COMMUNITY SEDIMENT TRANSPORT MODEL

W. Rockwell Geyer
Woods Hole Oceanographic Institution
MS 11, Woods Hole, MA 02543
phone: 508-289-2868   fax: 508-457-2194 email: rgeyer@whoi.edu
Award Number: N00014-06-1-0945

Christopher R. Sherwood
U. S. Geological Survey
384 Woods Hole Road, Woods Hole, MA 02543-1598
Phone: (508) 457-2269   Fax: (508) 457-2310   email: csherwood@usgs.gov

Timothy Keen
Naval Research Laboratory, Code 7322, Stennis Space Center, Mississippi, 39529
phone: (228) 688-4950   fax: (228) 688-4759   email: timkeen@charter.net
Document Number: N0001406WX21379
http://www7300.nrlssc.navy.mil
https://www.myroms.org/projects/cstm

LONG-TERM GOALS

The goal of this project is to produce an open-source model that couples hydrodynamics (circulation and waves), sediment transport, and morphodynamics. The need and value for such a model has been well established by previous NOPP-supported planning efforts (Sherwood et al., 2000; 2002) and the feasibility of the proposed approach has been demonstrated by incorporation of sediment-transport and morphology algorithms into the ONR-supported Regional Ocean Modeling System (ROMS). The model is intended to be used as both a research tool and for practical applications. An accurate and useful model will require coupling sediment-transport with hydrodynamic forcing and stratigraphy. The development of a coupled, modular, modeling system that includes all of these components (waves, circulation, sediment-transport, morphology, and stratigraphy) will increase our ability to predict the fate and distribution of sediment in coastal environments and provide a tool for advancing our understanding of these processes.

OBJECTIVES

The model provides a framework for testing sediment-transport hypotheses that have been formulated as computational algorithms and coded into modules. When the modeling system is complete, it will be possible to choose among several process modules or replace existing modules with new ones developed using alternative hypotheses, allowing scientists to compare results from alternative sediment-transport formulations in identical modeling environments.

The model is focused on cohesive and non-cohesive coastal sediment-transport, including shelves, estuaries, and nearshore environments. Processes include:

• Bedform evolution and moveable bed roughness and bottom drag

- Nonlinear-wave processes (e.g., asymmetry) and associated sediment transport
- Wave-current interaction and associated sediment transport
- Influence of sediment on flow properties(including stratification and fluid mud)
- Bed stratigraphy, consolidation, mixing, and armoring
- Nearshore boundary conditions (including surf zone processes)
- Water quality

The model is intended for regional scale applications, but it can also address more localized process studies (Figure 1). Domain size can range from 100s of meters to 100s of kilometers and simulated time scales may range from individual transport events (minutes) to decades. Dynamical and computational considerations restrict the model resolution: horizontal spatial resolution ranges from ~10 m to ~1 km and time steps range from seconds to minutes. We include higher-resolution sediment-transport calculation modules for research problems but, for practical applications, small-scale processes are parameterized or integrated to longer time steps and larger spatial scales.
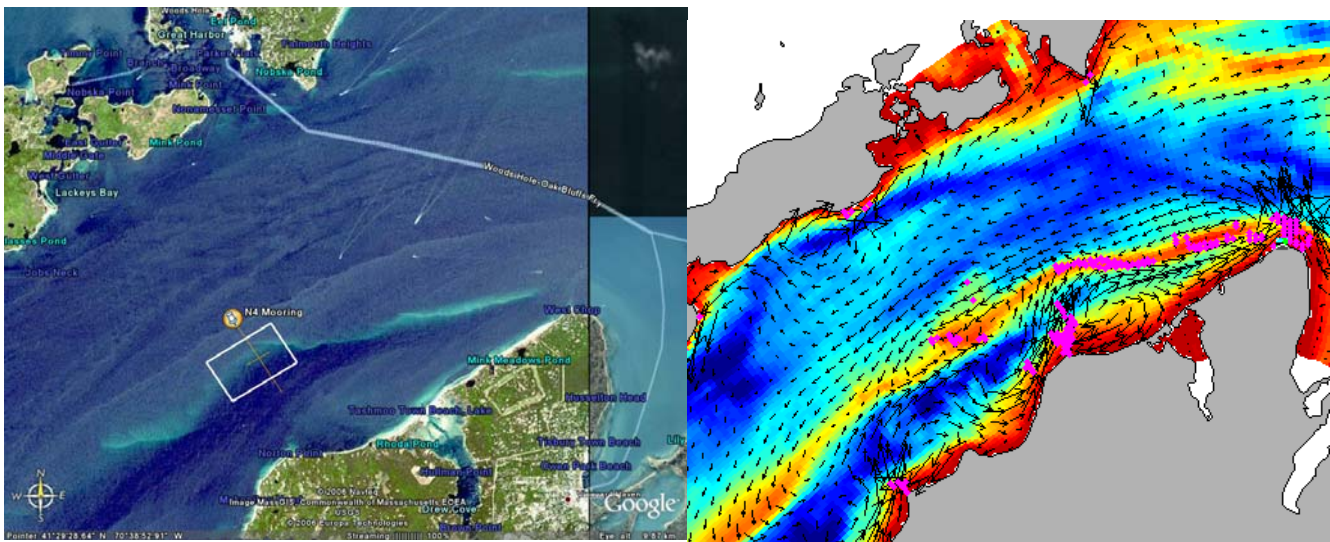

Figure 1. Example application of the CSTM to shoal formation at Middle Ground, Vineyard Sound, MA. Middle Ground is apparent in the air photo (left panel; Google Earth with IKONOS imagery). The tidal-residual circulation (arrows, right panel) in the CSTM simulations generates sediment transport consistent with observed bedform migration patterns. Modeled long-term deposition (magenta symbols) occurs on the crest of the shoal (bathymetry is shown in color). Courtesy R. P. Signell.

The model code is open-source, with an unrestricted license for both commercial and non-commercial use. Model code is written in modern, well-documented Fortran90/95 for multi-threaded computations. The model will compile and run on a range of computers, including those using modern Windows, Macintosh, and Unix/Linux operating systems.

In addition to source code, the project will also deliver model documentation, test cases, and results of applications to real-world examples. During the life of the project, collaborative interactions among the community of scientists, model developers, and users is hosted on a web site, most of which is open to the public. At the end of the project, the collaborative web site will either be maintained by project participants or turned over to the public at a venue like SourceForge.

APPROACH

The overall approach is to start with existing code for two working sediment-transport models, restructure the code into a modular modeling system with standardized interfaces and data conventions, develop new sediment-transport model algorithms and add these to the modeling system, add user tools, documentation, and test cases, and demonstrate the system with selected applications. The project involves several concurrent tasks. Meetings of scientific and technical planning and review committees are held on a regular basis, and project management occurs throughout the project (Task 1). The core of the project involves design and implementation of the modular model framework (Task 2), development of standards and conventions for data exchange and tools for pre- and post-processing and analysis (Task 3), and development of modules from new sediment-transport algorithms (Task 4). A collaborative web site hosting code, test cases, documentation, and discussions was established early in the project and will be maintained throughout the project (Task 5). Finally, application of the model to real-world applications is being conducted by the Partner Investigators and others (Task 6).

Task 1. Science and Technical Management and Review
The overall project is managed jointly by Geyer and PIs from the Federal entities. PIs from partner institutions manage their individual work scopes. Technical aspects of the project are guided by the Scientific Advisory Committee and a Technical Advisory Committee comprised of project PIs and invited outside experts.

Task 2. Model Development and Coupling
Most existing numerical sediment-transport models are either standalone models or are tightly integrated with more extensive models of circulation and/or water quality. They are not, in general, written as portable modules that can be exchanged for alternative formulations or used with alternative circulation models. Instead, modelers (usually scientists, not software engineers) tend to recode these formulations from scratch or adapt code from other models. Furthermore, the models are often not designed for parallel or multi-thread computing.

In this project, we are building a modular model suitable for multiple processers. We are organizing existing and new sediment-transport code into discrete modules to be coupled in an efficient framework using MCT. We will also work with developers of other models (e.g., Morphos, ADCIRC, NCOM, SWAN) and coupling systems (e.g., ESMF) to develop standards for coupling physical-system models (e.g., atmospheric, ocean, wave, sediment bed) using tools like ESMF. Ultimately we hope that this will lead to simpler and more-efficient model coupling.

Task 3. Software Tool Development and Model Usability
A significant and essential part of this system is the development of the software tools that make the system work more effectively for users. Specifically, we will construct better tools for configuring and running the modeling system, and for analyzing, visualizing and sharing the results with collaborators

Task 4. Algorithm Development

An essential part of the project is to develop, test and distribute code that incorporates the most advanced algorithms for sediment transport processes. This involves both the development and refinement of algorithms and the translation of those algorithms into efficient code suitable for parallel processing. A number of generally accepted algorithms have already been incorporated into the CSTM model code, including non-cohesive bottom boundary layer formulations, suspended and bedload transport processes, wave-current interaction, and bed morphology evolution. Algorithm and model code development are also proceeding in the more challenging topics related to cohesive sediment transport, particle aggregation, fluid mud dynamics, hindered settling, wave-current interactions, time-dependent bedform evolution, and the sediment transport processes in the near-shore.

The approach to algorithm development in this project includes the application of process models for initial development and testing of the algorithms, followed by translation into the CSTM model code, followed by the development of test cases and applications (see Tasks 5 and 6) to ascertain the fidelity and robustness of the parameterizations. The process models include Large Eddy Simulations (LES) for parameterization of sediment suspension, high-resolution RANS model (DUNE3D) for flow-bedform interaction studies, non-hydrostatic nearshore models for developing parameterizations of surf- and swash-zone processes, and two-phase transport modeling for investigations of high-concentration suspensions (Figure 2). These process models are not considered end-points in the CSTM model development, but they provide critical guidance and testing in the algorithm and code development.
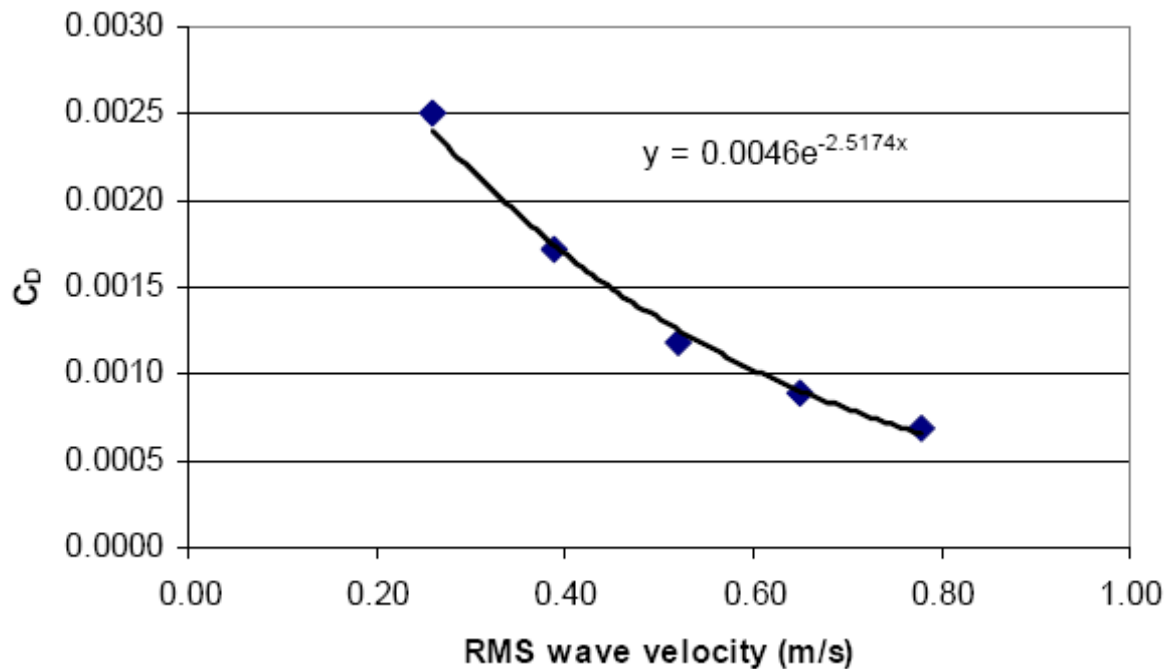

$$y = 0.0046e^{-2.5174x}$$

Figure 2. Decrease in the apparent drag coefficient C_D associated with a fluid mud layer as near-bottom wave-orbital velocity increases. This is an example of process parameterization suitable for the CSTM derived from a high-resolution 1D (vertical) model of the bottom boundary layer. Courtesy T-J. Hsu.

Task 5. Community Engagement

<u>Web site</u> **–** We maintain a collaborative web site with project news, source-code version control, discussion / forum, download site, documentation, toolkit library, links, and other resources at https://www.myroms.org/projects/cstm.

<u>Documentation</u> – We are writing documentation for the system and each module, describing the scientific basis, implementation, and usage. We are also providing tutorials and examples for model use.

<u>Test Cases</u> – We are developing a standard suite of test cases. Test cases examine the skill of a particular model configuration relative to theoretical, empirical, or established computational sediment-transport results and provide demonstration configurations for model users. Regression tests are used to determine that model results are consistent across compilers, platforms, and computer architectures, and to ensure that changes in code do not have unforeseen consequences in other aspects of model performance. Regression tests will be automated and eventually will be run nightly. Other tests will be used to evaluate the implementation of sediment-transport algorithms, based on comparison with analytic solutions, data from the lab or field, results from other models, or expected results from thought problem. All of the required model code, start-up files, boundary conditions, initial conditions, forcing conditions, and expected results will be provided for test cases, so they will serve as practical examples for users.

<u>Host town meeting and training session</u> – We are engaging the broader community by discussing the CSTM in seminars, professional meetings, and journals. In FY2008, we plan to host an open Town Hall meeting at Ocean Sciences 2008 (Orlando, February 2008). Later in the project, we will host a training workshop that will allow scientists and modelers an opportunity to try the model on their own applications.

Task 6. Applications – Most of the project partners have specific applications for the CSTM that they will refine throughout the life of the project. The USGS is applying the model for nearshore processes in South Carolina and is examining sandbank formation on Middle Ground in Vineyard Sound; WHOI and the USGS are using the model to simulate complex morphology and sediment distributions at the Ripples DRI site near the Martha's Vineyard Coastal Observatory; NRL is using their implementation of CSTM to simulate optical properties in various locations; the USACE will apply the model to Gulf Coast regions affected by recent hurricanes; and UCLA is applying the model to the Southern California Bight. In addition to these applications the project is encouraging "early adopters" to use the CSTM for diverse applications by supporting their efforts with training, documentation, site visits, and providing travel funds to project meetings.

Participants

The project team (Table 1) includes three Federal agencies, eleven academic institutions, three businesses, and one non-governmental organization, with representation from the USA, United Kingdom, The Netherlands, and Denmark. In addition, several researchers and students not funded by this project, including C. K. Harris at VIMS and P. L. Wiberg at Univ. of Virginia, are actively developing and testing CSTM code and participating in project meetings, and an even larger number of researchers are applying the model and participating in the on-line forum.

Table 1. Summary of project partners and roles

Partner (type)	Key Personnel	Oversight and management	Module development	Software tools	Algorithm development	Community engagement	Model application
Woods Hole Oceanographic Institution (Academic)	R. Geyer J. Trowbridge P. Traykovski	X			X		X
U.S. Geological Survey Coastal and Marine Geology Program (Federal Government)	C. Sherwood R. Signell J. Warner B. Butman	X	X	X	X	X	X
Naval Research Lab (Stennis) (Federal Government)	T. Keen T. Campbell	X	X		X		X
U.S. Army Corps of Engineers (ERDC) (Federal Government)	D. Resio J. Hanson	X	X	X	X		X
HR Wallingford (Business)	R. Soulsby R. Whitehouse	X	X		X		X
Mississippi State University (Academic)	S. Bhate	X		X		X	
Ohio State University (Academic)	D. Foster J. Fredsoe	X			X		X
Oregon State University (Academic)	E. Skyllingstad N. Perlin		X				
Rosenstiel School of Marine and Atmospheric Science (Academic)	Y. Chang				X		
Rutgers University (Academic)	H. Arango D. Robertson	X	X			X	
Stevens Institute (Academic)	A. Blumberg	X			X		
UNESCO-IHE Institute for Water Education (NGO)	D. Roelvink	X					X
University of California, Los Angeles (Academic)	J. McWilliams Y. Uchiyama	X	X		X		X
University of Delaware (Academic)	J. Kirby F. Shi	X	X		X		
University of Florida (Academic)	T. Hsu				X		
University of Maryland (Academic)	L. Sanford				X		X
WL|Delft Hydraulics Laboratory (Business)	B. Jagers J. Winterwerp	X					
Woolpert, Inc. (Business)	D. Froehlich	X	X				

The following significant accomplishments were completed by the project as a whole. These are listed according to the tasks.

Project Management – Subcontracts from WHOI were negotiated with all of the subcontractors. A series of web meetings were held to plan and initiate the project. Two project meetings were held, one in Woods Hole in May, and a second at UCLA in October.

Model Development and Coupling – ROMS 3.0 was released in April 2007. More than 100 subsequent bug fixes and enhancements have been added since then, and users can easily update their copy of the code with single commands. This version of ROMS includes all of the CSTM sediment-transport routines developed by the USGS and UCLA, including non-cohesive bedload and suspended-load transport, ripple predictors, bed armoring and stratigraphy, and morphological evolution. It also has routines for physical processes that are key to useful and practical sediment-transport models, including a positive-definite advection schemes, two-way coupling with the wave model SWAN, wave-induced circulation, generic length scale two-equation turbulence submodels, and grid coupling.

A prototype driver for model coupling with ESMF was developed and tested with ROMS; however, similar efforts will be required for each model to be coupled.

Software Tool Development – Ongoing development of Matlab routines for preparing model input and examining model output has occurred. Libraries of Matlab routines have been identified and placed under version control.

Algorithm Development – Key algorithms required for a robust coastal sediment-transport model were identified at the May project meeting. CSTM code for cohesive and mixed sediment beds, bioturbation, and has been written and is being tested. Other algorithms have been coded in Matlab or 1-d implementations for and are being ported to CSTM demonstrated in models time-dependent ripple evolution

Community Engagement – Source code for ROMS and the CSTM have been copyrighted by the ROMS/TOMS Group, a self-selected group of developers and users that contribute to the code. As copyright owner, the ROMS/TOM Group has licensed the models using an open-source license modeled after the MIT/X license. This license ensures that all potential users have the right to view, modify, and redistribute the code with virtually no restrictions.

Domain names myroms.org and cstm.org have been acquired, and a dedicated server was purchased to host the ROMS and CSTM websites at www.myroms.org. Software for source-code control, issue-tracking, file sharing, and documentation have been set up at this site for ROMS and the CSTM. Branches where developers can store (and share) their modified versions of the code have been established, and more than 1100 revisions to the CSTM repository have been made.

Applications – The CSTM is being applied by project members and early adopters in a wide range of coastal environments.
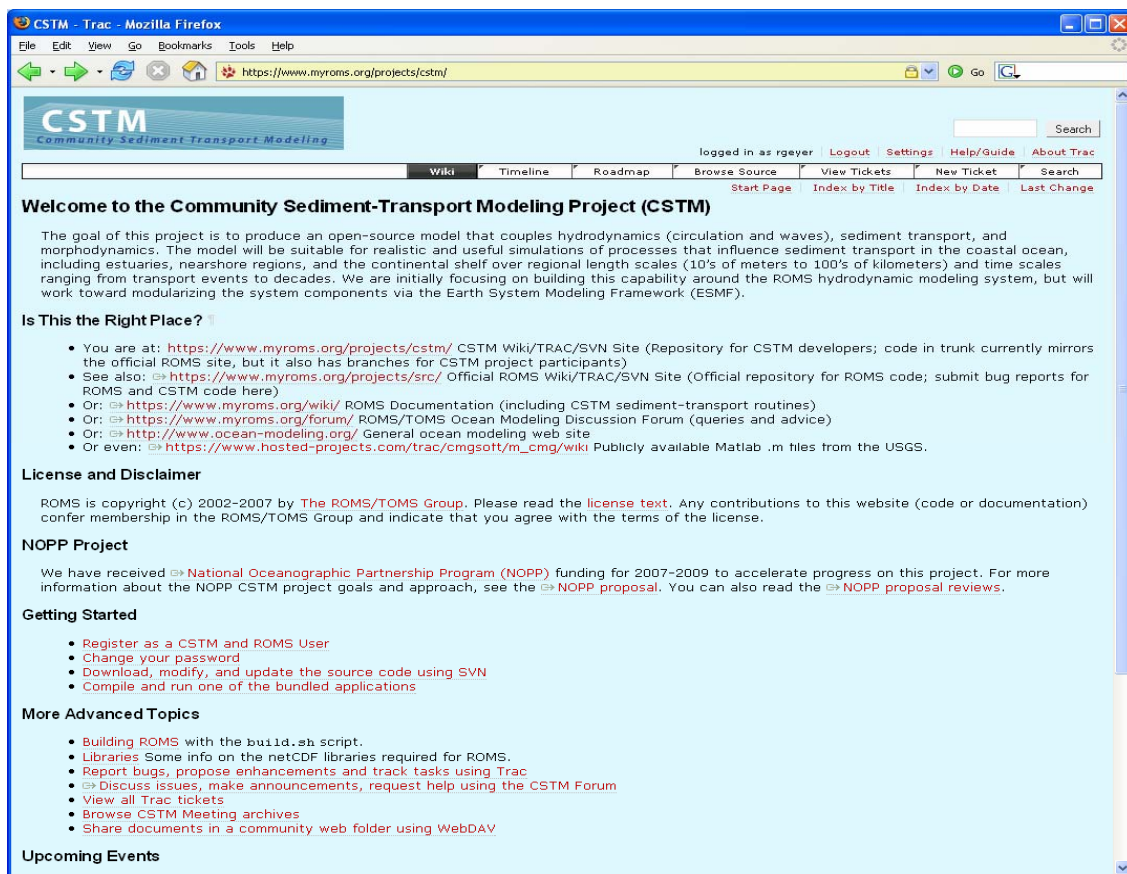
Figure 3. Screen grab of the CSTM website at https://www.myroms.org/projects/cstm. This site, including Wiki documentation, Trac issue tracking, file sharing, and Subversion source code repository, is freely accessible after registering as a ROMS user and indicating interest in the CSTM.

WORK COMPLETED BY PARTNERS

This section describes the work completed by partner institutions, in the same order as presented in Table. 1.

Woods Hole Oceanographic Institution: Geyer, Trowbridge, and Trakovski

WHOI has provided the administrative management of the project. Geyer has worked with Sherwood at USGS to organize and execute two workshops, the first in May, 2007, on algorithm development and scientific applications of CSTM, and the second in October, 2007, on the technical elements of CSTM, including model coupling, software management and tools. The WHOI team is also involved with algorithm development, in the areas of bedload transport, non-equilibrium bedform dynamics, and wave-current interaction in the bottom boundary layer, and fluid mud dynamics. Traykovski has developed and tested an algorithm for time-evolution of bedforms and is comparing it to an alternative formulation by Soulsby and colleagues. Traykovski is working with Hsu to test parameterizations of fluid mud dynamics with Traykovski's high-resolution observations and 1D models. Traykovski and Trowbridge are working on the parameterization of wave-current interactions in the presence of cohesive sediments and fluid mud. Geyer is working with Warner at USGS on the implementation of an application of CSTM in the Hudson River estuary.

U. S. Geological Survey: Sherwood, Signell, Butman, Warner

The objective of the USGS participation in this project is to lead and facilitate development of a state-of-the-art research model for studying coastal sediment-transport phenomena and addressing practical problems. The USGS has provided project leadership and management in partnership with WHOI. The USGS has implemented most of the existing sediment-transport routines in ROMS, and has also enhanced the model with advanced two-equation turbulence submodels, postive-definite advection routines, wave-induced circulation, two-way nesting with the wave model SWAN, and grid decomposition. In addition, the USGS has participated in developing the CF conventions for model and data file exchange, has developed key modeling tools, supplied model documentation and on-line advice for the modeling community, and is applying the CSTM to practical problems of interest to ONR, NOPP, and the USGS.

Naval Research Lab, Stennis Space Center: Keen, Campbell

The NRL team has selected a method for estimating surface sediment concentrations from AVHRR using the method described in Myint and Walker (2002). Water quality parameters for input as tracers representing a range of water constituents will be estimated using the MODIS sensor data after Hu et al. (2004). We have acquired several potential Mie scattering codes for computing the IOPs. We have acquired the EODES model for computing laser performance (Shirron and Giddings, 2006). We have implemented ESMF versions of the SWAN wave model, COAMPS atmospheric model, and the ADCIRC and NCOM hydrodynamic models. We have completed software beta level for the atmosphere/ocean coupling in COAMPS using ESMF. We have provided consultation to other CSTM researchers on lessons learned and best practices for software implementation using ESMF.

U.S. Army Corps of Engineers, ERDC: Resio, Hanson

ERDC has provided, via Froehlich, updates on the status of the Morphos project. Presently, Morphos developers are using custom code for model coupling, but they are monitoring progress in ESMF development and plan to adopt ESMF if it is advantageous.

HR Wallingford: Souslby, Whitehouse, Chesher

The PIs and other members of the Wallingford team have participated in Webex meetings with the NOPP partners and exchanged information to complete the project kick-off phase.

Discussions have taken place within the Wallingford team and with NOPP partners about the implementation of the modular framework for the modelling which was discussed during the preparation of the proposal (i.e. the Open-MI approach). The CSTM team has adopted a modular framework implemented using the ESMF approach. The Wallingford team has started to prepare a comparative note on the two systems to see whether there any recommendations that can be developed regarding wider interoperability.

Relating to sediment transport modules three aspects have been pursued. A report and step-by-step algorithm for wave-current interaction has been provided to the project (Soulsby and Clarke, 2004). The explicit algebraic approach applies to laminar, smooth-turbulent and rough-turbulent regimes. It

has also been written as FORTRAN code which can be implemented by CSTM partners. Also a time-dependent ripple predictor developed by Soulsby and Whitehouse (2005) for waves and current, as part of the DRI Ripples program (ONR), has been provided to the project. The step-by-step algorithm can be implemented by CSTM partners. The Wallingford team has discussed how it will bring the latest developments in sediment transport modelling into the CSTM project.

The team has also started considering the test cases based on our own experience of coastal area modelling of hydrodynamics, sediment transport and morphological change at Teignmouth (UK), as part of the COAST 3D programme. Three test cases will be proposed (for example two tidally dominated cases and one case with large wave forcing of nearshore circulation).

Tim Chesher attended the WHOI project meeting 21-23 May 2007 and participated in discussions about partnering on the CSTM testing, and initial plans for the testing. Further preparatory work was completed for presentation at the UCLA meeting 4-5 October 2007, which Tim Chesher attended.

Mississippi State University: Bhate

During the early months of this project, the focus was on understanding ROMS-CSTM model, architecture, and output data from developer's perspective**.** This effort was required in order to build an efficient Regression test package as well as NetCDF-Java interface/toolkit for reading data into Matlab. Travel to Unidata's training workshops in Boulder, CO provided important information related to the Netcdf-Java API and Unidata Integrated Data Viewer (IDV).

The initial regression package was developed for ROMS 2.2, but when the package was finished, ROMS 3.0 had been released, using a completely different build strategy. The regression test package 1.1beta has now been upgraded to work with ROM3.0 and has been delivered to the selected ROMS-CSTM developers for testing. A new release will provide users with an XML interface for defining ROMS test cases, and is scheduled to be delivered at the end of the September, 2007. The package has been tested to run on Linux (2.6.15) and Windows under Cygwin.

Significant time was spent in understanding Matlab interface, Unidata's NetCDF-Java API, and Integrated Data Viewer (IDV), as these areas are fundamental in designing NetCDF-Java interface/toolkit for Matlab. A conceptual view of the toolkit has been demonstrated with few functional prototypes, which can read ROMS local and remote gridded CF compliant NetCDF dataset, extract data variables, perform vertical transformation etc. A prototype interface in Java to replicate Matlab interface for n-dimensional data array access (e.g. colon ':' operator) is in progress and will most likely be completed by the end of the current reporting period.

Ohio State University: Foster, Fredsoe

The Dune model is being used for process studies of bedform evolution and bedload transport as part of the overall CSTM effort. The trunk line for Dune has been created and is accessible at the following website: <https://svn1.hosted-projects.com/cmgsoft/dune/ >. The code is accessible to the larger CSTM community.

The quasi-three dimensional version of the Dune code is running for a wave-current angles of less than 90 degrees. The code solves for cross-shore velocity (x direction) and partially solves for along-shore velocity velocity. Ongoing modifications to the code include a full solution for the along-shore velocity and for wave-current angles through 90 degrees. Currently, the grid is set up to be layers of 2D grids in the along-shore dimension rather than a fully operational and linked 3D grid. Future modifications may include a fully three-dimensional solutions.

Oregon State University: Skyllingstad, Perlin

ESMF was installed and tested on a Linux cluster at Oregon State University. Testing included building a sample ESMF application and determining which tools were needed for model coupling. These tools were used to adapt a stand-alone ROMS model to operate under ESMF superstructure; it helped to develop a common approach for integrating model codes into CSTM. The schematic approach and introductory ROMS-ESMF working code were demonstrated and discussed at the meeting in July 2-3, 2007 at WHOI, and generated valuable feedback and new suggestion of further development of the code. To keep track of the CSTM coupling tasks, and to enable code sharing among other developers, major ROMS code modifications along with the new routines were placed onto the CSTM SVN repository under *nperlin_branch* (https://www.myroms.org/svn/cstm/branches/nperlin_branch/ESMF_tests/WHOI_Jul07). Further, improved ESMF-ROMS code was also installed and tested on a cluster at WHOI (pikmin), and stored in CSTM SVN repository at:
https://www.myroms.org/svn/cstm/branches/nperlin_branch/ESMF_tests/ESMF_ROMS

Univ. Miami, RSMAS: Chang

Our work on this project is primarily focused on the calculation of sediment flux based on numerical simulations with a large-eddy simulation model. LES is employed for the generation of turbulent wave boundary layer flows over sinusoidal rippled seabeds, solving numerically the 3-D Navier-Stokes equations. The trajectories of individual particles are determined by solving the modified Maxey and Riley(1983) equation. The advantage of this method over the conventional advection-diffusion equation method is that velocities of sediments can be separated from the fluid velocity, and can be more easily and accurately obtained. Therefore, the sediment flux caused by the upward convective sediment motions can be measured by this approach

Numerical data sets of sediment and flow motions over sinusoidal ripple have been obtained for unsteady flow conditions. The probability distribution of particles as a function of elevation above the bed has been determined for various sediment and flow conditions. One of the most difficult tasks in this project is to estimate the suspended sediment concentration. This is because the number of sediment particles that can be employed in the numerical simulation is strictly limited, and it is basically not feasible to generate the suspended-sediment concentrations that are as high as natural

flows, where volumetric sediment concentrations can approach 0.65. Therefore, one of the focused tasks of this project has been to estimate the volumetric SSC of the numerical data whose actual concentration is far below than the real field. So far, two approaches have been attempted to find a relationship that connects the simulated sediment distribution to realistic SSC field. One is to calculate the mean distance between the suspended sediment particles, $L(t,z)$, as SSC is expected to be proportional to the inverse of the cubic of distance between particles ($C \sim 1 / L^3$). The second approach is to find the ratio of SSC by counting the numbers of sediment particles inside unit volumes at various locations. These two methods are now being tested to estimate the SSC from numerical data, and this will be one of the main research subjects for the next term. In addition to estimating the SSC, research has also been focused on finding the probability function $F(z)$. This has been done by counting the number of sediment particles at each vertical segment. In Figure 4 $F(z)$ is compared for different size particles. It is shown that the pattern of $F(z)$ depends on the grain size and decreases rapidly with increasing size. However, it is not easy to fit a curve on those lines as the decreasing rate varies with height (see panel (a)). More tests are planned with different flow conditions.
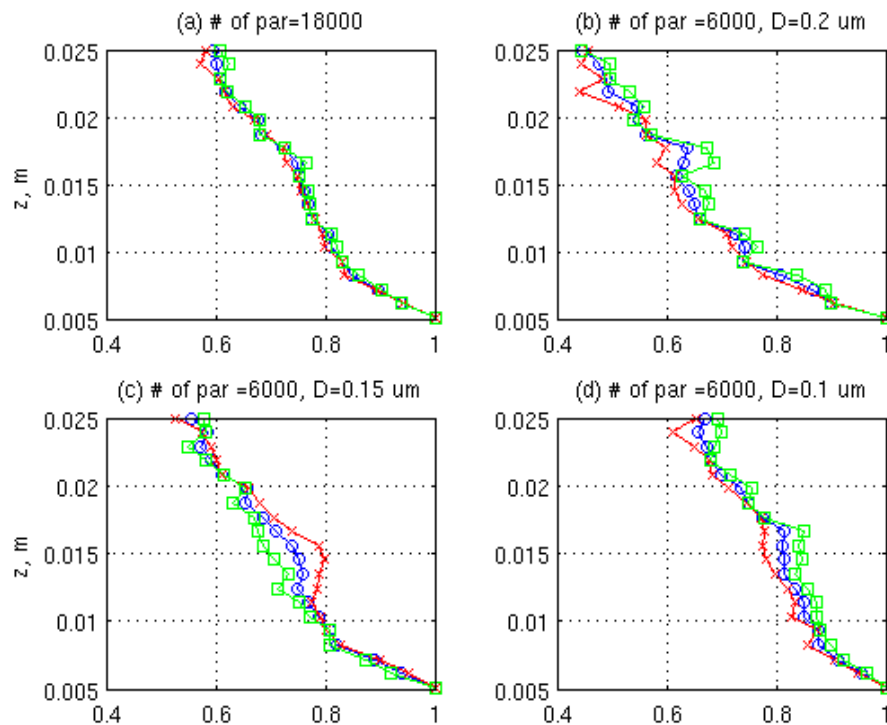

Figure 4. Estimation of particle probability function profiles $F(z)$ for various sediments above a ripple crest at $z_r = 5$ mm. (a) mixture of all three different size particles, (b) largest sediment size, D=0.2 μm, (c) D=0.15 μm, (d) D=0.1 μm. Averaged over one wave period (T=2 sec.) with different colors representing different periods.

Rutgers University: Arango, Robertson

The Rutgers team is most directly responsible for maintaining the compatibility between CSTM developments and ROMS. Since the start of this project the Rutgers team has completed the following tasks:

- Updated the official version of ROMS with the latest USGS research version maintained by John Warner. This included new developments in model coupling and radiation stresses, updates to the bottom boundary and sediment models, and new idealized and realistic test cases.

- After several years of development, ROMS version 3.0 was released to the entire user community on April 27, 2007. This version includes the tangent linear, representer, and adjoint model versions of ROMS. It also includes several adjoint-based algorithms for variational data assimilation, ensemble prediction, adaptive sampling, and circulation stability and sensitivity analysis.

- ROMS version 3.0 is now an open-source code. It is distributed to the ocean modeling community under similar conditions to the MIT/X License (http://myroms.org/license), using Subversion (svn) revision control software,

- A dedicated 4-CPU Linux box was purchased to host all ROMS web services and code distribution. A new domain https://www.myroms.org was acquired to host all ROMS web-sites which include the forum (https://www.myroms.org/forum), developer's blog (https://www.myroms.org/blog), and wikiROMS (https://www.myroms.org/wiki).

- Two code managing web sites, based on Trac, were developed to maintain the official and research branches of ROMS. They can be used for version and bug tracking, code browsing, and development timelines and roadmaps. The official community version is located at https://www.myroms.org/projects/src whereas the research sediment branches are located at https://www.myroms.org/projects/cstm. Both links are password protected so only registered users have access to the source code.

- Started working on the nesting capabilities in collaboration with John Warner (USGS). This will allow the temporal and spatial coupling between a hierarchy of parent and child grids. Three types of nested topologies are possible: grid refinement, mosaic grids (contact through a boundary), and composed grids (superposition).

- Started working on a generic model coupling interface using the Earth System Modeling Framework (ESMF) library. This will allow concurrent or sequential coupling between models. Currently, three model coupling systems are considered: atmosphere (WRF), wave (SWAN), and ocean (ROMS).

- Rutgers, UCLA, and the USGS sponsored a ROMS user's workshop at the University of California, Los Angeles October 1-5, 2007. The formal workshop presentations were held October 1st and 2nd, followed by a training session on October 3rd. The CSTM meeting was held October 4th and 5th.

Stevens Institute: Blumberg

Work by Stevens Institute is not scheduled to start until Year 2 of the CSTM NOPP project.

UNESCO-IHE: Roelvink

The objective of UNESCO-IHE participation is to provide scientific and technical advice to the NOPP project. The approach is to attend web meetings and workshops, hold discussions over email and during conferences, provide overviews and to a limited extent carry out testing or implementation of algorithms. More extensive involvement is foreseen in year 3.

The following work was completed:
- Participated in web meetings and May science committee workshop in Woods Hole;
- Provided input to overview of wave-induced circulation modeling approaches;
- Presented XBeach model, part of MORPHOS effort and discussed interaction with ROMS-SED during workshop;
- Started installing and getting acquainted with ROMS-SED;
- Attended Gordon Research Conference and presented ideas on morphodynamic modeling of interest to CSTM;
- Brought XBeach source under subversion system;
- Developed fast wave solver that can be used as an alternative to SWAN in nearshore morphology modeling

The following results were obtained this year. A simple stationary wave solver was developed within the XBeach model, as an addition to the nonstationary (time-varying at wave group scale) solver. Advantages over SWAN is that it is dedicated to the surf zone, fast and has well-behaved lateral boundaries. This could easily be coupled to ROMS-SED; alternatively, an offline or online coupling may be created between a larger-scale ROMS model and local XBeach models focusing on surf, swash and overwash processes.

Univ. California Los Angeles: McWilliams, Uchiyama

The specific objectives of UCLA participartion are to implement a theoretical formulation of the effects of wind waves and swells on coastal currents (McWilliams et al. 2004) and to extend the present capability of the sediment transport module by Blaas et al. (2007) within the Regional Oceanic Modeling System (ROMS) code and then investigate the consequences of these effects in different coastal circulation regimes.

We are investigating how wind-sea/swell propagates and breaks, and also how it act to influence the more slowly evolving oceanic currents and erodible aquatic bed. A multi-scale, fluctuation-averaged, asymptotic theory for the conservative evolution and interaction of currents and waves typical of stratified coastal shelf waters (McWilliams et al., 2004) is extended to a strong current regime, such as in surf zone where wave-breaking dominates the momentum transfer between waves and currents. The equations in this theory are implemented in ROMS to obtain numerical solutions under both instructively idealized and typically realistic conditions. Implementation of a non-cohesive, suspended sediment transport module into ROMS has recently been completed (Blaas et al., 2007). For further

realistic coastal sediment transport experiments, a bed-load transport model, a multiple-layered bed model, a minimum set of sediment cohesiveness, and land-derived fluvial sediment load have essential importance. Some of these features are newly implemented into the existing sediment transport model. Also essential is modeling wave generation, dissipation, and propagation. A third-generation spectral wave model, SWAN (Booij et al., 1999) is coupled with ROMS. An alternative approach is to model WKB ray equations for monochromatic waves directly within ROMS, suitable for fully-coupled wave-current process experiments in idealized configurations. Once ROMS is capable of representing these wave-averaged effects and sediment dynamics, a sequence of test problems will be designed, solved, and analyzed to expose the wave influences in competition with other, more familiar coastal dynamics.

The principal activities during the past year are the following:

A full three-dimensional wave-current interaction model is underway for a high-resolution study of the inner-shelf field experiment in Huntington Beach, CA. A new three-dimensional ROMS configuration has been established for the Southern California Bight (Figure 5) with 1 km horizontal resolution (parent grid) and with embedded 200 m resolution around Palos Verdes and Huntington Beach areas (child grid). So far the wave-averaged effects are implemented merely in the bed boundary-layer dynamics. Progress toward a ROMS with the fully three-dimensional wave effects based on the multi-scale asymptotic theory (McWilliams et al., 2004) is planned for the coming year, and the child grid resolution will be further refined (down to 100 m at least).
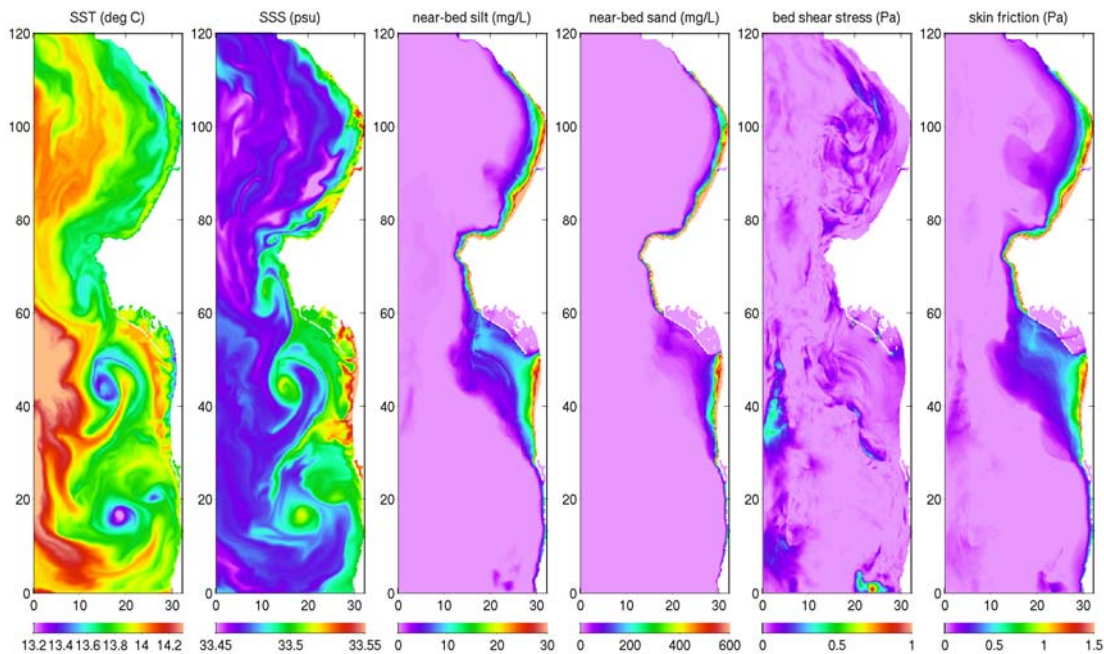

Figure 5. Instantaneous fields of sea-surface temperature, salinity, silt and sand, bed shear stress, and bed skin-friction shear stress from the high-resolution (200 m) Palos Verdes ROMS simulation embedded in the 1-km Southern California Bight grid.

The asymptotic wave-current interaction theory of McWilliams et al. (2004) is extended for a strong current regime including surf zones. A horizontal two dimensional subset of this extended theory is implemented as wave-averaged forcing terms into a barotropic version of ROMS suitable for classical

nearshore wave-driven current dynamics. WKB ray equations for refracting and shoaling monochromatic waves are also implemented in ROMS to conduct fully coupled wave-current interacting experiments in canonical and realistic configurations. The barotropic ROMS with wave-averaged effects was tested through a comparative simulation targeting the DUCK94 experiments (http://www.frf.usace.army.mil) with an empirical breaking dissipation parameterization by Thornton and Guza (1983). Numerical results from the WKB wave model and ROMS are compared to the observations lasting for about three months, and they exhibit good agreement with the field data.

We have successfully developed a high-resolution (200 m) regional configuration for non-cohesive sediment transport simulation in Santa Monica Bay and San Pedro Bay, CA, embedded in the parent Southern California Bight domain with 1 km resolution, along with a compatible nested wind-sea/swell prediction with SWAN. The extensive upwelling event occurred in March 2002 and associated sediment-transport processes are well represented. In particular, submesoscale eddies are more actively generated in the high-resolution grid, and suspended sediments are partially trapped in these eddies and transported with them. A horizontal two-dimensional subset of the extended wave-current interaction theory by McWilliams et al. (2004) are implemented into a barotropic version of ROMS to compute classical longshore current problems around surf zones. The model output reasonably agrees with the DUCK94 field experiments given offshore wave statistics, surface wind stress, and the low-frequency surface displacement (e.g. tides) are properly applied.

Univ. Delaware: Kirby, Shi

The objective of Univ. Delaware partners is to provide improvements to wave forcing and shoreline boundary condition algorithms in wave-averaged models for hydrodynamics and sediment transport.

Our approach is as follows:
- Analyze theoretical wave force formulations for wave-averaged circulation equations; Implement appropriate 3D form of wave force in the 3D circulation model;
- Use theoretical and numerical methods to develop the wave-averaged parameterizations for cross-shore and longshore transport at wave-averaged shoreline boundaries.

Our results this year are as follows.

1) Wave-current interactions.

Based on some theoretical studies on different formulations of surface wave force in wave-driven coastal circulations (McWilliams et al., 2004, Smith, 2006, Arduin and Jenkins, 2006, Shi et al., 2006, Lane et al, 2007, and others), numerical experiments have been conducted to investigate model-coupling effects on wave-current interactions in the cases of strong wave-driven currents with strong flow shear. We basically focused on two types of wave force formulations, radiation stresses and CL-vortex formulation, with an aim to examine the numerical differences caused by 1) different forms of surface wave force, 2) model coupling frequencies, and 3) monochromatic wave driver vs. spectral wave driver. Numerical consistency between the radiation stress formulation and the CL-vortex wave force formulation is found in rip current simulations with wave-current fully coupled. In practical applications with large model coupling intervals numerical differences caused by different formulations may occur and the discrepancies basically depend on model coupling frequencies. Figure 6 (left) demonstrates a time series of rip-current velocities at the middle of a rip channel computed

from the cases with different coupling frequencies. Generally the model with a larger coupling interval tends to over-predict rip-current velocities and predict a larger standard derivation of the currents as shown in Figure 6 (right). The model with CL-vortex formulation has a better convergence rate, than the radiation stress model, with respect to model coupling frequencies. A model with a spectral wave driver has a better convergence rate than a monochromatic wave driver. Optimized coupling frequencies are suggested based on the statistics through a series of numerical experiments with both a monochromatic wave driver and a spectral wave driver (Shi, Kirby, and Haas, 2007, wave-current interactions involving different wave force formulations, in preparation).
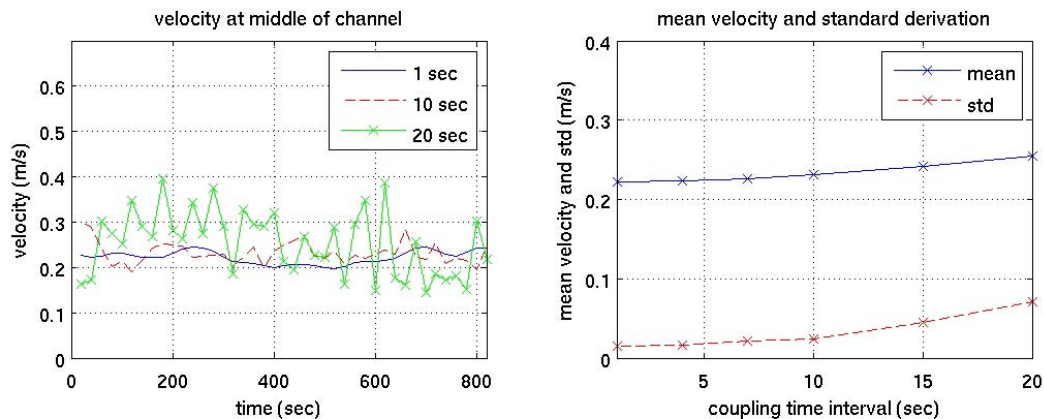

Figure 6. Time series of rip-current velocity at the middle of a rip channel computed from coupling intervals as 1 sec, 10 sec and 20 sec, respectively (left panel). Time-averaged velocities and standard deviations at the middle of a rip channel (right panel)

2) Shoreline boundary conditions.

The wetting-drying moving shoreline scheme has been enhanced in a testing code with more options in applications to small-scale nearshore domains. The options include periodic lateral boundaries and periodic boundaries with imposed extra volume flux. This technique has been applied to the modeling of sediment transport in the FRF domain.

3) Implementation of Soulsby's total load sediment transport formula.

Soulsby's total load sediment transport formulas were implemented in a Fortran subroutine. This Fortran program has been tested in an application to prediction of an erosional hot spot evolution at Ocean Beach, California. Figure 7 shows predicted sediment transport rate which is used to explain the hot spot development (Shi, Hanes, Kirby, Erikson, Eshleman, and Barnard, 2007, Incorporation of large-scale forcing into Nearshore Community Model for modeling of an inlet-adjacent beach, in preparation).

4) Experience in development of model coupling framework in MORPHOS-3D.

As ESMF is not available for unstructured grid applications, USACE has promoted to develop a temporary ESMF-like coupler which specifically couples the circulation module ADCIRC and the wave module STWAVE. The top levels of model structures in ADCIRC and STWAVE are being

modified, according to the ESMF conventions, in order to effectively plug into the ESMF-like framework as well as the future ESMF framework. The integrated model is expected to run the parallel ADCIRC and to capitalize on parallel efficiencies by coupling multiple single-thread STWAVE models in multiple nearshore domains.
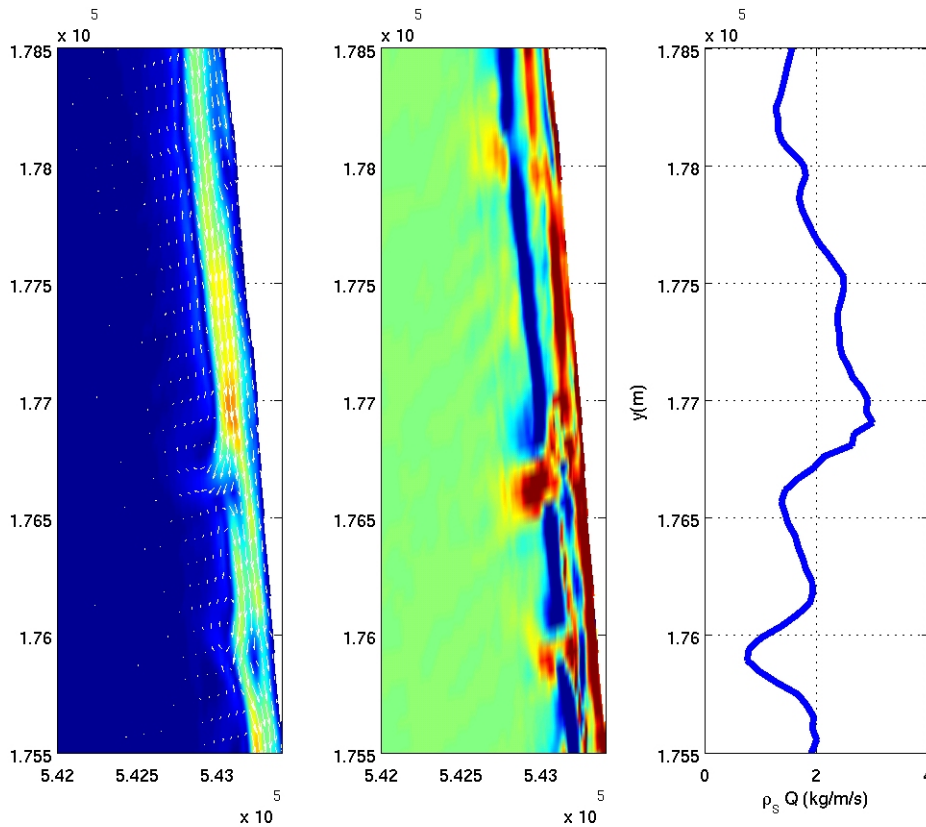

Figure 7. Sediment transport rate calculated from Soulsby's total load formulas under wave and current conditions at Ocean Beach, California. (left) Spatial distribution of sediment transport rate (arrows: transport rate vector, color: magnitude). (middle) Divergence of sediment transport rate. (right) Transport rate along a longshore profile in the surfzone.

Univ. Florida: Hsu

Typical coastal models, such as the ongoing NOPP-Community Sediment Transport Model (NOPP-CSTM) are not designed to resolve the thin wave boundary layer near the seabed. Hence, processes that occur within the wave boundary layer need to be parameterized as a sub-module to provide a bottom drag coefficient and sediment transport rate for CSTM to further predict large-scale coastal sediment transport. A high resolution numerical model for fluid mud transport (Hsu et al. 2007) is utilized to study fluid mud transport in the wave-current boundary layer. Specifically, model results are used to provide parameterizations for wave-boundary-layer-scale transport processes that are useful for NOPP-CSTM. The nature and existence of wave-supported gravity-driven mudflows (Traykovski et al. 2007) are diagnosed by varying the floc properties, bed erodibility and rheological stresses. By selecting representative downslope fluid mud transport events, numerical experiments are conducted to study the effect of wave and long-shelf current intensities on the fluid mud transport, and its

parameterization (Wright et al. 2001). Model results suggest that the drag coefficient decreases with increasing wave intensity (Figure 2), and seems to follow a power law. The bulk Richardson numbers is less sensitive to wave intensity but has a magnitude about 0.08, which is factor 3 smaller than the critical Richardson number. The dependence of wave-supported gravity-driven mudflows on long-shelf current intensity is also less sensitive compared with that on wave intensity. However, when the long-shelf current is as large as 1.0 m/s at about 1 m above the bed, auto-suspension may occur. In the following year, we will provide more comprehensive parameterizations and work closely with NOPP-CSTM coastal modeler on implementing these parameterizations into the coastal model.

Univ. Maryland: Sanford

The objectives of the Univ. of Maryland partners is as follows:
1. Work on an improved algorithm for modeling consolidation, erosion, and mixing of fine sediments, either alone or in combination with sands.
2. Work as an early adopter and tester of CSTM code.

Our approach is as follows.

Objective 1 - Collaborate closely with other colleagues interested in fine sediment bed dynamics (especially Sherwood and Harris at VIMS) to modify the current bed and erosion algorithms in ROMS. The modifications will be based on recently developed MATLAB code that realistically simulates interactions between erosion, deposition, consolidation, bed armoring, and bioturbation with minimal computational burden (Sanford, 2007). The MATLAB code has been adapted by Sherwood to work in the CSTM sediment subroutine. The model approximates consolidation as a first order approach to an empirical equilibrium, which appears reasonable but has not been extensively tested against data. In addition to existing data, considerable new data will be collected as part of a parallel NSF program entitled MUDBED (C. Friedrichs, lead PI), a detailed study of the interactions between physical and biological mixing of muddy sediments in which I am a co-PI.

Objective 2 – To utilize the CSTM model to examine interactions between secondary circulation and sediment transport in an idealized estuary. This work is being carried out by Mr. Shih-nan Chen, a PhD student working under my supervision. Our work with C. Harris and her student J. Paul Reinheimer to model sediment transport in the York River (described above) also may be considered an early adoption effort.

Several subtasks have been completed in 2007 towards achieving our objectives. The description of the mixed sediment bed model with consolidation, erosion, deposition, and bioturbation has been written up and accepted for publication in a special issue of Computers and Geosciences (Sanford, 2007). The MATLAB code has been carefully annotated and distributed to a number of interested parties, including Sherwood and Harris and their groups, but also P. Wiberg, P. Hill, T. Hsu, C. Jones, etc. I attended the CSTM Sediment Transport Processes workshop in Woods Hole in May 2007, gave a presentation, and led a discussion about modeling fine sediment transport processes. Our fine-sediment bed subgroup (Sherwood, Harris, Reinheimer, and Sanford, plus occasional others) met twice in Annapolis, MD to discuss our approaches and progress. Chen has used the original version of CSTM to model lateral circulation and sediment transport due to boundary mixing in an idealized v-shape estuarine cross-section, and a manuscript has been submitted to Continental Shelf Research.

Sherwood, Harris, and Sanford have worked with the USACE modelers developing a new sediment transport algorithm for the USEPA Chesapeake Bay Water Quality Model to incorporate features of the new CSTM bed model as well.

Considerable progress has been made towards implementation of the new algorithm in the CSTM bed model, with preliminary but tentative success. An unanticipated sticking point was the active layer implementation in the original CSTM code, which is fundamentally a different approach from the Sanford (in press) MATLAB code. Sherwood et al. presented some of these modeling results at the INTERCOH 2007 meeting in September 2007, as applied to the Palos Verdes, CA outfall dispersion problem. Reinheimer will present his preliminary results on modeling York River sediment transport at the Estuarine and Coastal Modeling Conference in November 2007.

Chen and Sanford's ms on lateral circulation and sediment transport due to boundary mixing (Chen and Sanford, in review) is now in its second revision before publication in CSR, with a reasonable certainty of acceptance in the near future.

In the near future, we plan on continuing along our present course. Once the bed model algorithms are successfully implemented in ROMSSED, we can move on to addressing the relationship of the scheme to data on sediment erodibility. A particularly intriguing question is how to best specify the equilibrium erodibility profile and consolidation rate parameters based on limited field or laboratory data.

Chen plans on incorporating the newest version of ROMSSED in the final chapter of his PhD dissertation as an example calculation of the potential effects of limited sediment erodibility. He expects to complete and defend his dissertation in May 2008.

WL|Delft Hydraulics: Jagers, Winterwerp

The goal of the Delft Hydraulics team is to collect state-of-the-art environmental knowledge as much as possible into an open and consistent framework of numerical components suitable for further research and operational use.

The primary objective of the overall project is to produce a coastal sediment-transport model to be used as both a research tool and for practical applications. Delft Hydraulics' contribution to this effort concerns scientific advice regarding the modeling of cohesive (and non-cohesive) sediment transport and technical advice regarding the software implementation aspects.

Delft Hydraulics' contribution to this effort concerns (1) scientific advice regarding the modelling of cohesive (and non-cohesive) sediment transport, mainly via involvement of Winterwerp in the Scientific Advisory Committee, and (2) techical advice regarding the software implementation aspects via involvement of Jagers in the Technical Advisory Committee. The investigators will participate in CSTM project web-meetings and one meeting of the Scientific and Technical Advisory Committee, respectively, per year.

Besides participation in a couple of web-meetings, work in fiscal year 2007 has been limited to the participation of Jagers (as substitute for Winterwerp) in the meeting of the Scientific Advisory Committee in Woods Hole in May 2007; furthermore he has acquainted himself with the general

implementation of CSTM/ROMS. The first meeting of the Technical Advisory Committee was be held in Los Angeles in October 2007 (fiscal year 2008) and Jagers participated.

During the first Scientific Advisory Committee much insight was gained in the role of various participants in the scope of the project; this was needed to get an idea of the flexibility required for the modeling sytem. Furthermore, a general overview of the current implementation of ROMS/CSTM has been obtained; based on this knowledge Delft Hydraulics can effectively participate in the Technical Advisory Committee.

Woolpert, Inc.: Froehlich

The objective of Woolpert participation in this project is to facilitate technical exchange between the Morphos and CSTM projects. Froehlich has participated in Webex meetings and the meetings in Woods Hole and at UCLA as a representative of the Morphos project, and has informed the CSTM project of Morphos plans.

RESULTS

A useful open-source numerical model for coastal sediment-transport was produced. The model source code is licensed and freely for use by academics, government agencies, and private industry. Significant improvements in the model have been made, and are ongoing. Partial documentation and example applications are available on line. Specific results of the efforts of the subcontractors are indicated in the previous section.

IMPACT/APPLICATIONS

The CSTM will provide a starting point for a wide range of numerical investigations. It provides a tool for scientists who are interested in coastal and estuarine processes and need the numerical context of a high-quality physical oceanographic model. The physical oceanographic model ROMS and the non-cohesive sediment-transport algorithms in the CSTM associated with ROMS are sufficiently mature for a wide range of applications, and are being actively used by researchers worldwide.

TRANSITIONS

Researchers not funded by the NOPP project are presently using the model in the Adriatic Sea, Chesapeake Bay, Louisiana, and other locations. The CSTM is likely to be used in the

RELATED PROJECTS

Testing and application of the CSTM has benefited, or will benefit, from field measurements obtained during ONR STRATAFORM., EuroSTRATAFORM, the Mine Burial Experiment, CBLAST, the Ripples DRI, SandyDuck, NCEX, the Mud Flats DRI, and the Coherent Structures MURI. Data from USGS projects in Massachusetts Bay, Vineyard Sound, South Carolina and Palos Verdes have been used, as have data from the NSF and Hudson River Foundation studies in the Hudson River. The model has been informed by process studies conducted as part of Nearshore NOPP project, OASIS, the Ripples DRI, CBLAST, Hudson River studies, and various USGS and NRL projects. This project

parallels the USACOE Morphos project, and will provide a template and model modules for the NSF CSDMS project.

REFERENCES

Booij, N., Ris, R. C., and Holthuijsen, L. H., 1999. A third-generation wave model for coastal regions. Part I - Model description and validation. *Journal of Geophysical Research* **104**, 7649-7666.

Hsu, T-J, Traykovski P. A., and Kineke, G. C., (2007) On modeling boundary layer and gravity driven fluid mud transport, *Journal of Geophysical Research,* 112, C04011, doi:10.1029/2006JC003719.

Hu, C., Z. Chen, T. D. Clayton, P. Swarzenski, J. C. Brock, and R. E. Muller-Karger (2004) Assessment of estuarine water-quality indicators using MODIS medium-resolution bands: Initial results from Tampa Bay, FL. *Remote Sensing of Environment,* **93**, 423-441.

McWilliams, J. C., Restrepo, J. M., and Lane, E. M., 2004. An asymptotic theory for the interaction of waves and currents in coastal waters. *Journal of Fluid Mechanics* **511**, 135-178.

Myint, S. W. and N. D. Walker, (2002) Quantification of surface suspended sediments along a river dominated coast with NOAA AVHRR and SeaWiFS measurements: Louisiana, USA. *Int. J. Remote Sensing*, **23**, 3229-3249.

Sherwood, C. R., R. P. Signell, C. K. Harris, and B. Butman (2000) Workshop Discusses Community Models for Coastal Sediment Transport, *Eos, Transactions, American Geophysical Union*, 81(43): 502.

Sherwood, C. R., C. K. Harris, W. R. Geyer, and B. Butman (2002) Toward a Community Coastal Sediment-Transport Modeling System: Report of the Second Workshop, *Eos, Transactions, American Geophysical Union*, 83(51).

Shirron, J. J. and T. E. Giddings (2006) A comprehensive model for performance prediction of electro-optical systems. ONR Report for Contract No. N00014-06-C-0070.

Soulsby, R. L. and Clarke, S. (2004). Bed shear-stresses under combined waves and currents on smooth and rough beds. Report TR137, HR Wallingford Ltd (Rev 1.0).

Soulsby, R.L. and Whitehouse, R.J.S. (2005). Prediction of ripple properties in shelf seas. Mark 2 Predictor for time evolution. HR Wallingford Report TR154, December, 2005.

Traykovski, P., P. Wiberg, and W. R. Geyer (2007), Observations and modeling of wave-supported sediment gravity flows on the Po prodelta and comparison to prior observations from the Eel shelf, *Continental Shelf Research*, 27, 375-399.

Wright, L.D., Friedrichs, C.T., Kim, S.C., Scully, M.E., 2001. The effects of ambient currents and waves on gravity-driven sediment transport on continental shelves. *Marine Geology*, 175, 25–45.

PUBLICATIONS

Blaas, M., C. Dong, P. Marchesiello, J.C. McWilliams, & K.D. Stolzenbach, 2007: Sediment transport modeling on Southern Californian shelves: A ROMS case study. *Continental Shelf Research*. 27, 832-853. [published, refereed]

Chen, S.N. and Sanford, L.P., 2007. Lateral Circulation Driven by Boundary Mixing and the Associated Transport of Sediments in Idealized Partially-Mixed Estuaries. *Continental Shelf Research* [submitted, refereed]

Haidvogel, D. B., H. Arango, W. P. Budgell, B. D. Cornuelle, E. Curchitser, E. DiLorenzo, K. Fennel, W. R. Geyer, A. J. Hermann, L. Lanerolle, J. Levin, J. C. McWilliams, A. J. Miller, A. M. Moore, T. M. Powell, A. F. Shchepetkin, C. R. Sherwood, R. P. Signell, J. C. Warner, and J. Wilkin (2007) Ocean Forecasting in Terrain-following Coordinates: Formulation and Skill Assessment of the Regional Ocean Modeling System, *Journal of Computational Physics*, 10.1016/j.jcp.2007.06.016. [in press, refereed]

Harris, C. K., C. R. Sherwood, R. P. Signell, A. J. Bever, and J. C. Warner (2007) Sediment dispersal in the northwestern Adriatic Sea, *Journal of Geophysical Research* [in press, refereed]

Sanay, R., G. Voulgaris, and J. C. Warner (2007) The influence of tidal asymmetry and residual circulation on sediment transport in linear sandbanks: a processes-oriented numerical study, *Journal of Geophysical Research* [submitted, refereed]

Sanford, L.P., 2007. Modeling a dynamically varying mixed sediment bed with erosion, deposition, bioturbation, consolidation, and armoring. *Computers and Geosciences* [in press, refereed].

Signell, R. P., S. Carniel, J. Chiggiato, I. Janekovic, J. Pullen, and C. R. Sherwood (2007) Collaboration tools and techniques for large model datasets, *Journal of Marine Systems* [in press, refereed]

Warner, J. C., B. Butman, and P. S. Alexander (2007) Storm-driven sediment transport in Massachusetts Bay, *Continental Shelf Research* [in press, efereed]

Warner, J. C., N. Perlin, and E. Skyllingstad (2007) Using the Model Coupling Toolkit to couple earth system models, *Environmental Modelling and Software* [submitted, refereed]

Warner, J. C., C. R. Sherwood, and W. R. Geyer (2007) Sensitivity of estuarine turbidity maximum to settling velocity, tidal mixing, and sediment supply, *in* Maa, J. P.-Y., L. P. Sanford, and D. H. Schoellhammer, eds., *Estuarine and Coastal Fine Sediment Dynamics*: Amsterdam, Elsevier, 355-376 [published, refereed]

Warner, J. C., C. R. Sherwood, R. P. Signell, C. K. Harris, and H. G. Arango (2007) Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, *Computers & Geosciences* [in press, refereed].