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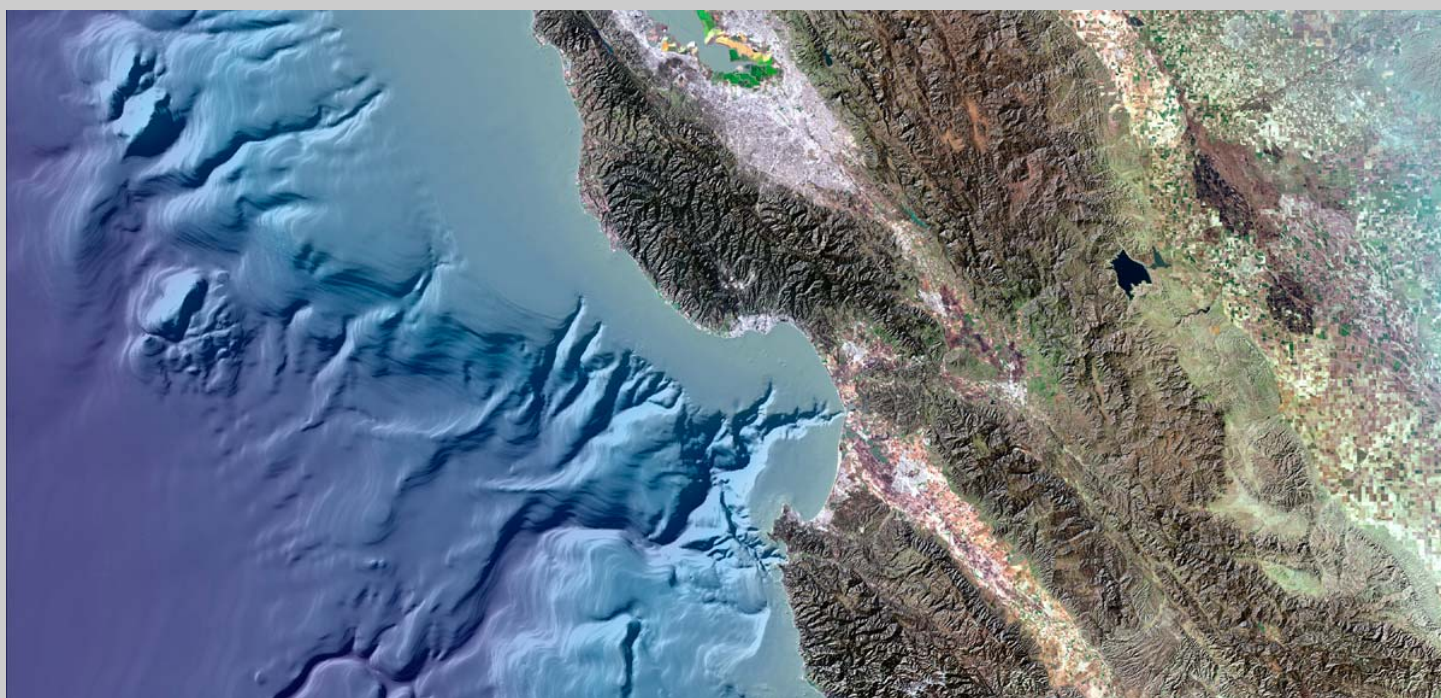
Community Surface Dynamics Modeling System (CSDMS)
Science Plan

CSDMS Working Group

with contributions from participants in NSF Workshops in Boulder, CO (February 2002) and Minneapolis, MN (May 2004)

A Report to the National Science Foundation

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CSDMS Science Plan Writing Group (alphabetical order):

Robert S. Anderson (University of Colorado)

William E. Dietrich (University of California, Berkeley)

David Furbish (Vanderbilt University)

Dan Hanes (US Geological Survey Coastal and Marine Geology Program)

Alan Howard (University of Virginia)

Chris Paola (University of Minnesota)

Jon Pelletier (University of Arizona)

Rudy Slingerland (Pennsylvania State University)

Bob Stallard (US Geological Survey)

James Syvitski (University of Colorado)

Charles Vörösmarty (University of New Hampshire)

Patricia Wiberg (University of Virginia)

Cover Illustration: Terrestrial and submarine topography of the San Francisco Bay area (image by Benjamin L. Sleeter, USGS)

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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 inter-woven physical, biological, and chemical systems, is the setting for most life and human activity. People tend to think of the surface as relatively static. But in reality, our planet's surface is dynamic in ways that parallel the more familiar dynamism of the atmosphere or the oceans. Environmental forecasting and responsible resource management on and under Earth's dynamic surface require predictive tools comparable to those routinely applied to the atmosphere and oceans. Today's fragmented and often qualitative understanding of surface-process science is retarding progress towards this goal.

To address this state of affairs, some eighty scientists have participated in two NSF-sponsored workshops in 2002 and 2004 (see Appendices I and II for lists of participants). The central recommendation of these workshops is that:

Our science community move toward creating a unified, predictive science of surface processes by investing in the development of a *Community Surface-Dynamics Modeling System* (CSDMS). CSDMS is envisioned as a modeling environment containing a community-built, freely available suite of integrated, ever-improving software modules aimed at predicting the erosion, 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 Earth-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.

Scientific Challenges

The "Critical Zone" — essentially the active soil, rock, and sediment layer that forms the Earth's surface — has been singled out as a focus area for intensive research in the Earth sciences. The CSDMS effort would be at the heart of an integrated, quantitative approach to understanding the Critical Zone. Six fundamental scientific questions form the core research that CSDMS would address:

1. What are the *fluxes, reservoirs, and flow paths* associated with the physical, biological, and chemical transport processes in the Critical Zone? How do these depend on substrate properties like morphology, geology, and ecology, and on human activities?
2. What processes lead to *self-organization and pattern formation* in surface systems? How do self-organized patterns mediate surface fluxes and evolution?
3. How do material fluxes and surface evolution vary across *time and space scales*?
4. How are *physical and biological* processes coupled in surface systems?

5. How is the *history of surface evolution* recorded in surface morphology and physical, chemical, and biological stratigraphic records?
6. How do *linked surface environments* communicate with one another across their dynamic boundaries? How do changes in one part of the global surface system affect other parts?
7. How does the Critical Zone couple to the tectosphere, atmosphere, hydrosphere, cryosphere, and biosphere and serve as the *dynamic interface* among them?

Societal Applications

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. Such a framework helps to formalize knowledge, initiate a dialog across disciplines, and so move our science forward. An emphasis on the interface of existing disciplines is at the heart of the CSDMS effort.

Recommendations

We recommend that:

(1) NSF together with other interested agencies and industrial partners establish an initiative called the *Community Surface-Dynamics Modeling System* (CSDMS).

(2) CSDMS be developed as 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 over a variety of environments and space and time scales.

(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 coordinate community 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) Mechanisms be established to obtain continuing community input and involvement in CSDMS, as described in the accompanying Implementation Plan.

(8) CSDMS support education of the next generation of quantitative Earth scientists through education programs that make CSDMS tools accessible to students, especially at the undergraduate level.

(9) CSDMS distribute results and support broad applications and public awareness through outreach efforts to allied research communities, policymakers, educators, and the general public.

CSDMS would be a virtual numerical laboratory existing in each of our computers. The scientific ideas contained within are never out of date because they are continuously updated 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 by allowing non-specialist users to use pre-packaged models and assemble modules in a user-friendly, graphical environment, allowing users to focus on science and engineering rather than programming details.

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

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 a kind of "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. *Responsible 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 a 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 thought of 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. *Responsible 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 have learned much about the myriad 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 surface-process research:

1. Surface-process research 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.*

2. The state of understanding of critical surface processes is very uneven. In many areas, it is only qualitative, and inadequate for predictive modeling. 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

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 develop a comprehensive approach to Earth-surface systems like the Mississippi that span a range of environments and spatial scales.

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 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?

We can do better by developing 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 the scientific basis for developing an

integrated system for surface-process modeling through an initiative called the Community Surface-Dynamics Modeling System: CSDMS. The companion to this report presents a plan for implementing and running the

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

WHY IS CSDMS THE RIGHT PROJECT?

CSDMS program.

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 [*e. g.,* Wolfram, 2002]. 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

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

WHY A "COMMUNITY MODEL"?

variety of disciplines express their ideas in a precise, consistent format.

Because a comprehensive modeling of Earth-surface dynamics requires community input

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

One of the main application products of CSDMS will be 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 technical skills 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 security 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** by helping us understand the intimate connection between the surface and the fabric of life within and upon it. Major application areas would include land-use planning, forest management, waste disposal, habitat protection, management of scenic recreational areas, and river and coastline restoration.

Gully erosion, SW United States

Another major CSDMS environmental application area is that of climate change and other global change areas with direct societal impact. Scientific assessment support for environmental policy, such as that provided by the Intergovernmental Panel on Climate Change (IPCC) would greatly benefit from new insight into the reciprocal interaction of atmospheric, oceanic, and Earth-surface processes. In addition, UN Conventions on desertification, wetlands (RAMSAR), and biodiversity all have strong linkages to land-surface dynamics and so would benefit from CSDMS and the integrative, predictive approach it embodies.

Finally, although **terrestrial surveillance** *per se* is mainly a matter of observation, modeling is an attractive alternative where the desired data are fragmentary or 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 by understanding its past and predicting its 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 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. Finally, NSF has recently funded a new Science and Technology Center called the National Center for Earth-surface Dynamics (NCED), which promotes an integrated, quantitative approach to 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 a collaborative modeling effort referred to informally as the "Community Sediment Model". This realization led to two workshops (Boulder, Colorado in February, 2002, and Minneapolis, Minnesota in May, 2004), sponsored by the National Science Foundation. This report is an outgrowth and summary of those workshops.

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 incorporated 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;

- adaptive mesh-generation techniques for problems requiring variable spatial resolution; and

- new methods for handling problems with internal boundaries, which include boundaries between surface 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.

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).

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

Developing the CSDMS as envisioned, will be a large, complex task. The details of realizing the CSDMS are presented in the Implementation Plan. With adequate and coordinated funding, we expect the first tools to appear within a year, and the first generation system to be up and running in less than five years. The development of a 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.

We cannot overstress that the "community" in CSDMS is not just a word but the core of the CSDMS vision. CSDMS cannot succeed without broad, consistent community participation. This extends from researchers and developers who will contribute algorithms and code to application specialists who will use it, test it, and keep the program grounded in reality. The two workshops on which this report is based involved nearly 100 participants from a range of disciplines and including academia, government, and industry. Both groups offered enthusiastic support for CSDMS, along with many of the ideas in this and the companion report. We take this as a good start; these workshops represent kind of

broad participation that we need if the CSDMS project is to succeed. The CSDMS organizers intend to insure continued community involvement by offering an variety of ways to participate in CSDMS: workshops and working groups; focus sessions at major meetings representing the full range of CSDMS communities; participation in CSDMS disciplinary groups and committees; and a clear, consistent system for incorporating community-generated algorithms and modules into the CSDMS structure.

We stress that for the foreseeable future, funding for CSDMS is expected to be limited to direct support for the National Center. The role of the National Center is primarily organization and support. The scientific cutting edge will be the researchers who study the processes and develop the modeling techniques that will make CSDMS work.

TABLE 2

CHALLENGE	RESPONSE
CSDMS will be perceived as a "closed shop"	Encourage community participation via workshops, town halls and sessions at major meetings; provide clear and consistent methods for contributing and using code; and maintain an open, participatory management structure
CSDMS involves a multiplicity of fields, scales, interests, and applications	Emphasize flexibility, adaptability, and modularity
CSDMS modules and models must be tested against data	Maintain close ties with application specialists and field and experimental programs; insist that both individual modules and integrated models be tested under a wide range of conditions
CSDMS should not stifle individual creativity	Provide a suite of tools ranging from basic support (e.g. graphics, pre- and post-processing) through fully worked out simulators, to allow users to interact with CSDMS in a variety of ways
Important aspects of surface processes are still not well understood	Avoid "locking in" to a particular approach or algorithm. Link with laboratories and research groups worldwide to incorporate new insights into critical processes
CSDMS will be large and complex to manage	Provide for a centralized facility to manage CSDMS development. Learn from experienced colleagues in other fields (e.g. atmospheric science)
CSDMS must deliver useful products in a timely manner	Start by adapting existing code to a common framework with community managed protocols

This research will be carried out and supported as it has always been: in the community, via standard research grants.

Another key issue for CSDMS centers on testing its predictions against data. The size, complexity, and generally slow evolution of the surface system guarantee that it is easier to generate computer models of it than the data to test them. The answer to this is to make sure that CSDMS evolves in close collaboration with data-collection efforts. We believe that CSDMS can play an important role in helping structure observational programs. CSDMS simulations can help locate gaps in our understanding, and CSDMS predictions can suggest specific targets for experiments in the field and laboratory. We believe that CSDMS can help bring about a new era of quantitative, analytical field and experimental studies in surface dynamics.

The main challenges and our responses to them are summarized in Table 2.

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 by proposing a set of challenge problems that would serve to guide and illustrate the power of CSDMS. Plans for implementing the CSDMS are presented in a separate report. 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 existing models and algorithms 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 The Science of CSDMS

CSDMS will provide the core modeling framework for understanding and predicting the dynamics of the "Critical Zone" (Box). The following fundamental scientific questions will form the foundation of CSDMS:

What are the *fluxes, reservoirs, and flow paths* associated with the physical, biological, and chemical transport processes in the Critical Zone? How do these depend on substrate properties like morphology, geology, and ecology, and on human activities?

Transport in the critical zone involves both particulate matter and solutes. These are produced into the surface environment by weathering. Particulate matter includes both mineral sediments, primarily quartz, feldspar, and clay minerals, and critical geochemical actors such as carbon and nitrogen. Solutes include carbon, nitrogen, and phosphorus. Both particulate and dissolved phases alternate intervals of storage in reservoirs and active transport as they make their way through the surface system.

Flow and storage of both particulate and dissolved phases influence life. Substrate stability and character are primary controls on habitat suitability, while plants and animals are primary actors in both stabilizing (e.g. binding and flow-baffling) and destabilizing (by mixing and bioturbation) of sediment surfaces. A major emerging area of sediment-biota interaction involves microorganisms, whose myriad roles are being clarified by increasingly sophisticated microbiological techniques. The issue of physical-biological coupling is addressed in more detail later in this section.

What is the "Critical Zone"?

The "Critical Zone" is defined as "the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources." The NAS BROES report from which this quote was taken identified the Critical Zone as one of six major focus areas for Earth sciences research in the 21st century.

What processes lead to *self-organization and pattern formation* in surface systems? How do self-organized patterns mediate surface fluxes and evolution?

Self-organization refers to the spontaneous formation of spatial and/or temporal patterns that reflect the system's internal dynamics as opposed to being imposed externally. For example, most river basins show a dendritic channel pattern in which small headwater channels successively merge down the basin, eventually producing a single large channel that carries water and sediment out of the basin. This spatial pattern, which influences biological, chemical, and physical processes within the basin, Though the pattern may adjust locally to accommodate externally imposed structure (faults and fractures, lithologic variability), its overall structure arises from self-organization of the processes of erosion and channelization.

A kaleidoscope of more or less regular forms including ripples, dunes, bars, furrows, mudwaves, and spaced erosional scours decorate the floors of the Earth's rivers, oceans, and deserts. The apparently spontaneous appearance of these beautiful and enigmatic forms has long attracted the attention of researchers, but only limited progress has been made in understanding their origin. The traditional approach has been via linear stability analysis, employing techniques similar to those used to study pattern formation in, for example, fluid mechanics. More recently, a variety of cellular techniques has been used to allow for spontaneous pattern formation. Development of models capable of handling the spontaneous formation of complex patterns is a forefront research problem, and CSDMS must be flexible enough to handle emerging new approaches to it. In addition, spontaneously developed spatial structures can strongly mediate sediment and water fluxes by storing and releasing sediment and changing bottom roughness. Thus pattern formation below grid resolution will have to be accounted for in paratmeterizing larger-scale CSDMS models.

How do material fluxes and surface evolution vary across *time and space scales*?

Spatially, critical-zone dynamics span the scale range from atomic to conti-

Table 1: 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.

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.

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.

Interwoven biology, chemistry, and human dynamics To progress as quickly as possible, CSDMS must begin with existing models, which emphasize physical processes. But the intimate connection among physical, biological, and chemical processes must be accounted for in program design. Moreover, it is now clear that human influence is comparable in magnitude to natural processes in shaping the Earth's surface (Hooke, 2000). From the start, CSDMS must be multidisciplinary and integrative, where we have less experience as a community. The next generation of researchers will be trained in a new style of working; in this sense they will be learning alongside their teachers.

nental; in time, from fractions of a second to billions of years. This extreme range of space and time scales demands an array of approaches rather than a single monolithic structure. CSDMS will use as its point of departure techniques developed in the atmospheric and marine sciences communities which also deal with a wide range of length and time scales. The most direct approach is simply to develop models at different scales, with length and time scales generally increasing together. At each scale, proc-

esses below the resolution of the model are parameterized in some way, much as ensembles of complex particle dynamics are parameterized by bulk diffusion coefficients.

A more sophisticated approach is to use nested models, in which large-scale models using coarse grids interact with finer-scale models with shorter time steps that in effect run within subdomains or single grid cells of the larger model. In the simplest version, the large-scale model simply provides

boundary and initial conditions for the smaller-scale model. In more sophisticated schemes, the output of the smaller-scale model feeds back to the larger scales as well.

A new set of tools of great potential power in spanning wide scale ranges in surface modelinig is based on the widespread occurrence of self-similarity and other forms of systematic behavior across scales. These include the similarity across ranges of spatial scales embodied in the science of fractals, and

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
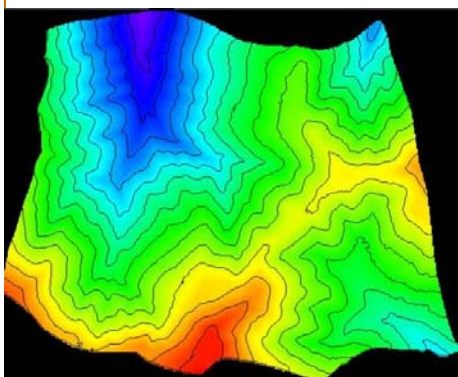

Figure 1. Topographic Map of Coos Bay, OR, area based on 2-m horizontal resolution LIDAR data; total east-west distance is 425 m, contour interval is 20 m.

sets. For example, what is the emergent behavior at coarse resolution of physicochemical processes operating at fine resolution?

For diffuse transport operating at meter scales, the horizontal length scale associated with topographic curvature sets an upper

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

limit on the grid size that contains meaningful dynamical 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
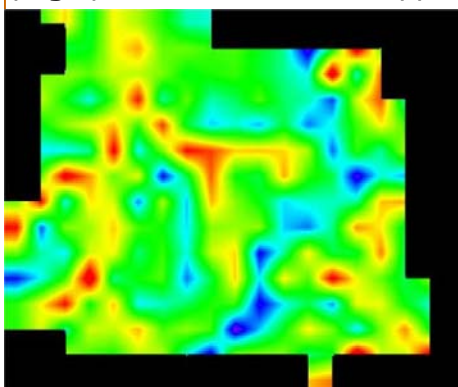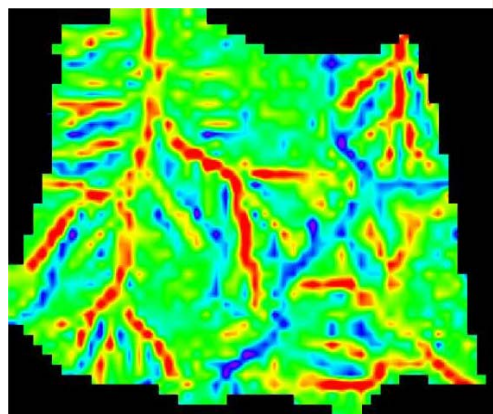

Figure 3. Map of topographic curvature based on 40 m resolution data.

resolution. Thus, a key challenge is to elucidate how to model sub-grid scale processes like diffuse transport that manifest themselves at coarser scales.

more general behaviors like power   laws and other forms of systematic

scale dependency.

How are *physical and biological processes coupled in surface systems?*

One of the most important areas of research in which the CSDMS effort will play a key role centers on problems in ecology involving the spatiotemporal dynamics of organisms whose behaviors are fundamentally connected to the abiotic parts of their environment. Key, collaborative research areas where advances and innovations will require perspectives of both ecology and surface-dynamics science include predicting the response of critical coastal areas to rising sea level, and the increasingly important, applied research area of river restoration.

Understanding the dynamics of organisms is challenging because of the many scales of organization — from the level of individual organisms, to populations, to communities to ecosystems — over which important operative processes simultaneously operate, and must be coupled. Virtually all organisms, moreover, are members of environments that are spatiotemporally heterogeneous, exhibiting varying degrees of aggregation and "patchiness" with respect to key biotic and abiotic elements, notably substrate habitability and resource availability. To find and use resources, behavior can involve a wide range of strategies whose efficacy depends on the patchiness and connectivity of the resources, as well as by biomechanical constraints on rates of motion and sensory input during foraging. Thus, understanding organism behavior (e.g. foraging strategies) requires understanding how this behavior is influenced by the distribution of resources; in turn, understanding the spatiotemporal structure of resources requires gaining a sense of how the organisms exploit them.

For some ecological phenomena the

Self-organization at work: eolian sand dunes, Namibia

physicochemical template serves mostly as a passive substrate for the ecological play that unfolds on it. In contrast, numerous systems exist where the biotic and abiotic parts are strongly interconnected, such that the ecological structure and function, and the physical template, co-evolve. A classic example is the bioturbation of sediments, in which the physical and chemical characteristics of the sediment influence the type and behavior of biota that burrow within them for food or safety and, in turn, this biological behavior and associated biogeochemical processes fundamentally alter the physical and chemical structure (e.g. porosity, organic carbon content) of the sediments. Similarly, biomechanically and biogeochemically induced weathering of rock materials (in concert with hydro-geochemical processes), together with bioturbation, fundamentally represent a biotic-abiotic dynamic wherein the relative importance of roles of the two parts is equal. The biology does the stirring/mixing of the physical template (soil); in turn the soil structure provides a suitable substrate for the biology. Indeed, semiempirical treatments of part of this dynamic underlie recent, significant advances in our understanding of the larger-scale dynamics of soil-mantled hillslopes undergoing biomechanically driven soil production and transport ("creep").

Particularly important unsolved problems in ecology — focusing on the spatiotemporal dynamics of organisms and trophic structure — center on aquatic ecology in riverine, estuarine and coastal settings. Here the physical template consists of: (i) the working fluid (water) containing inorganic and organic sediments, nutrients, and dissolved constituents; (ii) the structure, morphology and geochemistry of the fluid-sediment interface, whether this involves channels, floodplains or tidal flats; and (iii) external forcing imposed on this template, whether it be thermal loading, or fluxes of water, sediment and nutrients across boundaries. How, then, does the biological play unfold in these heterogeneous, patchy environments? How does the spatiotemporal structure of the physical template influence biotic behavior and, in turn, how might biological organization at all levels influence the physical template? In these settings, organismic strategies for obtaining resources and habitable substrate now strongly depend on the working fluid and external forcing, as these mechanically and geochemically organize habitant, and (re)distribute resources, including organisms that are intermittently transported passively with flows.

For example, important coastal environments such as salt marshes and muddy shorelines are still in early stages of analysis. How do, for example, plant growth, nutrient flow, and mud trapping converge to create salt marshes? And, once formed, how stable are they, and to what extent can they "bend but not break" in the face of rising sea level? CSDMS will provide a framework for coupling the marine and terrestrial sides of the coastal complex, seamlessly integrating physical processes like wave, tidal, and fluvial sediment dynamics with biological processes and nutrient flow in critical habitats like salt marshes.

How is the *history of surface evolution* recorded in surface morphology and physical, chemical, and biological stratigraphic records?

Traditionally, the study of surface processes has been pursued separately on human and geologic time scales. Since the founding of modern geology by Hutton and Lyell, the assumption has been that one can understand ancient systems by studying modern ones — not the other way around. Yet Earth-surface dynamics plays itself out on time scales that usually are too slow to allow for routine observation of system evolution. Nonetheless, "slow" geologic processes control important boundary conditions that influence overall sediment supply and surface elevation. And, especially as we understand the full extent of human influence on the surface environment, we see that we must use geologic records to understand the full dynamic range of Earth-surface behavior. Thus the past can teach us about the present. The challenge involves combining and using to best advantage archived information from the full available range of time scales. The merging of insight

over geologic and human time scales will be a new frontier in surface dynamics, just as it is in, for example, atmospheric dynamics as global climate models and geologic climate proxies are played off against one another to learn how the climate system works. CSDMS will be help bring this about by providing a common framework for modeling over the full range of relevant time scales.

How, then, is the history of surface evolution archived in surface morphology and in physical, chemical, and biological stratigraphic records? Some four billion years of Earth history, including the evolution of life and the atmospheric, oceanic, hydrologic, glacial, and tectonic systems, are recorded in the stratigraphic record. This archive records, among other things, alternative states of the surface system (e.g. greenhouse climatic periods, glacial-interglacial intervals, "snowball" Earth) and rare events (e.g. extreme floods and storms, meteorite impacts). These 'alternative Earths' provide information on the variability of the surface system, give context to short-term observations, and allow us to test surface dynamics models under a the full range of planetary conditions. Sedimentary deposits also host crucial water and hydrocarbon reservoirs. Their economic value has prompted the acquisition of billions of dollars of seismic and other subsurface data in sedimentary basins. This data, slowly making its way into the open research community, forms a repository of information that will be invaluable in evaluating CSDMS depositional-system models.

Erosional landscapes, in contrast, archive information about surface evolution in the geometry of landforms (e.g. spatial arrangement and magnitudes of hillslope gradients and curvature), and in the dynamic stratigraphy represented by soils and rock regolith. For example, incised channels and knickpoints, specifically their arrangement within drainage networks, contain information about changes in rates of channel incision related to, for example, changes in rates of tectonic mo-

Human surface dynamics

One of the most remarkable developments in geomorphology in recent years has been the realization of the extent and magnitude of human impact on the Earth-surface environment. This is manifested, for example, in pulses of sediment delivery to rivers associated with the spread of modern agriculture and in the suppression of sediment delivery to deltas due to damming, with associated land loss. The most striking summary analysis of human impact is that of Hooke (2000) who concluded that the total volumetric turnover by human activity (farming, construction, etc.) is now comparable to that by natural processes globally.

These developments have an interesting parallel in atmospheric sciences, where new (and still controversial) research suggests that humans may have significantly influenced atmospheric composition and global temperature since the spread of farming some 8000 years ago (Ruddiman, 2003).

As great as the challenge of integrating chemical and biological processes into Earth-surface models is, that of including human effects is greater still. Human dynamics does not fit comfortably into the model frameworks that physical scientists typically use to represent systems. There is no quick fix here, but we can make sure that as techniques for including human effects are developed, CSDMS will be ready to accommodate them. CSDMS science working groups will include social scientists as appropriate. Furthermore, the CSDMS steering committee will include representatives from key social sciences (economics, policy and decision-making) who can help us keep CSDMS open to inclusion of human effects and insure that CSDMS tools will be useful to policy makers and others who can influence human activity.

tion, or changes in climate, vegetation cover or land use. Yet many landforms whose dynamics and history we wish to understand evolve too slowly to directly measure their rates of change, so extracting basic kinematic information from these landforms to test dynamical models aimed at describing their geomorphic behavior is problematical. CSDMS, together with emerging field techniques (e.g. the use of cosmogenic isotopes to constrain geomorphic erosion and transport rates), will provide a computational laboratory for assimilating a variety of field and remote-sensing (e.g. DEM) data to extract dynamical and historical information about erosional landscapes.

How do *linked surface environments* communicate with one another across their dynamic boundaries? How do changes in one part of the global surface system affect other parts?

The land-ocean interface (the coastal zone and adjoining shallow ocean) is the most dramatic example of a boundary between major transport environments. This crucial region, home to a disproportionate share of the world's human population, resources, and infrastructure, is a highly dynamic interface that has shifted by hundreds of kilometers over geologic time. At any time and place, the location of the shoreline reflects a subtle balance among terrestrial and marine proc-

esses. Low-lying coastal areas are vulnerable to even slight changes in sea level, making an understanding of coastal dynamics especially critical as the global warming debate progresses.

The land-ocean interface is only the most obvious of many dynamic boundaries among distinct transport environments. The need to link environments becomes clear as we ask how changes in one part of the surface system affect other parts. How does damming of a river affect wetlands in a delta hundreds of km downstream? Could changes in beach nourishment cause aggradation in upland rivers? With the advent of global geospatial data sets and models, our community can now begin developing a fully global view of many processes and thus investigate long-range connections such as these. We can also view the surface system holistically and begin developing a global view of the fluxes, reservoirs, and flow paths of geocritical materials as we discussed above.

The modular design of the CSDMS will be well suited to accommodating coupling of transport environments across dynamic moving boundaries. Its integrative, multienvironmental nature will make it well suited to developing a global view of our highly interconnected surface system.

How does the Critical Zone couple to the tectosphere, atmosphere, hydrosphere, cryosphere, and biosphere and serve as the *dynamic interface* among them?

Above all else, the Earth's surface is an interfacial region, the dynamic boundary among the solid Earth and its fluid envelopes. As emphasized in the BROES report, the Critical Zone has 'soft' boundaries, extending from the instantaneous solid surface of the Earth (soil or rock) down through the saturated groundwater zone. As such, it might be appropriate to use a fluid-mechanics analogy and think of the Critical Zone as the Earth's 'outer boundary layer'. The mechanisms by

More on Boundary Dynamics

In dynamic models of specific Earth-surface domains — hillslopes, rivers, salt marshs, the continental shelf — definition of the boundary and specification of boundary conditions often are matters of convenience. There are two end members. On one hand, a boundary condition may be regarded as independent of the internal dynamics of a model domain. A simple example is the specification of mean sea level at the seaward boundary of an estuary or coastal salt marsh. Despite the exchange of water mass across the boundary, the mass of the ocean relative to that involved in the exchange (the tidal wedge) is so large that the ocean may be regarded as an infinite source. On the other hand, far more challenging are boundary conditions that are determined by near-field dynamics on either side of the boundary. An example is the channel-floodplain boundary during overbank flooding. As the floodwave rises, water and sediment are decanted from the channel into storage on the floodplain, which contributes to attenuation of the flood wave. The rate of export to the floodplain depends on the *fully coupled* hydrodynamics of the channel and floodplain, as the characteristic timescales of transport processes are similar in the two domains. In these two examples, the boundary position is fixed over the relevant hydrodynamical timescales. In contrast, of special importance in many Earth-surface dynamics problems are *moving boundaries*, where boundary motion depends on the near-field dynamics in one or both of the juxtaposed domains, and the boundary location must be found as part of the solution to the overall surface evolution problem.

Concern for boundary dynamics goes beyond the task of programming modules to interact effectively. Understanding the behavior of environmental boundaries is at the heart of describing landscape behavior involving multiple domains governed by different sets of transport processes and different characteristic length and time scales. How, then, do *linked surface environments* communicate with one another across their dynamic boundaries? How do changes in one part of the global surface system affect other parts?

which surface morphology and evolution influence the Earth's oceans, surface and ground water, atmosphere, and ice masses are both obvious (water flows over and around topography) and subtle (topographically mediated vegetation distribution both influences and is influenced by soil moisture). On the other hand, until recently it was taken for granted that the connection between the tectonic and surface-transport system was largely one-way — the idea of, for instance, erosion driving mountain uplift seemed like a case of the tail wagging the dog. Now it is clear that this coupling too is strongly two-way. The relative roles of climate and tectonics in driving orogenesis are now the subject of intensive research.

The import of this for CSDMS is that the

design must include, right from inception, interfaces to allow for flexible connection to comparable modeling systems for these other "spheres" with which the surface interacts. At present the state of modeling of these related systems is uneven. The leaders are the highly developed community models for the atmosphere and ocean systems. The groundwater and glacial communities have also been active in developing model systems that should b e able to interface with CSDMS. Tectonic modeling, while quite sophisticated for particular systems, does not yet have a community structure or a comprehensive approach. Given the highly developed state of its best models, it seems likely that these will develop in parallel with CSDMS.

3   What would CSDMS be?

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, for instance, 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 com-

munities that will provide its scientific 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 Requrement 3: Best methods

CSDMS must make available to its users the most advanced methods available to treat processes and properties of the surface system (Table 2). Since there is often room for debate about which method is best, and since this may also depend on the application, CSDMS must strive to be open to input from the community on both new ideas and evaluation of proposed methods. Evolving geoinformatics ideas on data handling and analysis must also be included.

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 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.

USER COMMUNITIES

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 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 Navy analyst has been asked to evaluate the likely seismic signture of shallow subsurface strata in an area where no data are 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.

DESIGN ELEMENTS

The above constraints, together with the ideas and desires of the community as expressed at the 2002 and 2004 workshops, 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 sediment/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 components 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 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 mathematics (e.g. cellular automata);

DESIGNING WITH USERS IN MIND

- 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 Geo-*

graphic Environmental Modeling System for air quality studies (Bruegge and Riedel, 1994), *Global Hydrological Archive and Analysis System* (Vorosmarty et al., 2004) for hydrological analysis, *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.

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. For sediment, for instance, 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

large-scale problems cannot resolve all the small-scale processes occurring within each environment. Models or modules will 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-
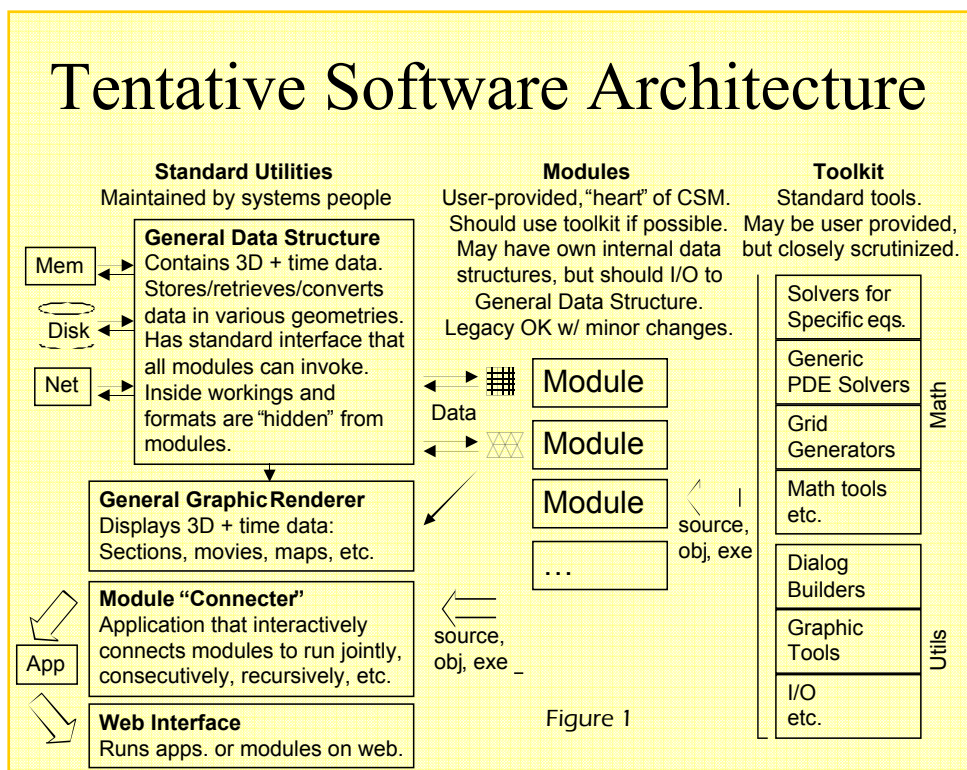
retained as we move across nested structures.

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.

Tentative Software Architecture

Standard Utilities
Maintained by systems people

General Data Structure
Contains 3D + time data. Stores/retrieves/converts data in various geometries. Has standard interface that all modules can invoke. Inside workings and formats are "hidden" from modules.

Mem

Disk

Net

General Graphic Renderer
Displays 3D + time data: Sections, movies, maps, etc.

Module "Connecter"
Application that interactively connects modules to run jointly, consecutively, recursively, etc.

App

Web Interface
Runs apps. or modules on web.

Modules
User-provided, "heart" of CSM. Should use toolkit if possible. May have own internal data structures, but should I/O to General Data Structure. Legacy OK w/ minor changes.

Data

Module

Module

Module

...

source, obj, exe

source, obj, exe

Figure 1

Toolkit
Standard tools. May be user provided, but closely scrutinized.

Solvers for Specific eqs.

Generic PDE Solvers

Grid Generators

Math tools etc.

Dialog Builders

Graphic Tools

I/O etc.

Math

Utils

Figure 1

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

The CSDMS modeling system will encompass the entire "source to sink" suite of surface environments. Even with the most powerful computers possible, CSDMS formulations aimed at

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) that cannot readily be parameterized at the longer time scales of the main model architecture.

An additional issue is scaling and preserving geomorphometric attributes across nested models. Methods that preserve flow pathway topologies across a variety of spatial scales will enable a systematic testing of the generality of CSDMS algorithms and lend insight into key attributes that must be

4 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? —Rivers and Lakes

River systems are one of the best understood of all major transport systems, due to their accessibility and importance to commerce, recreation, water supply, and infrastructure. 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 compared to the oceanic realm. 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 km^2. 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 re-meshing, 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 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. Major efforts include US Army Corps of Engineers modeling of sediment flow and coastal change on relatively short (year to decade) time scales, and US Geological Survey research on coastal-zone processes on short and long 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. Nonetheless, because of the complexity of flow and sediment dynamics under breaking waves, even basic prediction of sediment transport in the surf zone is difficult, and is currently done using semi-empirical methods. To redress this shortcoming an effort is underway to build a Community System for Coastal Sediment-Transport Modeling (http://woodshole.er.usgs.gov/project-pages/sediment-transport/williamsburg_report.htm#text).

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.

Table 3
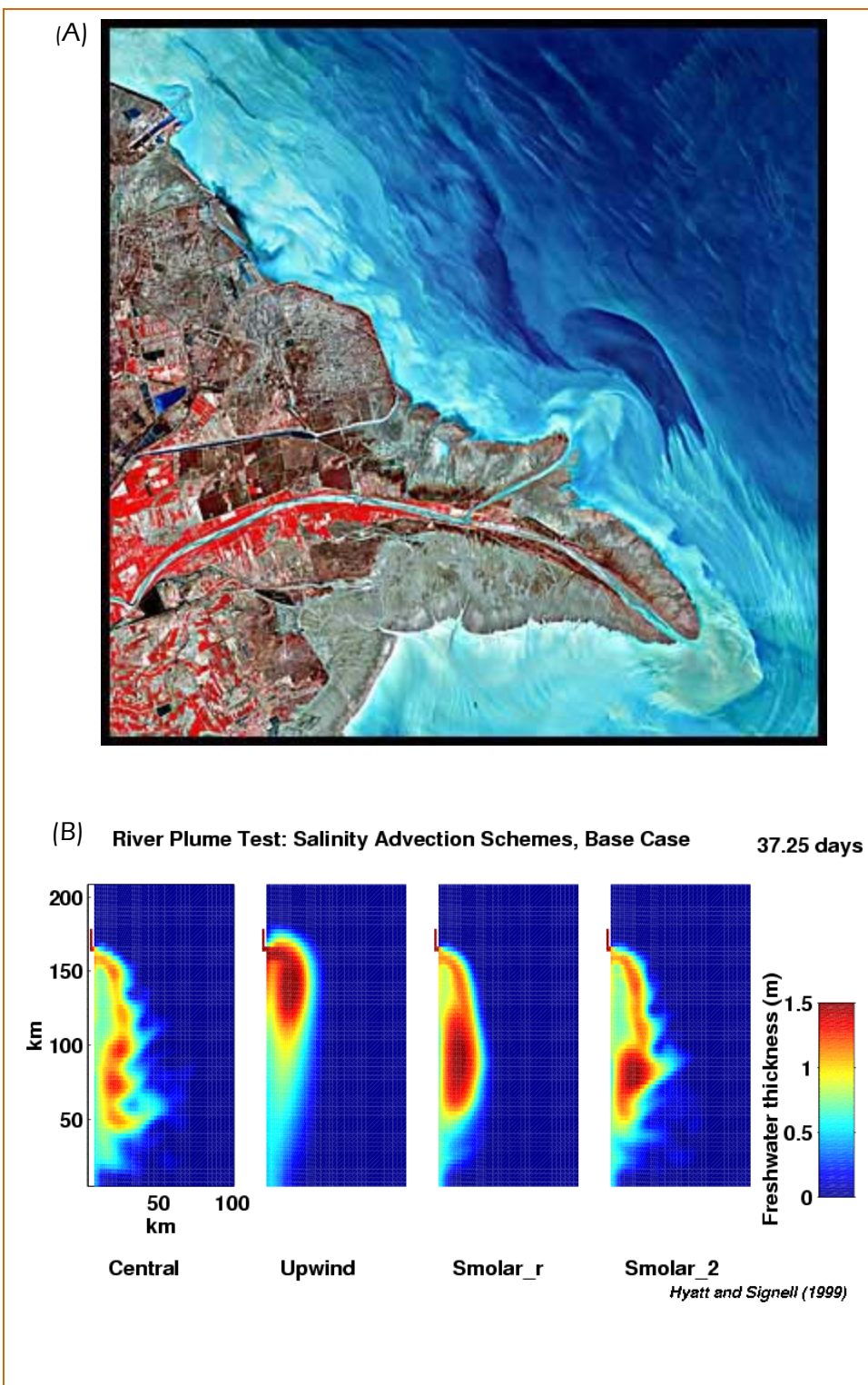## Some Common Surface Process Models

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	2D & 3D fluvial & coastal hydro- & morphodynamics
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 Univ UK/OSU	landscape evolution
SIBERIA	Willgoose, Univ Leeds UK	landscape evolution
landscape model	Howard , Univ VA	landscape evolution

alters the rate laws, leading to a self-evolving system. Typically, the rate laws used for erosion and mass transport represent long-term average rates rather than discrete events, although some models now include a stochastic, 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

(A)

(B) **River Plume Test: Salinity Advection Schemes, Base Case**   **37.25 days**

Central   Upwind   Smolar_r   Smolar_2

Hyatt and Signell (1999)

as typical landforms such as convexo-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-

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

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 waste-rock landforms on mining sites.

There are a number of important challenges 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 Sidebox 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
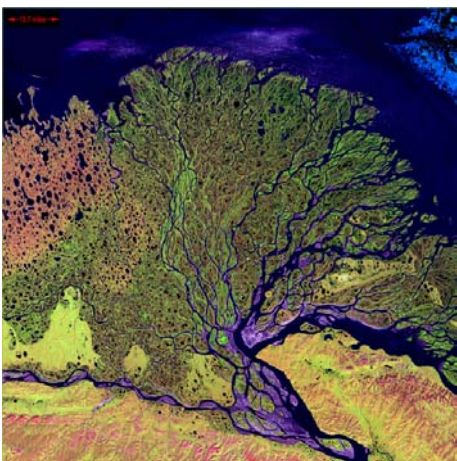
Lena Delta

What Do We Know Now? —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.

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 SHELF 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.

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 marine environment.

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 algorithms. 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,

What Do We Know Now? —Carbonates

The distinctive aspect of carbonate sediments is how they are produced, 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.

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 will be 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? —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.

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 100-10,000 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,

Preserved Oligocene fluvial channels, eastern Spain

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 strati-

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

Models of turbidity currents range from simple one-dimensional integral models (e.g., Parker et al., 1987) 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. Pratson 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, 2001; Kostic 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).
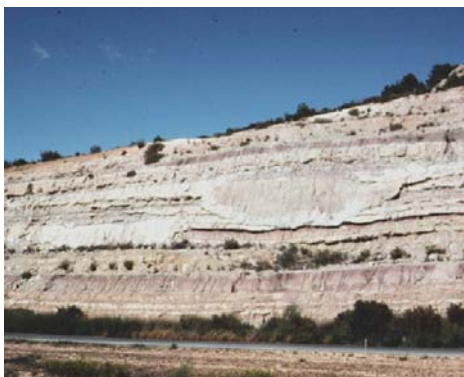
graphy, so that we can predict their response to perturbations, such as climatic and tectonic variability, relative sea-level change, and land-use practices. *Source to Sink* consists of focused field investigations of landscape and seascape evolution, and of sediment transport and accumulation in selected 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.

including hosting the second CSDMS workshop in 2004. NCED is focused on providing scientific insight and modeling algorithms for surface processes. It does not have the personnel or the resources to create the comprehensive computer-modeling environment called for in CSDMS. NCED would continue to be a major partner in the CSDMS effort, providing scientific support, modeling methods, and experimental and field data, and cooperating in leading the workshops and meetings that would be required to maintain community involvement with CSDMS. We see a close partnership between NCED and CSDMS as the heart of our effort to develop an integrated, predictive science of Earth-surface dynamics.

CONSORTIUM OF UNIVERSITIES FOR THE ADVANCEMENT OF HYDROLOGIC SCIENCE (CUAHSI)

CUAHSI is a non-profit consortium aimed at supporting the hydrologic community through a variety of efforts, including synthesis centers and hydrologic observatories. We expect CUAHSI to be a significant source of data and insight for the hydrologic aspects of CSDMS, and we anticipate working closely with CUAHSI as both efforts evolve.

THE NATIONAL CENTER FOR EARTH-SURFACE DYNAMICS (NCED)

NCED is a recently funded NSF Science and Technology Center devoted to the integrated study of surface processes. At present it involves Principal Investigators in civil engineering, Earth sciences, and ecology, as well as industrial and government partners.

The interests of NCED are closely aligned with CSDMS, and NCED has supported CSDMS in a variety of ways

Mouth of the Yangtze River (photo courtesy of J. Syvitski); 1998 flooding in Bangladesh (photo by Shahidul Alam (DRIK) (http://www.drik.net/flood98/)

5 Using CSDMS: proof of concept projects

CSDMS CHALLENGE PROBLEMS

Because CSDMS is a new and untested idea, it is important that we show as quickly as possible what it can do for the scientific community. While we expect a broad range of applications, including many we cannot predict, we plan a coordinated, community-wide effort on three proof-of-concept challenge problems that will show the power of CSDMS across a representative sampling of its application areas. This effort will be concurrent with the development of an CSDMS infrastructure, and will be coordinated by the National Center and Working Groups. The demonstration challenges will provide the initial focus needed by the National Center to coordinate with the science community.

Challenge Problem 1: Predicting the Transport and Fate of Fine Sediments and Carbon from Source to Sink

Increasing attention has been focused in recent years on the behavior of silt and clay size sediment. The behavior of this fraction is important for several reasons: it represents the majority of the world's sediment mass; and its geochemical properties, especially its relatively high specific surface area, make fine sediment important to the behavior of a number of important geochemical actors. In the context of the present debate on global warming, carbon flux and storage are of particular interest. Carbon dynamics is influenced by a wide array of processes that CSDMS will address, primarily those involving fine sediments. These undergo fluid transport as well as impoundment in environments like coastal marshes, floodplains, and muddy shelf and deep marine settings. In dissolved form, carbon participates even more strongly in organic processes, once again illustrating the importance of including these in the CSDMS framework.

The intertwined fates of fine sediments and carbon in the surface system represent a remarkably complex coupled physical-chemical problem. Focusing on it is a good way both to insure that CSDMS incorporates key geochemical linkages in its design and also to bring CSDMS immediately to bear on a comprehensive scientific debate with major societal implications.

Challenge Problem 2: Sediment Dynamics in the Anthropocene

The "Anthopocene" refers to that part of the Earth's recent history in which humans have become a major force for change in Earth systems. Nowhere is the rise of humans as geologic agents more marked than in the surface system. By combining CSDMS transport models with data sets from modern, human-influenced as well as

Response of fluvial systems to natural and man-made perturbations: the example of post-fire erosion

Following a century of fire suppression, the western U.S. has seen an unprecedented increase in the number and severity of wildfires in recent years. Most experts agree that these devastating fires are just the beginning of a new fire regime characterized by frequent catastrophic fires. How will drainage basins respond to this new regime? How will landslides, soil erosion, and flood risk be affected? How can we best mitigate soil erosion in the crucial time immediately following wildfires?

Observations indicate that sediment yields can increase by 1-2 orders of magnitude following intense wildfires, and that this increase in sediment can modify the morphology and behavior of the entire channel system for decades. Field observations and measurements have provided guidelines for predicting geomorphic response to wildfires, but it is difficult to predict how a specific drainage basin will respond to a wildfire due to differences in relief, regolith cover, and bedrock type between basins. We need integrated process-based numerical models of fluvial-system response, designed to work with remote-sensing imagery and numerical models of fire spreading. Integration of physical processes with biological, hydrological, and human effects will be crucial, making the post-fire problem an ideal target for CSDMS modeling.

pre-human conditions, we should be able to quantify the human influence on landscape evolution and sediment dynamics. Specific topics include;

1. Anthropogenic consequences for landscape modification from headwaters to the shelf/slope. One approach to studying this would be to trace a large human perturbation (e.g. Eel, Waipaoa, Po, Rhone) through the

source to sink pathway.

2. Effects of agricultural and timber-harvesting practices on sediment de-lilvery and consequent changes to riv-ers and coastal systems.

3. Post-fire erosion and its downstream propagation.

Focusing on the human time scale is important and will allow for a CSDMS to better forecast the cumulative ef-fects of human activities on the envi-ronment, from the headwaters to the shelf. The model suites developed for this exercise should allow for better evaluation of the decline in ecosys-tems, and provide guidance in their restoration. The models would track perturbations on sediment generation, sediment routing and storage (i.e. res-ervoirs), and impacts on coastal ecosys-tems, for example. This exercise will allow the CSDMS to evolve with access to modern global databases (e.g.


10-m deep gully formed in 2 years following the 1994 Rattlesnake fire, Chiricahua Mtns, AZ (courtesy of Tom Swetnam, U. Arizona)

Space Shuttle Radar, satellite imagery, DEMs, meteorological data, ocean data). In addition, this exercise would reach out to the global change re-search community.

Challenge Problem 3: Tracking surface dynamics through Pleisto-cene glacial cycles

The sequence of high-frequency sea-level and climatic cycles that character-ize Pleistocene time poses an exciting challenge to the CSDMS modeling sys-tem. Modeling the full suite of surface-system responses to glacial cycles in-volves coupled changes in drivers such as ice cover, water and sediment deliv-ery, base level, and wave/current cli-mate, plus associated changes in eco-systems. The results — fluvial valley de-velopment and filling, major shoreline migration, and glacial advance and retreat — are sufficiently well docu-mented to provide relatively strong constraints on CSDSMS modeling re-sults. The glacial-cycle problem will test the ability of CSDMS to handle critical features such as dynamic moving boundaries (e.g. the shoreline) be-tween transport domains, abrupt cli-mate changes, ice-river interactions, and ice-ocean-sediment interactions. The project will also allow CSDMS to evolve with access to global paleo-databases (e.g. paleoclimate proxy data, vegetation history data) and simulations (e.g. climate model predic-tions, glacial simulations, paleo-ocean predictions). The research would reach out to the Quaternary and gla-ciological communities, including the International Ocean Drilling Project.
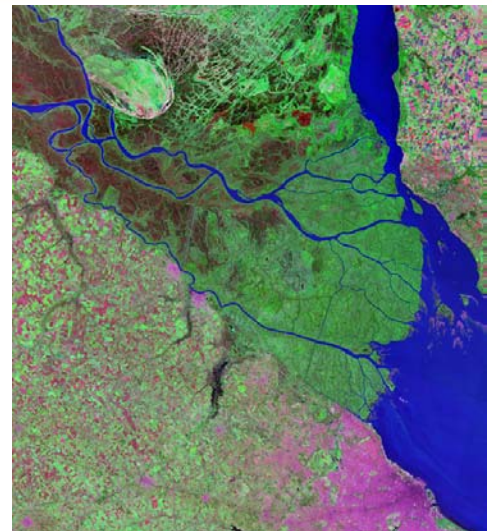
Paraná Delta and part of Buenos Aires, Argentina

ADDITIONAL CSDMS APPLICATIONS

The three proof-of-concept projects described above represent only a small subset of the range of problems to which the CSDMS will be applicable. It is impractical to list all the possibilities, but here we provide further examples of problems for which CSDMS can make a difference.

River restoration. At present, billions of dollars are being spent in the US alone to "restore" rivers to more natural con-ditions that are only vaguely under-stood. River restoration involves a se-ries of basic scientific questions about how rivers work: how are channel di-mensions and plan pattern set by sto-chastic water and sediment supply? How are river channels coupled to hill-slopes and floodplains, and how must these be handled to maintain desired channel properties? What factors de-termine the areas of upstream and downstream influence in fluvial sys-tems, which in turn affect how large an area must be considered for a resto-ration project to be viable? How can we predict natural variability (spatial

and temporal) in topography, a fundamental control on habitat and ecosystem function?

Tools exist for approaching many of these issues, but they are dispersed, incomplete, sometimes inconsistent, and in many cases available only to a privileged few. CSDMS can play an important role by providing a consistent platform for integrating and making available to everyone the best algorithms for designing restoration projects as they become available.

Flood hazard and landscape instability. Millions of people worldwide live in areas with high risk of flooding and channel instability. One area where the problem is acute is the western U.S., where extensive development has taken place on alluvial fans. These are subject to rapid-rise floods and abrupt channel shifts, both difficult to predict. Flood waters are conveyed by a complex network of interfingering channels and adjacent overbank areas. In addition to this hydraulic complexity,

channels on many alluvial fans have shifted, or avulsed, in recent years. Flood behavior is also linked to climatic change directly through precipitation events and indirectly through the vegetation that determines the hydraulic surface roughness and cohesion of overbank areas. How will future climatic changes influence flood hazards?

Major strides are being made in alluvial-fan flood prediction using a combination of remote sensing, numerical modeling, and geomorphic mapping. New remote sensing techniques, using multispectral image bands sensitive to sedimentation and opportunitistic vegetation, can determine the inundation extents of recent floods, but they cannot predict the extents of extreme events that have not yet occurred. Numerical modeling, in conjunction with high-resolution DEM data, can fill that gap. NSF-funded programs such as NCALM (National Center for Airborne Laser Altimetry) are providing the geomorphic community with topographic
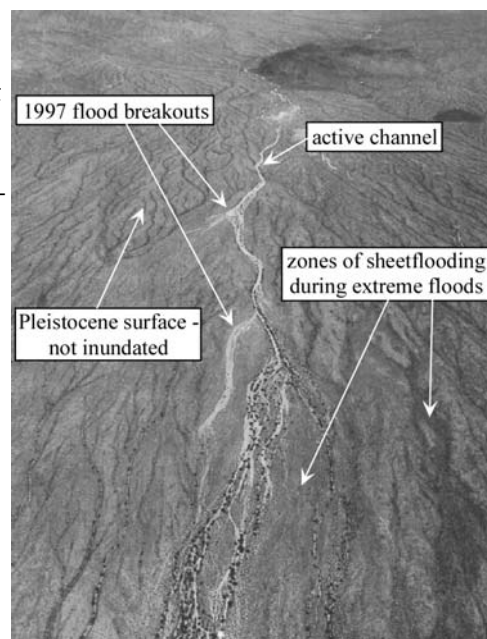
Recent channel shifting in Tiger Wash, Harquahala alluvial fan, AZ

data with better than 1 m resolution. The current challenge is to develop models that can use high-resolution topographic and hydrologic data to predict erosion, deposition, and channel shifting. CSDMS will facilitate the development of a coupled hydrologic-geomorphic model for alluvial-fan flooding and evolution. This model will be able to predict future channel changes so that areas that have not been subject to flooding but are poised to capture flow in the future can be identified. This model will be important for more than just natural hazards: Models of aquifer recharge require accurate models for surface hydrology of alluvial fans, and groundwater models require better information about the subsurface alluvial architecture in order to predict recharge pathways. The linked short-term (geomorphic) and long-term (stratigraphic) fan dynamics addressed by CSDMS will also link surface and subsurface hydrology, leading to better prediction of flooding and groundwater flow.

Coastal zone dynamics. As discussed above, the land-ocean interface is one of the most critical, both scientifically and societally, in the surface environment. It is also one of the most complex. The flow of sand in the surf zone,
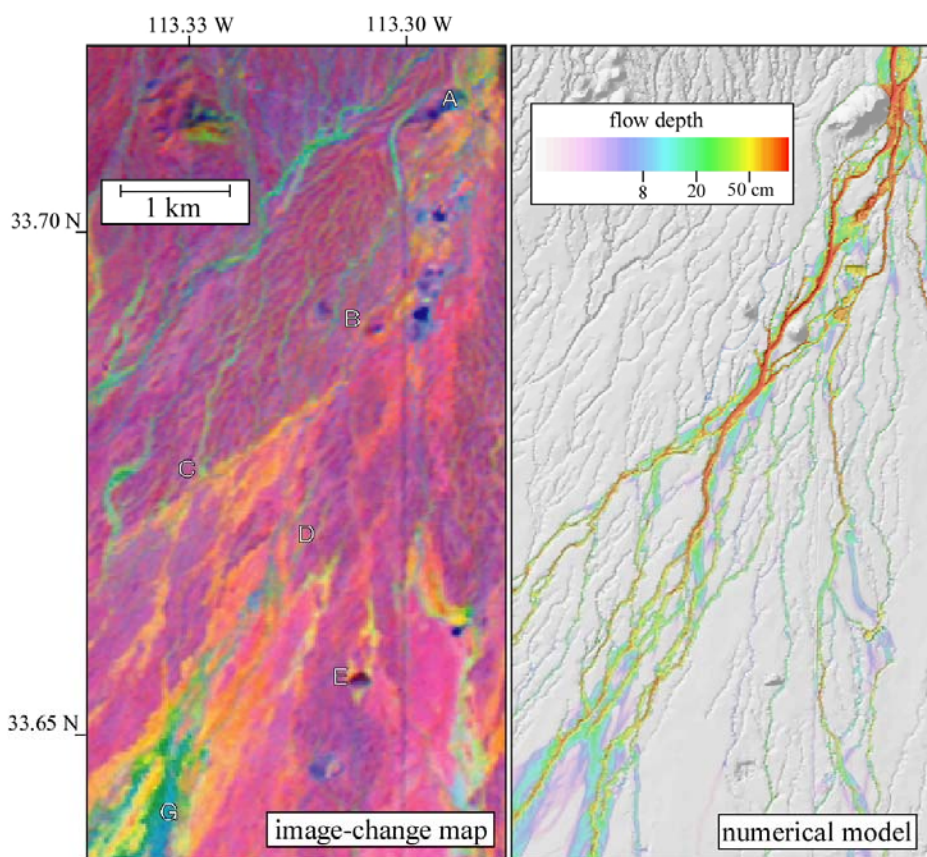
Comparison between satellite-image analysis of flood inundation (left) and numerical model prediction using a high-resolution DEM (right).

driven in large part by episodic storms, involves particle dynamics, bedforms and sand bars (prime examples of self-organized patterns), highly localized rip currents, and nonlinear, breaking waves and their associated turbulence. Can new analysis methods for complex systems help improve existing semi-empirical predictors of sediment flow? Important coastal environments such as salt-marshes and muddy shorelines are still in early stages of analysis. How do, for example, plant growth, nutrient flow, and mud trapping converge to create salt marshes? And, once formed, how stable are they, and to what extent can they "bend but not break" in the face of rising sea level? CSDMS will provide a framework for coupling the marine and terrestrial sides of the coastal complex, seamlessly integrating physical processes like wave, tidal, and fluvial sediment dynamics with biological processes and nutrient flow in critical habitats like salt marshes.

Global connections. As we begin to comprehend the surface system at global scale, one of the first questions will center on whether the whole is the sum of the parts. Everything we know about nonlinear systems, which the surface system certainly is, suggests that this cannot be. Rather we expect


Deltaic channels, Rann of Kutch, India

that small-scale individual changes interact with one another in complex ways that lead to unexpected large-scale behaviors. CSDMS, as the first-ever fully integrated modeling system for the Earth's surface, will provide the tools to investigate these large-scale connections and behaviors, as well as helping motivate and shape collection of the data sets needed to document them.

Tectonics and surface dynamics. One of the great debates in Earth sciences in recent years has centered on cause-and-effect questions about the relative roles of tectonic uplift and erosion in creating mountain chains. To what extent does surface erosion drive rock uplift as opposed to being driven by it? By improving our ability to quantify and predict erosion, transport, and deposition rates, CSDMS will allow us to provide better answers to these fundamental questions about Earth history and orogenesis. Similar questions about the interplay of surface processes and tectonics can be applied to other systems, like evolving rifts and sedimentary basins. Given the extent of current interest in these questions, and parallel efforts to develop integrated numerical models in the tectonics community, we are confident that there will be fruitful interaction between CSDMS and tectonic modeling related to these questions as both programs evolve.

Integrating past and present. Traditionally, study of surface processes has been done separately on human and geologic time scales. Since the founding of modern geology by Hutton and Lyell, the assumption has been that one understood ancient systems by studying modern ones – not the other way around. Earth-surface dynamics plays itself out on time scales that are usually too slow to allow for routine observation of system evolution, but not slow enough to ignore entirely – for instance, "slow" geologic processes control important boundary conditions
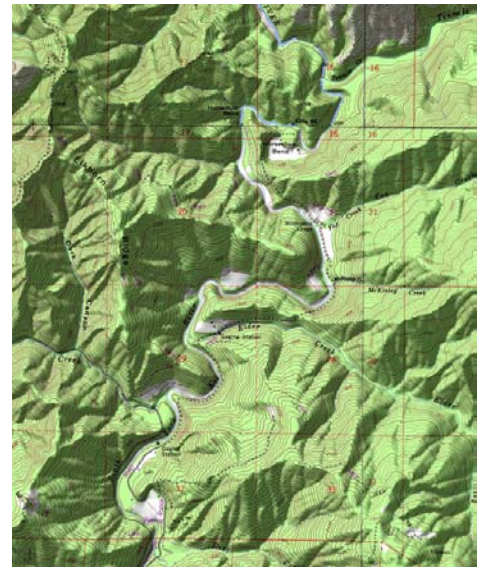
High-resolution (LIDAR) topography, Angelo Coast Range Reserve, Eel River basin, northern California

like overall sediment supply and surface elevation. And, especially as we understand the full extent of human influence on the surface environment, we see that we must use geologic records to understand the full dynamic range of Earth-surface behavior. Thus the past can teach us about the present. It may be better to just ask: How can information over this great range of time scales be combined and used to best advantage? The merging of insight over geologic and human time scales will be a new frontier in surface dynamics, just as it is in, for example, atmospheric dynamics as global climate models and geologic climate proxies are played off against one another to learn how the climate system works. CSDMS will be help bring this about by providing a common framework for modeling over the full range of relevant time scales.
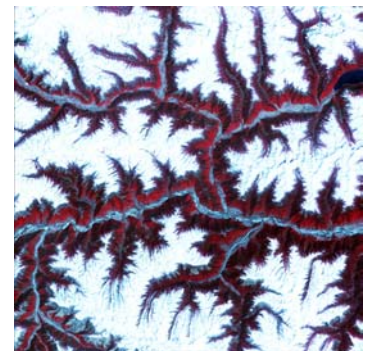
Erosional channel network, Himalayas

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APPENDIX I WORKSHOP PARTICIPANTS
NSF CSM WORKSHOP PARTICIPANTS
BOULDER. CO , FEBRUARY 2002

Robert Anderson	Department of Earth Science, UCSC Earth Sciences Santa Cruz
Suzanne P. Anderson	Center for Study of Imaging and Dynamics of the Earth, Earth Sciences Department, University of Calafornia
Mike Blum	Department of Geosciences, University of Nebraska-Lincoln
James Buttles	Earth, Atmosheric and Planetary Sciences, Massachusetts Institute of Technology
Robert M. Carter	Marine Geophysical Laboratory, James Cook University
Tom Drake	Department of Marine, Earth and Atmospheric Sciences, North Carolina State University
William E. Dietrich	Department of Earth and Planetary Science, University of California
Carl T. Friedrichs	Physical Sciences, Virginia Institute of Marine Science
Sergio Fagherazzi	Department of Environmental Sciences, University of Verginia
David Jon Furbish	Department of Geological Sciences and Center for Earth Surface Processes Research, Florida State University
Jeffrey Geslin	ExxonMobil Upstream Research Co.
W. Rockwell Geyer	Applied Ocean Physics and Engineering Department at Woods Hole Oceanographic Institution (WHOI)
Daniel M. Hanes	Department of Civil and Coastal Engineering, University of Florida
Courtney Harris	Virginia Institute of Marine Science
Bil Haq	National Science Foundation
Rachael D. Hilberman	Institute for Arctic and Alpine Research (INSTAAR), University of Colorado
Phil Hill	Geological Survey of Canada, Sidney
Alan Howard	As-Environmental Sciences, University of Virginia
Eric Hutton	Institute for Arctic and Alpine Research (INSTAAR), University of Colorado
Chris Jenkins	Institute for Arctic and Alpine Research (INSTAAR), University of Colorado
Garry Karner	Columbia University
Christopher Kendall	University of South Carolina
Albert J. Kettner	Institute for Arctic and Alpine Research (INSTAAR), University of Colorado
David Kinner	Institute for Arctic and Alpine Research (INSTAAR), University of Colorado
H. Richard Lane	National Science Foundation
Dawn Lavoie	Office of Naval Research
Shawn Marshall	University of Calgary
David Mixon	Institute for Arctic and Alpine Research (INSTAAR), University of Colorado
A. Brad Murray	Division of Earth and Ocean Sciences, Nicholas School of the Environment and Earth Sciences/ Center for Nonlinear Systems

Damian B. O'Grady   ExxonMobil Upstream Research Co.

Irina Overeem   Institute for Arctic and Alpine Research (INSTAAR), University of Colorado

Chris Paola   Department of Geology & Geophysics, University of Minnesota

Nana Parchure   U.S. Army Engineer Research and Development Center (ERDC)

Gary Parker   St. Anthony Falls Laboratory, University of Minnesota

Scott D. Peckham   Institute for Arctic and Alpine Research (INSTAAR), University of Colorado

William Tad Pfeffer   Institute for Arctic and Alpine Research (INSTAAR), University of Colorado

Nathaniel G. Plant   Neval Research Lab., Stennis Space Center, Mississippi

Ross D. Powel   Department of Geology and Environmental Geosciences, Northern Illinois University.

Lincoln F. Pratson   Earth & Ocean Sciences, Duke University

Marina Rabineau   Centre National de Recherche Scientifique (CNRS)

Chris Reed   URS Greiner Corporation

Rick Sarg   ExxonMobil Upstream Research Co.

Mark Schmeeckle   Florida State University

Steve Scott   U.S. Army Engineer Research and Development Center (ERDC)

Rudy L. Slingerland   Department of Geosciences, The Pennsylvania State University

Lawson M. Smith   U.S. Army Engineer Research and Development Center (ERDC)

Michael S. Steckler   Lamont-Doherty Earth Observatory of Columbia University

J. Scott Stewart   Institute for Arctic and Alpine Research (INSTAAR), University of Colorado

John B. Swensen   University of Minnesota Duluth

Donald Swift   Old Dominion University

James P. Syvitski   Institute for Arctic and Alpine Research (INSTAAR), University of Colorado

Dan Tetzlaff   Western Geco Corp.

Torbjörn E. Törnqvist   Department of Earth and Environmental Sciences, University of Illinois, Chicago

Gregory Tucker   School of Geography & the Environment, University of Oxford

Bill Ussler   Monterey Bay Aquarium Research Institute

Gert Jan Weltje   Department of Applied Earth Sciences, Delft University of Technology

Pat Wiberg   Department of Environmental Sciences, University of Virginia

NSF CSDMS WORKSHOP PARTICIPANTS
MINNEAPOLIS, MN , MAY 2004

Robert Anderson	University of Colorado
Suzanne P. Anderson	University of Colorado
William E. Dietrich	University of California
Sergio Fagherazzi	University of Virginia
David Jon Furbish	Vanderbilt University
Bill Goran	US Army Corps of Engineers
Daniel M. Hanes	US Geological Survey
Bilal Haq	National Science Foundation
Russell Harmon	US Army Research Office
Courtney Harris	Virginia Institute of Marine Science
Alan Howard	University of Virginia
Helena Mitasova	North Carolina State University
A. Brad Murray	Duke University
Fred Ogden	University of Connecticut
Chris Paola	University of Minnesota, Minneapolis
Jeff Parsons	Universitiy of Washington, Seattle
Scott D. Peckham	University of Colorado
Jon Pelletier	University of Arizona
Eugene Rankey	University of Miami (Florida)
Dogan Seber	University of California, San Diego/GEON
Sybil Seitzinger	Rutgers University
Rudy L. Slingerland	Pennsylvania State University
Bob Stallard	US Geological Survey
John B. Swensen	University of Minnesota, Duluth
James P. Syvitski	University of Colorado
Alexy Voinov	University of Vermont
Charles Vörösmarty	University of New Hampshire
Pat Wiberg	University of Virginia

APPENDIX II
A COMPILATION OF CURRENT RELATED 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 cloimate 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 baratropic (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 hydrodynamics 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 multivariate 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 provide 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) and US Bureau of Reclamation been leaders in developing these models. In Europe, some of the principal groups include the Danish Hydraulics Insitute, Delft Hydraulics (NL), and ETH Zurich. Well developed river models include:

- The HEC and related series from the US Army Corps of Engineers;

- The GSTARS series from the US Bureau of Reclamation;

- MIKE from the Danish Hydraulics Institute;

- DELFT3D from Delft Hydraulics, and

- The ETH 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 disgorge 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 paramaterization 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 continu-

ous 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 multipupose environmental analysis system

QUAL2E – EPA Enhanced stream water quality model

RORB 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

WQRRS – 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

WBM/WTM/DBM – U. New Hampshire water budget, transport, and drainage basin model

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 International 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 were 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 document and primitive states within the academic community.

Examples of simple half-graben models (Schlische, 1991) include extensional basin or continental filling models that can 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

SEDPAK – Univ. South Carolina geometric continental margin model

SEDSIM – Stanford sedimentary facies model

NOPP nearshore model

NCSTM Coastal Community Sediment Transport Model (under construction)

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.