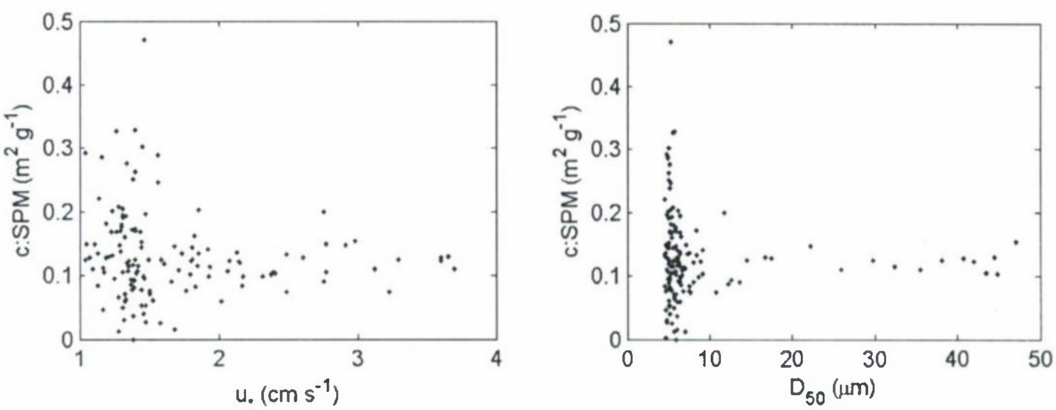

Figure 2. Scatter plots of the mass-normalized particulate attenuation coefficient versus shear velocity and median suspended particle diameter. As stress grows, the mass normalized particulate attenuation coefficient stabilizes around values 0.1-0.15. Its value is not sensitive to suspended particle size when median sizes are larger than 10 μm. The larger particle sizes are associated with flocculation, suggesting that mass normalized particulate attenuation coefficients are not as sensitive to flocculation as previously supposed.

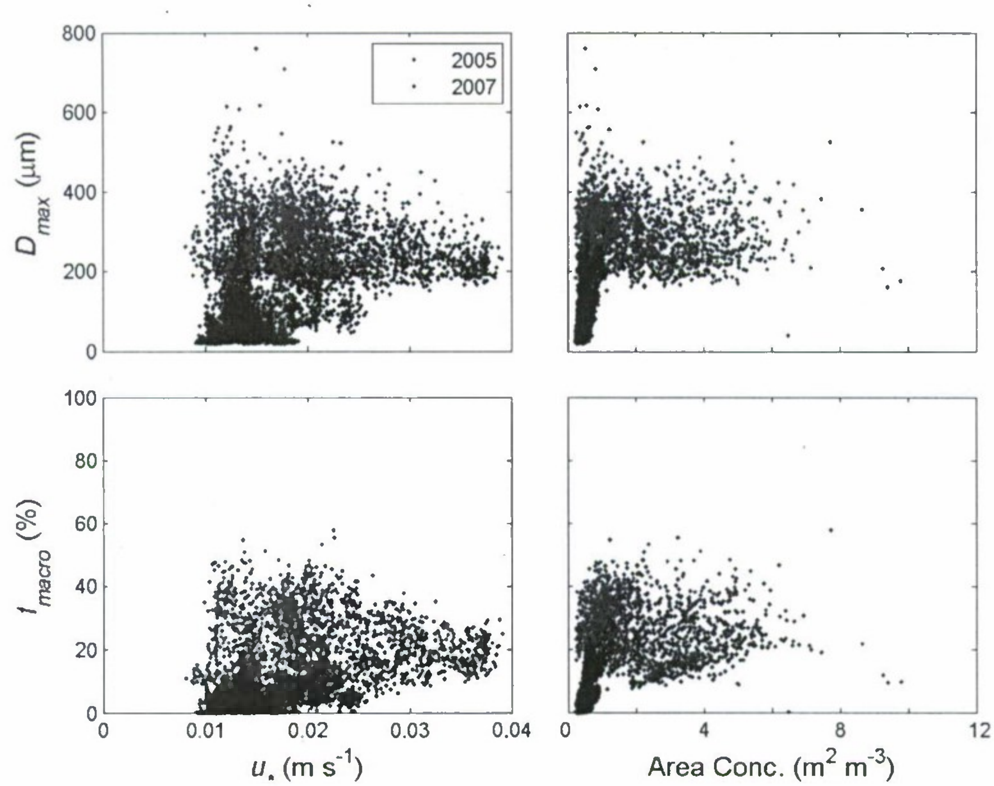

Figure 3. Scatter plots of maximal floc and macrofloc fraction (diameter > 133 μm) versus shear velocity and area concentration, which scales approximately with suspended sediment mass (e.g. Boss et al., 2009). Data from the 2005 OASIS field deployment are shown in red, and data from 2007 are shown in blue. When shear velocity is small, floc size and floc fraction are variable, but as stress grows, the values of these two variables decrease and stabilize. These trends reflect the increasing control exerted by turbulence on the properties of suspended flocs, and they help to explain why variability in mass normalized particulate attenuation coefficients decreases as stress increases.

The basic behavior of the model should be to drive mass out of macro-flocs at high stress, and to drive mass into macro-flocs at high concentration and low stress. A mathematical form that captures these behaviors is

$$f_{\max} = 1 - \left(\frac{k_f + \left(\frac{G^r}{k_G + G^r} \right) C}{k_f + C} \right)$$

In this equation, f_{max} is the maximum macro-floc mass fraction for a given small-scale shear, G, and sediment mass concentration, C. In order, the parameters k_f, k_G, and r specify the concentration at which macro-floc fraction increases rapidly, the shear at which macro-floc fraction decreases rapidly, and the sensitivity of macro-floc fraction to small-scale shear. Calibration of these coefficients would rely on theory and observations from our own work as well as on published studies. Linked formulae similarly would assign mass to the micro-floc and single-grain fractions in a way that conserves overall sediment mass. Such formulations have been used to model biological processes in ROMS (the model underlying CSTMS), so significant experience exists regarding implementation.

IMPACT/APPLICATIONS

The high resolution time series of particle, optical, and acoustical properties will enhance understanding of the rates and mechanisms by which the water column clears following storm events. The development of a floc module for CSTMS will enable the implementation of a module that converts sediment to optical properties. The latter advance will provide the sedimentology community with a simple tool to test their model predictions against the most ubiquitous measurement of suspended matter in coastal waters, and it will lead to prediction of in water optical properties based on predictions of seabed stress.

RELATED PROJECTS

Hill has a project funded by NSERC (Canada) that investigates the effect of in situ particle size distribution on the interaction of oil and sediment in suspension. This project funded the purchase of the LISST-100 on the MINSSECT. Hill, Milligan and Law are funded by ONR Coastal Geosciences to investigate depositional and erosional fluxes on tidal flats. As part of that work, we are measuring particle size, particle mass and particle settling velocities, optical attenuation, and seabed stress.

REFERENCES

Boss, E., W. H. Slade, and P. S. Hill. 2009. Effect of particulate aggregation in aquatic environments on the beam attenuation and its utility as a proxy for particulate mass. Optics Express, 17, 9410-9420.

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Dalhousie University
Department of Oceanography
1355 Oxford Street
Halifax, Nova Scotia B3H 4J1

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Paul S. Hill

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902-494-2266