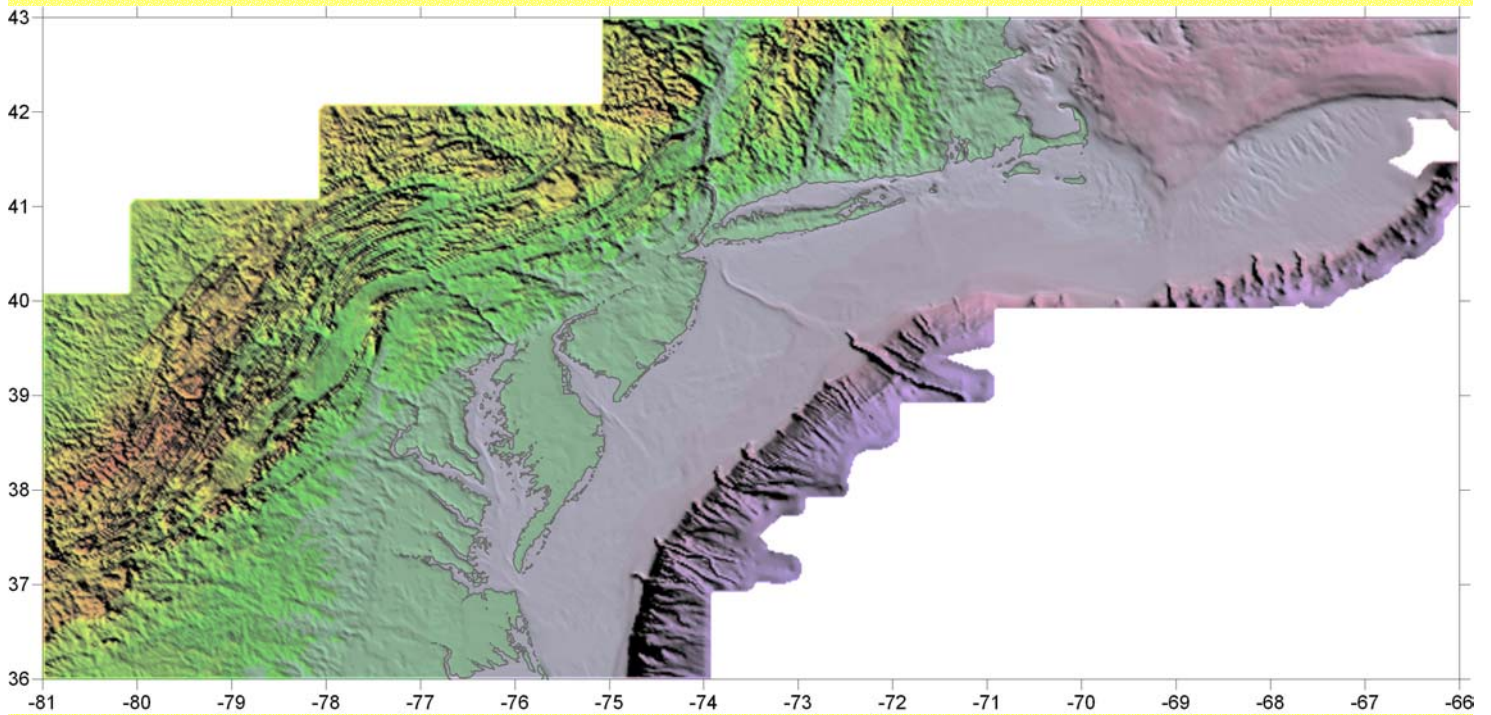


May 2003

Building a Community Surface Dynamics Modeling System Rationale and Strategy



A Report from the Scientific Community to
the National Science Foundation

ACKNOWLEDGEMENTS

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Cover Illustration: Simulated topography of New Jersey continental shelf in response to Quaternary glacial-eustatic sea level variations (courtesy of Alan Howard)

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Photo courtesy of USGS: http://ak.water.usgs.gov/glaciology/m7.9_quake

Executive Summary

The Earth's surface, with its interwoven physical, biological, and chemical systems, is the setting for most life and human activity. Most of us tend to think of the surface as relatively static. But, viewed on a slightly longer time scale, our planet's surface is dynamic in ways that parallel the more familiar dynamism of the atmosphere or the oceans. Wise management of resources and wastes on this dynamic surface requires predictive tools comparable to those routinely applied to the atmosphere and oceans. Yet today's fragmented and often qualitative nature of surface-process research is retarding progress towards this goal.

To address this state of affairs, 68 scientists attended an NSF-sponsored workshop in February, 2002 (see Appendix I for a list of participants). The workshop's central recommendation is that:

Our science community invest in a unified, predictive science of surface processes through the development of a *Community Surface-Dynamics Modeling System* (CSDMS). CSDMS is envisioned as a modeling environment containing a community-built and freely available suite of integrated, ever-improving software modules predicting the transport and accumulation of sediment and solutes in landscapes and sedimentary basins over a broad range of time and space scales.

This modeling environment would catalyze surface process research over the coming decades by:

empowering a broad community of scientists with computing tools and

knowledge from interlinked fields, *streamlining* the process of idea generation and hypothesis testing through linked surface dynamics models, and

enabling rapid creation and application of models tailored to specific settings, scientific problems, and time scales.

In 2001 the National Research Council defined five "national imperatives" for future Earth-science research: (1) *discovery, use, and conservation of natural resources*; (2) *characterization and mitigation of natural hazards*; (3) *geotechnical support of commercial and infrastructure development*; (4) *stewardship of the environment*; and (5) *terrestrial surveillance for global security and national defense*. CSDMS will play a key role in all five imperatives. Wise development and use of water and liquid hydrocarbons requires a clear understanding of the origin and structure of the underground reservoirs that host them. Many natural hazards such as landslides, river floods, and coastal erosion will be better predicted only through improved understanding of feedbacks among complex and distant parts of the Earth surface system. At present, fragmentation of understanding is a major obstacle to the development of "best available" integrated methods for solving problems in these areas. Quantitative modeling provides a framework in which researchers from a variety of disciplines can express their ideas in a precise, consistent format.

Key Scientific Challenges

Six fundamental scientific questions form the core research that CSDMS would address:

- What are the *material fluxes* associated with the main physical, biological, and chemical transport processes? How do these fluxes depend on hydrologic, climatic, tectonic, and lithologic boundary conditions?
- How are *surface processes* coupled, and how does this coupling affect the rates of transport?
- How do these material fluxes *shape the surface* of the Earth?
- How do material fluxes vary across *time and space scales*?
- How is the *history of surface evolution* recorded in surface morphology and stratigraphy?
- How do *linked surface-process environments* communicate with one another across their boundaries, and co-evolve in time?

Recommendations

We recommend that:

- (1) NSF together with other interested agencies and industry establish an initiative called the Community Surface-Dynamics Modeling System (CSDMS) with an initial life span of ten years.
- (2) CSDMS be a modular modeling system aimed at providing tools for scientists to tackle problems at a variety of time and space scales.
- (3) An initial steering committee formulate a detailed interdisciplinary implementation plan and

supervise execution of the initiative.

- (4) Observational and experimental research be coordinated to test CSDMS predictions at a variety of levels.
- (5) A Community Surface-Dynamics Data Bank for existing and newly acquired surface-process data be established under a separate NSF Geoinformatics program.
- (6) A national center be established to help the community coordinate its efforts, ensure standards for code are maintained, and enhance protocols for information exchange. The Center should contain a dedicated CSDMS server and support personnel.
- (7) Distributed nodes within and outside the US provide shorter-term homes to sub-discipline working groups to foster information exchange and the development of specific modules.

CSDMS is a virtual National Science Foundation Lab existing in each of our computers. The scientific ideas contained within are never out of date because of continuous updates by the community. A national infrastructure links modelers together, reduces duplication, and facilitates model testing. Applications of models to problems of societal interest are promoted as non-specialist users assemble models in a user-friendly, graphical environment, requiring relatively little knowledge of computers or computer programming.



The goal is to develop a unified, predictive science of surface processes.....

1 INTRODUCTION

WHY IS EARTH-SURFACE DYNAMICS IMPORTANT?

Because the surface *is* the environment

The world's media make frequent reference to "the environment", but rarely do we ask exactly what is meant by this term. Often what is meant is the Earth's surface, with its interwoven physical, biological, and chemical systems, all overprinted by human influences. Instinctively, we are drawn to the living parts of this tapestry – the "ecology" – that is both the most appealing and the most threatened. But the Earth's surface itself is the cradle and the arena for its biological systems, from terrestrial alpine regions to the depths of the ocean. *The physical, chemical, and biological systems of the Earth's surface are so deeply interwoven that the surface is more like the living skin of our planet.*

Most of us tend to think of the surface as relatively static. But, viewed on an appropriate time scale, our planet's surface is dynamic in ways that parallel the more familiar dynamism of the atmosphere or the oceans. And the time scale need not be very long. Dramatic events like landslides can occur in seconds. Subtle but common forms of landscape change can control nutrient flow and population stability, especially in steep terrains. Over years to decades, changes in critical surface features like beaches and rivers can affect

large areas and the populations that inhabit them. *We need only extend our time horizon slightly to see that a quantitative understanding of surface dynamics is the cornerstone of environmental science.*

As our human population grows, so will the stresses associated with the give and take between humans and the terrestrial and ocean environments. Often the places we find most desirable to visit and inhabit – coastlines, riverbanks, and alpine environments – are the most unstable and dynamic parts of the planetary surface. Agriculture is almost entirely a surface-based industry, and as events like the infamous "Dust bowl" illustrate, can be dramatically affected by poor management. Sediment particles, especially fine ones, often adsorb chemicals whose fate we need to follow and control. Often this particulate flux exits to the ocean seafloor, where "out of sight" often means "out of mind". The seafloor represents roughly 70% of the Earth surface, and therefore "out of mind" is not the wise pathway to our understanding natural and anthropogenic fluxes. *Wise management of surface-related resources and wastes requires predictive tools comparable to those routinely applied to the atmosphere and oceans.*

The Earth remembers: the past as the key to the present

There is another, more subtle but equally important way in which surface dynamics affects all of us. Over the span of geologic time, the ceaseless working of the Earth's tectonic

engine brings fresh rock to the surface, where it is eroded and deposited as layers of sediment. These "layers" are better visualized as a three-dimensional complex of buried geomorphic forms: beach ridges, river channels, deep sea fans, etc – the tendons and integuments that underlie our planet's skin. This subterranean architecture, in addition to being an archive of Earth history, is the repository of nearly all hydrocarbons, groundwater, and a variety of other economic mineral deposits. *Wise development and use of these economically crucial resources requires a clear understanding of the origin and structure of the underground reservoirs that host them.*

Not all of the record of surface history is buried. Because the Earth's surface evolves relatively slowly, geomorphic forms at any instant carry a memory of past conditions. Recent research indicates that some present-day surface forms could have ages in excess of 200 million years. A careful reading of surface forms can provide insight as to how the surface environment has responded to past environmental changes. *Extracting the information recorded in landscapes requires a sophisticated understanding of how landscapes and seascapes work.*

WHAT'S WRONG WITH THE PRESENT APPROACH?

We know a great deal about the myr-

ial processes that shape the Earth's surface, transport material over it in particulate and dissolved form, and provide the arena for surface life. But there are two major shortcomings to the present state of organization of surface-process research:

- It is highly fragmented. Research that bears directly on major surface processes is conducted in Earth sciences, civil engineering, oceanography, meteorology, biology (mainly ecology), forestry, agriculture, soil science and, increasingly, physics and mathematics. The multiplicity of fields that are now contributing to surface-process science is all to the good – it is reinvigorating the field and bringing a host of new ideas and methodologies. But it also means that the knowledge base is highly fragmented. This poses a significant challenge, particularly for planners and other practitioners, because many important problems, like ecosystem management in morphologically unstable areas, cut across disciplinary boundaries. *Fragmentation of understanding is a major obstacle to the development of "best available" integrated methods for solving problems.*
- The state of understanding of critical surface-dynamics processes is very uneven. In many areas, it is still qualitative. It is not hard to see that the surface is one of the most complex systems on Earth. Faced with such complex systems, in which a particular outcome or state can be exquisitely sensitive to the details of history or setting, it is natural to begin by describing and cataloging what is there and what seems to have happened. But to provide the tools we need for living wisely on our planet's surface, we must move from description of what we see to prediction of what we have not seen. This includes both prediction of surface evolution in the future, and prediction of parts of the system that have

The Promise of CSDMS.... Can Better River Management in Illinois Save the Coastal Zone of Louisiana?

Coastal erosion is a major problem in Louisiana, yet it can not be reliably forecast or mitigated at present. To better predict its occurrence requires better prediction of sediment delivery to the coast. This in turn, requires an improved understanding of the coupling between the coastal system and fluvial transport systems upstream. An objective of CSDMS is to build an infrastructure that allows exploration of these coupled systems to answer questions like the one posed above.



not yet been observed. We stress that *any* form of prediction, as opposed to simple cataloging, is a major step in the evolution of a science. Because quantitative predictions are more specific than qualitative ones, they are more useful and also more testable than qualitative predictions. *To realize the potential of surface-process science, we must strive for quantitative prediction.*

HOW CAN WE DO BETTER?

What we need is a unified, predictive science of Earth-surface dynamics. At the heart of this effort lies the development of tools to promote quantitative

modeling of surface processes. The fragmented and often qualitative nature of surface-process research at present gives us a unique opportunity to develop these tools in a collaborative, modular fashion from an early stage. In this report, we present a blueprint for developing an integrated, quantitative framework for surface-process modeling through an initiative called the Community Surface-Dynamics Modeling System: CSDMS.

WHY IS CSDMS THE RIGHT PROJECT?

Because mathematical analysis and modeling lie at the heart of quantitative prediction

The core of this proposal is to develop mathematically based models.

Mathematical analysis can be done with pencil and paper. But if the target system is complex, the models usually end up in numerical form, either because numerical methods are a convenient way of solving well understood equations, or because some computational models have no analytical equivalent [Wolfram, Casti REFs]. But in either case, the goal remains the same: to provide testable, usable, quantitative predictions.

There is a more subtle motivation to emphasize modeling in our quest for integration and prediction. One of the great practical obstacles to integration of knowledge across disciplines is differences in language (jargon) that arise from disciplinary traditions. Mathematics can help bridge this divide because quantitative modeling provides a framework in which researchers from a variety of disciplines express their ideas in a precise, consistent format.

Why a 'community model'?

We envision CSDMS to be a modular, flexible modeling environment that will provide tools for a broad spectrum of users with diverse aims, skills, and interests. This kind of flexibility requires in-

CSDMS will be a community-built and freely available suite of integrated, ever-improving software modules predicting the transport and accumulation of sediment and solutes in landscapes and sedimentary basins over a broad range of time and space scales.



A goal of CSDMS is to better predict the occurrence of natural hazards, such as this 30 million cubic meter landslide at Jo Feng Her Shan, Taiwan, triggered by the Chi Chi earthquake. Twenty people were buried in the slide and two streams were dammed. (photo courtesy of Greg Tucker).

put from all of the communities that could benefit from CSDMS products.

One of the main practical products of CSDMS will be one or more complex models, pre-assembled from CSDMS components. These will be used for practical predictive modeling of surface evolution, much as weather and climate models are used now. Modeling surface dynamics is a problem of comparable complexity to modeling oceanic and atmospheric dynamics. The experience of the oceanic and atmospheric communities, discussed in more detail later, teaches us that development of such large, complex numerical models rapidly becomes a task for an entire research community. The community approach, in which many researchers pool their efforts, allows efficient development of models that are more powerful than any single group could achieve on its own. It also inherently maximizes the diverse and ad-

vanced skill sets in the research community.

WHAT WOULD BE THE BENEFITS OF CSDMS?

In its recent report on *Basic Research Opportunities in the Earth Sciences*, the National Research Council (NRC, 2001) identified five "national imperatives" that future Earth-science research must address:

- discovery, use, and conservation of natural resources;
- characterization and mitigation of natural hazards;
- geotechnical support of commercial and infrastructure development;
- stewardship of the environment; and
- terrestrial surveillance for global se-

curity and national defense.

The CSDMS program will contribute fundamentally to all five of these imperatives by providing, for the first time, an integrated, cross-disciplinary set of quantitative modeling tools for Earth-surface dynamics.

Natural resources, including virtually all hydrocarbons, most groundwater, and many commercial minerals, are hosted in sedimentary strata. Prediction of key properties of these subsurface strata would be a prime target of CSDMS research and would lead to better technology for finding, developing, and managing these critical resources. As hydrocarbons are collected from deeper and deeper offshore reservoirs, characterization with CSDMS models would allow increased efficiency in recovery.

Surface-process related **natural hazards** include landslides, floods, and coastal erosion. None of these can be reliably forecast or mitigated at present; landslides alone account for some thousands of deaths and billions of US dollars in damage worldwide in a typical year. The same is true for the impact of storm surge, river floods, and coastal erosion. The foundation for mitigating natural hazards is a well-grounded, predictive understanding of how the surface environment, with its myriad interconnected subsystems, actually works.

Sediment geotechnical properties in many cases are controlled by the production, transport, and deposition of the sediment, and are critical to safe construction of structures ranging from oil pipelines to housing developments.

CSDMS model products would become a routine part of **environmental stewardship** through the intimate connection between the surface and the fab-

ric of life within and upon it. Major application areas would include land-use planning, forest management, waste disposal, habitat support, management of scenic recreational areas, and river and coastline restoration.

Finally, although **terrestrial surveillance** *per se* is mainly a matter of observation, modeling is an attractive alternative where the desired data are not available. This is particularly true for marine seafloor environments where uncertainty in our knowledge is of growing concern. For all inaccessible areas, CSDMS models would provide a viable means of predicting and characterizing the terrain and strata.

In summary, CSDMS will provide integrated, quantitative modeling tools

that will help us live sustainably on the Earth's dynamic surface and understand the past for prediction of the present and future.

WHY IS NOW THE RIGHT TIME?

A Community Grass-roots Effort has Already Begun

A panel convened in March 1999, by NSF identified a "Community Sedimentary Model" as a high priority NSF research initiative in sedimentary geology. The science plan of the Margins Source-to-Sink Program calls

TABLE 1

| CHALLENGE | RESPONSE |
|---|--|
| Involves a multiplicity of fields, scales, interests, and applications | Emphasize flexibility, adaptability, and modularity |
| Although 'big science', CSDMS should not stifle individual creativity | Provide a suite of tools at a variety of scales for researchers with novel or unorthodox ideas |
| As a highly visible program, CSDMS must deliver desirable products in a timely manner | Start by adapting existing code to a common framework with community managed protocols |
| Large, complex models like those produced by CSDMS are difficult to test | Maintain close ties with field and experimental programs; insist that both individual modules and integrated models be tested by all available means |
| Large and complex program requires management | (1) Provide for a centralized facility to manage CSDMS development (2) Learn from experienced colleagues in other fields (e.g. atmospheric science) |
| Important aspects of surface processes are still not well understood | Allow for paradigm shifts. Link with laboratories and research groups worldwide that continue to develop new insights into critical processes |

for “the progressive development of a community-level suite of earth surface dynamics models for mass routing, deposition, and morphodynamic prediction as a conceptual framework and as a central focus for the Source-to-Sink project” (MARGINS Science Plan, Source-to-Sink Studies). And the U.S. Office of Naval Research STRATAFORM program, which began in 1996 and continues to the present, demonstrates the Navy’s commitment to collaborative efforts to develop an integrated, predictive model for the continental margin sedimentary system. NSF has also recently funded a new Science and Technology Center called the National Center for Earth-surface Dynamics, whose primary mission is to promote the integrated, experimental study of surface dynamics.

As the research community began to organize around these ideas and programs, it became clear that it was time to set up the structure for an integrated, collaborative modeling effort referred to informally as the “Community Sediment Model”. This realization led to the first Community Sediment Model workshop, held in Boulder, Colorado in February of 2002, sponsored by the National Science Foundation. This report is an outgrowth and summary of that workshop.

The Tools and Background are in Place

The skin of the Earth – the “Critical Zone” – is one of the most complex systems known. If we had to start from scratch, CSDMS would require a Herculean effort to complete. Luckily, that is not the case. Rather, CSDMS can be built using techniques and experience from across science and engineering, particularly drawing on allied fields that have developed analogous models. Key developments to be incorpo-

rated in this enterprise, include:

- rapidly evolving techniques for graphics and visualization that will make the results of complex simulations and datasets comprehensible,
- new methods for handling systems that span a wide range of length scales (see sidebox “Elucidating Scale Dependence in Numerical Models”),
- adaptive mesh-generation techniques for problems requiring variable spatial resolution, and
- new methods for handling problems with internal boundaries, which include boundaries between surface transport environments.

Furthermore, we can draw upon the management experience of communities that have already embarked on construction of collaborative models like CSDMS. Several prominent representatives from oceanography and meteorology joined us at the February workshop. Their advice is summarized later in this report.

There are also many components of surface modeling in place. Indeed, we expect that CSDMS development would begin by putting these existing models in a consistent and accessible framework. These are reviewed in Appendix II.

WHAT ARE THE MAIN CHALLENGES, AND HOW WILL WE ADDRESS THEM?

Developing the CSDMS as envisioned, will be a large, complex task, with timelines discussed at the end of this report. With adequate and coordinated funding, we expect the first tools to appear within a year, and

the first generation system up and running in less than five years. The development of the full suite of components and fully evolved “best available” models would take approximately ten years. The program should begin with the array of fields that contribute to surface-process science, to help form a substantial base. The main challenges are listed in Table 1.

The next section gives some broad scientific background and illustrates what the CSDMS might look like. This is followed by a discussion of how the CSDMS effort would build on existing efforts already underway across the Earth sciences. We close with a plan for implementing the CSDMS. Supplemental materials, including an assessment of the current scientific basis for the CSDMS, organized by transport environment, are contained in the Appendices.

CSDMS—the Right Program at the Right Time

Surface-process science today is reminiscent of atmospheric science in the early-mid twentieth century. The transition from qualitative to quantitative analysis is underway across many of the relevant subfields, but the work is fragmented and in many cases available only to research specialists. Integrated, predictive surface-process models do not exist. Yet living on the Earth's surface in the face of competing demands on the environment and changing climate require the best quantitative tools science can provide. The existing dispersed and uncoordinated research structure is not an effective way to develop these tools. We need a community surface modeling system now because:

- CSDMS addresses **research imperatives** that are critical to society;
- The stage has been set by previous research; and
- CSDMS will **enhance the value of existing observational programs** and help unify the broad range of scientific communities that work on surface processes.



2 NATURE OF A COMMUNITY SURFACE DYNAMICS MODELING SYSTEM (CSDMS)

Sidebox 1

GENERAL REQUIREMENTS

The objectives outlined in Chapter 1 require a new vision of how we study surface dynamics. We must synthesize quantitative process models that can be applied to problems ranging from modeling landslide risk in a national park to predicting the subsurface geometry of hydrocarbon reservoirs formed over millions of years.

General Requirement 1: Inclusivity

CSDMS must include both physical and non-physical processes that directly affect surface evolution or mass fluxes. Examples of non-physical processes include soil formation, which is chemical and biological as much as physical, mass wasting by dissolution, surface stabilization by plant roots, and sediment stirring by submarine fauna. Sidebox 1 elaborates on the challenges of coupling physical and biological systems.

General Requirement 2: Modularity

Because there is no single research group or program that can produce a system this wide-ranging, CSDMS must be structured so that it will attract and support the best efforts of the diverse research communities that will provide its scien-

The Emerging Challenge of Coupling Physical and Biological Systems

Although the initial focus of the CSDMS effort will be on physical processes, a particularly exciting challenge facing the Earth-surface dynamics community is to increasingly incorporate key ingredients of physical-biological coupling in models of landscape and stratigraphic evolution. This is important for two essential reasons. First, in many situations the physical dynamics of a system provide an underlying abiotic template for the existence of life, fundamentally influencing the spatiotemporal structure and function of this life. It is becoming clear that, to holistically understand the biotic structure and function of an ecological system requires understanding the coupled behavior of its biotic and abiotic parts together. Perhaps the best studied example is that involving advection-dispersion-reaction systems in riverine, estuarine and marine environments, where physical advection and dispersion combine with autotrophic-heterotrophic-nutrient interactions to produce rich spatiotemporal distributions in biotic concentrations. An understanding of the dynamics of this coupled behavior is essential for enlightened stewardship of ecological systems, balancing preservation against exploitation associated with growing, worldwide socioeconomic pressures. Second, in many situations strong physical-biological feedbacks occur such that to understand the physical dynamics of a system fundamentally requires understanding its biological parts. A brief list of key examples among many includes:

- the strong interaction between river flow, channel-boundary stress, and the stabilizing effects of vegetation on sediment mobility, as these influence river stability and switching between braiding, meandering and avulsion behavior;
- the strong interaction between vegetation and flow on tidal-marsh platforms, as this influences inundation frequency, sedimentation rates, nutrient fluxes, and plant productivity and zonation in coastal-marshes;
- the production of soil from bedrock associated with biogenic disruption of the soil-bedrock interface in conjunction with hydro-geochemical and biogeochemical processes; and
- bioturbation of marine sediments, as this attenuates high-frequency signals in the stratigraphic record, and therefore bears on interpreting the fidelity of such signals as records of external forcing.

tific understanding. The “research interface” of CSDMS must be a highly modular development environment that allows researchers to concentrate on CSDMS components in which they are expert.

General Requirement 3: Cutting Edge

CSDMS must treat key properties of the surface system (Table 2) using the latest concepts in Geoinformatics.

General Requirement 4: Extensible

If CSDMS to be durable, it must be

constructed so that it can be readily adapted as new scientific understanding and new computational tools are developed. Modular structure is key here, with data structures that allow new variables and algorithms to be implemented without damaging the rest of the model code. This requirement implies an object-oriented, extensible framework for CSDMS.

General Requirement 5: User Friendly

In many cases, the people posing the problems to be solved by CSDMS are

managers, not scientific researchers. Thus CSDMS must provide “application interfaces” that make it usable by non-specialists, and products that can be easily understood and managed. We envision these as complete models, assembled from CSDMS modular components.

General Requirement 6: Living with Uncertainty

We take for granted that sophisticated predictions of the weather will be readily available and that these

Table 2: Key Properties of Surface Systems

Most models are usually constructed by combining basic principles (e.g. conservation laws, constitutive laws) with insight about what the important aspects of the dynamics are likely to be. In our view, the following are the critical issues that are generic to surface-dynamics models. Most of these are associated with nonlinearity in one way or another:

Self-organization. The myriad fascinating spatial patterns that develop in surface morphology, from bedforms to drainage networks, are largely self-generated – they form spontaneously due to system’s internal dynamics as opposed to being imposed from without. Model structures must be flexible enough to anticipate and accommodate self-organization.

Localization. One of the recurring features of self-organization is strong localization of key quantities such as material flux and strain. Channelization of flow in streams is a common and dramatic example of this. Localization implies the need for computation structures with adaptive, variable resolution.

Thresholds. A common form of nonlinearity in surface-morphology processes is a threshold at which some phenomenon (e.g. sediment movement) begins. Thresholds can lead to abrupt changes, which can confound models if not accounted for correctly.

Strong coupling/interconnection. Particularly as one goes to longer time scales, coupling between environments (e.g. fluvial and shoreline) and across scales becomes critical. Even at short time scales, landscapes cannot be modeled without properly coupling hillslopes and river channels, even though the two regimes have very different transport dynamics. This means that, as we strive for modularity in design, communication among computational elements is critical.

Scale invariance. The Earth’s surface is covered with fractals; indeed, many ‘type example’ fractals are associated with surface patterns. The lack of a single well-defined length scale as implied by fractal behavior, makes division by scale harder. But it can also be exploited to extrapolate model results, or deal with subgrid-scale dynamics.

Interwoven biology and chemistry. To progress as quickly as possible, the CSDMS must begin with existing models, which tend to emphasize physical processes. But the intimate connection among physical, biological, and chemical processes must be accounted for in program design. This means including colleagues in these disciplines from the outset, and enlisting their help in designing modules that can accommodate biological and chemical processes smoothly.

predictions will be uncertain; indeed, the uncertainty is routinely expressed as part of the prediction. In this sense, the weather-forecasting community has done the rest of science a great service: it has accustomed the public to the idea that, even with the best possible technology, there are natural systems whose behavior simply cannot be predicted exactly.

The Earth's surface changes much more slowly than the atmosphere does, but one similarity that we expect is the presence of high-dimensional dynamical chaos, with its associated unpredictability. Surprisingly little effort has been made to study chaos formally in Earth-surface dynamics. Our assertion is based mainly on the observation that many kinds of surface patterns from sand dunes to river channel networks appear to behave stochastically, and on the fact that many surface processes involve turbulent fluid flow, which is itself one of the type examples of high-dimensional chaos. The chief implication for modeling is that model structures must be designed from the beginning to handle stochastic behavior, and to provide estimates of uncertainty along with predictions.

DESIGNING WITH THE USERS IN MIND

To make the potential uses of CSDMS more tangible, we present here five vignettes to illustrate how members of different communities might use CSDMS:

Researcher

A researcher in soil science is working on a new model of clay-mineral transformations in soils and wants to place

it in the context of weathering dynamics. She quickly finds relevant CSDMS modules for sediment production and diffusive transport. She gets the input her model needs without having to write code for processes outside her main area of interest. She also uses the extensive set of pre- and post-processing and visualization tools from CSDMS to provide input and visualize and analyze her results. Her model adds new predictive capabilities for the mineralogy of clays in fluvial sediment loads, which could influence the behavior of the clay fraction throughout the transport and depositional system. It is adapted for use in CSDMS and placed in the "untested" category to await her testing and integration.

Civilian planner

A planner in the US Forest Service is working on a set of scenarios for managing a national forest. He selects a pre-packaged CSDMS model that is optimized for studying short-term erosion processes and coupled to a hydrological model that provides runoff data. He quickly sets this model up for his specific case using GIS interface tools provided through CSDMS to input topography and vegetation cover information. The model provides predictions of likely sediment yield to local streams for the scenarios he has in mind.

Military planner

A lieutenant has been asked to evaluate the likely seismic structure of shallow subsurface strata in an area where there is no data available. He uses CSDMS stratigraphic components along with known recent sea level, tectonic, and climate history to construct a simulation of the likely stratigraphy, along with estimates of uncertainty for the simulation.

Petroleum geologist

An exploration geologist is working on

a prospect located in shallow-marine deposits. She has some information about paleogeography from seismic data and wants to evaluate the likelihood of sand reaching the area in question. She uses a CSDMS stratigraphic package to evaluate a range of scenarios conditioned by information on stratal geometry and sand content of up-dip strata. The simulations do not provide a definitive answer but do help quantify the risk associated with the prospect.

Maverick

A researcher who does not use large, comprehensive models and is not a member of any CSDMS-related group has an idea for a new scheme for modeling stratigraphy using game theory. She checks the CSDMS web site out of curiosity and finds that there is no indication that anyone has ever used this approach. Despite the fact that her algorithms are entirely novel, she is able to use CSDMS components to quickly build a GUI around her model, and to visualize and analyze the results.

KEY DESIGN ELEMENTS

The above constraints, together with the ideas and desires of the community as expressed at the 2002 February workshop, form the basis for the proposed structure of CSDMS. We also rely on information science principles and the experience of allied groups such as NCAR, whose ESMF, a high-performance framework for Earth science modeling & data assimilation, offers many parallels to CSDMS.

CSDMS should be a community-built and freely available suite of integrated,

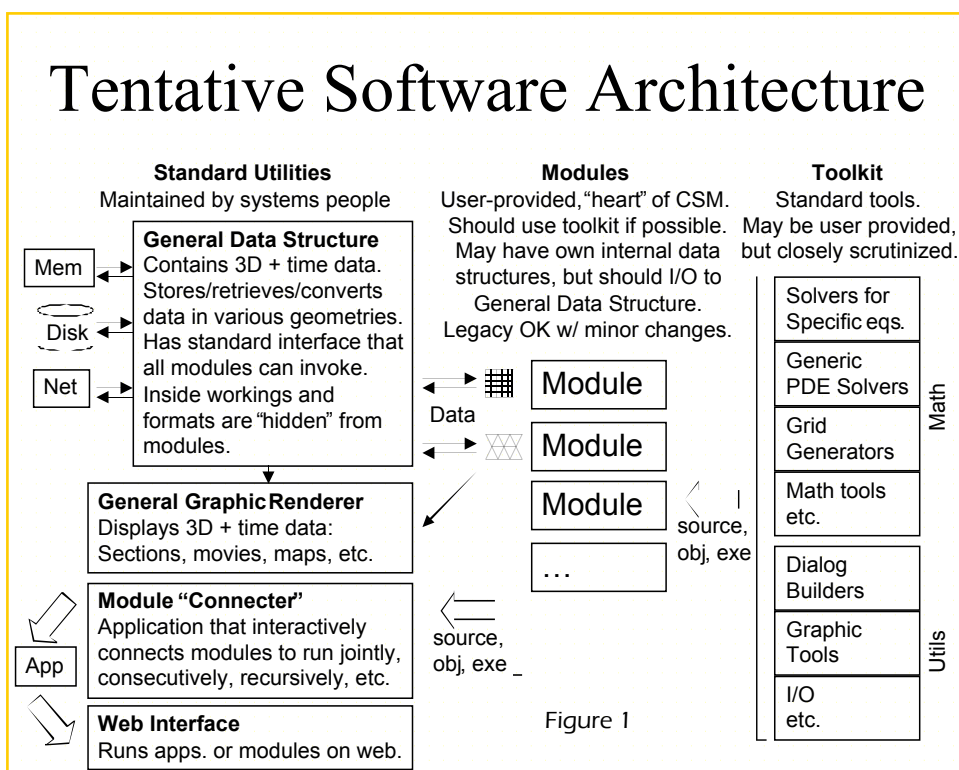
ever-improving software modules predicting the transport and accumulation of sediment and solutes in landscapes and sedimentary basins over a broad range of time and space scales. The system should be based on algorithms that mathematically describe the processes and conditions relevant to sedi-

ments to serve as a toolkit for earth system modeling. These components would include a series of model components, input/output routines, pre- and post-processing routines, visualization methods, archives of modules. Workshop participants agreed that CSDMS should be an environment or

ics (e.g. cellular automata);

- tools for model nesting and interaction across scales (see Sidebox 2);
- protocols and techniques for linking modules or domains with different solution techniques (e.g. classical differential equation and rule-based)

One possible configuration for a CSDMS architecture is presented in Figure 1. It draws heavily upon ideas tested in *RiverTools*, a software toolkit for the analysis of digital terrain and river networks (Peckham, 2003), the *Modular Modeling System* for hydrologic studies (Leavesley, 1997), *A Geographic Environmental Modeling System* for air quality studies (Bruegge and Riedel, 1994), *Spatial Modelling Environment* for simulation of spatial systems, and *DEVS-C++*, a project to develop a high performance modeling and simulation environment to support modeling of large-scale, high resolution landscape systems. CSDMS in this configuration contains three major components: **Standard Utilities**, **Modules**, and a **Toolkit**. A system supervisor, in the form of GUI, provides an interactive environment for user access.



ment/solute transport and deposition in a complete suite of earth environments, and should contain input/output, visualization, and data management tools to form a user-friendly modeling environment. The scientific infrastructure for CSDMS should be coordinated and funded by government agencies and industry and should be structured to allow sedimentary modelers from the geological, oceanographic, and engineering communities to determine the optimum algorithms, input parameters, feedback loops, and observations to better predict sedimentary processes and their products.

CSDMS needs to contain many compo-

system for conducting modeling studies, containing the following elements:

- a user-friendly graphical interface;
- interchangeable community-contributed process modules;
- i/o and visualization tools;
- linkers and interfaces to transfer data among different modules;
- protocols for linking modules;
- grid generators;
- equation solvers;
- tools for developing grids adapting dynamically;
- tools for unconventional mathemat-

The **Standard Utilities** component maintains and stores all data and variable arrays in a compact and quickly retrievable format. It also contains tools used to input, analyze, and prepare spatial and time-series data for use in model applications, and GIS tools for domain definition and spatial data analysis. An important component is the Module Connector, an application that allows users to easily link together process-modules from the module library to build a model, thus providing graphical, icon-based model construction.

The **Module Component** contains a variety of community-supplied, compatible computer programs simulating

sedimentary processes. Several modules for a given process may be present, each representing an alternative conceptualization or approach to simulating that process. Conceptualizations in a module may be of the traditional PDE form, cellular, or rule-based. Each module will be built around basic conservation equations, beginning with conservation of mass. This is typically expressed via the Exner equation, which states that the change in surface elevation at a point is proportional to imbalances in the particulate fluxes and loss or gain of material to geochemical and tectonic processes. In this manner the resulting morphological evolution of the Earth's surface can feed back into the processes causing the particulate fluxes. It is particularly important that biological, as well as chemical and physical effects be incorporated into each process module.

The **Toolkit** contains the basic information technology for generating grids and solving equation sets, such as high-order PDE and hybrid PDE/cellular solvers, adaptive meshes, automated mesh and algorithm selection, time-stepping, and domain coupling procedures. Automatic code generators will construct spatial simulations and enable distributed processing over a network of parallel and serial computers, allowing the user transparent access to a network of computing facilities.

Ideally the dynamic grid generators would use combinations of physically-based criteria for morphodynamic stability as well as recognition of internal self-organizing dynamics to optimize and regenerate grids "on the fly" during simulations. The generic PDE solvers would be adaptable high order methods aimed at efficient PDE solutions for typical (e.g. fixed mesh) cases as well as more difficult cases such as

front/boundary tracking.

Requirements of each module

The 2002 workshop group thought that each module should have some "common approach". One possibility would be a finite volume/ finite difference approach to mass conservation and momentum conservation. There was some concern that this might not allow for other approaches (e.g. those not based on differential equations) to be incorporated into the modeling system. For example, could a biologist who uses a rule-based approach work with a module with this underlying structure? Would it be able to accommodate moving boundaries? The conclusion is that the modeling system should be able to incorporate novel computational strategies such as particles, agents, and cellular automata. The model system also must accommodate dynamic moving boundaries and allow the modeled geomorphology to evolve. This includes sophisticated handling of material and momentum exchange across boundaries. Finally, the model system must be able to accommodate distributed "source terms", which can be notoriously difficult to handle in conservation algorithms.

Model nesting

Models or modules would be nested in temporal or spatial scales (1) at high resolution to bring high resolution to particular regions or (2) at low resolution to track evolving boundary conditions. High-resolution grids could be embedded in lower resolution grids (e.g., for floodplains or channels in drainage basin models). Also, high-frequency solutions could be used in some modules to characterize system components (e.g. bedforms or mixed-grain sediment transport) than cannot readily be parameterized at the longer time scales of the main model architec-

ture. The CSDMS modeling system will encompass the entire "source to sink" suite of surface environments.

Managing community input

One of the most difficult management issues in designing a community-based model is allowing input from a diverse community while maintaining standards for both compatibility and prediction quality for the code. The 2002 workshop group, based on input from experienced colleagues, thought that this could be handled by establishing a hierarchy of module categories ranging from "proposed but untested" to "fully tested and recommended for routine application".

Data structures

The 2002 workshop group called for definition of a unified data structure that might provide a backbone for the various model components, and to link the various modules. The data structure must be defined so that model components can communicate with each other and pass information back and forth. The data structures also must have the flexibility to evolve as modules evolve. They will probably not be constant in space during a long-time-series model run, and different values within the data structure will be updated in response to disparate time-and-space scales, as the wide variety of modules rely on the data structure. Therefore, links between the data structure and modules will require crucial (and complex?) interpolation methods.

Sidebox 2

Elucidating Scale Dependence in Numerical Models

An overarching challenge in the CSDMS effort is to develop sound theoretical and numerical foundations for accommodating the many orders of magnitude in space and time scales that are of interest in modeling Earth-surface processes. This is a multi-part challenge involving issues of spatiotemporal averaging and sub-grid parameterization, enlightened mesh generation and time stepping, multi-scale resolution and interpolation, and availability and use of varying-resolution data sets. For example, what is the emergent behavior at coarse resolution of physicochemi-

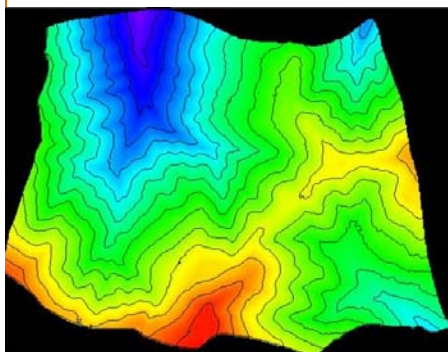


Figure 1. Topographic Map of Coos Bay, OR, area based on 2-m horizontal resolution LIDAR data; total east-west distance is 425 m, contour interval is 20 m.

cal processes operating at fine resolution?

For diffuse transport operating at meter lengthscales, the characteristic horizontal lengthscale associated with topographic curvature sets an upper limit on the grid size that contains meaningful dynamical

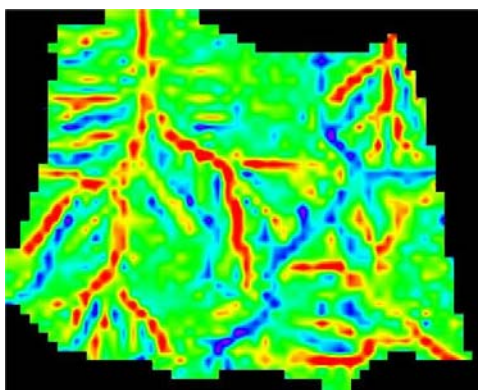


Figure 2. Map of topographic curvature based on 16 m resolution data.

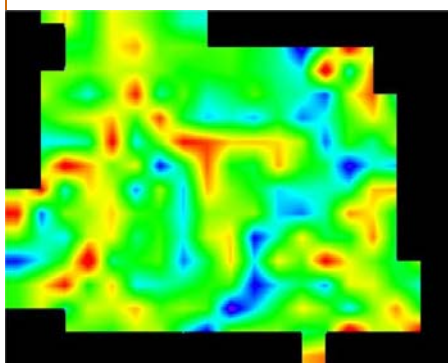


Figure 3. Map of topographic curvature based on 40 m resolution data.

cal information for modeling the evolution of the topography by diffuse transport. At Coos Bay, OR (Fig. 1), this lengthscale is about 15 m (Fig. 2). Larger grid sizes (Fig. 3) do not adequately “see” this essential dynamical information. Many areas of Earth’s surface have 30-m (or coarser) resolution DEM data coverage; and large-scale numerical models often must be run at coarse resolution. Thus, a key chal-

lenge is to elucidate how to model sub-grid scale processes like diffuse transport that manifest themselves at coarser scales.

3 BUILDING TOWARDS CSDMS

The CSDMS program represents a culmination and integration of a set of independent, grass-roots efforts that have been going on for some time. These programs embody the momentum the research community has already built up toward integrative, comprehensive surface-process models. They also will provide the starting point for CSDMS development. We review some of them here, but stress that this is only a sample to give an idea of what has been done. Table 3 provides a summary of some of these models; Appendix II presents a compilation of existing models in allied disciplines with which CSDMS must interact.

LANDSCAPE MODELS

Landscape evolution models simulate the flux of mass across a topographic surface and the changes in topography that result. Although pioneering efforts were underway as early as the 1970's, most landscape evolution models have been developed since the early 1990s. Landscape evolution models, by definition, operate on time scales relevant to the development of landforms, be they hillslope forms such as scarps and cuestas, short-term fluvial features such as fill terraces, or entire river basins and mountain ranges. Target timescales used in landscape modeling studies have ranged from 10^2 to 10^7 years, and target spatial

What Do We Know Now? —The Case of Rivers and Lakes

River systems are one of the best understood of all major transport systems, due to their accessibility and importance to commerce and recreation. Most of our understanding of basic sediment transport in unidirectional flow comes from experimental and field work motivated by problems of river engineering. The last twenty years have seen physical scale models largely replaced by numerical modeling for solution of routine hydraulic-engineering problems. Computational fluid-dynamics (CFD) techniques have developed to the point where even fairly complex, three-dimensional flows can be modeled accurately.

In recent years there has been increasing appreciation of the interplay of physical and biological processes in controlling river dynamics. The most influential biological processes involve riparian vegetation. Major effects include binding of sediment particles by plant roots, and flow resistance offered by above ground vegetation. Many researchers believe these effects play a predominant role in determining channel form and behavior.

Existing engineering-oriented river models include the US Army Corps of Engineers HEC series and associated models for sediment motion, as well as comparable models developed in Europe (listed more completely in Appendix II). At larger scales, a series of simulation models for alluvial stratigraphy, with an emphasis on avulsive channel switching, have been developed with the aim of predicting three-dimensional stacking of channel bodies. At the largest scales, the space- and time-averaged evolution of river long profiles is usually modeled with some form of the diffusion equation. In this approach, coefficients are determined by suitable averaging of dynamics at smaller time and space scales.

Frontier areas in modeling river dynamics include: locally complex three-dimensional geometries (e.g. channel confluences and strong bends), where common turbulence closures can break down; problems involving both flow and sediment transport (e.g. channel evolution over decadal or longer time scales); transport of typical mixed-size sediments under natural conditions; channel-floodplain interaction; biological effects; understanding the self-organization of river networks; modeling the dynamics of steep and/or infrequently occupied channels; coupling river channels to hillslope sediment-delivery systems; and controls, spatial and temporal statistics, and predictability of avulsions and other channel shifts.

Sediment transport in lakes has received relatively little attention from the research community. One of the byproducts of CSDMS would be a transfer of knowledge from the marine realm to the problem of lake sedimentation.

scales from 10^0 to 10^4 km². Examples of current landscape evolution models include CAESAR, CASCADE, CHILD, DRAINAL, EROS, GILBERT, GOLEM, SIBERIA, and ZSCAPE. These are steadily maturing in terms of the range and level of detail in the processes represented.

Despite the wide range in time and space scales of interest, all or most landscape evolution models share several common ingredients. Topography is represented in the form of a discrete set of cells or elements. Most models use a uniform (raster) grid representation, but there are at least two examples (CASCADE and CHILD) that use an irregular triangulated framework. This latter approach allows for adaptive remeshing, and in that respect provides a useful input to CSDMS. Precipitation is applied as a boundary condition, and the resulting runoff is routed across the discretized topographic surface. The combination of runoff, local surface slope, and material properties then drives a set of process rate laws. These alter the topography, which in turn

What Do We Know Now? —The Case of the Coastal Zone

Because of the importance of coastal areas to society, a good deal of effort has been put into understanding and predicting coastal sediment transport, especially that of sand. The US Army Corps of Engineers has a large coastal program including advanced methods of predicting sediment flow and coastal change on relatively short (year to decade) time scales. Comparable programs are well developed in Europe as well. Recently the US Navy sponsored a coordinated, intensive study of coastal sediment transport at Duck NC (REF). Nonetheless, because of the complexity of flow and sediment dynamics under breaking waves, even basic prediction of sediment transport in the surf zone is still difficult, and is currently done using semi-empirical methods.

Prediction of the dynamics of fine sediment in this environment is less well developed. In particular there is a critical need for methods that can account for the strong biological influence in fine-sediment dynamics. Passage of fine particles through the gut of filter-feeding organisms can result in conversion of fine, cohesive particles to silt or sand-size, noncohesive pellets. In-sediment biological processes (e.g. burrowing, deposit feeding) also influence erodibility and transport of coastal sediments.

alters the rate laws, leading to a self-evolving system. Typically, the rate laws used for erosion and mass trans-

port represent long-term average rates rather than discrete events, although some models now include a stochastic,

Table 3
Some Common Surface Process Models

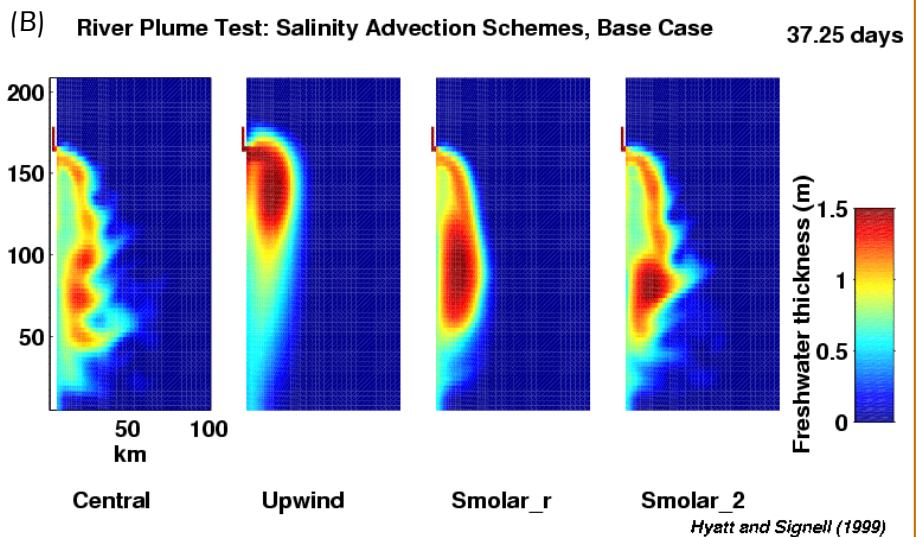
| Model | Developer | Use |
|--------------------|-----------------------------|--------------------------------------|
| SEDFLUX | INSTAAR | 2D & 3D event-based stratigraphy |
| NCSTM | USGS, NOPP, ONR | continental-shelf sediment transport |
| SLICE shelf model | URS | shelf stratigraphy |
| HEC series | US ACE | river engineering |
| DELFT-3D | DELFT | coastal erosion |
| MIKE | DHI | river flow and sedimentation |
| SEQUENCE | LDEO | 2D time-averaged stratigraphy |
| ETH river model[s] | ETH | river and delta engineering |
| CHILD | Tucker, MIT/Oxford | landscape evolution |
| SIBERIA | Willgoose, Univ Leeds UK | landscape evolution |
| landscape model | Howard, Univ VA | landscape evolution |

event-based representation of processes such as flooding (e.g. CHILD) and bedrock landsliding (e.g., ZSCAPE).

Spatial scales represented by landscape evolution models range from small upland catchments to entire orogens. In the former case, the models resolve smooth hillslope topography and are able to apply transport laws for both hillslopes and channels. In the latter case, grid resolution is normally too coarse (on the order of one to tens of square kilometers) to capture individual hillslope and headwater topography, and hillslope processes therefore are treated as sub-grid scale.

The list of processes incorporated in landscape evolution models is growing rapidly. In addition to basic rate laws for runoff erosion and hillslope diffusion, some models now incorporate additional rate laws or algorithms to describe landsliding, vegetation, multiple grain sizes, stream meandering, floodplain (overbank) sedimentation, groundwater sapping, quasi-2d surface flow, ice sheet growth, non-steady and non-uniform hydrology, orographic precipitation, simple treatment of marine deposition and shoreline movement, and coupling with normal-fault or thrust-fault displacement models. Many of these “exotic” process models are in an experimental stage, and will continue to mature over the next several years.

Landscape evolution models have succeeded at the most basic test of reproducing fundamental properties of river basin landscapes (both in terms of pattern and statistical signatures), as well as typical landforms such as convex-concave hillslopes, ridge-valley topography, faceted spurs, alluvial fans, and similar features. Along the way, they have shown promise as devices for enhancing insight into landscape dy-



namics, for yielding counter-intuitive “surprises,” and for generating and exploring quantitative, testable hypotheses. Landscape modeling has also been applied to engineering problems, such as the long-term stability of

Fresh water plumes from the Huanghe (A), and a numerical model (B) (photo courtesy of James Syvitski).

waste-rock landforms on mining sites. There are a number of important chal-

allenges to further development and application of landscape evolution models. Many of these are shared with other Earth surface transport models, and have been discussed elsewhere in this report. Our knowledge of many of the important process laws is still fairly rudimentary, and much work remains to be done in testing and refining these. There are also important scaling challenges. For example, bankfull channel width is a fundamental spatial scale in fluvial transport and erosion, and yet it remains difficult to resolve explicitly in a domain that consists of an entire drainage basin (see also Side-box 2). Likewise, flood duration is a basic timescale in fluvial systems, yet it is many orders of magnitude smaller than timescales associated with drainage basin formation. Finally, there remains a need for good validation tests for landscape evolution models, both from experimental and field cases. CDSMS will help to overcome many of these challenges by (1) making it easier to design and test alternative approaches to scaling problems, (2) fostering the refinement of rate laws and facilitating their incorporation in landscape models, and (3) empowering the communication across disciplines that will be essential to developing data sets for model testing, validation, and refinement.

COASTAL AND CONTINENTAL SEDIMENT TRANSPORT MODELS

The coastal zone and continental shelf are characterized by strong coupling between currents, waves, sediment transport, and bed morphology that must be captured in sediment transport and morphodynamic models.

What Do We Know Now? —The Case of Continental Shelves

Modeling of sediment transport on the continental shelf is relatively highly advanced at present due to strong collaboration between the marine sediment-dynamics and circulation modeling communities. Much of the interest in model development in these regions stems from concerns about seabed stability, contaminant transport, anthropogenic effects and links to ecosystems, leading to an emphasis on models that resolve processes at relatively short time scales. The time scales necessary to represent transport processes and seabed response generally decrease with decreasing water depth, making it challenging to construct models that couple shallow and deep regions of the ocean.

New community initiatives are underway to develop modeling systems for the coastal zone and continental shelf. These efforts aim to treat nearshore hydrodynamics, sediment transport and seabed morphology using a tightly coupled set of process modules for waves, circulation, and the seabed. Another major focus is to couple three-dimensional ocean circulation models, such as the Princeton Ocean Model, with boundary-layer formulations for wave-current interaction and sediment transport algorithms. Examples of related ocean-circulation models are given in Appendix II.

Beyond dealing with the complexity of the wave-current interactions that drive continental-shelf sediment transport, a major challenge in shelf transport modeling is integrating these physical processes with biological processes that influence sediment dynamics. This is particularly important for correctly predicting the behavior of the fine fraction of the sediment load.

marine environment.

A currently funded NOPP (National Ocean Partnership Program) project is devoted to developing and verifying a comprehensive community model to predict nearshore hydrodynamics, sediment transport and seabed morphology using a tightly coupled set of process modules for waves, circulation, and the seabed (chinacat.coastal.udel.edu/~kirby/NOPP). In this region, complex wave hydrodynamics drive persistent and often intense sediment transport capable of significantly altering bed morphology on short time scales (minutes to hours). The highly dynamic nature of this region and the strong feedbacks among flow, transport and morphology necessitates a level of spatial and temporal resolution exceeding that required in any other part of the

A second modeling effort, led by the USGS with preliminary funding from NOPP, is aimed at developing a community sediment-transport modeling system for the coastal ocean (continental shelf and estuaries) (woodshole.er.usgs.gov/project-pages/sediment-transport/; Sherwood et al., 2002). Shelf morphodynamics are closely tied to the wave environment and ocean circulation. As a result, a major focus of sediment transport model development for shelf regions is to couple three-dimensional ocean circulation models, like the Princeton Ocean Model, with boundary-layer formulations for wave-current interaction and sediment transport algo-

rithms. Examples include ROMS (Regional Ocean Modeling System, Rutgers), DELFT3D (WL/Delft Hydraulics), ECOM-SED (HydroQual) and EFDC (TetraTech). A goal of the community modeling initiative is to use one or more of these models as a starting point to develop an open architecture, modular model with a three-dimensional circulation model as a backbone and a variety of tested sediment transport modules that can be plugged into the main model. An important aspect of the nearshore and coastal ocean community modeling programs is development of a suite of test cases that can be used to test modules before accepting them into the modeling system.

While most nearshore and shelf sediment transport models are designed to investigate processes over short time scales (hours to months), some two-dimensional, integrated models have been developed to investigate longer

term stratigraphic and seascape evolution of continental margins. The time scales addressed in these models generally prohibit detailed treatment of sediment of fluid dynamics, relying instead on parameterizations of the important processes. These types of models are discussed in the next section.

A goal of the community modeling initiative is to use one or more of these models as a starting point to develop an open, modular architecture with a three-dimensional circulation model as a backbone and a variety of tested sediment transport modules that can be plugged into the main model. An additional important aspect of the nearshore and coastal ocean community modeling programs is development of a suite of reference cases that can be used to test modules before accepting them into the modeling system.

What Do We Know Now? —The Case of Hillslopes and Sediment Production

Versions of the standard diffusion equation, usually in one spatial direction, have been used extensively over the past three decades or more to model hillslope evolution (e.g. Fernandes and Dietrich, 1997). These implicitly refer to vertically-integrated soil transport under restrictive conditions pertaining to the porosity (or bulk density) of the soil, the boundary conditions imposed on the hillslope, and the time scales of evolution considered. However, despite its popularity and apparent empirical success, the diffusion model does not yet have a clear theoretical basis. Only limited work has been undertaken to describe the details of diffusive transport, and only a few field-based studies have been undertaken specifically to provide empirical evidence to test it (e.g. Clarke et al. 1999; Gabet 2000). In general, little is known about how diffusive transport actually works — in particular, how quasi-random motions of individual soil particles collectively contribute to *en masse* motion.

Current geochemical modeling is based on simplified “box” models: conservation of mass within soil/bedrock system is coupled with reaction kinetics for major minerals/ions, loosely connected with hydrology (water input/loss). Microbial effects are just beginning to be investigated in detail using modern methods of microscopy and genetic analysis. Biogeochemical effects have not yet been incorporated in sediment production models.

What Do We Know Now? —The Case of Carbonates

The distinctive aspect of carbonate sediments is their production, so most effort in carbonate modeling has gone to developing production functions. This work has been done largely in the carbonate sedimentary-geology community. In models that also account for transport and re-deposition of carbonate sediments, these are handled by the same methods as are used for clastic sediment transport. At present, there has been limited communication between researchers working on carbonate dynamics and the physical transport process community. The importance of carbonate structures as morphodynamic elements, the influence of physical processes on carbonate-producing ecosystems, and the common occurrence of mixed clastic-carbonate sediments on the coastlines and shelves of the world, all highlight the need for closer collaboration between these communities in surface-process modeling.

STRATIGRAPHIC MODELS

“Stratigraphic” surface-dynamics models are those intended for study of depositional systems over geologic time scales. Generally speaking, geologic time scales are those on which tectonic subsidence and/or eustatic sea-level change become important. Their main hallmark is that they track not just the current topographic surface but also a stack of surfaces that represent recorded stratigraphic information. In a

sense, stratigraphic models are a surface-dynamics analog of climate models in atmospheric sciences, in that they use spatially and temporally averaged representations of short-term processes. Long-term stratigraphic models of fluvial systems, for example, often use some form of diffusion equation to represent evolution of the surface morphology. The diffusion coefficient in this representation is a parameterization of high-frequency channel dynamics (typically of the order of 1-1000 yr). Analogous parameterized models have been developed for the coastal and continental shelf regions (eg., Storms et al., 2002). Coupling of shelf/coastal and fluvial models, for example, allows modeling of shoreline transgression and regression in response to changes in sea level.

Development of quantitative, process-based stratigraphic models began in earnest in the 1970s and 1980s after development of the first geodynamic models of basin subsidence. Since then there has been a proliferation of models, with somewhat slower progress in applying and testing them. A comprehensive review of stratigraphic models that can provide a basis for the long-term components of CSDMS can be found in Paola (2000).

SOURCE TO SINK PROGRAM: NSF MARGINS

The overarching goal of the *MARGINS Source-to-Sink* initiative is to develop a quantitative understanding of margin dispersal systems and associated stratigraphy, so that we can predict their response to perturbations, such as climatic and tectonic variability, relative sea-level change, and land-use prac-

tices. *Source to Sink* consists of focused field investigations of landscape and seascape evolution, and of sediment transport and accumulation in selected dispersal systems. A key feature of this program is the collective effort to investigate well-selected field sites, where the complete source-to-sink system can be analyzed. Quantitative modeling is integrated into the research: model predictions help guide aspects of select field programs; field observations validate/verify model outputs; numerical

modeling explores forward and inverse source-to-sink questions; and a comprehensive modeling effort is to link the suite of products through a Community Sediment Model, akin to the Princeton Ocean Model or the Community Climate Model.

What Do We Know Now? —The Case of Continental Slopes and the Deep Ocean

Models of turbidity currents range from simple one-dimensional integral models (e.g., Parker et al., 1986) that predict current speed, thickness, and density along the flow path to complex two-dimensional models that resolve details of the vertical structure of a turbidity current (e.g. Felix, 2002). Most of these models account in some fashion for entrainment of ambient water into the turbidity flow, entrainment (or deposition) of bed sediment, and friction with the bed. They have been used to simulate the formation of a submarine fan, including channel-levee systems, (Imran et al., 1998) and stacked turbidite deposits (Pratson et al., 2000). Internal tides may affect slope sedimentation (Cacchione et al., 2002), but this effect has yet to be included in models of slope morphology.

Models of submarine debris flows are not as advanced as those for subaerial debris flows or turbidity currents. Most of the existing models (e.g. Imran et al., 2001) are one-dimensional models that conserve mass and momentum for one or more possible debris flow rheologies (e.g., Bingham, Hershel-Bulkley). Among the potentially important processes not well represented in existing submarine debris flow models are disaggregation, hydroplaning, and secondary turbidity current generation. The debris flow model BING has been used to simulate runout and deposition on submarine fans, as well as the stratigraphy created by stacked debris flows (Pratson et al, 2000; Marr et al., 2002). Two-dimensional, and ultimately three-dimensional, models are needed to understand the spatial patterns of deposition and the cumulative depositional record of debris flows and turbidity currents.

Close coordination with observational (field and laboratory) studies is critical for model testing and innovation. For example, field observations made in the STRATAFORM program suggested that gravity-driven flows of fluid mud are an important mechanism for redistributing flood sediment on the Eel shelf, northern California. This has prompted development of models for the formation, transport and deposition of fluid mud on the continental shelf (Traykovski et al., 2000; Scully et al., in press).

THE NATIONAL CENTER FOR EARTH-SURFACE DYNAMICS

The National Center for Earth-surface Dynamics (NCED) is a recently funded NSF Science and Technology Center devoted to integrated study of surface processes. At present it involves ten Principal Investigators from five research institutions as well as industrial and government partners.

Thus its interests are closely aligned with CSDMS. However, NCED's mission is to provide scientific insight on key surface processes. It does not have the personnel or the resources to create the comprehensive computer-modeling environment called for in CSDMS. NCED would be a major partner in the CSDMS effort, providing scientific support, experimental and field data, and cooperating in leading the workshops and meetings that would be required to maintain community involvement with CSDMS.

4 A STRATEGY FOR MOVING FORWARD

LEARNING FROM OUR COLLEAGUES

One of the most important features of the 2002 workshop was a series of presentations by leaders of existing collaborative modeling efforts in various areas of the Earth sciences.

These focused less on the technical details of the models than on how they are organized and managed. Some of the features these colleagues considered essential to the success of a project of this type were:

- A single central coordinating facility to manage the project over the long term;
- Communication among project participants;
- Recognition of individual contribution to the project while maintaining public access to, and ownership of, the products;
- Highly modular design so that individual model components can be replaced without side effects;
- High-quality graphical interfaces for both pre-processing and post-processing;

In addition to giving us advice and guidance, these associated modeling efforts will also communicate directly with CSDMS as we attempt to model highly integrated, coupled problems. Critical parts of the Earth system that are not part of CSDMS itself but that will interact strongly with it include

the atmosphere, oceans, groundwater, glaciers, and lithosphere. Predictive, quantitative models for these subsystems already exist in some form, and are listed in Appendix II. We also expect that as CSDMS develops, models for ecosystems and human behavior will progress to the point where they can be connected to CSDMS as well.

Ocean modeling systems provide a good example of current practices in collaborative modeling (for a valuable review from the perspective of the U.S. Navy see Preller, 2002). The most general ocean modeling system, and thus perhaps the most directly applicable to CSDMS, is the Geophysical Fluid Dynamics Laboratory's Flexible Modeling System (FMS). FMS is a software framework for supporting the efficient development, construction, execution, and scientific interpretation of atmospheric, oceanic and climate system models. FMS comprises the following:

- A software infrastructure for constructing and running atmospheric, oceanic and climate system models. This infrastructure includes software to handle parallelization, input and output, time management, data exchange between various model grids, makefiles, and simple sample run scripts. This infrastructure should largely insulate FMS users from machine-specific details.
- A standardization of the interfaces between various component models.
- Software for standardizing, coordi-

nating and improving diagnostic calculations of FMS-based models, and input data preparation for such models. Common preprocessing and post-processing software are included to the extent that the needed functionality cannot be adequately provided by available third-party software.

- A rigorous software quality review and improvement process to assist in contributed component models. The development and initial testing of these component models is largely a scientific question, and would not fall under FMS. The quality review and improvement process includes consideration of (a) compliance with FMS interface and documentation standards to ensure portability and interoperability, (b) understandability (clarity and consistency of documentation, comments, interfaces, and code), and (c) general computational efficiency without algorithmic changes.
- A standardized technique for version control and dissemination of the software and documentation.

PROPOSED ORGANIZATION OF A CSDMS PROGRAM

The administrative structure proposed for CSDMS is borrowed directly from the climate modeling community. It consists of an advisory

board, a steering committee, and a series of working groups. The working groups will be defined by disciplines and by themes (scaling, computational methods I/O and IT, etc.) in that some groups are disciplinary, some are cross-cutting themes, and some are groups that consider issues concerning technology.

Steering committee

The CSDMS scientific steering committee should be an interdisciplinary body with members from both the process-level research community and monitoring agencies. It would provide coordination, scientific vision, and decide on resource allocation. The 2002 workshop group also proposed that the steering committee should decide on version control and the release of model components. They will serve as a liaison between the technical expertise expressed in the disciplinary groups and funding agencies and the wider community.

Disciplinary groups

Disciplinary working groups would be responsible for creating and managing the various process modules, and providing continuity to meet long-term project objectives. They will be set up to cover general areas of research – such as coastal environments. It is important to prevent these from becoming overly specialized (the whole structure would become unwieldy if, for example, it had separate dune, near-shore, estuarine, mid-shelf, outer-shelf, etc. groups). These disciplinary groups will also be set up to be “permanent” structures to provide continuity to the project. Several disciplinary groups would cut across disciplinary science, including scaling, testing (field/lab), advanced computational, IT, software engineering, software and data management, benchmark data, and protocol development.

Sidebox 3

The Role of Applied Mathematics and Computational Science

There is an important, ongoing role in the CSDMS effort for applied mathematicians and computational scientists. Specifically, ours is a science (and culture) that has not yet fully enjoyed the benefits of strong interactions with these allied disciplines, as have fields like fluid dynamics, ocean and atmospheric sciences, and more recently, biological and medical sciences. Earth-surface dynamics research is ideally poised for quantum advances as we increasingly, and fully, engage applied mathematicians in pursuing a deeper understanding of the complex dynamical systems that are a hallmark of this field. Moreover, this is not only an opportunity for achieving significant advances consonant with the vision of the NSF Mathematical Sciences and Geosciences (CMG) initiative, but is also an opportunity to increasingly incorporate applied mathematics as an essential, innate part of our science culture, including the training of students. Examples of topics in applied mathematics that are particularly relevant to Earth-surface dynamics include:

- homogenization theory applied to Earth-surface transport processes;
- the physical and chemical basis for sub-grid parameterization in numerical models;
- inverse theory applied to parameterization and optimal resolution; and
- information and complexity theory applied to multi-scale Earth-surface systems.

By “computational scientists” we mean individuals possessing a blend of expertise in disciplinary science, applied mathematics and computing techniques – and a flair for developing and applying advanced computing techniques to science problems. Engaging such scientists at ground level in the CSDMS effort is particularly important in view of the accelerated rate at which innovations in numerical methods and computer technology are occurring. Examples that are particularly relevant to CSDMS include:

- algorithm development, notably involving mesh generation and optimal resolution;
- advanced visualization, notably involving large multi-scale 4-D fields; and
- the co-designing of architecture, algorithms and data-processing software.

As “keepers of the code” these groups will make decisions on what tools or processes are in the disciplinary toolkit (Fig. 2). They are responsible for quality-control for the algorithms and processes that are included for their area of expertise. They set the priorities for modeling within a discipline, and facilitate the movement of these priorities

up the hierarchy from technology group to steering committee to advisory board.

Responsibilities of the disciplinary working groups include:

- technical quality control
- adequacy of testing

- setting scientific priorities for the group
- Making recommendations for resource prioritization
- stimulating proposals and input from the community
- scientific review, and
- technical documentation.

disciplinary science. Several ideas were proposed as themes for these types of groups, including scaling, testing (field/lab/comp), advanced computational, IT, software engineering, software and data management, benchmark data, and protocol development.

Geographic distribution

A national center is envisioned to house the core server and information

surface is not inadequate computer code but inadequate scientific understanding. Developing models that are both computationally sophisticated and scientifically sound requires that code development proceed in parallel with, and interact strongly with, field, experimental, and analytical studies aimed at filling gaps in our understanding.

The vision we have laid out in this report is quite broad. We believe it is essential to begin a project like CSDMS with a view that is as comprehensive and inclusive as possible. But the first steps in building something usable will require that we focus on those processes that are currently best understood and for which quantitative models are available.

Initial priorities

The 2002 workshop group provided input as to which activities should have the highest priority in the early stages of the project. Legacy codes and least-effort methods would be used where appropriate to provide initial deliverables from the project (Figure 2). As a first step, we recommend that legacy codes be modified/engineered so that they can interact with each other within the CSDMS modeling system.

Two things must be done at the outset of the design phase: 1) define the master data structure and linking methods so that different modules can exchange data with each other 2) develop and make available tools for building or incorporating new modules.

Thus, we will begin work on CSDMS by collecting and systematizing the models we have, starting with the disciplines where surface-dynamics modeling has been central: geomorphology, engineering, oceanography, and sedimentary geology. Initial CSDMS models

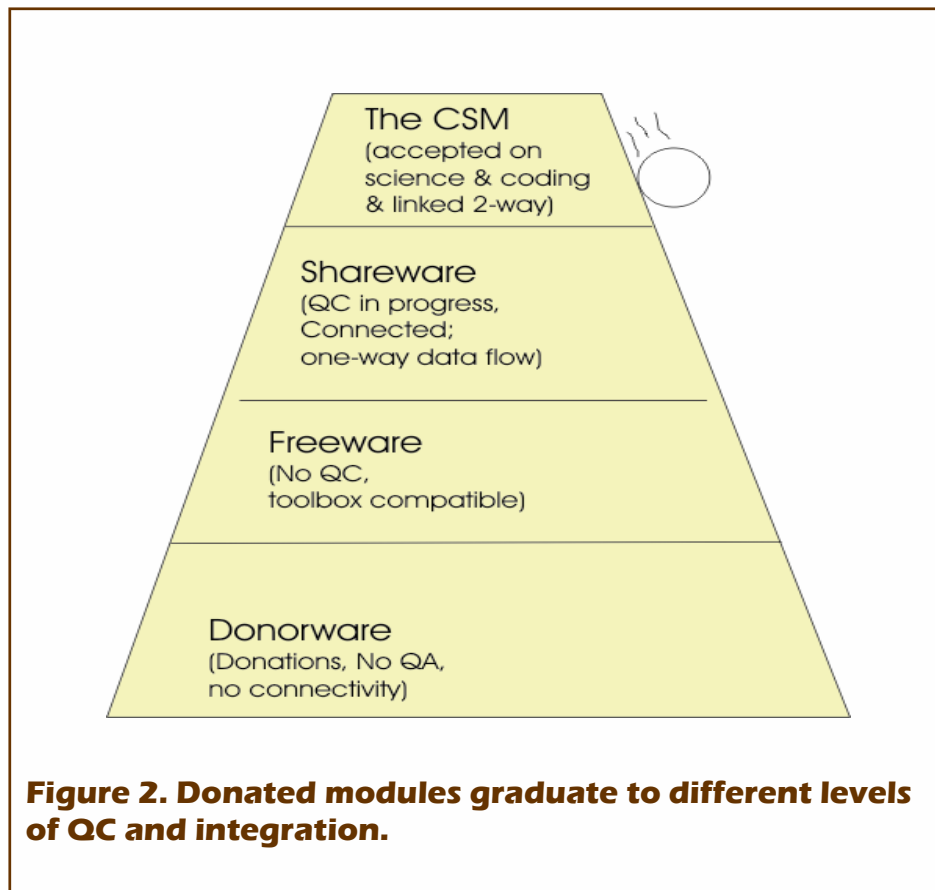


Figure 2. Donated modules graduate to different levels of QC and integration.

Technology groups

These groups cut across disciplinary science, and are primarily concerned with the technical-computational aspects of the CSDMS. They ensure that the modeling system functions properly and is accessible to users. Their charge includes software protocols and technology, and model standardization.

Crosscutting groups

Several of the groups will cut across

technologists responsible for keeping the system running, whereas distributed nodes should provide homes for working groups and support their functions.

THE NEXT STEPS

We stress that the greatest obstacle to predicting the behavior of the Earth's

will inevitably reflect the biases of those disciplines. But we see the CSDMS expanding in many directions from there. Most importantly, we see the influence of integration to come reflected now in the design of our modeling strategy. The watchwords will be modularity, flexibility, and expandability. By this we mean that modules will be structured to allow for inclusion of neglected processes or connections as smoothly and cleanly as possible. For example, perhaps for a variety of reasons a first-pass hillslope evolution module cannot explicitly include vegetation effects. The goal will be to design the module so that such effects could readily be added in the future.

As pointed out above, integrated modeling is more advanced in some of our sister sciences, including hydrology (e.g. MODFLOW), glaciology (e.g. EIS-MINT), oceanography (e.g. Modular Ocean Model), and atmospheric science (e.g. NCAR Community Climate Model). We are taking advantage of our later start by learning all we can about community model development from colleagues with experience with these model packages. The communication we began in the 2002 workshop will be continued with ongoing contact and advice from our colleagues in allied fields.

Objectives and deliverables

This report is intended to provide a blueprint for the first five to ten years of what we hope will be an ongoing project. We believe it is crucial that the scientific community realize benefits from CSDMS within the first five years of the project. The linked models should be applied to answer important scientific questions that are intractable with individual modules. The applications must address national needs. Indeed, one of the initial avenues for

broad community involvement should be to develop a list of "grand challenge" problems for CSDMS.

Objectives: first five years

- Develop a functioning management structure. This is to address unresolved core issues such as computing platforms, protocols, and refining the roles of working groups.
- Develop protocols for linking modules.
- Define common data structures and interfaces to link transport processes.
- Incorporate and standardize "legacy code" from the modeling community.
- Develop communication tools such as web sites and forums through professional societies.
- Develop and make available the first toolkits for pre- and post-processing, and model visualization.
- Develop standards for benchmarking and testing modules with the setup of standardized data sets.
- Develop and make available the first set of standard computational tools, including low-level routines (I/O error handling and data exchange); as well as grid generators and PDE/flux solvers.
- Develop and make available the initial graphical user interface (GUI) and documentation.

Objectives: first ten years

Our objective in ten years is to provide a fully functioning, tested, and internally consistent CSDMS with capability of addressing practical as well as research problems in surface-process science across a range of time scales from human to geologic time scales. We expect that in ten years we could largely eliminate "legacy" code and have a system written from the ground

up to work in the CSDMS framework.

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APPENDIX I

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APPENDIX II

A COMPILATION OF CURRENT ALLIED MODELS

ATMOSPHERIC AND CLIMATE MODELS

The atmospheric science community is the progenitor of earth system modelers. The advanced stage of this community reflects the immediate practical need for weather forecasting in all of its manifestations, and the concern for heating up of the atmosphere due to the greenhouse effect. The trade-offs in atmospheric modeling are between the need and use of very powerful computers and the application of less complex models. Weather forecasts models like the Univ. of Michigan's CMF (Coupled Model Forecast) system provides one-week, two-week, four-week, and long lead forecasts. Weather models come in the following flavors:

- Short term models (ETA, NGM - Nested Grid Models, AVN - Aviation models, RUC - Rapid Update Cycle models);
- Medium range forecast models (MRF; ECMWF – the European Centre for Medium Range Weather Forecasting, UK-MET);
- Mesoscale and experimental models (MESO-ETA, MM5 –mesoscale weather model generation 5, MASS – Mesoscale Atmospheric Simulation System, WRF – Next generation weather research and forecast model);
- Regional models (RSM – Regional Spectral Models, RAMS – Regional Atmospheric Modeling System, ARPS – Advanced Regional Prediction System);
- Coupled and global prediction systems (NOGAPS - Navy Operational Global Atmospheric Prediction System, COAMPS – Coupled Ocean Atmosphere Mesoscale Prediction System, GEM – Canada's Global Environmental Multiscale Model, SEF – Canada's Global Spectral Model, IFS – EC Spectral Integrated Forecasting Systems)

Weather models have become so common, that there are few developed countries that do not operate such models for weather predictions. The advanced models all have assimilation schemes that allow new environmental data, from ground or remote (i.e. satellite, balloons, other platforms) observations, to work in tandem with the numerical predictions, to correct for the inevitable drift in model predictions over time. The most advanced models have been used in conjunction with a (NCEP) reanalysis of historical (last 40 years) observations to learn where model algorithms succeed and fail, and where observations are spatially biased.

The goal of climate modeling is to develop a complete set of climate sub-system models, each with their unique time scale range, a feature very much relevant to the advancement of a community sediment model. The Atmosphere sub-system models include processes that cover time scale of hours to days. The biosphere sub-system models include dynamics across months to decades or longer. The cyrosphere and the oceanic sub-system models include developments across days to centuries. Paleo climate models include dynamics that see the polar ice caps grow and shrink along with sea level across centuries to hundreds of thousands of years. The disparity in these time scales forces climate models to become modular or hierarchical in their form, with different manifestations employed depending on the nature of the scientific problem. For example the atmosphere with an oceanic mixed layer, the atmosphere with the global ocean, the ocean with carbon cycles, and even ice sheets with a simplified ocean-atmosphere model.

Climate models include 3D general circulation models (GCMs), coupled ocean-atmosphere models (AOMs), Energy Balance models (EBMs), and radiative-convective models. The primary goal of climate model is to investigate the sensitivity of climate to changes in the forcing functions (solar radiation, green house gases, trace elements, etc.). Atmospheric GCMs or AGCMs consist of a 3D representation of the atmosphere coupled to the land surface and the cyrosphere and is similar to that used for numerical weather prediction. An AGCM has to be provided with data for sea surface tempera-

ture and sea ice coverage. An AGCM coupled to a slab ocean predicts the sea surface temperatures, and the ocean transport is specified and remains constant for the model run. A coupled atmosphere-ocean general circulation model (AOGCM) is complex and attempts to provide a more complete suite of feedbacks between the circulation dynamics within the ocean and those within the atmosphere. Regional Climate Models (RCMs) take their regional boundary conditions from AOGCMs and local features, such as mountains, which are not well represented in the coarser resolution of global models.

With such a rich history of model development, the atmospheric community has begun to develop a number of Atmospheric Model Intercomparison Projects (AMIPs). The WCRP AMIP is a standard experimental protocol for global atmospheric general circulation models (AGCMs). It provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyze AGCMs in a systematic fashion, a process that serves to facilitate model improvement. Virtually the entire international climate modeling community has participated in this project since its inception in 1990. The ICRCCM III project is the Intercomparison of Radiation Codes in Climate Models Phase III. This is a typical example of how the atmospheric community comes together to share their expertise and code on 1D solar radiative transfer codes, especially those used in NWP and GCMs to interpret and handle unresolved clouds. PIRCS is a Project to Intercompare Regional Climate Simulations so as to provide a common framework for evaluating strengths and weaknesses of regional climate models and their component procedures through systematic, comparative simulations.

OCEAN MODELS

Oceanographers have largely recognized the difficulty in building a “universal” ocean model that can treat accurately phenomena on all spatial and temporal scales in the various ocean basins of the world. The limitation is computer size and CPU speed and an imperfect parameterization of the physical processes, such as turbulence. Ocean modeling efforts have diversified, some concerned with the turbulent surface boundary layers, some with continental shelves, and many with the meso-scale eddy-resolving circulation in a given part of, or a whole, ocean basin (considered state-of-the-art). Models that aim to give real-time nowcasts/forecasts have become coupled with real-time observations (i.e. satellite altimetry and IR sensing). Ocean models can be hydrodynamic, thermodynamic or both and designed to resolve estuaries, seas or whole oceans. Some of the models have a free surface, others simply the computation and have a rigid lid. The vertical degrees of freedom type models as fixed level, isopycnal, sigma-coordinate, reduced gravity-coordinate and semi-spectral. Models are typically typed as barotropic (vertical integration of currents) or baroclinic, depending on their handling of density variations. Further, each of the ocean models can be classified on how they handle boundary friction (such as with the sea floor), and how they are forced (such as the nature of the wind field). Model solutions include (1) both implicit and explicit schemes; (2) both profile (multi-level) and bulk (mixed layer –deep layer exchange) schemes; and (3) tidally-averaged and tide-forcing models.

List of Popular Ocean Models

[ACOM - Australian Community Ocean Model \(after MOM\)](#)

[ADCIRC – Advanced Hydrodynamic Circulation model for shelves, coasts and estuaries](#)

[BOM – Bergen Ocean multipurpose Model for shelf and coastal waters](#)

[BRIOS – AWI Ocean circulation and sea ice model](#)

[CCAR – Colorado Global Tidal Model](#)

[COHERNS - European multipurpose model for shelf and coastal waters](#)

[DieCAST - a 3D lake or ocean model from Sandia Labs](#)

[ECBILT/CLIO –Dutch atmosphere ocean general circulation model](#)

[ECOM-si - Estuarine, Coastal and Ocean Model \(semi-implicit\)](#)

[FMS = Flexible Modeling System from GFDL](#)

[HAMSOM - A 3D German - Spanish model.](#)

[HIM](#) – Hallberg Isopycnal Model
[HOPE](#) – Hamburg Ocean Primitive Model
[HYCOM](#) – Hybrid Coordinate Ocean Model from Miami
[MICOM](#) - Miami Isopycnic Coordinate Ocean Model
[MITgcm](#) – MIT general circulation model
[MIKE 3](#) - A 3D model from DHI
[MOM-GFDL](#) - Modular Ocean Model
[NCOM](#) - NCAR CSM (Climate System Model) Ocean Model
[NRLLSM](#) – Navy Research Laboratory global thermodynamic model
[PC TIDES](#) – rapidly relocatable tidal model
[POM](#) - Princeton Ocean Model (see TOMS)
[QUODDY](#) - A 3D finite element code from Dartmouth college
[QTCM](#) – Quasi-equilibrium Tropical Circulation Model
[ROMS](#) – Rutgers Regional Ocean Modeling System
[SCRUM](#) - S-Coordinates Rutgers University Model
[SEOM](#) – Spectral Element Ocean Model
[SHORECIRC](#) – nearshore circulation model
[SPEM](#) - S-coordinate Primitive Equation Model
[SWAN](#) – simulating waves nearshore
[TOMS](#) – Terrain Following Ocean Modeling System
[WAM](#) – 3rd generation Wave Action Model
[WW3](#) – Wave Watch III global next generation wave model

Many of these models have families with genealogical aspects to their extensive history. MOM, POM and TOMS are examples that can provide valuable insight to the CSDMS initiative. For example the GFDL Flexible Modeling System (FMS) is a software framework for supporting the efficient development, construction, execution, and scientific interpretation of atmospheric, oceanic and climate system models.

Code for most of these models is available through the web, although an extensive learning curve is needed to properly modify and even use these model systems. Often time the code comes with an extensive documentation of code implementation (e.g. Kantha and Clayson, 1998).

Along with the development of ocean models, has been supporting databases that are used for initialization and dynamical forcing. These include bathymetry, wind stress, and salinity and temperature climatology. Most of these database atlases are available on line to the public. Data assimilation systems include [OCEAN MVOI](#) (a 3D ocean multi-variate optimal interpolation system), [MODAS](#) (modular 3D ocean data assimilation system), and [HYCOM](#) a consortium for data assimilative ocean modeling.

A valuable aspect to the ocean modeling community is in the production and sharing of visualization products (stills and movies). These have become very popular with the K-12 community and college students. The best of the sites include government labs that have the infrastructure to produce these visualization tools (e.g. <http://vislab-www.nps.navy.mil/~braccio/mpeg.html>).

With such a rich history of model development, the ocean community has begun to develop a number of Ocean Model Intercomparison Projects (OMIPs). These include:

[AOMIP](#) (Arctic Ocean Model Intercomparison Project)
[CMIP](#) (Coupled Model Intercomparison Project)

[DYNAMO](#) (Dynamics of North Atlantic Models): Simulation and assimilation with high resolution models

[DAMEE-NAB](#) (Data Assimilation and Model Evaluation Experiments) - North Atlantic Basin

[DOME](#) (Dynamics of Overflow Mixing and Entrainment)

[OCMIP](#) (Ocean Carbon-Cycle Model Intercomparison Project)

As a result, knowledge is being rapidly gained on the fundamentals and on the quality and methods of data ingestion and model verification and uncertainty.

In summary there are several comprehensive ocean-modeling families that exist worldwide. The community is both large and mature. There already exist a number of overlapping projects that bring sediment transport and stratigraphic modelers together with the ocean modeling community.

COUPLED OCEAN-ATMOSPHERE AND OTHER EARTH SYSTEM MODELS

While ocean models and atmospheric models did not develop in complete isolation of one another, there was enough of a community jump to make this kind of interaction and system development a large undertaking. Here are a few of the key developments in this area.

CCM3 - The NCAR Community Climate Model is a stable, efficient, documented, state of the art atmospheric general circulation model designed for climate research on high-speed supercomputers and select upper-end workstations. The model is both developed by the community and is freely available from NCAR along with source code and documentation. CCM4 is in development and NCAR has provided the community with coding standards (i.e. <http://www.cgd.ucar.edu/cms/ccm4/codingstandard.shtml>)

CSIM - The NCAR **CSIM** Sea Ice Model includes active thermodynamic and dynamic processes. The model is driven by the heat, momentum, and freshwater fluxes provided at the upper and lower ice boundaries by the atmospheric and oceanic model components, respectively. CSIM, in turn, provides the appropriate boundary fluxes required by the atmosphere and ocean in the presence of ice.

CSM – Climate System Model with four component models (atmosphere - **CCM3**, land - **LMS**, ocean - **MOM**, sea-ice) coupled through a Flux Coupler (**FC**) that allows separate development of the components with unique spatial resolution and time step. Individual components can be created, modified, or replaced without necessitating code changes in other components. CSM components run as separate executables, communicate via message passing, and can be distributed among several computers. The FC controls the execution and time evolution of the complete CSM by controlling the exchange of information between the various components.

FMS - The Flexible Modeling System is a coordinated effort among all global modeling groups at GFDL to produce a shared modeling infrastructure that enhances communication while reducing redundant efforts among GFDL scientists. At present, the FMS includes two global atmospheric models, a large assortment of atmospheric physical parameterizations, a comprehensive atmosphere-ocean-land-ice coupler, and an array of support tools. Initial efforts to produce a new version of the Modular Ocean Model (MOM) that would build upon FMS tools are underway. The FMS is key to minimizing the stress of GFDL's anticipated transition to scalable parallel computer architectures by isolating parallel memory management and I/O issues in a few modules that are shared by all FMS components.

LSM – NCAR Land Surface Model can be used stand-alone or coupled to the global model (**CCM** or **CSM**) to investigate land surface physics. LSM examines biogeophysical and biogeochemical land-atmosphere interactions, especially the effects of land surfaces on climate and atmospheric chemistry. The model has several components including biogeophysics, the hydrological cycle, biogeochemistry, and dynamic vegetation.

PCM – NCAR/DOE Parallel Climate Model is similar to CSM but has been adapted to execute on scalable parallel computers with the goal of running long-duration simulations. Increases in spatial resolution also requires smaller time steps be taken for stability and accuracy, increasing the computational cost to simulate a specific period.

Global coupled ocean-atmosphere general circulation models are complex and thus the Ocean-Atmosphere communities have come together and developed intercomparison projects such as **CMIP** – the Coupled Model Intercomparison Project. CMIP began in 1995 under the auspices of the Working Group on Coupled Models (WGCM) of WCRP-CLIVAR. CMIP has received model output from the pre-industrial climate simulations ("control runs") and 1% per year increasing-CO₂ simulations of about 30 coupled GCMs. A recent phase of CMIP extends the database to include all output originally archived during model runs. **PMIP** – the Paleoclimate Modeling Intercomparison Project is the WCRP-CLIVAR equivalent for coupled models designed to produce simulations in the geological past. The PMIP experiments are designed to evaluate model sensitivity to climate forcing, Tropical Climates at 6 kyr and at 21 kyr BP, Extra-Tropics at 6 kyr and 21 kyr BP, Ocean Forcing At The Last Glacial Maximum, and Ice Sheet Mass Balance to study the impact of LGM boundary conditions on the simulated climates of the tropics.

A valuable aspect of the climate modeling community has been the development of educational images and movies from numerical simulations, such as the high resolution T170 simulations from the NCAR CCM (e.g. <http://www.scd.ucar.edu/vets/vg/CCM2T170/ccm2t170.html>)

RIVER MODELS

Modeling packages for analysis of river dynamics have largely been developed for solving engineering problems. Thus they tend to focus on short time scales and assume the topography is known. In North America, the US Army Corps of Engineers (US ACE) has been a leader in developing these models. In Europe, some of the principal groups include the Danish Hydraulics Institute, Delft GET NAME, and ETH Zurich. Well developed river models include:

- the HEC series from the U. S. Army Corps of Engineers;
- MIKE from the Danish Hydraulics Institute; and
- ETH, a series of river-evolution models developed at the Swiss Federal Institute of Technology, Zurich.

GLACIER AND ICE SHEET MODELS

The cryosphere is important in many ways in shaping the landscape, some direct and some indirect. This includes the impact of sea ice, permafrost, glaciers and ice sheets. Glacial dynamics modeling is farther along than morphodynamic or stratigraphic modeling. Glaciology is more traditionally viewed as being part of geophysical sciences, thus scientists from this field are typically well trained in computational science. The first generation of comprehensive ice sheet and glacier models is now coming into play.

EISMINT (European Ice Sheet Modeling INiTiative) Model Intercomparison activity has the objective to test and compare existing numerical ice-sheet, ice-shelf, and glacier models as they are run by several groups worldwide, in order to narrow down uncertainties and to enable participating groups to upgrade their own models. The groups [aims_{is}](#) to compare the performance of models under real-world situations and under much more challenging conditions. Areas of activity include the comparison of Greenland ice sheet models, Antarctic ice sheet models, ice-shelf models, tests involving thermomechanical coupling, and grounding-line treatments.

Other international programs include:

ACE - Antarctic Climate Evolution, focusing on long time scales (50My). It will make use of the sedimentary record, and any earthscape modeling effort that handles such processes may become relevant.

SCAR - Scientific Committee on Antarctic Research, an international effort, linking from sediment to climate.

IMAGES – high resolution marine records focusing on ice-rafted debris. Components include entrainment of sediment subglacially, transport of sediment within the ice to the calving front, generation of icebergs by calving, transport of icebergs in oceanic currents, and decay of the icebergs so that they discharge their sedimentary particles over the site of deposition.

Major issues in ice-sheet modeling is in the handling of iceberg calving, basal hydrology, basal flow with implications for ice stream dynamics. Advances in these subjects would have direct link to the modeling of sediment entrainment, transport and deposition from flowing ice. The basis of ice sheet modeling is continuum-mechanical models of ice deformation under gravity. There are several 3D models that resolve 3D velocity, temperature, stress fields and well as ice sheet thickness. These models can be solved in finite element or finite difference schemes at a 5 to 100 km resolution. Other approaches to modeling glacier flow exist, including flowline or planform models that permit higher resolution and in some cases, higher order dynamics.

Ice sheet models are generally successful with large scale areas and volumes such as Greenland or Antarctica. They can resolve the formation and destruction of ice sheet at the time scale of a glacial cycle. They are presently well integrated with climate and isostatic models. The community has considerable experience with intercomparisons and in establishing benchmarks.

Ice sheet model uncertainties include a full understanding or parameterization of ice rheology (complications include anisotropy, impurities, water content). Mass balance problems typically relate to the skill of the climate model employed, model resolution and how ablation is parameterized. Future advances in ice sheet modeling will be in capturing subglacial drainage, including storage and routing, developing non-deterministic approaches to iceberg calving, and modeling basal flow and ice streams at different scales and time. The Glaciological community is also working to improve 3D simulation of glacier flow across complex terrain.

It is worth emphasizing the degree to which glaciers have impacted continents, directly or indirectly. Where ice-sheets or glaciers have not overridden the landscape, the impacts are more subtle, but can be very large: (1) the glacially-derived loess blankets deposited across a large fraction of Europe, Asia, and North America; (2) the down-stream fluvial systems that deliver paraglacial pulses of sediment to the ocean; (3) the flexural isostatic response within some hundreds of km from the ice edge; and (4) the impact of the ice sheets on the atmospheric and thus ocean circulation. The influence of glaciers is therefore far-reaching.

HYDROLOGICAL MODELS

The hydrological community has developed as diverse groups of experts and academics, and these include geographers, geoscientists, environmental scientists, ecologists, civil and environmental engineers, and reservoir scientists. This diversity in training and expertise has also been mirrored in the how the community has developed their kitbag of tools and models. With so many small-scale environmental problems and societal needs that require nowcasts and forecasts, hydrological models are often packaged as commercial software, or poorly documented one-of-a-kind software. While some model intercomparison studies have occurred, the hydrological community still needs to come together as a community.

Hydrological models became an integral part of storm drainage planning and design in the mid-1970s. Several agencies undertook major software developments and these were soon supplemented by a plethora of proprietary models, many of which were simply variants on the originals. The proliferation of PCs in the 1990s has made it possible for most engineers to use state-of-the-art analytical technology for purposes ranging from analysis of individual pipes to comprehensive storm water management plans for entire cities. Hydrologic models are used to extend time series of flows, stages and quality parameters beyond the duration of measurements, from which statistical performance measures then may be derived. Often the models are used for design optimization and real-time control.

Rainfall is the driving force for all hydrologic simulation models. Continuous simulation or statistical methods offer alternatives to the use of pre-defined design rainfalls. For example, a selection of historic storms can be made from a continuous simulation on the basis of the return period of the runoff or quality parameter of interest, e.g., peak flow, maximum runoff volume, maximum stage, peak runoff load, peak runoff concentration. These events, with their antecedent conditions for runoff and quality, can then be analyzed in more detail in a single-event mode. Rainfall is variable in space as well as in time; some models can simulate storm motion and spatial variation that can strongly affect runoff.

Hydrologic, hydraulic, and water quality models can be classified either as *deterministic*, or *stochastic*, or *some combination of these two types*. Processes that are too complex or poorly understood to be modeled deterministically may be represented by statistical characteristics, while many statistical models also employ simple process-type mechanisms. Quantity models convert rainfall into runoff and perform flow routing. Quality models often begin with calibration and verification data. Public-domain software usually is produced by either government agencies, particularly in the USA, or academic institutions. Below is short list of commonly used models:

- [BASINS](#) – EPA multipurpose environmental analysis system
- [QUAL2E](#) – EPA Enhanced stream water quality model
- [ROB RAFTS](#) – Australian rainfall-runoff and streamflow routing models
- [HEC](#) – US ACE surface runoff model suite
- [SWMM](#) – EPA Storm Water Management Model
- [IDRO](#) – Italian rainfall-runoff and storm-forecasting model
- [IRIS](#) – Cornell U. Interactive River System Simulation program
- [WORRS](#) – US ACE Water Quality for River-Reservoir System
- [TOPMODEL](#) – hillslope hydrology simulator
- [HydroTrend](#) – Colorado U. climate-driven sediment discharge simulator
- [WEPP](#) – DOA Water Erosion Prediction Project model
- [MODFLOW](#) – USGS groundwater model (see details below)
- [ANSWERS 2000](#) – Virginia Tech Areal Nonpoint Source Watershed Environment Response Simulation
- [FHANTM](#) – U. Florida Field Hydrologic And Nutrient Transport Model
- [FEFLOW](#) – Finite element multipurpose groundwater model
- [MIKE 11](#) – River flow simulation model with data assimilation
- [WATFLOOD](#) – Canadian integrated models to forecast watershed flows

There is one hydrological software package that deserves attention as we go forward with the development of a Community Sediment Model: the U.S. Geological Survey Modular Ground-Water Flow Model ([MODFLOW](#)). [MODFLOW](#) was developed in the 1970's to handle 3D, transient groundwater dynamics. It was an effort to reduce redundancy so efforts by the community would be more productive. By the 1980's MODFLOW external users exceeded use within the USGS. By the commercial efforts start building up around MODFLOW, although the latest release, MODFLOW-2000, can be downloaded free from the USGS. During the 1999-2000 period, 23,000 copies were downloaded from the web. Lessons learned from the effort (after M. Hill, 2002):

- Only modular, carefully programmed, well-documented software can form a foundation for good future science.
- Achieving this takes substantial extra time.
- Arranging for this extra effort to be rewarded is very important and can be very difficult.
- Some of those involved also need to publish white literature to stay current and avoid isolation.
- Need a 'keeper of the code' who keeps things modular. This person's edicts can seem burdensome and petty, but if done well is worth the aggravation. It's very important to support this person because they will get hassled a lot.
- Such a program can provide a superhighway for researchers to get their ideas used
- Contributions from many types of efforts can be invested instead of lost

There are many international programs that promote large-scale hydrological modeling and experiments. The World Meteorological Organization's World Climate Research Program offers the Global Water and Energy Experiment (GEWEX). This program couples studies of land-atmosphere and databases for regional and global modeling. The Inter-

national Geosphere-Biosphere Program offers the Biospheric Aspects of the Hydrological Cycle (BAHC) that is designed to enhance land surface-atmosphere transfer schemes. The Global Runoff Data Center (GRDC) housed in WMO-GRDC, Federal Institute of Hydrology, Koblenz, Germany offers the world's largest storehouse of global runoff data. Individual countries also provide national data repositories (e.g. U.S.G.S., Water Survey of Canada, etc.).

LITHOSPHERE MODELS

Lithospheric models have direct links to morphodynamic and stratigraphic models via tectonic forcing of landscapes and basins at long time scales. Present models are the products of individuals or small research groups, so there are many models of modest size and scope but few comprehensive ones. Lithospheric models come in three flavors: (1) thermal models where a heat source drives hydrothermal (plastic, viscous) circulation within the lithosphere; (2) mechanical models, where motion is prescribed and material is deformed either through fracturing or faulting; and (3) thermomechanical models where the two processes are combined to understand the plate motion or mountain building episodes. Lithospheric models are typically developed to study singular environments, such as the oceanic lithosphere, the continental lithosphere, hot-spots, subduction zones, extensional environments, thermal blanketing, underplating, and the development of passive margins. Lithospheric models are used to study of earthquake seismology, geodynamics, modern tectonics, geothermics, and the development of continental margins. Some of the models are commercial (e.g. [ANSYS](#) – coupled thermomechanical finite element software). Most of the models are unnamed and exist in poorly documented and primitive states within the academic community.

Examples of simple half-graben models (Schlische, 1991) include extensional basin or continental filling models that can be separated into detachment fault models, domino-style fault block models, and fault growth models. Other simplified models include force balance models (Mountney and Westbrook, 1997), and fold and thrust models (Stuart et al., 1998). More advanced lithospheric models include stretching and subsidence models, and fault movement models (Dehler et al., 1997; Voorde et al., 1997). Below is an assortment of academic models:

[Zscape](#) – landscape evolution model (tectonics + surface processes)

[CITCOM](#) – 2D finite element model of mantle dynamics

[FISR](#) – Forward and Inverse Strain Rate model

[FGM](#) – Edinburgh Fault Growth Model

[FCM](#) – Dutch Frontal Convergence Model

CSDMS STARTING POINTS

The CSDMS project is not starting from scratch. Morphodynamic modeling is best developed in the arena of fluvial systems and the coastal ocean. There are a number of landscape models that simulate evolution in topography with time; these are mainly aimed at erosional systems (Beaumont et al., 1992, Tucker and Slingerland, 1994; Ellis et al., 1999). Existing models for surface dynamics that will provide a point of departure for CSDMS development include:

[CASCADE](#) – Australian surface process model

[SEQUENCE](#) – LDEO stratigraphic continental margin model

[SedFlux](#) – INSTAAR modular continental margin model

[SEDPACK](#) – USC geometric continental margin model

[SEDSIM](#) – Stanford sedimentary facies model

[NOPP nearshore model](#)

[NCSTM](#) Coastal Community Sediment Transport Model

[NCSTM](#) the National Community Sediment Transport Model initiative (NOPP, USGS) is promoting the development of an open-source numerical model for sediment-transport in coastal regions (Sherwood et al., 2000). The NCSTM initiative provides a forum for collaboration between U.S. federal agencies, academic institutions, and private industry, with the goal

of adopting and/or developing one or more models for use as scientific tools by the research community working on coastal issues.