The Sedimentary Record

CSDMS — A Modeling System to Aid Sedimentary Research

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Have you ever tried to gain access to someone else's sediment transport or stratigraphic numerical model before 2007? To look inside the source code and investigate how its formulations were implemented? Did you ever want to couple two or more models but could not because they were written in different languages? Have you ever desired to test out some interesting hypothesis but knew a particular model needed to run on a supercomputer, and you did not have access to a high performance computing cluster? Was access to gridded data for model initializations a bother? Have you considered building intuition in your students by employing "what-if" model runs, or developing case studies that integrate field data and model simulations?

For these and other reasons the National Science Foundation together with other environmental agencies and companies have been supporting a community effort called CSDMS to address two long-range goals:

- *Develop a modular modeling environment capable of significantly advancing fundamental earth-system science*
- *Develop fully functional and useful repositories for models, supporting data and other products for educational and knowledge transfer use.*

For Sedimentary Record scientists, these CSDMS goals could offer the following:

- Improve our predictive capability at all scales of stratal architecture;
- Improve our ability to discover, use, and conserve natural resources, and to characterize and mitigate natural hazards;
- Aid our understanding of chemical processing within the hydrologic cycle;
- Help recover evidence of global and regional environmental change and better understand the role of humans during the Anthropocene.
- Track surface dynamics through glacial cycles

For further insight into these goals we refer readers to the Millennium overview by Paola (2000) that surveys the use of models in sedimentary research, and highlights critical research questions such as: How do self-organized patterns mediate surface fluxes and evolution? How do material fluxes and surface evolution vary across time and space scales? How are physical and biological processes coupled in surface systems? How do changes in one part of the global surface system affect other parts?

Below we describe this international program by employing a Question & Answer style to maximize information content and orient SEPM readers towards areas of interest.

WHAT IS CSDMS?

CSDMS (pronounced 'systems') is the Community Surface Dynamics Modeling System, a 500-person community effort to create models that predict the transport of fluids, sediment and solutes through landscapes, seascapes and sedimentary basins. As a modeling environment, CSDMS offers open-source, ever-improving software modules, developed and shared by those concerned with earth-surface dynamics. The CSDMS Model Repository offers a growing library of community-generated models to streamline the process of idea generation and hypothesis testing through both stand-alone and linked models. The CSDMS modeling environment enables the rapid creation and application of models tailored to specific settings, scientific problems, and time scales. CSDMS activities are funded through a cooperative agreement with the National Science Foundation with additional support provided from other U.S. agencies and industry.

WHAT NEED DOES CSDMS SERVE?

Prediction, as opposed to cataloging, is a major step in the evolution of a science. Quantitative modeling provides a framework in which researchers express their predictive ideas in a precise, consistent format. However, new coders often reinvent the wheel as they attempt to enter the modeling world. A community-based modeling environment, built of tools created by and provided for a broad spectrum of users with diverse skills and interests offers the flexibility required by those who will benefit from its products. A community approach allows efficient development of models that are more powerful than could be developed by any single group. Redundancy is reduced, models are better vetted, and the capability for innovations expanded. Importantly energy can be focused towards earth-surface dynamic domains that are poorly represented, or controversial.

WHAT IS IN THE CSDMS MODEL REPOSITORY?

There are more than 160 models and tools affiliated with the Repository (Table 1): 72% are available for download through the CSDMS web site (e.g. CHILD, SedFlux), 28% are available after separately registering with other community efforts (e.g. ROMS, NearCOM). Of the 4 million lines of code already in the repository, 53% of the CSDMS models are written in C or C++; 30% are written in Fortran, with Python and MATLAB code comprising most of the remaining models.

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Model Category	Domain	Example models in the CSDMS Repository
Terrestrial	landscape evolution	CHILD, SIBERIA, Caesar, Erode, GOLEM, MARSSIM, WILSIM
	fluvial morphodynamics	LOGPRO, BEDLOAD, MIDAS, TISC, SUSP, YANGs
	eolian transport	Eolian Dune Model
	cryosphere	GC2D, ISGR, Ice ages
	geodynamics	TAo, TISC, LavaFlow2D
Hydrology	reaches	STVENANT, SWMM, FLDTA
	basins	DR3M, TopoFlow, GEOtop, HydroTrend, PIHM, ParFlow, MFDrouting, MODFLOW
	continental	ANUGA, CREST, DHSVM, PIHM
	global	WBM-WTM, VIC
	biogeochemistry & water quality	QUAL2K, OTEQ, OTIS, SPARROW, GNE, HSPF, LOADEST, RHESSys, SWAT
Coastal	flow dynamics	2DFLOWVEL, ADCIRC, NearCoM, ROMS
	wave dynamics	REF-DIF, STORM, STWAVES, SWAN, WAVEREF, WINDSEA, FUNWAVE, ROMS
	coastal evolution	CEM, Delta, XBeach, CrevasseFlow, Avulsion, AquaTellUs
Marine	physical oceanography	FVCOM, ROMS, POM, Symphonie, WAVEWATCH-III
	sediment transport	Diffusion, Plume, SedPlume, SedBerg, Sedtrans5, WSGFAM, SedFlux, Sakura, Hyper, Bing, Bio
	geodynamics	Subside, SedFlux
	stratigraphy	cyclopath, SedFlux
Climate, Weather		WRF, WACCM+, and MITgcm
Tools		ADI2D, LOGDIST, TopoToolbox, TauDEM, Zscape, TURB, TOPOG, Parker Ebook, SVELA, SETTLE, PsHIC, FTCS, Compact

Table 1. Example of named models within the CSDMS Model Repository, sorted by environment and domain. Modeling tools are also identified.

This alphabet soup of models and tools has the underpinnings of thousands of peer-reviewed papers associated with them. Metadata describing each model, along with key references are available through the CSDMS web site. CSDMS-hosted models are expected to double in the next few years. But not all earth-surface domains and physics are covered.

WHAT SURFACE DYNAMIC MODELS ARE MISSING?

Missing models include lacustrine and reservoir models, 2D debris flow and 3D sediment failure models, and full-ocean geostrophic and thermohaline circulation models. There are presently few eolian-domain models. We look forward to receiving ocean circulation models that can interact with hyperpycnal current, turbidity current and contour current models. We are missing advanced tidal flat models. Unfortunately some of these models are written, but their source code is not freely available.

WHY OPEN SOURCE?

Code transparency is important because source code provides the scientific hypotheses embodied in a numerical model, and reveal their implementation. Within the world of

software, details are important. A solution to a set of equations can take numerous forms, and
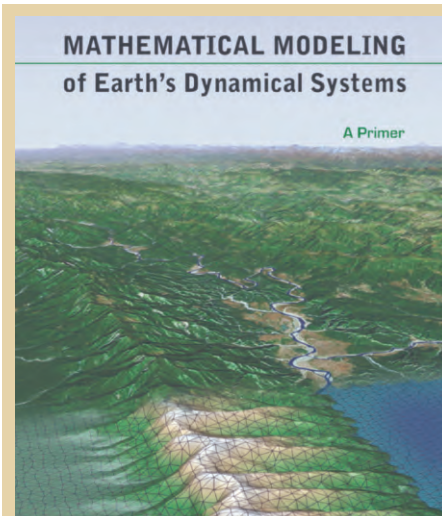

Figure 1. Book Cover image from the new instructional text (Slingerland & Kump, 2011) shows a topographic representation of the foothills of the Himalayas (Google Earth) in the upper part of the image, and a numerical simulation based on a modified version of the CHILD model. The CHILD model became open source with the launch of CSDMS, and has since been made into a plug and play component in the CSDMS Modeling Tool.

each solution has its pyramid of assumptions and limitations. Code transparency allows for full peer review and replication of results - the foundation of modern science. Code transparency also allows for reuse, often in new and clever ways, and reduces redundancy. In some cases, missing domains simply reflect that model development often lags behind observational or theoretical developments.

WHY COMMUNITY MODELING?

Large codes by their nature involve multiple environmental domains and thus a diversity of experts - the birthplace for community modeling. Community modeling involves the collective efforts of individuals that code, debug, test, document, run, and apply models often within modeling frameworks. Community modeling relies on code transparency to address the practical need of developers to examine and modify the code. Without access to source code, a model could not be converted into a 'plug and play' component (see below). Community modeling effectively allows for code vetting so as to determine whether: 1) the model behaves as advertised; 2) the code meets community specifications and protocols; and 3) the model provides for an acceptable depiction of nature.

WHAT IS THE ROLE OF FIELD OR LABORATORY SCIENTISTS WITHIN CSDMS?

Models are the encyclopedia of what we know, and importantly, what we cannot yet quantify. The CSDMS community includes application specialists, and those who conduct field and laboratory experiments, where individual modules and integrated models can be tested under a range of conditions. The CSDMS Data Repository has initially focused on well-described and well-vetted gridded data useful for model initializations: topography, bathymetry, climate, hydrography, discharge, cryosphere, soils, land cover, substrates, human dimensions, sea level, and oceanography.

The CSDMS Data Repository will begin to host laboratory data for the purposes of benchmarking model performance. Flume
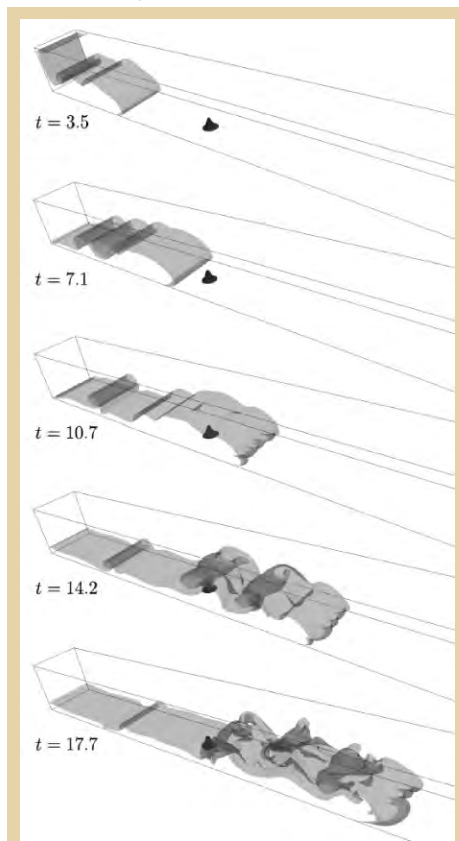
Figure 2. *TURBINS is a DNS immersed boundary, Navier-Stokes code for the simulation of turbidity currents interacting with complex topographies. Shown is the evolution of a concentration isosurface for a lock-exchange gravity current at Re = 2828. As the current interacts with a Gaussian bump shown in black, Span-wise instabilities and three-dimensional vertical structures appear in the frontal and wake regions of the current (from Nasr-Azadani & Meiburg, 2011). Simulations are from one of the many projects conducted on the CSDMS-dedicated high-performance computing cluster Beach.*

experiments have known boundary conditions and input. Even with scaling issues between laboratory experiments and field observations, models can still be rigorously tested. Laboratory experiments can be set up to test the entire range of models from those set up to describe landscape evolution to single event processes where computational fluid dynamic models can be tested (e.g. Direct Numerical Simulation models).

A valuable contribution that field campaigns can offer CSDMS would be to organize and grid their field data in a manner that allows for more direct comparison to a model's simulations. This also requires the provision of all input environmental values/files that a model would require. A full error analysis related to field observational grids would allow for a determination of both the spatial and temporal capabilities of a model. Most published papers within the Journal of Sedimentary Research or Marine Geology do not contain adequate error analysis. Three-dimensional deposit shapes, sequences of chronostratigraphic 2-D surfaces, dynamic observations of flow properties, and spatial properties within a sediment volume, are all examples highly valued by modelers. Different or future models could be tested later against these field data and also against the earlier model simulations. Benchmark testing is a prime task for the CSDMS community. CSDMS will post field or experimental data useful for model comparisons, as a recognized venue satisfying data requirements of the U.S. National Science Foundation.

HOW DOES CSDMS INCREASE THE EASE OF LEARNING NEW MODELS?

CSDMS addresses this issue with four approaches. Firstly, CSDMS models are being converted into components that can be run as standalone models within the CSDMS Modeling Tool (CMT) GUI. Users will thus find a similar feel about running each model, even though models may have been written by different authors and with different user interfaces. Submitted models without a GUI will automatically gain one when they become a CSDMS component. Secondly, each CSDMS component includes a help system that offers information on a model's main algorithms, and input/output files. Tools associated with CMT will also offer post-processing visualization services. Thirdly, components receive an initial pedagogical evaluation. There is often a "built" example with a loaded input file and an output file from which model runs can be compared. Faculty and students provide feedback on these built model systems. Fourthly, CSDMS

component protocols adopt community standards for handling data (e.g. NetCDF, WML). Standards reduce the wide range of available data formats and their inherent complexity. Further, CSDMS organizes instructional courses and workshops to familiarize its community with contributed models and modeling tools. The CSDMS Education Repository posts videos and PowerPoint or PDF presentations of lectures related to CSDMS components.

WHAT IS A MODELING FRAMEWORK?

When a model grows large and complex, as might be needed for example, to handle multiple environmental domains, it often transitions into a modeling framework that provides for an environment where components can be linked to form a more complex application. Frameworks deal with modeling complexity: data transfer, grid meshing, up- or down-scaling, time stepping, computational precision, multi-processor support, cross language interoperability, and visualization. Frameworks save time, reduce costs, provide quality control, re-purpose model components, ensure consistency and traceability of model results, and offer scalability to solve complex modeling problems.

WHAT IS A PLUG-AND-PLAY COMPONENT?

Components are functional units that once implemented in a particular framework are reusable by other units/models within the same (or other) framework with little migration effort. Component-based modeling offers the advantages of "plug and play" technology based on interface standards that allow different models to communicate. In essence, plug-and-play means that a user is able to swap components in and out without needing to recompile. Thus, a user builds a model from components, not a developer. CSDMS components differ from ordinary subroutine software, for example, in that they can communicate with other components written in different programming languages.

Component-based modeling recognizes the utility of subdividing a model's code into three separate functions: Initialize, Run (one or a few steps) and Finalize, otherwise known as an IRF interface. Such an interface provides fine-grained access of a model's capabilities to a calling program so that it can be used in a larger application. The calling program "steers" a set of components and is referred to as a driver. Components also require information on data exchange with other components, i.e. 'getter'

Framework Architecture	Start Year Year	Principal Domain	Principal Languages	Models	Model Coupling	Platforms	HPC oriented
CSDMS	2007/08	Ice, Terrestrial, Hydro, Coastal, Marine, +	C, C++, F77, F90, F95, F2003, Python (java)	>160 small to large codes	Interface components	OSX, Linux, (CMT can run on Windows)	yes
CCSM/CESM	1980's	Global climate	Fortran	4 large codes	Couplers	Linux	yes
ESMF	2002	Global climate	Fortran (C, C++)	15+ large codes	Couplers	OSX, Windows, Linux	yes
MMS/OMS	1990's	hydrologic, agricultural and soil erosion	Fortran (C, C++)	>100 small to medium codes	Annotated Components	Windows, Linux	no
OpenMI SDK	1990's	Hydrology	C# (java)	25 medium codes	Interface Components	Windows	no

Table 2. Framework architectures in the environmental domain: CSDMS - Community Surface Dynamics Modeling System; CCSM/CESM - Community Climate System Model / Community Earth System Model; ESMF - Earth System Modeling Framework; MMS/OMS - Modular Modeling System / Object Modeling System; OpenMI - Open Modeling Interface.

and 'setter' functions, so that connected components can query generated data as well as alter data and settings from the other model.

HOW HAS CSDMS ADAPTED TO PLUG-AND-PLAY TECHNOLOGY?

CSDMS has adopted, integrated and advanced powerful open-source tools to build its modeling framework. These services are largely invisible to users of the CSDMS Modeling Tool (CMT), a GUI based in part on the Common Component Architecture *Ccaffeine* a service for interactive model coupling. CMT offers: (1) language interoperability (C, C++, Java, Python, Fortran) using *Babel*; (2) component preparation and project management using *Bocca*; (3) low level model coupling within a HPC environment using *Ccaffeine*; (4) single-processor spatial regridding (OpenMI *Regrid*) or multi-processor spatial regridding (ESMF *Regrid*); (5) component interface standards advanced by OpenMI; (6) self-describing scientific data format (*NetCDF*) and the water markup language (*WMF*); (7) visualization of large data sets within a multiple processor environment (e.g. *VisIt*); (8) message passing within the HPC environment using *MPI* and *OpenMP*, along with *PETSc* a Portable, Extensible Toolkit for Scientific Computation.

WHAT HAPPENS WHEN A MODEL ENTERS THE CSDMS MODEL REPOSITORY?

After a model is received at the CSDMS Integration Facility, CSDMS software engineers determine if the code compiles on the CSDMS-dedicated supercomputer Beach. The model is exercised with whatever input files are provided

and model results are compared with the provided output files. If the results are identical then the model is made available to the community for download. If a CSDMS working group prioritizes the model for componentization, the model is queued for becoming a component: 1) if necessary, the model is refactored with an IRF interface, and 2) getters and setters are added.

CSDMS components are then made operational with CMT. This includes ensuring that output can be visualized (e.g. VisIt) and conforms to CSDMS protocols (e.g. NetCDF or WML). Each component is given input configuration details and provided with help pages. The model is then made available to the community within CMT for standalone runs on Beach. If a working group desires that the model be coupled with other CSDMS components, integration staff will then ensure that the time-stepping and regridding and other data services and exchanges work properly. There must be a realistic match between one component and another. Often the style of getters and setters depends on the nature of other components in the suite. This integrated suite of models is then made available within CMT for download, and eventual community testing and vetting.

WHAT IF MY MODEL IS NOT WRITTEN IN A CMT-SUPPORTED OPEN-SOURCE LANGUAGE?

CMT relies on the CCA-Babel language interoperability compiler. At present Babel supports most of the models contributed to the CSDMS Repository models (C, C++, Fortran, Python and Java). CSDMS has extended an

IDL-to-Python converter for our community. This converter has successfully converted a refactored hydrological model TopoFlow. Code written in MATLAB code is converted to Python (e.g. GC2D). Visual Basic code is also converted to 'c' (e.g. Parker's E-book code).

I DON'T HAVE ACCESS TO A SUPERCOMPUTER; WILL CSDMS MODELS OR CMT WORK ON MY COMPUTER?

CSDMS makes all contributed models available for free download. There is no guarantee however that the model will work on your computer. With more than 160 models and 30+ combinations of platforms and compilers, that is a task beyond our budget. Metadata provided with each model should allow you to determine compatibility issues and what platforms the model has been successfully run on. CSDMS does provide members with free access to its supercomputer Beach, where the model can be run. The University of Colorado together with the U.S. Geological Survey has purchased a CSDMS-dedicated High Performance Computing Cluster (HPCC). NSF covers computer system oversight costs, and remote data storage costs. There are more than 100 CSDMS members who run models on Beach. CMT allows Beach account holders to build (couple) and execute CSDMS models on Beach from their personal computers following cloud-computing principals. The CMT tool can be downloaded for later versions of Windows, OS X, and Linux.

CSDMS staff are examining convenient ways for members to run models without being subject to CU security protocols for such an open yet dedicated computing cluster. One
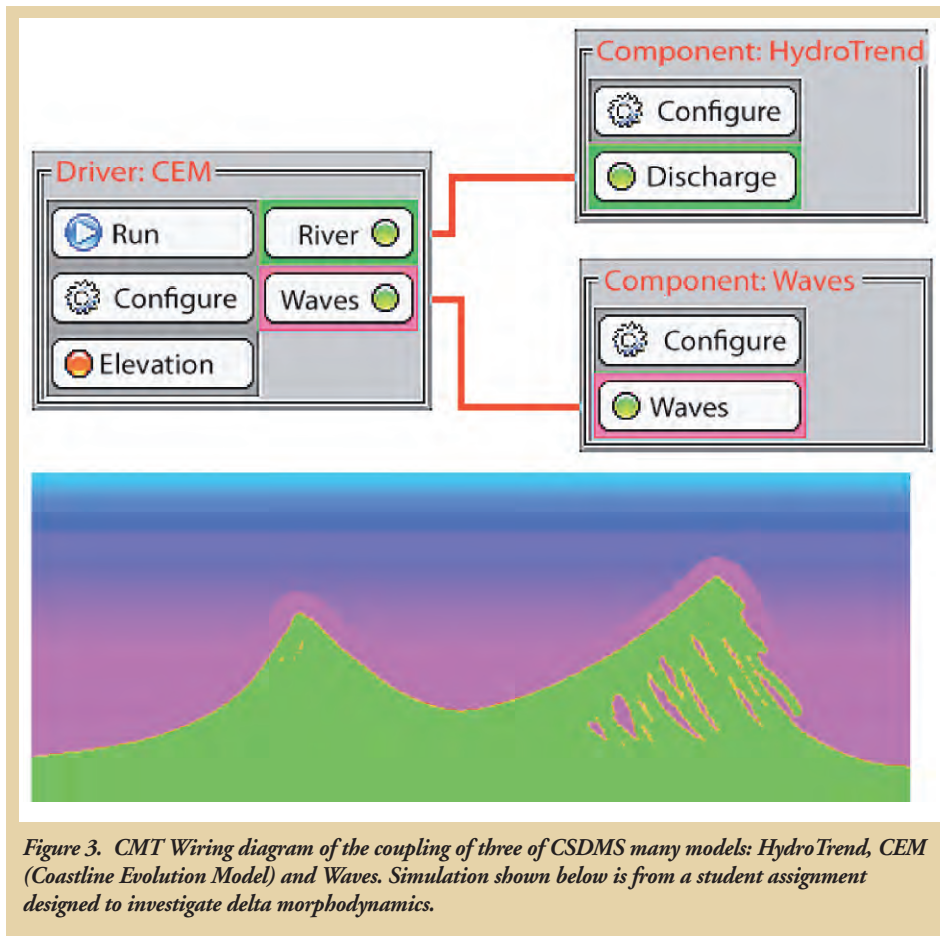
Figure 3. CMT Wiring diagram of the coupling of three of CSDMS many models: HydroTrend, CEM (Coastline Evolution Model) and Waves. Simulation shown below is from a student assignment designed to investigate delta morphodynamics.

future way might allow a CSDMS account holder to build 'coupled executables' on Beach and then freely make these executables available for use on other computers. This would allow students to manipulate input files and examine model simulations without a Beach account. The source code for model components remains available for examination. CSDMS staff have also discussed with CCA staff, the development of DVDs for multiplatform operation of models, a distant goal.

Most high performance codes (e.g. ROMS, WRF) have versions that can be run, albeit more slowly, on single processor computers. High performance codes are often poor performers on single processor machines, and are demanding with countless libraries to enable. Our experience has shown that some HPC models can take a couple of months to work out all the library compatibility issues and become fully operational on a new platform.

WHAT ARE THE CSDMS WORKING GROUPS (WGS), AND HOW ARE THEY DIFFERENT FROM CDSMS FOCUS RESEARCH GROUPS (FRGS)?

There are five WGs: Terrestrial, Coastal, Marine, Education & Knowledge Transfer (EKT), and Cyberinformatics & Numerics

(C&N), and CSDMS members align themselves with one or more groups. The Terrestrial WG with more than 235 members concerns itself with weathering, hillslopes, rivers, glaciers and ice sheets, deserts, lakes, hydrology, geodynamics and human dynamics. The Coastal WG (>170 members) studies Earth's coastlines, deltas, estuaries, bays, lagoons, and the impact of humans. The Marine WG (>130 members) focuses on continental shelves, slopes, carbonates, and the deep marine. The EKT WG (>60 members) equips researchers with model and visualization tools, planners with decision-making tools, educators with pre-packaged models, course material and tools to help illustrate surface processes and build intuition. The C&N WG (>90 members) focuses on high performance computing, visualization, and software protocols. Chairs of these working groups form the CSDMS governing body along with Steering Committee and Integration Facility representation.

CSDMS FRGs differ from WGs in that they serve a unique subset of our surface dynamics community, usually represent an already functioning community co-sponsored by another organization. Chairs of FRGs report directly to the CSDMS Executive Director, and to the Chair or Director of the co-sponsoring organization. The >145-member Hydrology

FRG is co-sponsored by CUAHSI and deals with models of the hydrological system. The 47-member Carbonate FRG is developing a numerical carbonate workbench. The Chesapeake FRG is the first 'geographically-focused' effort co-sponsored by the 32-member Chesapeake Community Modeling Program, with their unique collection of models and field data set.

WHAT ARE CSDMS MEMBER RESPONSIBILITIES?

The Chairs of WGs and FRGs need members who are willing to roll up their sleeves and volunteer time to this community effort. If the burden falls on too few shoulders progress is slow. Participation is through annual meetings, workshops, electronic forums, or through individual hero efforts related to adding, modifying or vetting CSDMS models, data and educational material. After reading this article we encourage interested participants to take the plunge, offer energy, insight and talent to this important community effort.

WHAT ARE MODELING CHALLENGES IN THE COMING DECADE FOR CSDMS?

1) Very few of the CSDMS models take advantage of today's high performance computers like Beach (teraflops) and there is no existing model able to scale up to petascale ($+10^{15}$ Flops) or exascale ($+10^{18}$ Flops) platforms of the future. Authors of models typically give up both spatial and temporal resolution and domain size (area covered, period simulated) in order to work on single processor systems. Most CSDMS model authors are not trained in MPI and OpenMP, the coding interfaces used to take advantage of multiple processors. NSF has recognized this lack of progress; CSDMS is addressing this shortcoming.

2) We are beginning to recognize the magnitude of human alteration of our landscape during the 20th century --- the Anthropocene epoch. Yet many of the measurements that we base or constrain our theories on contain the overprint of human interference. We need algorithms that can strip off human influences on the landscape (e.g. hardened river banks, hillslope terracing), or add them (e.g. accelerated wetland peat oxidation, mangrove removal).

3) We are further along in post-diction, then prediction, yet there is an urgent need to develop surface dynamics models that offer prediction capabilities, given our rapidly changing climate and landscape. Here the

resolution issue outlined in point 1) is particularly relevant, along with access to high performance code.

4) In deformed terrains, it is often difficult to interpret the rock record so as to recover the original depositional slopes of the rock units. Without the depositional slope it is often difficult to apply numerical models to constrain the transport dynamics that led to the deposit. This is a problem of too many degrees of freedom. Continental margin deposits are particularly problematic where individual beds might be deposited over a wide range of slopes (e.g. <1° to 15°). If crustal deformation is both spatially and temporally variable, then reconstruction of depositional slopes becomes nearly impossible. Monte Carlo set-up runs employing coupled geodynamic and sediment transport models might result in a series of believable matches to the deposit geometries. These results would then help develop statistical models for reservoir characterization.

5) CSDMS is helping to make environmental-domain coupling of models easier. Is enough research on hand to capture transition dynamics: terrestrial to coastal, coastal to marine processes, or perhaps reef dynamics with marine processes? If models do not include the appropriate transitional dynamics, there will remain a mismatch with observations.

6) Adding complexity to a model is a two-edged sword. Atmospheric models have always been better at getting temperature correct compared to precipitation, with early models needing better characterization of cloud physics. However, weather models often are so complex that predictions beyond a few weeks are near impossible. Climate models with simpler representations of atmospheric dynamics are more capable of predictions-of-state across decades. Thus earth scientists need to identify where complexity is needed and learn to scale this complexity over geologic time. Scaling of complexity will always remain the center of earth science.

7) The skin of the earth surface has become known as the **critical zone**. This zone represents the intersection between the hydrosphere, cryosphere, atmosphere, biosphere and the geosphere. Such complexity is not included in any single model. Model coupling offers a way forward in capturing the physics and chemistry of this complex zone, as long as components are developed to capture this complexity.

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NEWS FROM THE DIRECTOR

Did you know that SEPM has three main websites?

I am using this small extra space to announce a new web site feature. I will be posting various news items about SEPM and sedimentary geology at a new webpage called "Director's News" under the Home menu. I will include here items that come to my attention, especially from SEPM's various connections with other organizations, such as AGI and NSF and other sister societies.

The first news item that I will discuss concerns SEPM's web presence. I want to bring to your attention that at the 2010 GSA meeting, SEPM President Mitch Harris with the approval of the SEPM Council held an SEPM Web Presence Workshop. The workshop included council members and fourteen invited students. Each student presented their view of the current SEPM websites (www.sepm.org; www.sepmonline.org and www.sepmstrata.org) and suggestions on how to improve it. Based on their input we are putting together a plan to enhance our web presence. The recommendations included:

- clean up www.sepm.org, reduce the number of menu items and remove old material and keep it updated
- add a rolling banner to the main page to highlight the latest activities
- add a site search function
- investigate the use of 'social' networking for online discussions (such as Google Groups or LinkedIn)
- investigate the use of online videos such as on YouTube
- make sure that members are made aware of SEPM's three main websites
  - www.sepm.org - the main home of the society
  - www.sepmonline.org - the home of the online publications (journals and books)
  - www.sepmstrata.org - home of Chris Kendall's site for free access to material for learning and teaching areas of sedimentary geology, initially focusing on stratigraphy and sequence stratigraphy

Be sure to keep coming back to the SEPM home site (www.sepm.org) to see the continuous changes taking place!

Howard Harper