Submitted on: 05/03/2012
Principal Investigator: Friedrichs, Carl T.
Organization: William & Mary Marine Inst
Submitted By: Friedrichs, Carl - Principal Investigator
Title:
Collaborative research: A Real-time and Rapid Response Observing System for the Study of Physical and Biological Controls on Muddy Seabed Deposition, Reworking and Resuspension

Project Participants

**Senior Personnel**

Name: Friedrichs, Carl  
Worked for more than 160 Hours: Yes  
Contribution to Project:

Name: Harris, Courtney  
Worked for more than 160 Hours: Yes  
Contribution to Project:

Name: Diaz, Robert  
Worked for more than 160 Hours: Yes  
Contribution to Project:

Name: Kuehl, Steven  
Worked for more than 160 Hours: Yes  
Contribution to Project:

Name: Schaffner, Linda  
Worked for more than 160 Hours: Yes  
Contribution to Project:

Name: Brubaker, John  
Worked for more than 160 Hours: Yes  
Contribution to Project:

Name: McNinch, Jesse  
Worked for more than 160 Hours: Yes  
Contribution to Project:

**Post-doc**

Name: Palomo, Laura  
Worked for more than 160 Hours: Yes  
Contribution to Project:

**Graduate Student**

Name: Vandever, Justin  
Worked for more than 160 Hours: Yes  
Contribution to Project:
Contribution to Project:

Name: Cartwright, Grace
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Dickhudt, Patrick
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Kraatz, Lindsey
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Dharia, Payal
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Sturdivant, Kersey
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Rodriguez, Cielomar
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Rinehimer, J.Paul
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Fall, Kelsey
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Wilkerson, Carissa
Worked for more than 160 Hours: Yes

Undergraduate Student

Name: Bruno, Sam
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Lewis, Benjamin
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Gelinas, Morgan
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Newbill, Donte
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Clark, Isaac
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Paxton, Dominique
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Nelson, Todd
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Addington, Lisa
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Brylawski, Alice
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Perkey, David
Worked for more than 160 Hours: Yes

Contribution to Project:

Technician, Programmer

Name: Mroz, Emilee
Worked for more than 160 Hours: Yes

Contribution to Project:

Research Experience for Undergraduates

Name: Mroz, Emilee
Worked for more than 160 Hours: Yes

Contribution to Project:

Years of schooling completed: Junior
Home Institution: Other than Research Site
Home Institution if Other: St. Lawrence University
Home Institution Highest Degree Granted(in fields supported by NSF): Bachelor's Degree
Fiscal year(s) REU Participant supported: 2006
REU Funding: REU site award
Name: Simon, Margaret
Worked for more than 160 Hours: Yes
Contribution to Project:
Years of schooling completed: Junior
Home Institution: Other than Research Site
Home Institution if Other: Haverford College
Home Institution Highest Degree Granted (in fields supported by NSF): Bachelor's Degree
Fiscal year(s) REU Participant supported: 2007
REU Funding: REU site award

Name: Mulvey, Laura
Worked for more than 160 Hours: Yes
Contribution to Project:

Years of schooling completed: Junior
Home Institution: Other than Research Site
Home Institution if Other: Case Western Reserve University
Home Institution Highest Degree Granted (in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2007
REU Funding: REU site award

Name: Scott, Ryan
Worked for more than 160 Hours: Yes
Contribution to Project:

Years of schooling completed: Junior
Home Institution: Other than Research Site
Home Institution if Other: George Mason University
Home Institution Highest Degree Granted (in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2008
REU Funding: REU site award

Name: Darden, Leandra
Worked for more than 160 Hours: Yes
Contribution to Project:

Years of schooling completed: Junior
Home Institution: Other than Research Site
Home Institution if Other: University of Tampa
Home Institution Highest Degree Granted (in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2008
REU Funding: REU site award

Name: Wei, Emily
Worked for more than 160 Hours: Yes
Contribution to Project:

Organizational Partners
University of Maryland Center for Environmental Sciences

Other Collaborators or Contacts
Activities and Findings

Research and Education Activities:
See PDF version at end of report.

Findings:
See PDF version at end of report.

Training and Development:
So far, this project has provided extensive hands-on research experience and a focus for their research for 10 graduate students and 12 undergraduate students. All the students learn oceanographic research skills.

Outreach Activities:
-- CHSD Lab participated in NOSB 'Blue Crab Bowl' high school oceanography competition every year of this project.
-- CHSD Lab regularly hosts tours from high school and community college science classes.

Journal Publications


Books or Other One-time Publications


Scott, R., "The use of acoustic Doppler velocimeter measurements to infer the evolution of
seabed erodibility in the York River estuary"**, (2008). Project report, Published
Bibliography: Summer Intern Program, Virginia Institute of Marine Science, Gloucester Point, VA, 7 p.


Bibliography: Senior Thesis, Geology Department, College of William and Mary, Williamsburg, VA, 31 p.

Bibliography: Summer Intern Program, Virginia Institute of Marine Science, Gloucester Point, VA, 11 p.

Bibliography: Masters Thesis, School of Marine Science, College of William and Mary, Gloucester Point, VA, 86 p.

Bibliography: Senior Thesis, Geology Department, College of William and Mary, Williamsburg, VA, 35 p

Bibliography: Senior Thesis, Geology Department, College of William and Mary, Williamsburg, VA, 47 p

Fletcher, T., "The correlation of sediment profile images to dissolved oxygen concentrations found in hypoxic zones of the York River in Virginia and Pepper Creek in Delaware", (2006). Project Report, Published
Bibliography: Summer Intern Program, Virginia Institute of Marine Science, Gloucester Point, VA

Bibliography: Summer Intern Program, Virginia Institute of Marine Science, Gloucester Point, VA

Bibliography: Senior Thesis, Geology Department, College of William and Mary, Williamsburg, VA

Rodriguez-Calderon, C., "Spatial and temporal patterns in erosional and depositional processes: physical and biological controls in the York River, Chesapeake Bay, Virginia

Web/Internet Site

URL(s):
http://www.vims.edu/chsd
Description:

Other Specific Products

Contributions within Discipline:
A finding from the first year of this project that may affect the field of fine sediment dynamics is the idea that for sea beds dominated by mud, volume fraction mud (relative to larger grain size components plus water) is a more important indicator of potential erodibility than is the traditional measure of porosity alone. We tentatively conclude that at the relatively low concentrations present at our sampling sites, sand has relatively little or no effect on cohesivity. This trend is intuitively distinct to the commonly invoked effect of bed armoring, where sand decreases further mud suspension by blocking underlying sediment.

A key finding from the second year of this project is the result that differences in bed erodibility between sites and from season to season do not seem to be related to relatively small changes bed porosity (i.e., water content), defying classical expectations. Although erodibility is always observed to decrease into the bed as porosity increases at any one site, strong seasonal and spatial variations in observed erodibility do not correspond to notable changes in porosity. Rather, changes in erodibility seem to be associated mainly with deposition events and associated changes in bed fabric.

A similarly important finding from the third year is that particle settling velocity and bed erodibility appear to be linked in time and space such that high erodibility is associated with low settling velocity, whereas low erodibility is associated with high settling velocity. It appears that the combination of low settling velocity and high erodibility are both due to recent deposition of poorly consolidated, floc-rich sediment. In contrast, high settling velocity and low erodibility are the result of longer term, near-equilibrium biological reworking of the bed and biologically-induced pelletization.

A key finding from the fourth year is that the including time-varying erodibility and consolidation within the ROMS model enables simulation of feedbacks between sediment flux convergence and erodibility as seen in the field. Model results show the development of a highly erodible pool of sediment near the observed location of the ETM. Even when sediment convergence processes are diminished, suspended sediment concentrations remain high due to high sediment erodibility,
A finding from the fifth year that may similarly affect the field of fine sediment dynamics is observation of the common simultaneous occurrence of fragile flocs and biologically compacted pellets in biologically active turbid estuaries. Under such circumstances, mass concentration, mass settling velocity and the abundant smaller particles (~90 microns) tend to be in phase with velocity and stress, consistent with the suspension of relatively dense, rapidly settling and resilient pellets. Simultaneously, volume concentration of the abundant larger (~300 microns) particles peaks well after stress and velocity begin to decrease, consistent with the formation of lower density, slowly settling and fragile flocs.

In our no-cost-extension sixth year, a major result stemmed from a new approach of tidal phase averaging of Acoustic Doppler Velocimeter (ADV) data. Because of large number of tidal cycles averaged, confidence intervals could easily be tracked through multiple analysis steps. A key scientific result demonstrated by our first attempt at tidal phase averaging is that for cases with peak bottom stress of ~ 0.15 Pa, the floc setting velocity inferred from ADV data stays remarkably constant over the tidal cycle, suggesting that floc size at relatively low stress is limited by the turbulence associated with floc settling rather than the turbulence of the tidal current itself.

**Contributions to Other Disciplines:**

**Contributions to Human Resource Development:**
See other discussions of education activities.

**Contributions to Resources for Research and Education:**

**Contributions Beyond Science and Engineering:**
Our results in MUDBED have attracted the attention of developers of commercialized technology at LUNA, Inc., in Hampton, VA. Leveraging the correlations we have seen in MUDBED between sediment water content and x-ray response, the acoustics group at LUNA in 2008 submitted a SBIR proposal in collaboration with our group at VIMS to the Department of Energy to utilize x-radiography to ground-truth their acoustic techniques and help them further develop technologies to image and quantify the properties of hazardous sludges within nuclear reactor waste storage tanks. The SBIR was funded in late 2009 and the work in collaboration with LUNA was completed in 2010.

**Conference Proceedings**

**Categories for which nothing is reported:**

Any Product
Contributions: To Any Other Disciplines
Contributions: To Any Resources for Research and Education
Any Conference
PROJECT ACTIVITIES

Sediment sampling cruises

For physical erodibility studies: Sediment sampling cruises to collect cores at three contrasting muddy sites in the York River estuary (Figure 1) were completed in April, May, June, July, August, September and November 2006, in January, March, April, May, June, August, October and December 2007, and in February and March 2008. These three sites span a gradient from relatively less to relatively more physically impacted seabed conditions due to spatial variations in the intensity of sediment transport and deposition (Figure 1). The three sites were the Gloucester Point buoy site (GP, anticipated to be the least physically impacted) at approximately 37 deg, 14’30” N, 76 deg, 29’50” W, the Clay Bank channel site (CB, anticipated to be the most physically impacted) at approximately 37 deg, 20’00” N, 76 deg 37’04” W), and the Clay Bank secondary channel site (CS, anticipated to be intermediate). The purposes of the cruises were to quantify the spatial and temporal variability of the upper few cm of the seabed most relevant to controlling sediment erodibility and subsequent sediment suspension.

Depending on the specific cruise, up to ten box cores were collected at individual sites. In each case, two to three sub-cores were collected for digital x-radiograph and two additional sub-cores were used for Eh analysis. Eh readings were collected at 1 cm intervals down to 7 cm as a proxy for the redox state of each study site. Sub-cores extruded at 1 cm intervals were used to determine the sand/silt/clay content via standard pipette analysis and wet sieving, and water content and organic content were determined on aliquots of these samples using standard methods. Immediately following every cruise, two cores from each site were placed in a Gust erosion microcosm to measure the seabed surface erodibility (Figure 2). The erosion microcosm uses a spinning vane just above the sediment-water interface to apply a sequence of increasing shear stress to the intact cores. The eroded sediment is transported through a turbidimeter and collected for filtering and weighing in order to determine eroded mass as a function of increasing stress.
To characterize biological, biochemical and ecological conditions: For each of the above cruises since July 2006, colloidal carbohydrates were also measured at 5 mm depth intervals from 0 to 2 cm below the surface from eight cores at each site as an index for the presence of extracellular polymeric substances. This involved measuring EDTA-extractable carbohydrates in lyophilized sediment using a spectrophotometer. Additional analyses on cores from each site have included chlorophyll-a, C:N ratios, and fecal pellet properties. Samples have also been collected to characterized the temporal variations in meiofauna abundance and composition at the three main sampling sites. A small syringe was used to obtain meiofauna to a depth of 3 cm. Samples were fixed, washed over a 63 mm sieve and sorted by major taxa. Beginning in July 2007 additional biological sampling sites were added for the purpose of assessing regional spatial variation within similar habitats.

From March through March 2008, two cores were also collected for lipid biomarker analyses. Fatty acid composition was examined in the surface layers of sediment in order to identify the sources and diagenetic state of organic matter and to characterize phytoplankton and bacterial communities. Fatty acids were analyzed by combined gas chromatography-mass spectrometry. In parallel, down-core profiles of oxygen were measured.

Additional intense sampling cruises were conducted from March through June 2008. Samples were collected twice a week at the GP and CB sites over one spring-neap tidal cycle per month. Each sampling day, two cores were collected and placed in a Gust erosion microcosm immediately following each cruise to measure seabed erodibility and the erodibility of newly recruited and juvenile macrofauna. The eroded material was washed over a 63-mm sieve to collect any organisms. The eroded cores were extruded to collect the remainder of the top 2 cm of surface sediment that was not eroded by the microcosm. Two additional cores were collected per site each sampling day to act as control cores for the juvenile macrofauna. The control cores were extruded to collect the top 2 cm of the surface sediments. All of the faunal samples were fixed in a 10% buffered formalin solution with Rose Bengal. These fauna samples were washed through a nested sieve series (500, 250, and 125-µm mesh sizes). Any macrofaunal recruits and juveniles found will be identified to the lowest possible taxonomic level. Subcores were also
collected on each sampling day for colloidal carbohydrate and chlorophyll a analysis. Two additional cores were collected at each site per week for grain size analysis.

Sediment sampling cruises in support of dual frequency echo-sounder surveys were conducted from April 2008 to March 2009. Approximately 48 cores were collected each month for sedimentological, radiochemical and biological analyses. Sediment water content, grain size, and $^7$Be activity were determined. Sediment water content in the upper 2 cm was determined using standard wet weight/dry weight analysis. X-radiographs were taken using a portable x-ray generator and digital flat panel detector. The wet sieving/gentle agitation technique and the normal grain size analysis by the total disaggregation of the particles were used to determine the fecal pellet content in the top 2 cm of the seabed. The wet sieving/gentle agitation technique consists of a modification from the normal grain size procedure. Gentle hand agitation was used to disrupt mud clumps present before sieving through a 63 $\mu$m mesh to obtain the pellet/sand fraction. The fecal pellet content (among other organic materials) were calculated by determining the difference between the sand-size fraction percentage obtained in the wet sieving/gentle agitation technique and the acidified sand-size fraction obtained from the normal grain size procedure. The $^7$Be activities were measured using a semi-planar intrinsic germanium detector coupled with a multi-channel analyzer (Kniskern & Kuehl, 2003; Dellapenna et al., 1998). $^7$Be inventories (I) were also calculated for the upper 2 cm of each core.

Further analysis at the Clay Bank study site investigated the erodibility of surficial sediments using a Gust erosion microcosm in 2009 and 2010. In November 2009, Gust microcosm erodibility measurements were taken before and after Nor’easter Ida hit the lower Chesapeake Bay on November 12-14th. Two cores were collected on November 9th and 17th and were immediately processed in the Gust microcosm within a few hours of core retrieval. Field collected cores were exposed to consecutively increasing shear stress values (0.01 Pa, 0.05 Pa, 0.1 Pa, 0.2 Pa, 0.3 Pa, 0.45 Pa, 0.6 Pa) in order to obtain precise measurements of erosion of the seabed. Effluent of each shear stress was collected and run through a turbidimeter to determine NTUs (nephelometric turbidity unit) of the total suspended solids. The same methodology using the Gust microcosm was utilized in April and May of 2010, when a detailed study of sedimentological properties at Clay Bank was conducted every week. For this analysis, the
following tests were run on sediment samples collected on April 29th, May 5th, May 11th, May 20th, and May 27th: water content at centimeter intervals, Be\textsuperscript{7} at centimeter intervals between 0-10 centimeters and 2 centimeter intervals after a depth of 10 cm, grain size at centimeter intervals between 0-10 centimeters and 2 centimeter intervals after a depth of 10 cm, x-radiography of cores, logging p-wave and gamma density using CS\textsuperscript{137} at 1mm intervals on a standard Geotek multi-sensor core logger, in combination with Gust microcosm erodibility measurements.

Long term monitoring of seabed conditions at the Clay Bank secondary channel site continued in 2011, with additional baseline seabed sampling occurring biweekly to monthly from May to December (excluding November due to weather). Baseline sampling included Gust microcosm erodibility measurements and down-core profiling for percent sand/silt/clay, water content, bulk organics, x-radiographs, and fecal pellet content.

**Seabed imaging: Acoustic measurements**

SWATH, Chirp and Rotary Sonar: In April, June, August and October 2007 and in September, October and December 2008, surveys were completed to survey regions of the York River. These acoustic field surveys focused on Interferometric SWATH collection, supplying high-resolution bathymetry and sidescan data. Cruises in October 2007 and February 2008 completed the sub-bottom profile inventory of the study sites using two high-resolution sub-bottom profilers (SB-216S and SB-0512i Chirp). In addition to the SWATH and Chirp acoustic data collected, a tripod-mounted Imagenex 881A rotary sonar was deployed in February of 2008, to examine surficial changes of the seabed at various timescales. Continued studies focused on this rotary sonar technology, as we incorporated this instrument into our observation system. A communication cable was tethered from the rotary sonar to a radio modem on the surface buoy to allow in-situ tuning of the sonar settings and real-time observations of the seabed. The rotary sonar was deployed on August 29th and retrieved on September 30th, 2009, deployed on October 13th and retrieved in January 2010, and was deployed a final time on April 10th and retrieved in August 2010. Sidescan sonar was collected in addition to the October deployment to have a higher resolution data set of the seabed for comparison.
Dual frequency echo-sounder: Sub-bottom data collection, using a dual frequency echo-sounder (33 and 200 kHz), started in April 2008 at the Clay Bank and Gloucester Point sites. A total of 31 sub-bottom profiles across and along the York River channel were collected every month. Ten additional surveys were done during May 2008 through March 2009 making a total of 11 months of sub-bottom data. The acoustic profiles were used to digitize channel 1 (200 kHz) and channel 2 (33 kHz) upper reflectors. Through the digitalization of both channels it was possible to determine spatial and temporal variations in the thickness of the upper soft mud layer in the seabed. The digitized layer was mapped and presented as contour maps by using Surfer v8 software. Thicknesses changes through time and space were indicative of changes in erosional and depositional processes within the study site.

Seabed imaging: Camera and Video

In April, May and July 2007, and January and June 2008 cruises were completed in the York River using a digital seabed profile camera to examine the fine-scale resolution of seabed fabric near the sediment-water interface (Figure 3). Each of the three main field sites was visited during each of these cruises resulting in approximately 300 high-resolution seabed profile images. In addition, digital seabed profile video cameras were successfully deployed in time-lapse mode at Gloucester Point from 3/25 – 12/6/08 and in the Clay Bank Secondary Channel from 6/5 – 12/6/08. Each seabed system was linked to a shore station via radio and transmitted images hourly. Sediment conditions can be viewed in near real-time at http://www.vims.edu/~nelson.

Benthic tripod, platform and profiler deployments

Tripods containing an Acoustic Doppler Velocimeter (ADV) and CTD (including a turbidity sensor) (Figure 4) and often including a Laser In-Situ Scattering and Transmissometer (LISST) (*) have been deployed repeatedly at Gloucester Point and at the Clay Bank secondary channel sites. The Gloucester Point tripod deployments have been: 12/4/06 – 1/30/07, 7/31 – 8/30/07*, 8/31 – 11/12/07, 12/5/07 – 4/2/08*, 4/2 – 7/11/08*, 7/11 – 12/8/08*, 12/15/08 – 3/23/09*.
Clay Bank tripod deployments have been: 2/27 – 6/8/07, 6/12 – 8/30/07, 8/31* – 11/12/07, 12/05/07 – 2/4/08*, 2/8 – 6/23/08*, 6/23 – 9/22/08*, 9/30/07 – 2/11/09*, 2/27 – 4/30/09, 5/12 – 8/25/09*, 7/22 – 10/21/09*, 11/05/09 – 2/24/10*(last LISST deployment), 12/22/09 – 2/29/10 (upward looking ADV only), 2/24 – 9/8/10, 9/27/10 – 03/14/11, 05/06/11 – 07/05/11, 7/18/11 – 12/02/11, and 12/09/11 – 02/29/12. The 5/09 deployment at Clay Bank communicated via cable to our piling platform and then back to VIMS via directional radio modem. The 7/09 and later deployments have been cabled to a small buoy with a short-range radio link to the piling before being relayed by directional radio modem back to VIMS. Recently we deployed a downward looking Sontek Acoustic Doppler Profiler (ADP) from one of our tripods at the Clay Bank secondary channel site (from 08/12/11 – 12/02/11). The ADP provides observations of velocity and backscatter (which can be calibrated for sediment concentration) in 5 cm bins over the lowest meter of the water column. The ADV deployments from 05/06/11 – 07/05/11, 7/18/11 – 12/02/11, and 12/09/11 – 02/29/12 included 2 ADVs in order to better resolve near-bed vertical gradients in turbulence and its interaction with suspended particles.

ADCP surveys, including water column ADV/CTD/LISST profiles and sediment pump samples, have also been performed at the tripods to characterize circulation in the vicinity of the tripod and coring sites and to provide in-situ calibration measurements and further site characterization. Profiler deployments occurred at Gloucester Point on: 1/29/07, 8/21/07, 12/18/07, 4/16/08, 7/31/08, and 1/9/09. Profiler deployments occurred in the Clay Bank secondary channel on: 3/29/07, 7/18/07, 7/24/07, 12/17/07, 4/15/08, 7/29/08, 10/16/08, 2/26/09, 5/14/09, 8/11/09, 11/25/09, 10/12/10, 08/16/11, 08/18/11, 09/01/11, and 12/20/11. Profiler deployments occurred in the Clay Bank main channel on: 4/18/08, 5/5/08, 5/7/08, 5/14/08, 5/15/08, 6/3/08, 6/6/08, 6/9/08, and 6/10/08.

**Linkage to observing system**

In mid-2008, a set of three bound pilings were installed near the Clay Bank tripod site in the middle York River estuary with the goal to serve as a platform for relaying real-time data back to VIMS from the mid-estuary Clay Bank region. After several iterations of various combinations of communication equipment, we settled on an underwater serial-to-Ethernet converter to
transform the ADV and LISST output before sending it back to VIMS via a line-of-sight directional Ethernet radio. The first real-time ADV tripod was cabled directly to the piling in May 2009. Since July 2009, we have cabled our ADV tripod to a small buoy which then transmits the ADV output to the nearby piling for relaying on to VIMS, where it is stored on a VIMS PC and archived to our local servers.

Modeling

The Regional Ocean Modeling System (ROMS) framework is being used to evaluate the influence of seabed consolidation on turbidity. An idealized one-dimensional version of ROMS has been implemented to model small-scale erosion processes as observed on individual cores by the Gust microcosm. A three-dimensional version of ROMS has also been implemented to realistically simulate feedbacks between erodibility and spatial and temporal variability naturally present in the York River estuary. The three-dimensional model includes tidal and fluvial forcing and has been run to represent the first 200 days of 2007. Both models represent the seabed as a number of vertical levels and keep track of bed parameters like porosity, thickness and the mass and fraction of multiple sediment classes for each bed layer. In collaboration with Larry Sanford and Chris Sherwood, the seabed component of ROMS has been modified so that variations of critical erosion stress with depth are accounted for to simulate the behavior of cohesive beds. As sediment erodes from the top layer, additional sediment with a higher critical erosion stress is entrained into the top bed layer from lower layers. If net sediment deposits onto the top layer, it lowers the surface layer’s critical stress. In order to simulate consolidation, the instantaneous critical stress profile is nudged toward an empirically derived reference profile such that the bed consolidation evolves with time even in the absence of erosion or deposition.

Educational Activities

So far, this project has involved significant, hands on research experiences for 22 students, ten at the graduate level, and 12 undergraduate. To date, one post-doc has also worked on the project.
Graduate students: Grace Cartwright is a PhD student working with Carl Friedrichs to develop new technologies for observing and interpreting suspended particle properties. Payal Dharia is a MS student working with Linda Schaffner on the feedbacks between estuarine benthic communities and sediment transport. Patrick Dickhudt was a MS student who graduated in 2008 working with Carl Friedrichs to develop new approaches for using digital x-radiography and erosion microcosms to interpret relationships between seabed erodibility, water content and grain size. Kelsey Fall is a MS student working with Carl Friedrichs to examine controls on particle settling velocity using MUBED observations and numerical models. Lindsey Kraatz is a PhD student working with Carl Friedrichs applying acoustics to interpret seabed properties. J.Paul Rinehimer was a MS student who graduated in 2008 working with Courtney Harris on the effects of erodibility on turbidity using numerical models. Cielomar Rodreiguez was a MS student who graduated in 2010 working with Steve Kuehl on the relationship between spatial variations in seabed properties and patterns of erosion and deposition. Kersey Sturdivant was a PhD student who graduated in 2011 working with Robert Diaz on the effects of hypoxia on estuarine benthic production. Justin Vandever was a MS student who graduated in 2007 and who worked with John Brubaker on realtime telemetry and interpretation of estuarine wave climate. Carissa Wilkerson is a MS student working with Carl Friedrichs on our long term bed sampling program.

Undergraduate students: Sam Bruno was a geology major at William and Mary who graduated in 2008 and who did his senior thesis with Carl Friedrichs on seasonal and spatial variations in sediment settling velocity inferred from ADV data. Isaac Clark is a geology major at William and Mary who is doing his senior thesis on comparing field observations of acoustic and physical properties of the upper seabed. Leandra Darden was a VIMS REU student from the University of Tampa who worked with Bob Diaz to use benthic video to document changes in seabed conditions and associated benthic activity. Morgan Gelinas was a geology major at William and Mary who graduated in 2009 and did her senior thesis with Steve Kuehl on the storage of nutrients within the seabed of the York River. Benjamin Lewis was a geology major at William and Mary who graduated in 2009 and did his senior thesis with Carl Friedrichs on seasonal and spatial variations in suspended particle properties inferred from LISST data. Emilee Mroz was a VIMS REU student from St. Lawrence University who worked with Carl Friedrichs in summer 2006 on the relationships among biogeochemical and physical properties of cores from the
MUDBED sampling sites and observed sediment erodibility. Laura Mulvey was a VIMS REU student from Case Western Reserve University who worked with Linda Schaffner in summer 2007 on temporal variability in properties of meiofauna at the MUDBED sampling sites. Donte Newbill was a geology major at William and Mary who did his senior thesis with Carl Friedrichs examining the acoustic response of ADVs to sediments from different locations and with different concentrations and grain sizes. Domi Paxton is a geology major at William and Mary who is doing her senior thesis on comparing laboratory observations of acoustic and physical properties of the upper seabed. Ryan Scott was a VIMS REU student from George Mason University who worked with Carl Friedrichs in summer 2008 on estimating seabed erodibility from ADV data. Margaret Simon was a VIMS REU student from Haverford College who worked with Courtney Harris is in summer 2007 on tidal and seasonal variations in sediment erodibility in an idealized numerical model. Emily Wei was a VIMS REU student from Middlebury College who worked with Carl Friedrichs is in summer 2011 on spring-neap variations of seabed pellet content and its relationship to changes in seabed erodibility.

Post-doc: Laura Palomo was a post-doc with an independent fellowship who joined the MUDBED project in 2010 to study potential relationships between seabed disturbances and the nature of organic carbon in York river sediments.

Presentations


Bruno, S., 2008. Seasonal and spatial trends in biological versus physical influences on sediment settling velocity in the York River estuary. Senior Thesis Presentation, Geology Department, College of William and Mary, Williamsburg, VA, 21 April.


Dharia, P., 2008. Recruitment processes of benthic macroinvertebrates under varying physical conditions. Spring Seminar Series, Department of Biological Sciences, Virginia Institute of Marine Science, Gloucester Point, VA, 7 April.

Dharia, P., 2009. Erodibility and recruitment processes of benthic macroinvertebrates under varying physical conditions. Spring Seminar Series, Department of Biological Sciences, Virginia Institute of Marine Science, Gloucester Point, VA, 23 March.

Diaz, R.J., 2008. From hypoxia to worm cam. Fall Seminar Series, Department of Biological Sciences, Virginia Institute of Marine Science, Gloucester Point, VA, 15 September.


Dickhudt, P.J., 2008. Controls of erodibility in a partially mixed estuary: York River, VA. Master’s Thesis Seminar, School of Marine Science, College of William and Mary, Gloucester Point, VA, 1 July.


Conference on Nearshore and Estuarine Cohesive Sediment Transport Processes. Rio de Janeiro and Paraty, Brazil, 3-8 May.


Friedrichs, C.T., 2011. Damping of turbulence by suspended sediment in the bottom boundary layer. Virginia Institute of Marine Science, Department of Physical Sciences, Fall Seminar Series, Gloucester Point, VA, 22 September.


Harris, C.K., 2007. Mud, measurements, and models: sediment transport in the coastal ocean. Fall Seminar Series, Department of Physical Sciences, Virginia Institute of Marine Science, Gloucester Point, VA, 6 December.
Harris, C.K., 2009. Erodibility and Sediment Trapping in a Partially Mixed Estuary: A Modeling Study of the York River Estuary, Virginia. Fall Seminar Series, Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, Norfolk, VA, 8 October.


Newbill, D., 2010. Senior Thesis Presentation, Geology Department, College of William and Mary, Williamsburg, VA, 24 March.


Rodriguez-Calderon, C., 2009. Spatial and temporal patterns in erosional and depositional processes: physical and biological controls in the York River, Chesapeake Bay, VA. Master’s Thesis Seminar, School of Marine Science, College of William and Mary, Gloucester Point, VA, 16 December.


Schaffner, L.C., 2006. Benthic community responses to estuarine disturbance gradients. Fall Seminar Series, Department of Biological Sciences, Virginia Institute of Marine Science, Gloucester Point, VA, 6 November.

Schaffner, L.C., 2008. MUDBED: spatial and temporal variation in sediment transport processes and sediment erodibility in the York River estuary, implications for benthic communities. Fall Seminar Series, Department of Biological Sciences, Virginia Institute of Marine Science, Gloucester Point, VA, 3 November.


Simon, M., C.K. Harris, and J.P. Rinehimer, 2007. Seasonal sediment erodibility and tidal effects in an idealized numerical model of the York River estuary. Summer Intern Program Final Presentation, Virginia Institute of Marine Science, Gloucester Point, VA, 1 August.


PROJECT FINDINGS

Friedrichs, C.T., 2009. York River physical oceanography and sediment transport. Journal of Coastal Research, SI 57: 17-22. The York River is a partially-mixed, microtidal estuary with tidal currents in the mid- to upper estuary approaching 1 m/s. The upper York near West Point is generally less stratified than the lower York near Gloucester Point because of the shallower depths and stronger currents found upstream. Fluctuations in salinity stratification in the York River at tidal, fortnightly and seasonal time-scales are associated with tidal straining, the spring-neap cycle, and variations in freshwater discharge, respectively. Estuarine circulation in the York River, which averages ~5 to 7 cm/s, is often modulated by moderate winds. Waves are usually insignificant, although occasional severe storms have a major impact. The York River channel bed is predominantly mud, while the shoals tend to be sandier, and the mid- to upper York is marked by seasonally persistent regions of high turbidity. Fine sediment is trapped in high turbidity regions in response to tidal asymmetries and local variations in stratification and estuarine circulation. More work is needed to better understand the linkages between physical oceanography, sediment transport and turbidity in the York River system, especially during high-energy events and in response to ongoing climate change.

Gillett, D.J., and L.C. Schaffner, 2009. Benthos of the York River. In: (K.A. Moore and W.G. Reay, eds.) A Site Profile of the Chesapeake Bay National Estuarine Research Reserve, Virginia. Journal of Coastal Research, SI 57: 80-98. Major subtidal benthic habitats in York River estuary (YRE) include soft mud and sand bottoms, with only limited distribution of submerged aquatic vegetation and oyster shell. Major taxonomic groups of macrofauna dominating muds and sands of YRE include annelids, molluscs and crustaceans. The benthic communities of YRE are similar to those found in other temperate estuaries of the US Mid-Atlantic. Meiofaunal assemblages of YRE soft bottoms are dominated by nematodes and copepods. Species distribution patterns in YRE are strongly correlated with salinity and bottom type, while other factors such as eutrophication and hypoxia may be growing in importance. Species diversity of macrobenthos decreases from the polyhaline reaches of the lower estuary to tidal freshwater. Sediment-associated toxicity due to anthropogenic pollutants is limited in YRE and as a result is not a systemic problem for benthic biota. Much of the YRE benthos fails to meet the restoration goals
set by the Chesapeake Bay Program. The poor condition of the benthos is expressed as low biomass and abundance and may be associated with degraded water quality, hypoxia and sediment disturbance processes, which are significant in the middle to upper estuary.

Dickhudt, P.J., C.T. Friedrichs, and L.P. Sanford, 2011. Mud matrix solids fraction and bed erodibility in the York River, USA, and other muddy environments. Continental Shelf Research, 31 (10S): S3-13. A 14-month time series of sediment cores from the bed of the York River estuary, Chesapeake Bay, USA, were sampled with a Gust erosion microcosm and further analyzed to evaluate variability in a variety of physical bed properties. Variation in sediment solids volume fraction did not relate to variability in bed erodibility. However, solids volume fraction was found to be highly dependent on the sand fraction of the bed. The solids volume fraction of the mud matrix was calculated to evaluate changes in bed compaction not related to the sand fraction of the bed. The range of variability in solids volume fraction of the mud matrix was found to be significantly less than the variability of the total solids volume fraction. Reevaluation of erodibility data from the literature combined with that from this study revealed a strong correlation between solids volume fraction of the mud matrix and the initial critical stress for erosion when a large range in sand fraction and solids volume fraction were included. These results suggest that compaction within the cohesive portion of the bed is better related to erodibility than compaction of the bed as a whole (mud and sand). The poor correlation found within the York River data alone likely resulted from the relatively small range observed in the solids volume fraction of the mud matrix.

Dickhudt, P.J., C.T. Friedrichs, L.C. Schaffner, and L.P. Sanford, 2009. Spatial and temporal variation in cohesive sediment erodibility in the York River estuary: a biologically-influenced equilibrium modified by seasonal deposition. Marine Geology, 267: 128-140. Sediment erodibility was measured at three sites in the York River, a sub-estuary of the Chesapeake Bay, monthly to bimonthly from April 2006 through October 2007. Erodibility at the three sites was similar during the summer and fall. A site near the estuary mouth maintained this level of erodibility greater than 90% of the time while two sites in the more physically dominated mid-estuary region exhibited a consistent and pronounced increase in erodibility in the late winter and spring. Weak to non-existent between bed erodibility, solids volume fraction, and surficial
concentrations of organic matter, colloidal carbohydrate, and extracellular polymeric substances, were not sufficient to explain the observed seasonal pattern in bed erodibility. Digital X-radiographs revealed thick sequences (10 – 20+ cm) of laminated sediments at the surface in the middle estuary coincident with the period of highest erodibility and more biologically reworked sediment during the rest of the year, suggesting that periodic rapid deposition introduced new sediment that was seasonally easy to erode (Figure 6). The finding that seasonal deposition influenced erodibility at the mid-estuary sites is consistent with previous results indicating the occasional presence of a secondary turbidity maximum. Comparison of the biologically reworked, but still “low” erodibility condition in the York to other published Chesapeake Bay erodibility data revealed a consistent critical shear stress range and profile, suggesting this equilibrium critical stress profile may be representative of other similar estuarine environments in the absence of rapid deposition. At relatively low stresses and in the absence of rapid deposition, we speculate that burrowing and/or pelletization may play a role in maintaining high equilibrium bulk water content without reducing the strength of the surface of the seabed.

Friedrichs, C.T., G.M. Cartwright, and P.J. Dickhudt, 2008. Quantifying benthic exchange of fine sediment via continuous, non-invasive measurements of settling velocity and bed erodibility. Oceanography, 21(4): 168-172. New field applications of small, turbulence-resolving acoustic Doppler velocimeters (ADVs) are providing insights into fine sediment erodibility and settling. As part of the MUDBD Project, ADV backscatter was calibrated for suspended sediment concentration, was used to track local seabed elevation, and was combined with vertical velocity to determine turbulent sediment flux. Assuming a local balance between settling by gravity and upward turbulent transport then allowed estimation of the suspended sediment settling velocity. Output from ADVs also provided an indirect measure of bed erodibility. Because the ADV provided estimates of bottom stress, sediment concentration and settling velocity, a Rouse profile for sediment concentration could then be integrated in z to estimate total suspended sediment mass as a function of bed stress. Observations suggest that relatively high bed erodibilities and low settling velocities often occur at Clay Bank in the spring in association with periodic sediment deposition, whereas erodibilities are lower (and setting velocities higher) at both Clay Bank and Gloucester Point during the late summer when deposition is absent (Figure 7). Seasonal variations in bed erodibility derived from the ADV analysis are roughly consistent with
those observed directly by Dickhudt et al. (Marine Geology, submitted) using a Gust microcosm applied to cores collected within a few hundred meters of the ADV tripods.

Rinehimer, J.P., C.K. Harris, C.R. Sherwood, and L.P. Sanford, 2008. Estimating cohesive sediment erosion and consolidation in a muddy, tidally-dominated environment: model behavior and sensitivity, Estuarine and Coastal Modeling, 10: 819-838. Erodibility of cohesive sediment varies with sediment depth and with erosional and depositional history. A cohesive sediment bed model was implemented in the Community Sediment Transport Modeling System (CSTMS) to examine processes influencing sediment erodibility and water column turbidity. Estimates of eroded mass from the sediment bed model were calibrated and verified with erosion chamber measurements from the York River, Virginia, a tidally-dominated environment. The model performs well when a constant erosion rate parameter is used and critical stress is varied with depth. Sensitivity of total eroded mass to seasonal variations in erodibility and changes in consolidation time scale was evaluated during spring-neap variations in bottom stresses. Differences were greatest during spring tide and varied by as much as a factor of 2.5 (Figure 8). Consolidation created an asymmetry between the spring-to-neap and neap-to-spring transitions with more sediment being eroded during the decreasing phase of maximum tidal stress. Consolidation time scales controlled the magnitude of this asymmetry with larger asymmetries occurring when slower consolidation time scales were assumed. Eroded mass estimates were potentially as sensitive to uncertainties in the consolidation time scale as they were to observed seasonal variability in critical stress.

Rinehimer, J.P., 2008. Erodibility and sediment trapping in a partially mixed estuary: a modeling study of the York River estuary. In: Masters Thesis, School of Marine Science, College of Marine Science, Gloucester Point, VA, pp. 35-62. Estuarine suspended sediment concentrations are influenced by hydrodynamic forces and sediment and bed properties. Convergence of sediment fluxes and regions of increased erodibility can create estuarine turbidity maxima (ETMs), local areas of relatively high suspended sediment concentrations. A three-dimensional numerical model of the York River Estuary was developed based on the Regional Ocean Modeling System (ROMS) that included a sediment bed model with time-varying erodibility and consolidation to examine feedbacks between sediment flux convergence and erodibility.
Estimated sediment concentrations and erodibility exhibit high spatial variability in both the along and across channel directions. Model calculations of sediment concentrations and erodibility show similar patterns to observational data. Model results show the development of a highly erodible pool of sediment near the observed location of the mid-estuary ETM (Figure 9). Even when sediment convergence processes are diminished, suspended sediment concentrations remain high due to high sediment erodibility. Model estimates are shown to be less sensitive to variations in the consolidation rate than the configuration of the initial bed.

Dharia, P., 2012. The role of seabed erosion processes in controlling recruitment of benthic invertebrates in the York River estuary. Masters Thesis, School of Marine Science, College of Marine Science, Gloucester Point, VA, (in prep). Preliminary results from the recruitment erosion experiments are demonstrating interesting patterns. For example, early recruits of spionid polychaete worms, a dominant group in the estuary, are more susceptible to erosion than juveniles. Species-specific response patterns are expected to emerge based on factors such as living position, feeding and burrowing behaviors. At least one species, the polychaete *Streblospio benedicti*, is less erodible than expected based on its near-surface living position. This suggests that some species may exhibit active behaviors during erosion events that help retain juveniles within the bed.

Friedrichs, C.T., 2010. Barotropic tides in channelized estuaries. In: A. Valle-Levinson (ed.), Contemporary Issues in Estuarine Physics, Cambridge University Press, Cambridge, UK, pp. 27-61. This paper addresses the dynamics of cross-sectionally averaged tidal currents and elevation in channelized estuaries. A series of estuarine geometries are examined which attempt to encompass generic, reasonably realistic scenarios found in nature. Typically, the goal in each case is to determine the lowest order physical balances governing barotropic tides for a realistically relevant geometry, derive an analytical expression for the speed of tidal phase propagation, solve for the amplitude and phase of tidal velocity relative to that of elevation, and determine the lowest-order variation in tidal amplitude with distance along the estuary. A few less realistic, but classically studied cases (e.g., those involving an intermediate length, constant width channel) are also considered for completeness. For most cases, examples of estuaries from the literature are discussed which reasonably represent and justify the simplified dynamics being
examined. An essential step in this process is the identification of key length-scales, corresponding inverse length-scales (or “spatial rates of change”), and dimensionless ratios to be subsequently used to determine when and where to keep or neglect various dynamic or kinematic terms. Specific estuary geometries are then examined (e.g., short vs. long, shallow vs. deep, funnel-shaped vs. non-convergent) that allow simplifications to be made which are particularly relevant to better understanding fundamental dynamically the most simple, yet still observationally useful, towards somewhat more complicated but naturally common “equilibrium” and “near-equilibrium” estuaries. Along the way, controls on tidal asymmetries are considered in the context of short and/or shallow estuaries. For completeness, non-equilibrium channels and reflected wave cases are also briefly considered.

Cartwright, G.M., C.T. Friedrichs, P.J. Dickhudt, T. Gass, and F.H. Farmer, 2009. Using the acoustic Doppler velocimeter (ADV) in the MUDBED real-time observing system. Oceans 2009, Marine Technology Society/IEEE, CD ISBN: 978-0-933957-38-1, 9 p. As part of MUDBED project, we have deployed 5 MHz Sontek ADVs at two muddy sites along the York River estuary for the last 3 years. At both sites, internally recorded ADV data have proven invaluable in allowing reliable long-term estimates of water velocity, bottom stress, suspended sediment concentration, sediment settling velocity, and bed erodibility under spatially and seasonally variable conditions. Nonetheless, it has been challenging to reliably collect these ADV data in a real-time mode. Working with Franktronics, Inc., an automated terminal emulator has been developed to allow ADV data to be logged internally and burst data to be automatically transferred off the internal logger every 15 minutes in near real-time. To facilitate wireless data transmission, we have placed a serial-to-Ethernet converter in an underwater housing on our benthic tripod. This allows us to transmit near-bed ADV data via an Ethernet cable up to a relatively small surface buoy, wirelessly transmit the signal via an Ethernet radio and omni-directional antenna on the buoy to a nearby stationary platform, and relay the ADV data via a second Ethernet radio and a uni-directional antenna back to VIMS. At VIMS, the data stream is received into a local intranet, which isolates the wireless Ethernet links from general internet traffic (Figure 10).

suspended sediment in the presence of muddy flocs and pellets. In: N.C. Kraus (ed.), Coastal Sediments 2011, American Society of Civil Engineers, p. 642-655. Observations are presented from a benthic observatory in the middle reaches of the York River estuary, VA, USA, that show evidence for both muddy flocs and pellets in the lower 1 m of the water column. This study combines in situ time series estimates of (i) volume concentration and particle size distribution from a Laser In Situ Scattering Transmisometer (LISST) (for 2.5-500 μm) and a high-definition particle camera (for 20 μm to 20 mm), and (ii) water velocity, turbulent stress, mass concentration and settling velocity derived from an Acoustic Doppler Velocimeter (ADV). Mass concentration, mass settling velocity and the abundant 88 μm size class are in phase with velocity and stress, consistent with suspension of relatively dense, rapidly settling and resilient ~90 μm pellets. Volume concentration of the abundant 280 μm class peaks well after stress and velocity begin to decrease, consistent with the formation of lower density, slowly settling and fragile ~300 μm flocs (Figure 11).

Kraatz, L.M., A.D. Skarke, A.C. Trembanis, and C.T. Friedrichs, 2011. Approaches for quantifying seabed morphology – techniques for utilizing rotary sonar systems. In: N.C. Kraus (ed.), Coastal Sediments 2011, American Society of Civil Engineers, p. 1060-1073. Rotary sonar instrumentation is a versatile tool for the observation of seafloor morphology with a wide variety of potential applications. Here we present a review of rotary sonar development and implementation, followed by analysis of seafloor morphological evolution based on rotary sonar observations made in two contrasting depositional environments: the Delaware Bay mouth, a non-cohesive high-energy environment, and the York River Estuary (Figure 12), a low-energy cohesive environment. Additionally, we present a methodological approach for rotary sonar deployment, utilization, and data analysis.

Fall, K.A., 2012. Controls on particle settling velocity and bed erodibility in the presence of muddy flocs and pellets, York River estuary. Masters Thesis, School of Marine Science, College of Marine Science, Gloucester Point, VA, (in prep). Analysis of data collected at the MUDBED site during the summer of 2007 highlights two distinct regimes with contrasting sediment characteristics (Figures 13 - 16). Regime 1 represents periods dominated by easily suspended, flocculated muds, while Regime 2 represents periods strongly influenced by less easily
suspended, biologically formed pellets mixed together with flocs. During the floc-dominated Regime 1, erodibility ($\varepsilon$) averaged about 3 kg/m$^2$/Pa and $\tau_b$ for initiation of erosion ($\tau_{c\text{INT}}$) was only 0.02 Pa. During the pellet influenced Regime 2, $\varepsilon$ dropped ~ 1 kg/m$^2$/Pa, and $\tau_{c\text{INT}}$ increased to 0.05 Pa. During the floc-dominated Regime 1, a remarkably stable value of fall velocity $W_s = 0.85$ mm/s for the settling component of mass concentration (C) was observed, consistent with floc size limitation by settling-induced turbulence rather than turbulence associated with $\tau_b$. In contrast, during the pellet-influenced Regime 2, $W_s$ for the settling component increased with greater $\tau_b$, consistent with suspension of heavier pellets at higher $\tau_b$ and a limited supply of flocs due to bed armoring by pellets. Based on an estimate of 20% washload, 50% flocs and 30% pellets at peak $\tau_b$ during Regime 2, the mean $W_s$ for the pellets was calculated to be about 2 mm/s. Once $\tau_b$ had peaked and then started to decrease during a given tidal cycle, the pellet component of C was seen to decrease relatively quickly. But floc C did not rapidly decrease during either regime until $\tau_b$ dropped below about 0.08 Pa. This suggests that over individual tidal cycles, cohesion of settling flocs to the surface of the seabed is inhibited for $\tau_b$ larger than $\tau_{c\text{COH}} \approx 0.08$ Pa. Averaged over 25 hours, floc erodibility on a given day was positively correlated to the magnitude of $\tau_b$ observed over the previous 5 days, providing an in situ estimate of a consolidation-relaxation time-scale for homogeneous estuarine mud. In contrast, erodibility during periods strongly influenced by pellets was inversely correlated to $\tau_b$ with a zero time lag, which is more consistent with bed armoring.
Figure 1: Map of study sites in the York River, Virginia. Top left Clay Bank sites have previously been observed to be more physically impacted than the lower right Gloucester Point site. CS refers to Clay Bank shoal (~ 5 m depth), CB is Clay Bank channel (~ 9 m depth) and GP is Gloucester Point (~ 9 m depth). The along-channel distance between Gloucester Point and Clay Bank is approximately 16 km.

Figure 2: Gust microcosm being used to measure seabed erodibility within a few hours of sample collection in the York River estuary.
Figure 3: Digital seabed profile camera.

Figure 4: Deployment of tripod with ADV and CTD at Gloucester Point site in early December 2006 and retrieval in late January 2007.
Figure 5: Critical stress for initiation of erosion ($\tau_{c0}$) from this study and a number of published works as a function of the solids volume of the fraction of the mud matrix ($\phi_{sm}$).

Figure 6: Conceptual model for sediment transport in the York River estuary, including changes in seabed structure and patterns of erodibility and settling velocity in the Clay Bank region of the middle estuary as a function of river flow. The distance from Gloucester Point to West Point is about 45 km.
**Figure 7:** Acoustic Doppler velocimeter (ADV) time-series from the York River estuary of (a) seabed elevation (relative to the lowest elevation recorded during each deployment), (b) tidally averaged suspended sediment concentration, (c) sediment settling velocity, and (d) eroded mass at a bed stress of 0.2 Pa. Estimates of erodibility from Dickhudt (2008, MS Thesis) for adjacent sites based on a Gust Microcosm are shown in (d) by the larger corresponding symbols.

**Figure 8:** (a) Maximum bottom stress and (b) maximum total suspended sediment mass over a tidal cycle for varying values of the bed consolidation time (from 1 to 48 hours). Values in (a) and (b) represent the maximum estimated for each tidal cycle.
Figure 9: Modeled, tidally-averaged, along-channel hydrodynamic and sediment properties for model run Day 115 (26 April 2007). (a) Suspended sediment concentrations (filled contours), salinity (dotted contours), and along-channel velocity (arrows) along the southern channel flank. (b) Sediment erodibility (positive upward) and total bed mass (positive downward).

Figure 10: Flowchart of Ethernet communication between instruments mounted on tripod and computers in the lab connection real-time data.
Figure 11: Clay Bank (York River estuary, VA) time series for (a) mass concentration from ADV backscatter at 45 cmab, (b) uncalibrated volume concentration from the LISST (85 cmab) and RIPScam particle camera (90 cmab), (c) CTD salinity (85 cmab) and ADV current speed, (d) ADV Reynolds stress, (e) fall velocity estimated by instantaneous values of $w_f = \frac{\langle C'w' \rangle}{\langle C \rangle - C_{bgd}}$ (blue line) and by a running regression of $\langle C'w' \rangle$ vs. $\langle C \rangle$ using 12 bursts (red line), (f) volume concentrations for the LISST bins centered at 88 μm (~ size of pellets) and 280 μm (~ typical flock size approaching slack).
Figure 12: (a) Clay Bank (York River estuary, VA) 1 MHz rotary scan image, 1 meter above the bed (Range ~ 10 m, 24 dB gain). (b) Diagram highlighting position of furrow and showing the 4 transects analyzed for acoustic backscatter comparison. (c) Time series of backscatter amplitude at 5 meters from the rotary transducer along the 4 transects.
Tidal Analysis highlights differences in bed stresses and concentrations for Regime 1 and Regime 2.

Figure 13: Phase-averaged velocity, bed stress and sediment concentration for two regimes.

-- Once $\tau_b$ increases past a critical stress for initiation of floc suspension ($\tau_{cINT}$), $C$ continually increases for both Regime 1 and for Regime 2, consistent with either depth-limited erosion or bed arming.

-- As $\tau_b$ decreases for Regime 1, $C$ does not fall off quickly until $\tau_b \leq 0.08$ Pa, suggesting a critical stress for the start of floc cohesion to the bed at $\tau_{cCOH} \approx 0.08$ Pa.

-- As $\tau_b$ decreases for Regime 2, $C$ decreases more continually, suggesting pellets without as clear a $\tau_{cDEP}$.

But the decline in $C$ accelerates for $\tau_b \leq 0.08$ Pa, suggesting a transition to floc deposition.

-- The change in deposition rate for Regime 2 at $\tau = 0.08$ Pa provides an estimate of the maximum fraction of flocs relative to pellets.

Figure 14: Patterns of erosion and deposition for two particle regimes.
Analysis of $W_{sBULK}$ by removing $C_{WASH}$ and solving for settling velocity of the depositing component ($W_{sDEP}$) during increasing $\tau_b$ allows separate estimates for settling velocities of flocs ($W_{sFLOCS}$) and pellets ($W_{sPELLETS}$).

$$W_{sBULK} = \frac{c' \langle c' \rangle}{c} (\text{mm/s})$$

$$W_{sDEP} = \frac{c}{(c - c_{wash})} W_{sBULK} \quad (\text{mm/s})$$

Analysis of $W_{sBULK}$ by removing $C_{WASH}$ and solving for settling velocity of the depositing component ($W_{sDEP}$) during increasing $\tau_b$ allows separate estimates for settling velocities of flocs ($W_{sFLOCS}$) and pellets ($W_{sPELLETS}$).

(a) Sediment Bulk Settling Velocity, $W_{sBULK}$

(b) Depositing component of Settling Velocity, $W_{sDEP}$

(a) $W_{sBULK}$ and (b) $W_{sDEP}$ during periods of increasing tidal velocity for the top 20% of tidal cycles with the highest bed stresses. Error bars denote +/- 1 standard error.

**Figure 15:** Phase-averaged settling velocity for two regimes.

Daily-averaged erodibility is correlated either to 5-Day-averaged $\tau_b$ (Regime 1) or to daily-averaged $\tau_b$ (Regime 2), revealing two distinct relationships between $\varepsilon$ and $\tau_b$.

**Figure 16:** Influence of stress history on bed erodibility for two regimes.