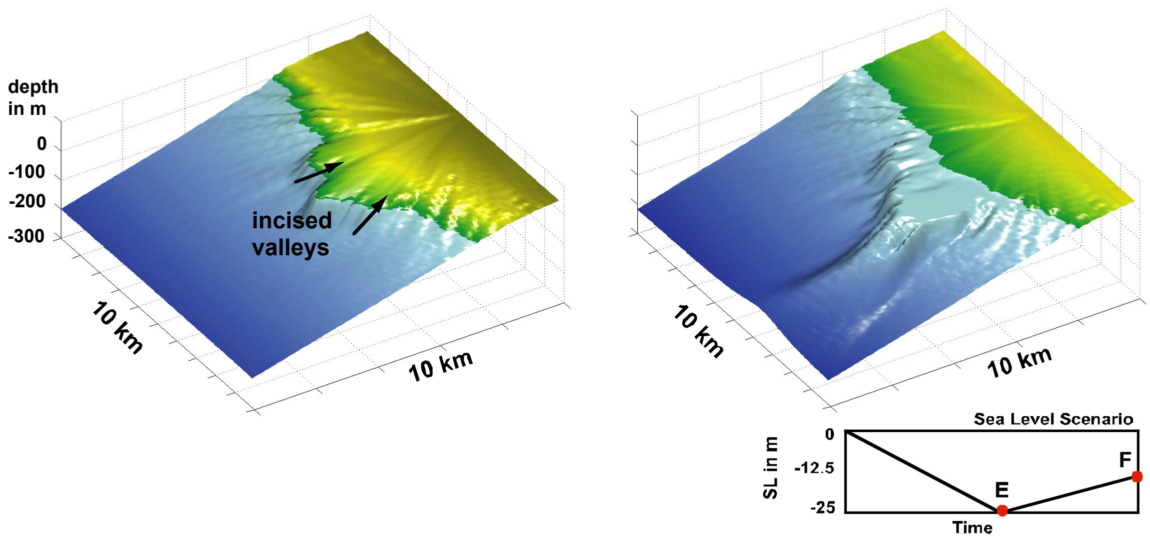
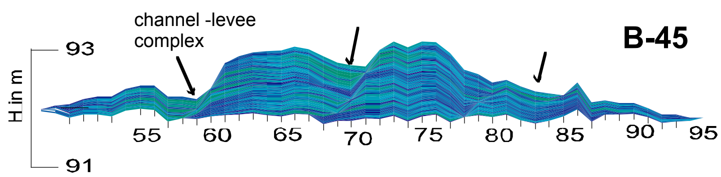
Community Surface Dynamics Modeling System





Implementation Plan

Aug 2004

Community Surface Dynamics Modeling System Implementation Plan

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http://instaar.colorado.edu/deltaforce/workshop/csdms.html

Contents

i) Executive Summary

This report is based on materials developed at two NSF-sponsored workshops (Boulder, 2002; Minneapolis, 2004) (see Appendix I for a list of participants). The workshops central recommendation is that:

Our science community should work together and create a unified, predictive science of surface processes through the development of a Community Surface-Dynamics Modeling System (CSDMS). CSDMS is a digital library of inter-connectable process modules able to predict the transport and accumulation of sediment and solutes in landscapes and seascapes, and how these surfaces evolve over a broad range of time and space scales. CSDMS is a complete Sediment Modeling Environment. CSDMS includes the protocols for community-generated, continuously evolving, distributed, open software.

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

• *empowering* a broad community of scientists with computing tools and knowledge from interlinked fields,

• *streamlining* the process of idea generation and hypothesis testing through linked surface dynamics models, and

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

The attributes of a CSDMS are *inclusivity*, *modularity, cutting edge, tracking of uncertainty, being user friendly*, and *extensibility.* The key properties of surface systems are self-organization, localization, thresholds, strong coupling/interconnections, scale invariance, and interwoven biology and chemistry with geology. The key system requirements include novel computational strategies, moving boundaries, distributed source terms, and nested modules that can accommodate time and space scales.

This *Implementation Plan* documents the initial "Demonstration Challenges" or Proof-of-Concept goals, the resources required to achieve these goals, and how a CSDMS program should interact with government, academic, and other agencies. The *Plan* outlines the basic mission requirements, the administrative organization. This report is complimentary to the **Community Surface-Dynamics Modeling System Stategy and Rational (2003)** and the **Community Surface-Dynamics Modeling System Science Plan (2004)**.

1. Introduction

The sciences concerned with the processes governing the Earth's surface have been advancing rapidly from largely descriptive origins toward a fully quantitative, theory-driven method of inquiry. As a result, surface-process science is now rich with models that use basic physical principles to understand, interpret, and predict a host of geological phenomena, from mountain-range development to deep-sea stratigraphy to human impacts on the landscape. These models are both guiding and being guided by quantitative observations, which themselves have grown tremendously in volume and sophistication, thanks to new techniques (e.g. satellite imagery, geochronology) and to global databases (e.g. waves, tides, precipitation).

However, technological barriers limit the impacts of these geosystem models. For example, numerical models describing various Earth-surface processes tend to remain in the domain of specialists in particular sub-disciplines. This tendency generates two types of obstacles. First, it presents barriers within disciplines, because the nature of research software is typically idiosyncratic, poorly documented, and difficult to use or modify. This means that there is often a great deal of "reinventing the wheel" when it comes to applying quantitative theory to new problems, or altering theory in light of new ideas.

Second, we face technological barriers between disciplines. The existence of many interconnections and feedbacks among Earth systems is well known, and it demands that we bring together knowledge across sub-disciplines – just as our colleagues in climate, hydrology and ecology have begun to merge their knowledge in the quest to understand the coupled atmosphere-hydrosphere-biosphere system. Much of the domain knowledge in the physical sciences takes the form of mathematical and numerical models. Limitations in our ability to understand, adapt and apply models across disciplines unnecessarily restrict cross-disciplinary research.

These limitations also imply high indirect dollar costs that impact the academic, governmental, and private sectors alike. For example, consider a researcher, consultant, or manager who requires a numerical solution for a coupled flow and sediment transport problem. The all-too-common experience is that existing solutions are unsuitable, either because they are inflexible, involve proprietary (non-modifiable) source code, are poorly documented, or are simply impossible to locate because they exist only in the confines of one or two research labs. The hapless scientist is therefore forced to re-create and re-test a model that already exists, at the cost of many hours of expert labor and at the risk of introducing new errors. At present, this scenario is usually the rule rather than the exception in the geosciences.

In 2002 and again in 2004, members of the Earth-surface process community came together in two NSF-sponsored workshops to explore solutions to these problems and develop a vision for a way forward. The workshops' central recommendation was as follows:

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

This report, which is an outcome of the second workshop, describes an implementation plan for developing a Community Surface-Dynamics Modeling System. CSDMS would catalyze surface process research over the coming decades by:

empowering a broad community of scientists with computing tools and knowledge from interlinked fields,

streamlining the process of idea generation and hypothesis testing through linked surface dynamics models, and

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

Importantly, the workshop participants felt that the CSDMS should be a highly inclusive and democratic endeavor (involving free exchange of tools, software modules, and the ideas and data these represent) that is designed intentionally to foster both scientific inquiry (by simplifying the process of creating, implementing, and exploring alternative hypotheses, models and software components) and research efficiency (by minimizing the need for any researcher to "re-invent the wheel" in terms of scientific programming). The scientific motivation and rationale for CSDMS is presented in a companion document, ***Community Surface Dynamics Modeling System Science Plan. The science plan outlines how the CSDMS will help answer the following questions:

- What are the *fluxes, reservoirs, and flow paths* associated with the physical, biological, and chemical transport processes in the Critical Zone — the skin of the earth? How do these depend on substrate properties like morphology, geology, and ecological and human activities?
- What processes lead to *self-organization and pattern formation* in surface systems? How do self-organized patterns mediate surface fluxes and evolution?
- How is the *history of surface evolution* recorded in surface morphology and physical, chemical, and biological stratigraphic records?
- 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?
- How does the Critical Zone couple to the tectosphere, atmosphere, hydrosphere, cryosphere, and biosphere and serve as the *dynamic interface* among them?

This *Implementation Plan* presents the community's vision for achieving these goals by making CSDMS a reality. It describes a vision for what CSDMS would look like, how it would function, what its initial "Demonstration

Challenges" or Proof-of-Concept goals will be, what resources are required to achieve these goals, and how a CSDMS program should interact with government, academic, and other agencies. The plan is written for those working in funding agencies (NSF, DOD, DOE, USGS, NASA, USDA, NOAA …), potential industrial partners, and the science community itself, both within the US and abroad. Chapter 2 provides a brief history of the CSDMS initiative. Chapter 3 outlines the community's vision for CSDMS's basic mission requirements, and how it might be designed to fulfill those requirements. The administrative organization is discussed in Chapter 4, describing the Advisory Board, Steering Committee, National Center, Working Groups, Role of Individual Scientists). The final chapter outlines the timetable of resources needs.

The CSDMS Implementation Plan calls for an initial 5-year effort to design and develop the basic technological components, and apply these in carefully chosen proof-of-concept projects. These CSDMS challenge problems relate directly to the science goals outlined in the companion report, and cover a range of time scales from human to geologic time:

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1. Predicting the Transport and Fate of Fine Sediments and Carbon from Source to Sink

Carbon dynamics as addressed by CSDMS will focus on those processes involving fine sediment: fluvial and marine transport, reservoir impoundment, environmental sequestering (floodplains, wetlands, continental shelves). Focusing on carbon will ensure that CSDMS incorporates key geochemical linkages in its design and will allow the System to contribute to an immediate scientific debate having societal relevance.

2. Sediment Dynamics in the Anthropocene

The Anthropocene refers to that part of the Earth's history in which humans have become a major force for change in Earth systems. Examples include: (i) anthropogenic consequences for landscape modification from headwaters to the shelf/slope, such as the large human perturbation in basins such as the Eel, Waipaoa, Po, and Rhone. through the source to sink pathway; (ii) effects of agriculture and timber-harvesting practices on sediment delivery and consequent changes to river and coastal systems; and (iii) post-fire erosion and its downstream propagation.

3. Tracking surface dynamics through Pleistocene glacial cycles

The sequence of high-frequency sea-level and climatic cycles that characterize Pleistocene time poses an exciting challenge to the CSDMS modeling system. Modeling the full suite of surface system responses to glacial cycles involves coupled changes in drivers such as ice cover, water and sediment delivery, base level, and wave current climate, plus associated changes in ecosystems. The results – fluvial valley development and filling, major shoreline migration, and glacial advance and retreat – are sufficiently well documented to provide relatively strong constraints on CSDMS modeling results. The exercise will allow the CSDMS to evolve with access to global paleo-databases (e.g. paleoclimate proxy data), and simulations (e.g. climate model predictions, glacial simulations, paleo-ocean predictions). The exercise would reach out to the Quaternary and glaciological communities, including the International Ocean Drilling Project.

The community, through its members attending the second workshop, has recommended that the CSDMS program be headquartered at a new National Center based at the University of Colorado in Boulder[1]. The administrative structure of the CSDMS program will be based, in part, on the experience of programs such as the NCAR/UCAR Community Climate System Model. A CSDMS Advisory Board will consist of members who can offer useful and insightful advice, act as advocates of the project, provide feedback on governance, deliverables and mission, and provide tie-in to national and international initiatives. The CSDMS Scientific Steering Committee will be an interdisciplinary "experts"

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1 (INSTAAR's Environmental Computation and Imaging Facility)

body and will function as the governing body of the CSDMS initiative, and provide coordination, direction and vision of the project. The National Center will house the core server and will be the public face of the CSDMS community (core office), housing the management, computational and educational staff to advance the CSDMS initiative. Disciplinary working groups will be responsible for creating and managing the various process modules, and providing continuity to meet long-term project objectives (technical quality control, adequacy of testing, setting scientific priorities, recommending resource prioritization, providing scientific review, and technical documentation). Individual scientists will interact with the CSDMS program in a variety of ways: by serving on one or more working groups, serving on the steering committee, designing research programs for synergy with CSDMS, contributing software components, or simply taking advantage of resources provided by CSDMS to assist their own research and teaching.

2. Brief History

What is the initiative?

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.

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 practical products of CSDMS will be a digital library of surface dynamic models, that can be assembled to communicate with each other as an integrated modeling system, able to address practical science questions related to surface evolution, much as weather and climate models are used now. Modeling surface dynamics is a problem of comparable complexity to modeling oceanic and atmospheric dynamics. The experience of the oceanic and atmospheric communities, discussed in more detail later, teaches us that development of such large, complex numerical models rapidly becomes a task for an entire research community. The community approach, in which many researchers pool their efforts, allows efficient development of models that are more powerful than any single group could achieve on its own. It also inherently maximizes the diverse and advanced skill sets in the research community.

Who is the community?

The community represented by this initiative, includes earth scientists who have expertise and interests in the fields of hydrology, fluvial processes, biogeochemistry, sedimentology, stratigraphy, geomorphology, glaciology, oceanography, marine geology, climate forcing, active tectonics, earth surface geophysics and remote sensing, geomathematics, computational fluid dynamics, computational science, and environmental engineering. This community typically holds academic degrees in Geological Sciences, Geography, Ecosystem and Environmental Biology, Environmental Sciences, Ocean Sciences, Engineering Physics, Civil and Environmental Engineering, Aerospace Engineering, Applied Mathematics, and Computer Sciences. However our intent is to keep the products open and user-friendly to the extent possible, allowing participation of other disciplines in their development, such as: socio-economics, biology, environmental and social sciences, as well as decision-makers from federal amd local agencies and NGOs

What is the history of this implementation plan?

The CSDMS effort began in the mid-1960s with the onset of academic computation (Bonham-Carter and Sutherland, 1967; Harbaugh and Bonham-Carter, 1970). This was a time when application of the Navier-Stokes equation to sediment transport remained in its infancy, and when computer cards were fed into memory-poor, slow-speed mainframes. Ten years later saw the first volume describing the full spectrum of numerical models related to ocean dynamics (Goldberg et al, 1977). The emphasis of these articles was on getting the dynamics correct and this resulted in some papers (e.g. Smith, 1977;

Komar, 1977) being conceptually ahead of available field tools and data.

Through the 1980's, as computers advanced along with our ability to develop code, the CSDMS community applied its maturing understanding of hydraulics and sediment transport to the formation and modification of sedimentary deposits. In 1988, a large representation of this community met in the mountains of Colorado, and the concept of quantitative dynamic stratigraphy (QDS) was born (Cross, 1989). At the meeting, a mechanistic view of QDS (see Syvitski, 1989) argued for a fuller understanding of regional boundary conditions, either over long periods of simulated time, or for conditions where we have little field data (i.e. extreme event modeling). Through the 1990's, the QDS community and discipline grew and influenced the entire geoscience community (Agterberg and Bonham-Carter, 1989; Martinez and Harbaugh, 1993; Franseen et al., 1991; Slingerland et al., 1994; Harff et al., 1998; Harbaugh et al., 1999; Paola, 2000; Syvitski and Bahr, 2001). In parallel, the geomorphological community developed exploratory numerical tools to understand how the landscapes and seascapes were modified (see Peckham, 2003).

During the 1990's, a group of earth system modelers began to explore the development of a suite of modular numerical models able to simulate the evolution of landscapes and sedimentary basins, on time scales ranging from individual events to many millions of years. They coined this concept the Community Sedimentary Model (CSM), at an international workshop entitled Numerical Experiments in Stratigraphy (University of Kansas, May 15-17, 1996), and further developed this interest at the 3rd conference of the International Association of Mathematical Geology (Barcelona, 1997: Syvitski, et al, 1997). A panel convened by NSF in March 1999, identified a "Community Sedimentary Model" as a high priority NSF research initiative in sedimentary geology (see *Geology Today*, 1999). The science plan of the NSF MARGINS Source-to-Sink Program called for the 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 Plans 2004). The U.S. Office of Naval Research, the Army Research Office and the U.S. Army Corp of Engineers all support collaborative efforts to develop an integrated, predictive model for continental and marine sedimentary system. In 2000, NSF initiates its Information Technology Research (ITR) initiative. In 2002, NSF funds a new Science and Technology Center called the National Center for Earth-surface Dynamics, whose primary mission is to promote the integrated, experimental study of surface dynamics.

As the research community began to organize around these ideas and programs, it became clear that it was time to set up the structure for an integrated, collaborative modeling effort. This realization led to the first Community Sediment Model workshop, held in Boulder, Colorado in February of 2002, sponsored by the National Science Foundation. In May 2003, at a MARGINS StoS community meeting held in New Zealand, the science plan was structured to support the CSM initiative. In July of 2003, an all agency meeting of program managers (ACE, ARO, ONR, NOAA, NSF, USGS) met at National Science Foundation in Arlington to receive info talks by the CSM Steering Committee, and to discuss the logistics of supporting the effort. Re-titled the Community Surface Dynamics Modeling System or CSDMS, a second NSF-sponsored Implementation Workshop was held in Minneapolis in May of 2004. This report combines the findings and discussion of this discourse.

3. The Nature of a CSDMS

CSDMS is to be a community-built and freely available **modeling environment** for 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 will 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 will be coordinated and funded by government agencies and industry and 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.

What is a Modeling Environment?

In order to clarify some of the technical issues that are anticipated in the implementation of the CSDMS, it is helpful to define some basic terminology. When we speak of a **model**, we are talking about a numerical or computational model, that is, a computer program that is designed to simulate a particular physical **system** that is evolving in time. The purpose of this kind of model is to make quantitative predictions; it is not meant to be merely conceptual or schematic. The word **system** also has many possible meanings, but in the current context a system can be defined in terms of its boundaries (like a control volume), which may be either open or closed. There is no material transport or flow across a closed boundary, so it is convenient to define a system so that it has as many closed boundaries as possible. A well-designed, modular model may consist of hundreds or thousands of individual **subroutines** (e.g. functions and procedures), some of which are very problem-specific and others that are quite general, often called **utilities**. Utilities might address issues such as file I/O (input/output), visualization, equation solving, dialog building, memory management, file format conversion or grid generation. Subroutines may employ a variety of different data structures and algorithms to achieve speed and computational efficiency. Examples of some physical systems, their boundaries, and models that have been developed to model them are summarized in the following Table:

Physical System	Boundaries	Models
watershed	drainage divide or basin boundary	TopoFlow, HydroTrend
evolving coastline	shoreline and shallow-water wave depth on seaward side	Genesis
river channel	banks and bed of the river	
evolving seafloor	coastline, ocean surface and initial seafloor surface	SedFlux
fluvial landscape	initial landscape, base-level	CHILD
nearshore waves	shoreline and shallow-water wave depth on seaward side	SWAN

Within a physical **system**, there are a number of **processes** that move mass, momentum and energy into, out of, or around in the system, subject to **contraints** such as conservation laws, initial conditions and boundary conditions. **Processes** typically involve a particular mechanism for the conversion, transport, or production/loss of mass, momentum or energy. Most processes have names that are built from a verb by adding the suffix "tion" or "sion". Examples include infiltration, evaporation, diffusion, soil production, solifluction, erosion, deposition, compaction, subduction, saltation and advection. There are usually many different **methods** that can be used to parameterize a given process, from very simple ones that require very little input data to complex ones that may require more input data than is available. A **method** is really nothing more than a set of equations that ingest input variables (independent variables; e.g. drivers) and produce output variables (dependent variables) that describe a physical process. An **equation**, in the current context, is a mathematical relationship between physical variables that may have been derived from theory or experiments. The equations used in analytical or numerical models may only be valid over particular ranges of the input variables. A **variable** represents a physical quantity (scalar, vector or field) that can be measured in space and time such as mass, length, time, discharge or shear stress. **Data** generally refers to variables that have already been measured for a system and that can be used as independent variables in a process method. In building models, it is helpful to understand this top-down hierarchy of **system**, **process**, **equation** and **variable**. Modelers know that while there is some arbitrariness to how the boundaries of a system are defined (such that a system may contain smaller systems), some decompositions are more natural than others.

Advanced models typically take many years to develop, and may have one or more authors. As they evolve, they become more sophisticated by:

1) including more processes, extending system boundaries,
2) refining methods by which processes are parameterized, or adding methods,
3) improving their computational algorithms, and
4) improving their user interface.

Nevertheless, the scope of a model is typically limited to the system that it was originally designed to simulate.

When we are faced with scientific questions that involve coupled systems, it usually becomes necessary to link several models together to create a **composite model**. Examples of composite models include the HydroTrend-Plume-SedFlux trio, and a commercial product known as Delft3D (e.g. modules include Flow-Swan-Sed-Mor-Waq-Part). A key requirement for models to be linked together is that each component model must be able to read its entire set of input parameters from an input file (some of which may be filenames of other files that contain input data) even if it can alternately collect them from the user with a graphical interface.

The CSDMS is envisioned as a **modeling environment** or framework, which is a computer program that simplifies the task of linking models together and that also allows users to build new models from a large library of standardized subroutines. The System will allow modules to pipe information directly to each other. Another problem that must be addressed by a modeling environment can be referred to as **choreography** (temporal sequencing). That is, the modeling environment must coordinate the activities of the component models and call them as they are needed in order to achieve a final goal. For a coupled system with feedbacks this may involve iteration between two or more component models. A modeling environment may also have a "visual programming" graphical interface (e.g. IDL), that allows users to rapidly link existing models and/or subroutines together to create programs that solve particular problems. Key functions of a modeling environment include:

- Model building
- Model linking
- Warnings: inappropriate linkages, usage, timesteps, etc.
- Choreography
- Resource management (I/O, data storage and archiving, distributed parallel computing)
- Debugging tools
- Pedagogy

There are many advantages to being able to link existing (advanced) models without the need to modify, rewrite or "assimilate" them. Perhaps the biggest advantage is the time savings, since writing or rewriting models is a pain-staking and time-intensive process. Another advantage is that component models will often continue to evolve and improve on their own, and as they do, the new features will be available to the composite model. As an example, it would be a waste of human resources to develop a separate version of SWAN for use within the CSDMS, since SWAN is a sophisticated, fourth-generation wave model that is maintained by an active team of developers.

We also realize that modules cannot be blindly plugged in, that their integration requires much more than reuse of code in object-oriented programming. In many cases we value modeling as a process that leads to further understanding of systems and processes. Our intent is to make CSDMS as useful as possible both for model application and model investigation and development. We will design special documentation tools and will keep modules transparent to make sure that the use of CSDMS contributes to the overarching goal of understanding system dynamics in the modeling process. Module transparency is also an important prerequisite to safeguard users from module inconsistencies in terms of both scale and structure.

General Requirements for the CSDMS

Workshop participants agreed on the following six general requirements for the CSDMS.

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, human engineering, and sediment stirring by fauna.

General Requirement 2: Modularity

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

CSDMS must treat key properties of the surface system using the latest concepts in Geoinformatics, including object-oriented methods, structures, flexible file formats and optimal algorithms.

General Requirement 4: Extensible

If the 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" and documentation 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.

Key Design Elements

The above requirements, together with the ideas and desires of the community as expressed at the 2002 and 2004 workshops, form the basis for our 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 and data assimilation, offers many parallels to CSDMS.

For further guidance in the design of the CSDMS, we have studied a number of existing models, composite models, GIS programs and modeling environments. These included *RiverTools*, a software toolkit for the analysis of digital terrain and river networks (Peckham, 1998), *TopoFlow*, an open-source, spatially-distributed hydrologic model (instaar.colorado.edu/topoflow), the *Modular Modeling System* for hydrologic studies (Leavesley, 1997), *A Geographic Environmental Modeling System* for air quality studies (Bruegge and Riedel, 1994), *Spatial Modelling Environment Environment* (Maxwell et al, 2004) coupled with the *Library of HydroEcological Modules* (Voinov et al, 2004) for simulation of landscapes and watersheds, *Delft3D*, a hydrodynamic modeling environment, and *DEVS-C++* , a project to develop a high performance modeling and simulation environment to support modeling of large-scale, high-resolution landscape systems. Based on our analysis of these and other programs, we have identified the key components of the CSDMS as outlined below.

Modeling Environment (CSDMS)

- Maintained/developed by IT staff members
- User-friendly graphical (point-and-click) user interface (GUI)
- Possible "visual programming" icon-based interface for model building/linking.
- Model building and linking tools
- Model analysis tools (calibration, statistics, etc.)
- Choreography
- Tools for model nesting and interaction across scales
- Resource management (e.g. available memory and disk space)
- Pedagogy (via help system, dialogs, documentation, etc.)
- Warnings about inappropriate linkages, usage, timesteps, etc.

Included Models

- Maintained/developed by IT staff members or users
- Built entirely out of the subroutine library and standard utilities contributed by the research community
- Callable and linkable from the modeling environment
- Will typically have their own GUI

External Models

- Maintained by their developers
- May or may not have a GUI
- Must be able to read all of their input from an input file
- Will have their own documentation and help system
- Examples: TopoFlow, SWAN, CHILD, etc.

Contributed Subroutine Library

- Contributed by the user community
- May include existing "legacy code"
- Should use the Standard Utilities whenever possible
- Programs for simulating sedimentary processes

Standard Utility Library

- Maintained/developed by IT staff members
- File I/O to a flexible, nonproprietary, standard "file format" such as netCDF, HDF, and/or GeoTIFF
- Visualization tools for grid viewing, contours, wire mesh, animations, etc.
- Dialog/GUI building tools
- Memory management
- Grid generation and conversion (from GridPak, etc.)
- Tools for dynamically adaptive grids
- File format converters
- GIS tools for domain definition and spatial data analysis
- Data preprocessing
- Equation solvers
- Computational geometry routines
- Web interface tools

Data Set Archive

- Sample data for testing & benchmarking models & subroutines

- Available measurements for specific study sites

Website

- Explains the mission of the center, protocols, etc. plus FAQ
- Accepts submissions of user-contributed code via web form
- Provides access to Contributed Subroutine Library & Standard Utilities
- Provides access to Data Set Archive
- Allows download of the modeling environment and included models

The **Modeling Environment** component is the main program that users interact with to build models and composite models. This component would include a Module Connector, or an application that allows users to easily link together process-modules from the Subroutine Library & Standard Utilities to build a new model, or to link together existing models (Included or External) to form composite models. It could have a "visual programming" interface for graphical, icon-based model construction.

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

The **Standard Utility Library** would largely be assembled from other open-source code projects. For example, GRASS is an open-source GIS developed by the U.S. Army Corps of Engineers that has many GIS and visualization tools. Similarly, there are many open-source code projects related to (1) grid generation, such as GridPak, (2) equation solving, such as Numerical Recipes, (3) file I/O to netCDF files (e.g. at www.unidata.ucar.edu and the .znetcdf library for compressed netCDF files), (4) graphics, such as NCAR Graphics and GEMPACK, to name a few. It will be the responsibility of the IT staff members to collect code from these other projects and to develop additional code, including the modeling environment itself, as necessary.

Support for Alternate Computational Strategies

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

Model Nesting and Multi-Resolution Grids

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

Unified 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 interpolation methods.

Key Properties of Surface Systems

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

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

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

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

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

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

Interwoven biology, chemistry and human factors**.** To progress as quickly as possible, the CSDMS must begin with existing models, which tend to emphasize physical processes. But the intimate connection among physical, biological, and chemical processes must be accounted for in program design. This means including colleagues in these disciplines from the outset, and enlisting their help in designing modules that can accommodate biological and chemical processes smoothly. Anthropogenic effects also play an important and growing role in shaping many of the biological and physical processes. The human factor may be dominant in some systems, and CSDMS will accommodate the appropriate modules as they become available.

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 transport environments.

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

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

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

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 evolution models simulate the flux of mass across a topographic surface and the changes in topography that result. 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 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 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.

CDSMS will help by (1) making it easier to design and test alternative approaches to scaling problems, (2) fostering the refinement of rate laws and facilitating their incorporation in landscape models, and (3) empowering the communication across disciplines that will be essential to developing data sets for model testing, validation, and refinement.

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, modular model with a three-dimensional circulation model as a backbone and a variety of tested sediment transport modules that can be plugged into the main model. An important aspect of the nearshore and coastal ocean community modeling programs is development of a suite of test cases that can be used to test modules before accepting them into the modeling system.

While most nearshore and shelf sediment transport models are designed to investigate processes over short time scales (hours to months), some two-dimensional, integrated models have been developed to investigate longer term stratigraphic and seascape evolution of continental margins. The time scales addressed in these models generally prohibit detailed treatment of sediment of fluid dynamics, relying instead on parameterizations of the important processes. These types of models are discussed in the next section.

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

"Stratigraphic" surface-dynamics models are those intended for study of depositional systems over geologic time scales. Generally speaking, geologic time scales are those on which tectonic subsidence and/or eustatic sea-level change become important. Their main hallmark is that they track not just the current topographic surface but also a stack of surfaces that represent recorded stratigraphic information. In a sense, stratigraphic models are a surface-dynamics analog of climate models in atmospheric sciences, in that they use spatially and temporally averaged representations of short-term processes. Long-term stratigraphic models of fluvial systems, for example, often use some form of diffusion equation to represent evolution of the surface morphology. The diffusion coefficient in this representation is a parameterization of high-frequency channel dynamics (typically of the order of 1-1000 yr). Analogous parameterized models have been developed for the coastal and continental shelf regions (eg., Storms et al., 2002). Coupling of shelf/coastal and fluvial models, for example, allows modeling of shoreline transgression and regression in response to changes in sea level.

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

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

Standards for User-Contributed Code

At the implementation meeting in Minneapolis 2004, standards for user-contributed source code were discussed. The two main themes that emerged were (1) good programming practices and (2) metadata. Good programming practices include:

1) descriptive variable names
2) comments in the code
3) indentation and use of white space for readability
4) use of well-named boolean flags to set options
5) breaking programs into smaller modules, and
6) use of library routines.
7) With regard to metadata, it was suggested that a web form be developed that contributors would fill out when making a submission. This web form would include entries such as:
8) authors and their contributions
9) revision history and version number
10) description of overall idea and the algorithms used
11) range of time and/or space scales
12) supporting documents and references as files (or links to them)
13) computer language used
14) dependencies, including which Standard Utilities were used
15) tree diagram (or flow chart) of supporting subroutines
16) variable definition list, with units
17) numerical scheme used and justification
18) test data and testing procedures used
19) known limitations, which may involve data types (int, float, double)

Note that a contributor may have written a visualization program or other utility in a high-level language such as IDL (Interactive Data Language) or MatLab. Such utilities can also be shared via the national center's website, even though they may not be directly linkable as components of new models. If they are especially useful, another user or staff member may later decide to translate them into a low-level language such as C or C++.

Learning from our colleagues

One of the most important features of the CSDMS workshops were presentations by leaders of existing collaborative modeling efforts in various areas of the Earth sciences (hydrology, climatology, oceanography). Organizational and management features considered essential to the success of a project of this type were:

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

These associated modeling efforts will also communicate directly with CSDMS as we attempt to model highly integrated, coupled problems. Critical parts of the Earth system that are not part of CSDMS itself but that will interact strongly with it include the atmosphere, oceans, groundwater, glaciers, and lithosphere. Predictive, quantitative models for these subsystems already exist in some form, and are listed in Appendix II. We also expect that as CSDMS develops, models for ecosystems and human behavior can be connected to the CSDMS.

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

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

- A standardization of the interfaces between various component models.

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

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

- A standardized technique for version control and dissemination of the software and documentation.

4. Organization

The administrative structure proposed for CSDMS is borrowed directly from the climate modeling community. It consists of an advisory board, a steering committee, a national center, a series of working groups, and individual scientists. The working groups will be defined by disciplines (environmental WGs) and by themes (integrative WGs).

Advisory Board

The CSDMS Advisory Board will consist of members who offer useful and insightful advice, are scientifically well-connected, and offer an international reach. Examples of such individuals include leaders of overlapping interest from the National Academy of Science, the International Ocean Drilling Project, the International Geosphere-Biosphere Project, and the World Climate Research Project. The size of the Board will be in the 5 to 7 range. Board members will have achieved a senior position in their field, and remain actively interested in the field of science. Among their roles will be:

1) to act as advocates of the project with government agencies, industry, and academic institutions.

2) to provide feedback on governance, deliverables and mission through an annual review process. The annual review will be conducted as part of an annual all-hands meeting.

3) to provide tie-in to national and international initiatives.

The CSDMS steering committee will choose the Board. Board members will have three year terms, with exception to accomplish overlap at the beginning phase of the project. The term limits will be staggered to allow for overlap. The Board expenses will be part of the budget run through the National Center.

Steering committee

The CSDMS scientific steering committee will be an interdisciplinary body with members from both the process-level research community and science agencies. It will operate as the governing body of the CSDMS initiative. Among its roles will be to:

1) Provide coordination and direction of the project
2) Provide overarching scientific vision of the enterprise,
3) Provide resource advice, including the endorsement of the deployment of National Center Resources through consultation with the National Center Director, or Managing Director,
4) Set scientific priorities,
5) Create and/or disband, and define the charter of, each working group,
6) Appoint the chair of each working group and approve the members proposed by the WG chairs, to ensure diversity of ideas and interests and the smooth operation of each working group,

7) Provide toolkit control and sign off on the release of model components. This includes the grading of model components based on the advice of the Integration working groups,

8) Serve as a liaison between the technical expertise expressed in the disciplinary groups and funding agencies and the wider community,

9) Approve and oversee the annual meeting, and provide formal documents and presentations to the Advisory Board,

10) Facilitate links to national and international data holders (e.g. NOAA, USGS, NASA, PANGAEA), in consultation with the National Center.

Working Group chairs will be non-voting ex-officio members of the Steering Committee. The Steering Committee would initially consist of CSDMS leaders, chosen to represent the community and shepherd the CSDMS initiative. Committee members will be drawn from research and end-user communities (academic, agencies, industry). The Steering Committee members will have three-year terms, with exception to accomplish overlap at the beginning phase of the project. The term limits will be staggered to allow for overlap. The Steering Committee expenses will be part of the budget run through the National Center. The Steering Committee will select its own chair and vice chair. The Director of the National Center will be voting member of the steering committee. The Managing Director of the National Center will be a non-voting member of the Steering Committee.

National Center

The National Center houses the core server and management, computational and educational staff to advance the CSDMS initiative. The National Center is responsible for:

1) Creating and maintaining the computational system,
2) Ensuring portability and interoperability of modules,
3) Ensuring clarity-consistency of documentation, interfaces, code,
4) Ensuring computational efficiency of system code,
5) Being the public face of the CSDMS community (core office),
6) Supporting working group and individual scientists with on-site and off-site (virtual) training, topical workshops, symposia, the annual meeting,
7) Linking to other national computational resources,
8) Providing information and advice to, and receiving advice from, the CSDMS Steering Committee and funding agencies,
9) Education and knowledge transfer (EKT) to the community and public.

The 2004 CSDMS Workshop unanimously voted that University of Colorado's INSTAAR should house the National Center on behalf of the CSDMS Community. The University of Colorado-Boulder is strategically situated in the central US, surrounded by large federal agency labs (NCAR, NOAA, USGS, NIST, EPA, DOE), and is near the Geological Society of America HQ. The city of Boulder is an attractive place to visit year-round. INSTAAR has two established academic centers: 1) Surface Processes (CUSP), and 2) Geochemical Analysis in the Global Environment (GAGE), together offering experts in hydrology, oceanography and marine science, landscape evolution, glaciology, active tectonics, planetary science, climate forcing, chemical processes, fluvial processes, and geochronological research. INSTAAR is a large multidisciplinary Institute that has onsite experts offering breadth and depth in the major fields of science. INSTAAR is supported by three research divisions: Ecosystems, Past Global Change, and Geophysics. INSTAAR has a strong history in surface dynamic modeling and an excellent reputation for leadership in community modeling efforts. INSTAAR has a functional unit already in place (its Environmental Computation and Imaging Facility) to support the CSDMS National Center.

Working groups

Disciplinary working groups represent the knowledge base and would be responsible for creating and managing the various process modules, and providing continuity to meet long-term project objectives. They will be set up to to solve integrated problems outlined in the science plan, identify gaps in knowledge, and foster interdisciplinarity within and between groups . It is important to prevent these from becoming overly specialized (the whole structure would become unwieldy if, for example, it had separate dune, near-shore, estuarine, mid-shelf, outer-shelf, etc. groups). These disciplinary groups will also be set up to be "permanent" structures to provide continuity to the project. Several disciplinary groups would cut across disciplinary science, including scaling, testing (field/lab), advanced computational, IT, software engineering, software and data management, benchmark data, and protocol development.

As "keepers of the code" these groups will make decisions on what tools or processes are in the disciplinary toolkit. They are responsible for quality-control for the algorithms and processes that are included for their area of expertise. They set the priorities for modeling within a discipline, and facilitate the movement of these priorities up the hierarchy from technology group to steering committee to advisory board.

Responsibilities of the disciplinary working groups include:

1) technical quality control
2) adequacy of testing
3) filter the codes according to interoperability
4) setting scientific priorities for the group
5) Making recommendations for resource prioritization
6) stimulating proposals and input from the community
7) scientific review, and
8) technical documentation.

The Working groups will need one face-to-face meeting per year. Members would be on a 3 to 5 year rotating basis, vetted through the Steering Committee. The three key Environmental Working Groups (EWG) are:

1) Terrestrial WG: weathering, hillslope, fluvial, glacial, eolian, lacustrial
2) Coastal WG: delta, estuary, bays and lagoons, nearshore
3) Marine WG: shelf, carbonate, slope, deep-marine

The key Integrative Working Groups (IG) are:

1) Education and Knowledge Transfer (EKT) WG: includes marketing to gain end-users, workshops to provide training for end-users, web-based access to simple models (e.g. K-12 teaching), access to archives of simulations.

2) Technology WG: technical-computational aspects of the CSDMS, to ensure that the modeling system functions properly, is accessible to users, software protocols are maintained, and model standardization. WG will integral with the National Center.

The Next Steps

The greatest obstacle to predicting the behavior of the Earth's surface is not inadequate computer code but inadequate scientific understanding. Developing models that are both computationally sophisticated and scientifically sound requires that code development proceed in parallel with, and interact strongly with, field, experimental, and analytical studies aimed at filling gaps in our understanding. It is essential that a project like CSDMS be comprehensive and inclusive. But the first steps in building something usable will require that we focus on those processes that are currently best understood and for which quantitative models are available. With adequate and coordinated funding, we expect the first tools to appear within a year, and the first generation system up and running in less than five years. The development of the full suite of components and fully evolved "best available" models would take approximately ten years. The CSDMS program should align itself with the array of fields that contribute to surface-process science, to help form a substantial base.

5. Priorities and Proof-of-Concept Experiments

The first year will be devoted to establishing the National Center, and through the center setting up the administrative structure (Steering Committee, Advisory Board, Establishment of Working Groups). The first year will also see the establishment of the digital library, module protocols, the CSDMS modeling framework, and web-based communication with the community.

Concurrent with the development of an CSDMS infrastructure, the National Center and Working Groups will organize a community-wide effort to address three demonstration challenges: 1. Predicting the Transport and Fate of Fine Sediments and Carbon from Source to Sink; 2. Sediment Dynamics in the Anthropocene; and 3. Tracking surface dynamics through Pleistocene glacial cycles. These 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 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 timberharvesting practices on sediment delilvery and consequent changes to rivers 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 effects of human activities on the environment, from the headwaters to the shelf. The model suites developed for this exercise should allow for better evaluation of the decline in ecosystems, and provide guidance in their restoration. The models would track perturbations on sediment generation, sediment routing and storage (i.e. reservoirs), and impacts on coastal ecosystems, for example. This exercise will allow the CSDMS to evolve with access to modern global databases (e.g. Space Shuttle Radar, satellite imagery, DEMs, meteorological data, ocean data). In addition, this exercise would reach out to the global change research community.

Challenge Problem 3: Tracking surface dynamics through Pleistocene glacial cycles

The sequence of high-frequency sealevel and climatic cycles that characterize Pleistocene time poses an exciting challenge to the CSDMS modeling system. Modeling the full suite of surfacesystem responses to glacial cycles involves coupled changes in drivers such as ice cover, water and sediment delivery, base level, and wave/current climate, plus associated changes in ecosystems. The results — fluvial valley development and filling, major shoreline migration, and glacial advance and retreat —- are sufficiently well documented to provide relatively strong constraints on CSDSMS modeling results. The glacial-cycle problem will test the ability of CSDMS to handle critical features such as dynamic moving boundaries (e.g. the shoreline) between transport domains, abrupt climate changes, ice-river interactions, and ice-ocean-sediment interactions. The exercise will allow the CSDMS to evolve with access to global paleodatabases (e.g. paleoclimate proxy data, vegetation history data) and simulations (e.g. climate model predictions, glacial simulations, paleo-ocean predictions). The exercise would reach out to the Quaternary and glaciological communities, including the International Ocean Drilling Project.

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 conditions that are only vaguely understood. River restoration involves a series of basic scientific questions about how rivers work: how are channel dimensions and plan pattern set by stochastic water and sediment supply? How are river channels coupled to hillslopes and floodplains, and how must these be handled to maintain desired channel properties? What factors determine the areas of upstream and downstream influence in fluvial systems, which in turn affect how large an area must be considered for a restoration 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.

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, driven in large part by episodic storms, involves particle dynamics, bedforms and sand bars (prime examples of selforganized patterns), highly localized rip currents, and nonlinear, breaking waves and their associated turbulence. Can new analysis methods for complex systems help improve existing semiempirical 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 that small-scale individual changes interact with one another in complex ways that lead to unexpected largescale behaviors. CSDMS, as the firstever 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 causeand- 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 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.

Initial Priorities

Legacy codes and least-effort methods will be used where appropriate to provide initial deliverables from the project. Legacy codes would need to be modified/engineered so that they can interact with each other within the CSDMS modeling system. Thus, we will begin work on CSDMS by collecting and systematizing the models we have, starting with the disciplines where surface-dynamics modeling has been central: geomorphology, engineering, oceanography, and sedimentary geology. Initial CSDMS models will inevitably reflect the biases of those disciplines. But we see the CSDMS expanding in many directions from there. Most importantly, we see the influence of integration to come reflected now in the design of our modeling strategy. The watchwords will be modularity, flexibility, and expandability. By this we mean that modules will be structured to allow for inclusion of neglected processes or connections as smoothly and cleanly as possible.

Objectives: First five years

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

Tasks:

- **Framework:** Define 'mission'

- **Scope:** Decide what is to be included in framework. This task should maximize the benefits worked out by other computational frameworks. Decide any limits of the framework.

- **Existing Model Issues:** Evaluate existing models (e.g. CHILD, Marshall Ice Sheet Model) and decide how these might define standards as well as their fit into standards once established.

- **Code Issues:** Assure independence from commercial/proprietary codes. Decide on limitations/benefits imposed by numerical methods (e.g. FEM vs. FD vs Raster). Standardize description/documentation/metadata embedded through Doxygen. Analyze existing standards, recommend specific standards (e.g. CSMS) to be developed or adopted. Seek discussion/feedback/confirmation from community. Adopt standard.

- **Standards for Data:** Commonality/compatibility of module interfaces and framework I/O (e.g. NetCDF).

- **Processes:** Given scope, define what processes are involved, which can be modeled adequately at present, which need development. Define how placeholders are to be created and implemented for processes that are not yet developed. Determine how scale issues (spatial and temporal) will be handled.

- **Framework building:** develop 'supercode' that links modules contributed by community. Bring in specialist.

- **Code gatekeeping:** oversee code contributions and accompanying documentation and user validation.

- **Metadata:** standardized documentation for code contributions; describes code function and structure.

- **Code adaptation/testing:** perform testing and adaptation on contributions; test module intercompatibility and interaction.

- **Code translation/standardization:** code translation, wrapping, adaptation of code nearly in standardized format.

- **Legacy Code:** Exists in many different languages, responsibility for adaptation lies with project personnel.

- **New Code:** Publish standardized code templates for C, C++, Fortran, Java, etc.

- **I/O and database standardization:** examine possibilities for 1) Observational data: e.g. OpenDAP, 2) Module/Subroutine I/O: e.g. NetCDF, GDAL, 3) Graphical/Image data: e.g. GeoTif, PDS.

- **Mesh generation** (e.g. GridPak, SeaGrid),

- **Subsequent Tasks:**

    Collect and adapt selected first-generation legacy code
    Publish templates and code/data standards, solicit module contributions
    Adapt and link modules
    Release working versions for community evaluation
    Release CSDMS sensitivity studies.

Objectives: First ten years

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

Metrics of Success

The community decided on examples of what would be considered a success in the evolution of a Community Surface Dynamic Modeling System. They include:

- Tracking the material flux with conservation of mass and energy, from the mountains to deep ocean
- ability to link modules,
- ability to flip modules in an out
- dynamic feedback of state variables/arrays between modules
- lots of research proposals that draw on or use CSDMS (out year)
- integrating the diverse community into the working groups
- numbers of incoming models to the center
- getting diverse community to work together to solve problems
- linking/using effort with community data centers, i.e. GEON, NGDC
- middle school-oriented web based pages/kits using portions of the tool kit
- number of workshops and participants
- number and quality of publications
- special / topical sessions at national / international society meetings
- improved prediction of natural earth system phenomena

6. Resource Requirements

Producing a successful Community Surface Dynamics Modeling System requires: 1) development of a National Center, and through the Center, development of a coherent community and administrative infrastructure (Advisory Board, Steering Committee, Working Groups); 2) funding of the science and technological efforts behind each of the Working Groups; and 3)acquiring the resources needed to integrate the CSDMS modeling efforts with ongoing or developing field (e.g. NSF Margins, NOPP CMST, ONR EuroSTRATAFORM), and experimental (NCED) programs. Below we provide a basic overview of these required resources with focus on the National Center, as its success will underpin the success of the entire initiative. The following description is built on workshop deliberations and input from Directors of National Centers already in existence.

The Human Resources requirements of the National Center:

The development and application of the CSDMS involve a diversity of individuals. A substantial number of these individuals will be supported by the National Center at INSTAAR, but many others would be supported through core agency funds and located at other universities, and national laboratory and federal agency participants, which would not be directly funded. This discussion of available human resources will exclude these contributions to the program since they are not strictly under CSDMS management authority. Instead the discussion will focus on direct-funded human resources assigned to the day-to-day coordination and infrastructure (both scientific and software engineering) needs of the CSDMS program (see National Center responsibilities and duties in Chapter 4).

- Executive Director 25% FTE (3 months): This position will be held by a senior professor who has experience in surface dynamic modeling, leadership skills to effect communication with advisory board and steering committee and individual scientists, management skills to oversee a complex research program, and elicit the strong support of the community. Being a professor is deemed important to ensure that the educational needs of transferring these modeling skills and tools to future researchers remains a priority. The host university would support the 9mo academic position. The Executive Director would be an ex-officio voting member of the Steering Committee and would work closely with funding agencies and the Advisory Board.
- Managing Director, 100%FTE (12 months): This position can be held by one or two individuals. In the divided model, two 6 month positions will be awarded to two mid-level professors: each non-overlapping six month term will alternate with professorial duties for the remaining six months. In this model the University partly underwrites the position, and allows further penetration of the modeling skills to other academic departments. In the single model, the managing director is responsible on a 12 mo basis to the CSDMS program with no distractions outside of the day to day operations of National Center. In both cases the Managing Director(s) will oversee the CSDMS development, integrate the National Center team with the Working Groups, are responsive to meeting the needs

stipulated by the Steering Committee, and provide appropriate documentation to host university, funding agencies, and Steering and Advisory Boards.

- 2 software engineers @ 100%FTE (12 months): These are to be proven and senior software engineers that have the breadth and depth of experience to understand the range in computer languages (both low and high end languages), grid and mesh generation, computational solutions (e.g. Lagrangian, Eulerian, implicit, explicit), graphical representations, and experience in working on surface dynamic problems. These individuals will need to interact with a variety of science and engineering disciplines, and individuals that who are contributing code in what may be at best described as moderately documented software. Two new software positions are to be added in year 4.
- 2 professional scientists (testers/code development/code documentation) @ 100% FTE (12 months): These are to be mid-level surface dynamic scientists who are able to understand and maintain system protocols, ensure adequate testing, code documentation and code dissemination. The will be responsible for applying the developing models in a geographical framework, for developing access and protocols for environmental databases and for working with field and experimental teams applying the developing CSDMS toolkit. One professional scientist are to be added in year 4.
- 1 EKT specialist @ 100% FTE (12 mo): This Education and Knowledge Transfer position will be responsible for the program outreach (K-12, mass media, publishers, undergraduate and graduate students, funding agencies, industrial partners). This position will be responsible for work packages, educational tools, educational graphics, and media interactions.
- 1 web technician @ 100% FTE (12 mo): This position will be responsible for the principal form of communication (web-based, and video-conferencing). All documentation, libraries of models, test case documentation and data, publications, power point presentations, numerical movies will be this positions responsibility.

Other Financial Resource requirements run through the National Center:

1) System administration support of the National Center servers (subcontract).
2) Administration support for secretarial and accounting demands (subcontract),
3) Advisory Board travel expenses (with secretarial support through the National Center), includes annual travel for 7+ individuals once per year. See Advisory Board responsibilities and Duties in Chapter 4.
4) Steering Committee budget (annual travel and meeting expenses). This includes annual travel for steering committee for fifteen individuals (includes the chairs of the five working groups). See Steering Committee duties and responsibilities outlinted in Chapter 4.
5) Working Group budgets (annual travel and meeting expenses). This includes the three science and two technical working groups. The main responsibilities for the working groups (outlined in detail in Chapter 4) are the coordination and dissemination of development activities within the working group, including the provision of comprehensive Web pagers, the

provision of limited technical assistance to working group members engaged in high-priority development activities, and the coordination of the working group computational advances. Each of the five working groups (of between 10 and fifteen scientists) would meet once a year.

6) A budget for four Post-doctoral fellows to be assigned to support the efforts of the Working Groups or the National Center. There would be 1 PDF funded in year 1, two PDFs in year 2, three in year 2, and four in each of years 4 and 5.

7) Computational resources: The National Center will maintain a dedicated fast multi-processor (64) server with appropriate peripherals, to meet the direct needs of the Center in maintaining the developing CSDMS system, testing the CSDMS toolkit, serving the needs of the working groups, and EKT communication with the agencies and public. Computational resources must serve a wide variety of needs for a project as complex as CSDMS. CSDMS requires ample capacity and capability to facilitate rapid turnaround of model development projects, at both the component model and the sstem level. Developers and working groups of the component models should periodically define their current canonical experimental configurations with associated turnaround requirements to ensure that those responsible for ongoing planning for computational resources are regularly apprised of these needs. It is the collective experience of all community modeling efforts that national centers often under-budget for the computation resources needed by the community. Ongoing operations expenses would include software, hardware, support and maintenance licenses.

8) Other Operations and Maintenance costs: communication, travel of center staff, meeting facility costs.

9) Planning or Training Workshops costs and associated costs of visiting scientists.

National Center Budget:

2005: $1.0M including start-up and computational needs

2006: $1.3M

2007: $1.4M

2008: $1.5M

2009: $1.6M not including new computational resources (estimate $0.4M).

Funding of Core Science of Working Groups

There are many funding models to support the efforts of individual scientists. Much of the money is expected to come from core programs in the federal agencies (NSF, ONR, ARO, ACE, NASA, etc). Some of these agencies are already funding individuals and other team efforts that could quickly form a part of this initiatives. Estimates of core funding that these agencies already spend on CSDMS-kind of efforts and projects are NSF $1.6M, ONR $1.0M, ARO & ACE: $0.5M, USGS $0.4M. This is $3.5M in uncoordinated efforts in present day funded activities per year. It is expected that there be growth in these levels of funding, and at a sustained $5.0M per year that fully 50% of these funds go to projects directly supporting the CSDMS project deliverables.

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References

Beaumont, Christopher; Fullsack, Philippe; Hamilton, Juliet, 1992, Erosional control of active compressional orogens. Thrust tectonics, ed: McClay, K. R., Chapman & Hall, London, United Kingdom.

Bruegge, Bernd, Riedel, Erik, 1994, A Geographic Environmental Modeling System: Towards an Object-Oriented Framework. ECOOP 1994: 474-492.

Cacchione, D A; Pratson, L F; Ogston, 2002, The shaping of continental slopes by internal tides. Science, vol.296, no.5568, pp.724-727.

Clarke, M F; Williams, M A J; Stokes, T, 1999, Soil creep; problems raised by a 23 year study in Australia. Earth Surface Processes and Landforms, vol.24, no.2, pp.151-175, Feb 1999.

Fernandes, Nelson F., Dietrich, William E., 1997, Hillslope evolution by diffusive processes; the timescale for equilibrium adjustments. Water Resources Research, vol.33, no.6, pp.1307-1318, Jun 1997.

Felix, M., 2002, Flow structure of turbidity currents. Sedimentology, vol.49, no.3, pp.397-419, Jun 2002.

Gabet, Emmanuel J., 2000,Gopher bioturbation; field evidence for non-linear hillslope diffusion. Earth Surface Processes and Landforms, vol.25, no.13, pp.1419-1428, Dec 2000.

Imran, Jasim; Parker, Gary; Katopodes, Nikolaos, 1998, A numerical model of channel inception on submarine fans. Journal of Geophysical Research, C, Oceans, vol.103, no.1, pp.1219-1238, 15 Jan 1998.

Kostic, Svetlana; Parker, Gary; Marr, Jeffrey G, 2002, Role of turbidity currents in setting the foreset slope of clinoforms prograding into standing fresh water. Journal of Sedimentary Research, vol.72, no.3, pp.353-362, May 2002.

Leavesley, George, 1997, The Modular Modeling System (MMS) - A Modeling Framework for Multidisciplinary Research and Operational Applications [For additional information, contact George Leavesley, FTS 303-236-5027; E-mail george@snow.cr.usgs.gov]

Maxwell, T., A. Voinov, R. Costanza, 2003. Spatial Simulation using the SME. In: Spatially Explicit Landscape Modeling. R. Costanza, A. Voinov (Eds.), Springer.

National Research Council, 2001, *Basic Research Opportunities in the Earth Sciences*.. Committee on Basic Research Opportunities in the Earth Sciences, Board on Earth Sciences and Resources, Commission on Geosciences, NATIONAL ACADEMY PRESS, Washington, D.C.

Paola, C., 2000, Quantitative models of sedimentary basin filling: Sedimentology, v. 47 (suppl. 1), p. 121-178.

Parker, G; Garcia, M; Fukushima, Y; Yu, W., 1987, Experiments on turbidity currents over an erodible bed. Journal of Hydraulic Research, vol.25, no.1, pp.123-147, 1987.

Peckham, S., 1998, Efficient extraction of river networks and hydrologic measurements from digital elevation data. In: Stochastic Methods in Hydrology — Rain Landforms and Floods. Ed. Barndorff Nielsen, et al., World Scientific, Singapore, 173-203.

Pratson, Lincoln E; Imran, Jasim; Parker, Gary; Syvitski, James P M; Hutton, Eric, 2000, Debris flows vs. turbidity currents; a modeling comparison of their dynamics and deposits. Fine-grained turbidite systems, ED: Bouma, Arnold H; Stone, Charles G., AAPG Memoir, vol.72, pp.57-71, 2000.

Pratson, Lincoln F; Imran, Jasim; Hutton, Eric W H; Parker, Gary; Syvitski, James P M., 2001, BANG1D, a one-dimensional, Lagrangian model of subaqueous turbid surges. Numerical models of marine sediment transport and deposition, ED: Syvitski, James P M; Bahr, David B., Computers & Geosciences, vol.27, no.6, pp.701-716, Jul 2001.

Slingerland, R., Syvitski, J. P., Paola, C., 2002, Sediment Modeling System Enhances Education and Research. EOS, Trans. American Geophysical Unnion, December 3, 2002, p. 578-579.

Storms, Joep E A; Weltje, G J; van Dijke, J J; Geel, C R; Kroonenberg, S B, 2002, Process-response modeling of wave-dominated coastal systems; simulating evolution and stratigraphy on geological timescales. Journal of Sedimentary Research, vol.72, no.2, pp.226-239, Mar 2002.

Syvitski, J. P., Paola, C., and Slingerland, R., 2002, Workshop on development of a community sediment model. NSF MARGINS Newsletter No. 8, MaARGINS ffice, Lamont-Doherty Earth Observatory, Palisades, NY.

Traykovski, P; Geyer, W Rockwell; Irish, J D; Lynch, J F., 2000, The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. In: Ocean flood sedimentation, ED: Wheatcroft, Robert A., Continental Shelf Research, vol.20, no.16, pp.2113-2140, 2000.

Voinov, A., C.Fitz, R. Boumans, R. Costanza. 2004. Modular ecosystem modeling. Environmental Modelling and Software.19, 3: p.285-304.

Wolfram, Steven, 2002, A New Kind of Science. Published by Wolfram Media.

Appendix I: NSF CSDMS Workshop participants

(Boulder , February 2002, Arlington, July 2003, Minneapolis, May 2004)

Robert Anderson	formerly UC Santa Cruz, presently INSTAAR U. Colorado Boulder
Suzanne P. Anderson	formerly UC Santa Cruz, presently INSTAAR U. Colorado Boulder
Enriqueta Barrera	National Science Foundation
Rodey Batiza	National Science Foundation
Dave Clark	NGDC/NOAA
Brad Clement	National Science Foundation
Mike Blum	formerly U. Nebraska-Lincoln, presently U. Louisiana, Baton Rouge
James Buttles	Massachusetts Institute of Technology
Robert M. Carter	James Cook University
Tom Drake	formerly North Carolina State University, presently Office of Naval Research
William E. Dietrich	University of California- Berkley
Carl Friedrichs	Virginia Institute of Marine Science
Sergio Fagherazzi	formerly University of Virginia, presently Florida State University
David Fountain	National Science Foundation
David Jon Furbish	formerly Florida State University, presently Vanderbilt University
Jeffrey Geslin	ExxonMobil Upstream Research Co.
W. Rockwell Geyer	Woods Hole Oceanographic Institution (WHOI)
Bill Goran	U.S. Army Corp of Engineers
Daniel M. Hanes	formerly University of Florida, presently US Geological Survey
Russell Harmon	Army Research Office
Courtney Harris	Virginia Institute of Marine Science
Bilal Haq	National Science Foundation
Rachael Hilberman	formerly INSTAAR CU, presently Oregon State University
Phil Hill	Geological Survey of Canada, Sidney
Alan Howard	University of Virginia
Eric Hutton	INSTAAR, University of Colorado
Chris Jenkins	INSTAAR, University of Colorado

Garry Karner	Columbia University
Christopher Kendall	University of South Carolina
Albert Kettner	INSTAAR, University of Colorado
David Kinner	formerly INSTAAR CU, presently US Geological Survey
H. Richard Lane	National Science Foundation
Dawn Lavoie	formerly Office of Naval Research, presently US Geological Survey
Shawn Marshall	University of Calgary
Brian Midson	National Science Foundation
Helena Mitasova	North Carolina State University
David Mixon	INSTAAR, University of Colorado
A. Brad Murray	Duke University
Fred Ogden	University of Conneticut
Damian O'Grady	ExxonMobil Upstream Research Co.
Irina Overeem	INSTAAR, University of Colorado
Chris Paola	SAFL/NCED University of Minnesota
Nana Parchure	U.S. Army Engineer Research and Development Center
Gary Parker	SAFL University of Minnesota
Jeff Parsons	University of Washington
Scott Peckham	INSTAAR, University of Colorado
Jon Pelletier	University of New Mexico
William Tad Pfeffer	INSTAAR, University of Colorado
Nathaniel Plant	Naval Research Lab, Stennis Space Center
Ross Powel	Northern Illinois University
Lincoln F. Pratson	Duke University
Marina Rabineau	formerly IFREMER, presently University of Brest, France
Eugene Rankey	University of Miami
Chris Reed	URS Greiner Corporation
Rick Sarg	ExxonMobil Upstream Research Co.
Mark Schmeeckle	formerly Florida State University, presently University of Arizona
Steve Scott	U.S. Army Engineer Research and Development Center
Dogan Seber	UC-San Diego
Sybil Seitzinger	Rutgers University

Rudy Slingerland	The Pennsylvania State University
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Donald Swift	Old Dominion University
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Pat Wiberg	University of Virginia
Zimmerman Herman	National Science Foundation

Appendix II: A compilation of current allied models

Atmospheric and climate models

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

• Short term models (ETA, NGM - Nested Grid Models, AVN - Aviation models, RUC - Rapid Update Cycle models);

• Medium range forecast models (MRF; ECMWF – the European Centre for Medium Range Weather Forecasting, UKMET);

• 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 temperature 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 model from DHI

MOM-GFDL - Modular Ocean Model

NCOM - NCAR CSM (Climate System Model) Ocean Model

NRLLSM – Navy Research Laboratory global thermodynamic model

PC TIDES – rapidly relocatable tidal model

POM - Princeton Ocean Model (see TOMS)

QUODDY - A 3D finite element code from Dartmouth college

QTCM – Quasi-equilibrium Tropical Circulation Model

ROMS – Rutgers Regional Ocean Modeling System

SCRUM - S-Coordinates Rutgers University Model

SEOM – Spectral Element Ocean Model

SHORECIRC – nearshore circulation model

SPEM - S-coordinate Primitive Equation Model

SWAN – simulating waves nearshore

TOMS – Terrain Following Ocean Modeling System

WAM – 3rd generation Wave Action Model

WW3 – Wave Watch III global next generation wave model

Many of these models have families with genealogical aspects to their extensive history. MOM, POM and TOMS are examples that can provide valuable insight to the CSDMS initiative. For example the

GFDL Flexible Modeling System (FMS) is a software framework for supporting the efficient development, construction, execution, and scientific interpretation of atmospheric, oceanic and climate system models.

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

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

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

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

AOMIP (Arctic Ocean Model Intercomparison Project)

CMIP (Coupled Model Intercomparison Project)

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

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

DOME (Dynamics of Overflow Mixing and Entrainment)

OCMIP (Ocean Carbon-Cycle Model Intercomparison Project)

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

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

Coupled Ocean-Atmosphere and other Earth System Models

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

CCM3 - The NCAR Community Climate Model is a stable, efficient, documented, state of the art atmospheric general circulation model designed for climate research on high-speed supercomputers and select upper-end workstations. The model is both developed by the community and is freely available from NCAR along with source code and documentation. CCM4 is in development and NCAR has 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) has been a leader in developing these models. In Europe, some of the principal groups include the Danish Hydraulics Insitute, Delft GET NAME, and ETH Zurich. Well developed river models include:

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

Glacier and Ice Sheet models

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

EISMINT (European Ice Sheet Modeling INiTiative) Model Intercomparison activity has the objective to test and compare existing numerical ice-sheet, ice-shelf, and glacier models as they are run by several groups worldwide, in order to narrow down uncertainties and to enable participating groups to upgrade their own models. The groupaimto 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.

Hydrological models

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

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

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

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

BASINS – EPA 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

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 – USC geometric continental margin model

SEDSIM – Stanford sedimentary facies model

NCSTM Coastal Community Sediment Transport Model

NCSTM the National Community Sediment Transport Model initiative (NOPP, USGS) is promoting the development of an open-source numerical model for sediment-transport in coastal regions (Sherwood et al., 2000). The NCSTM initiative provides a forum for collaboration between U.S. federal agencies, academic institutions, and private industry, with the goal of adopting and/or developing one or more models for use as scientific tools by the research community working on coastal issues.

Appendix III: Allied Initiatives, Programs, Organization

Below are a few key programs, initiatives and organizations that have through representatives voiced support for the CSDMS endeavor. Many of the programs and initiatives outline below receive funding from multiple sources. Occasionally only the principal source of funding is mentioned.

US Programs

NSF-MARGINS: Promoting research strategies that focus on the coordinated, interdisciplinary investigation of four fundamental initiatives; the Seismogenic Zone Experiment, the Subduction Factory, Rupturing Continental Lithosphere, and Sediment Dynamics and Strata Formation (Source to Sink — see below). Each initiative is associated with two focus sites, research locations selected by the community to address the complete range of field, experimental and theoretical studies, over the full range of spatial and temporal scales needed to address fundamental questions associated with each initiative.
http://margins.wustl.edu/

NSF-MARGINS: **Source-to-Sink (S2S): D**eveloping a quantitative understanding of margin sediment dispersal systems and associated stratigraphy. A predictive capability for dispersal-system behavior has critical implications for understanding geochemical cycling (*e.g.*, carbon), ecosystem change (tied to global warming and sea-level rise), and resource management (*e.g.*, soils, wetlands, groundwater, and hydrocarbons). The Source-to-Sink Focus questions are:

1. What processes control the rate of sediment and solute production in a dispersal system?
2. How does transport through the system alter the magnitude, grain size, and delivery rate to sediment sinks?
3. How is variability of sediment production, transport, and accumulation in a dispersal system preserved by the stratigraphic record?.

http://margins.wustl.edu/S2S/S2S.html

NSF-GEON: Cyberinfrastructure For The Geosciences: GEON is designed as a scientist-centered cyberinfrastructure, freeing researchers to think and be creative by relieving them of onerous data management tasks. Through a scalable and interoperable network, the project will provide scientists with a growing array of tools they can use without having to be IT experts. These include data integration mechanisms, as well as computational resources and integrated software for analysis, modeling, and visualization. In this way, GEON bridges traditional disciplines-an indispensable step in understanding the Earth as a unified system.
http://www.geongrid.org/about.html

NSF-CHRONOS: CHRONOS aims to create a dynamic, interactive and time-calibrated framework for Earth history. CHRONOS's main objective is to develop a network of databases and visualization and

analytical methodologies that broadly deal with chronostratigraphy - that is, with developing a better tool (the time scale) for understanding fundamental Earth processes through time. The CHRONOS platform provides a new investigative environment for interdisciplinary Earth history research that includes the evolution and diversity of life, climate change, geochemical cycles, rapid geologic events, magnetic field fluctuations, and other major Earth system processes. The goal is not only to produce a system for assembling and consolidating such a wide range of Earth history data, but also to provide a platform for modern, innovative Earth science research, and to empower the general public with new knowledge of Earth science facts and issues
http://www.chronos.org/splash/splash.html

NSF-NCALM: National Center for Airborne Laser Mapping. NCALM uses the Airborne Laser Swath Mapping (ALSM) system jointly owned by UF and Florida International University (FIU), based at the UF Geosensing Engineering and Mapping (GEM) Research Center . The state-of-the-art laser surveying instrumentation and GPS systems, which are installed in a Cessna 337 Skymaster twin-engine aircraft, collects data in areas selected through the competitive NSF grant review process.
http://www.ncalm.ufl.edu/

NSF-CUAHSI: Consortium of Universities for Advancement of Hydrologic Science. CUAHSI will maintain a set of Long-Term Hydrologic Observatories at which research can be conducted on pressing hydrologic problems by utilizing data generated by CUAHSI as well as by other entities in the environs of the observatories. CUAHSI will operate a hydrologic information technology program that will provide hydrologic scientists with user-friendly access to the data generated by the CUAHSI observatories as well as user-friendly interfaces with the complementary data sets generated by others. CUAHSI will operate a hydrologic measurement technology program that will provide a clearinghouse for instrumentation to support data collection at the Long-Term Hydrologic Observatories, to support research projects both at and away from the observatories, and provide the university research community with advice on the proper use and maintenance of the instrumentation. CUAHSI will establish a program of education and outreach that will foster knowledge about hydrologic sciences in the general public by interaction with science educators in the intermediate and secondary levels of public and private education. CUAHSI will establish a program of technology transfer that will assure that the hydrologic knowledge that is generated in the other CUAHSI programs will be converted to tools useful in the solution of the identified problems.
http://www.cuahsi.org/

NSF-CCSM: Community Climate System Model: The primary goal of the CCSM project is to develop a state-of-the-art climate model and to use it to perform the best possible science to understand climate variability and global change. The scientific objectives of the Community Climate System Model (CCSM) program are:

- Develop and continuously improve a comprehensive climate modeling system that is at the forefront of international efforts to understand and predict the behavior of Earth's climate.
- Use this modeling system to investigate and understand the mechanisms that lead to interdecadal, interannual, and seasonal variability in Earth's climate.
- Explore the history of Earth's climate through the application of versions of the CCSM suitable for paleoclimate simulations.

• Apply this modeling system to estimate the likely future of Earth's environment in order to provide information required by governments in support of local, state, national, and international policy determination.
http://www.ccsm.ucar.edu/

NSF-NCED: The National Center For Earth-Surface Dynamics: A National Science Foundation Science And Technology Center headquartered at the St. Anthony Falls Laboratory at the University of Minnesota. NCED works to enable landscape sustainability through research, education and knowledge transfer. The immediate mission is to develop integrated ecogeodynamic models of the channel systems that shape the Earth's surface through time, in support of landscape restoration, environmental forecasting, and resource development.
http://www.nced.umn.edu/home.html

NSF-IRIS: The Incorporated Research Institutions for Seismology is a university research consortium dedicated to exploring the Earth's interior through the collection and distribution of seismographic data. IRIS programs contribute to scholarly research, education, earthquake hazard mitigation, and the verification of a Comprehensive Test Ban Treaty. Support for IRIS comes from the National Science Foundation, other federal agencies, universities, and private foundations
http://www.iris.edu/

USGS - National Community Sediment-Transport Model (NCSTM): This modeling effort is to develop short time scale models capable of tracking the transport of modern sediment across the marine environment. The effort will

- Promote/test/select/develop/adopt/improve/maintain community sediment transport models
- Advance instrumentation and data analysis techniques for making measurements to test and improve sediment-transport models.
- Advance software analysis and visualization tools that support model applications
- Apply sediment transport models to benefit regional studies

http://woodshole.er.usgs.gov/project-pages/sediment-transport/

NOPP: The National Oceanographic Partnership Program: is a collaboration of fifteen US Federal agencies to provide leadership and coordination of national oceanographic research and education programs. NOPP facilitates new interactions among federal agencies, academia and industry; increases visibility for ocean issues on the national agenda; and achieves a higher level of coordinated effort and synergy across the broad oceanographic community. Through NOPP, the public and private sectors are brought together to support larger, more comprehensive projects, to promote sharing of resources, and to foster community-wide innovative advances in ocean science, technology, and education. Areas of interest include operational/routine observations, research "observatories," observational technique development, a "commons" for ocean information, and education/outreach. The focus of NOPP is the development of an integrated, sustained ocean observing system for the United States.
http://www.nopp.org/

International Programs

Integrated Ocean Drilling Program (IODP): An international research program that explores the history and structure of the Earth as recorded in seafloor sediments and rocks. IODP builds upon the earlier successes of the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP), which revolutionized our view of Earth history and global processes through ocean basin exploration. IODP greatly expands the reach of these previous programs by using multiple drilling vessels, including riser, riserless, and mission-specific platforms, to achieve its scientific goals. Research themes include

- The deep biosphere and the subseafloor ocean;
- Environmental change, processes and effects; and
- Solid earth cycles and geodynamics.

http://www.iodp.org/

EC and ONR - EuroSTRATAFORM: EUROSTRATFORM is an international program involving scientists from North America supported by ONR and European scientists supported by the European Commission. EUROSTRATAFORM aims to understand sedimentary systems from source to sink. A key aim is to gain a better understanding of how sediment particles are transported from river mouths, across the shallow shelf and/or through submarine canyons, down to the deep sea. EuroSTRATAFORM scientists are investigating the relationships between active sediment dynamics on the continental shelf, cross-shelf transport and accumulation of sediment, and the preserved stratigraphic record. EUROSTRATAFORM investigates a wide spectrum of hydrodynamic, sedimentary, geochemical and biological processes and their forcing conditions in contrasting areas representative of the European continental margin.

http://instaar.colorado.edu/deltaforce/projects/NA_euro_strataform.html
http://www.onr.navy.mil/sci_tech/ocean/321_sensing/prog_cg.asp
http://www.soc.soton.ac.uk/CHD/EUROSTRATAFORM/

ICSU-IGBP: International Geosphere-Biosphere Programme: IGBP's mission is to deliver scientific knowledge to help human societies develop in harmony with Earth's environment. Our scientific objective is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions.

http://www.igbp.kva.se/cgi-bin/php/frameset.php

IGBP-LOICZ: Land Ocean Interaction in the Coastal Zone: The primary goal of the LOICZ is to provide the knowledge, understanding and prediction needed to allow coastal communities to assess, anticipate and respond to the interaction of global change and local pressures in coastal change. LOICZ II will carry out science that addresses key issues of coastal change and use in light of future scenarios of human activity and environmental state change. The science of LOICZ is focused on the measurement of biogeochemical fluxes into and within the coastal zone:

- Biogeochemical fluxes of CO2 and trace gases are the key variables for scaling up to global climate change.
- Biogeochemical variables are the key constituents for connections across coastal boundaries i.e. from catchment to coast, from coast to ocean, and from coast to atmosphere.

• Biogeochemical fluxes include primary production, which underpins ecosystems and renewable resources.

• Water and sediment quality determine distribution of key habitats and affect human amenity and use.

• Biogeochemical processes and cycles include key positive and negative feedbacks in coupled coastal systems, which determine thresholds and boundaries for system resilience.

http://wwwold.nioz.nl/loicz/

IGBP-PAGES: Past Global Changes: Supports research aimed at understanding the Earth's past environment in order to make predictions for the future. PAGES supports all paleoenvironmental and paleoclimate research efforts directed at securing a quantitative understanding of natural and human-induced variations of the Earth system in the past, in order to make sound predictions of future climate, ecosystems and sustainability. PAGES initiative seeks to facilitate interdisciplinary and international cooperation in research and to involve scientists from developing countries in the worldwide paleo-community. PAGES' main areas of focus include integrating international paleoresearch, encouraging research partnerships, strengthening the involvement of scientists from developing countries, supporting educational programs, engaging with the climate modeling community, and facilitating public access to paleo-data.

http://www.pages.unibe.ch/

IGBP/IHDP-LUCC: Land-Use and Land-Cover Change: This Core Project is an interdisciplinary programme aimed at improving the understanding of the land use and land cover change dynamics and their relationships with the global environmental change. The project has actively engaged both the physical and social science communities, and this will continue to be an important *modus operandi* in the future. Primary Objectives:

- to obtain a better understanding of global land-use and land-cover driving forces.
- to investigate and document temporal and geographical dynamics of land-use and land-cover.
- to define the links between sustainability and various land uses.
- to understand the inter-relationship between LUCC, biogeochemistry and climate.

http://www.geo.ucl.ac.be/LUCC/lucc.html

ICSU-WCRP: World Climate Research Programme: The objectives of the programme are to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate. The programme encompasses studies of the global atmosphere, oceans, sea and land ice, and the land surface which together constitute the Earth's physical climate system. WCRP studies are specifically directed to provide scientifically founded quantitative answers to the questions being raised on climate and the range of natural climate variability, as well as to establish the basis for predictions of global and regional climatic variations and of changes in the frequency and severity of extreme events.

http://www.wmo.ch/web/wcrp/wcrp-home.html

ICSU-IHDP: International Human Dimensions Programme An international, interdisciplinary, social science programme to promote and co-ordinate research aimed at describing, analysing and understanding the human dimensions of global environmental change. IHDP focuses on:

- the way people and societies contribute to global environmental change;
- the way global environmental change affects people and societies; and
- ways and means for people and societies to mitigate and adapt to global environmental change.

At present, IHDP is developing a research framework that emphasizes the dynamics of the human driving forces of change and the socio-cultural and institutional influences on these forces. This international program is characterized by an emphasis on those processes that are cumulative or that transcend regional or national boundaries. IHDP seeks to integrate and stimulate co-operation among international and interdisciplinary scientists by establishing a network, which can be useful for communications and acquiring funds for research.
http://130.37.129.100/ivm/research/ihdp-it/index.html

ICSU-GWSP: Global Water Systems Project: A newly established joint project of DIVERSITAS, an international programme of biodiversity science, the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP) and the World Climate Research Programme (WCRP). These four global change programmes form the Earth System Science Partnership (ESSP). The Global Water System Project seeks to answer how are humans changing the global water cycle, the associated biogeochemical cycles, and the biological components of the global water system and what are the social feedbacks arising from these changes. Three major research themes follow this overarching question:

1. What are the magnitudes of anthropogenic and environmental changes in the global water system and what are the key mechanisms by which they are induced?
2. What are the main linkages and feedbacks within the earth system arising from changes in the global water system?
3. How resilient and adaptable is the global water system to change, and what are sustainable water management strategies?

http://www.gwsp.org/

UNESCO-IHP: International Hydrological Programme: An intergovernmental scientific co-operative program in water resources, is a vehicle through which Member States can upgrade their knowledge of the water cycle and thereby increase their capacity to better manage and develop their water resources. It aims at the improvement of the scientific and technological basis for the development of methods for the rational management of water resources, including the protection of the environment. As UNESCO's principal mechanism to contribute to the priority issue of water resources and related ecosystems, the IHP strives to minimize the risks to water resources systems, taking fully into account social challenges and interactions and developing appropriate approaches for sound water management.
http://www.unesco.org/water/ihp/index.shtml

UNESCO-IGOS: Integrated Global Observing Strategy: provide a comprehensive framework to harmonize the common interests of the major space-based and in-situ systems for global observation of the Earth. It is being developed as an over-arching strategy for conducting observations relating to climate and atmosphere, oceans and coasts, the land surface and the Earth's interior. IGOS strives to build upon the strategies of existing international global observing programmes, and upon current achievements. It seeks to improve observing capacity and deliver observations in a cost-effective and

timely fashion. Additional efforts will be directed to those areas where satisfactory international arrangements and structures do not currently exist.
http://ioc.unesco.org/igospartners/over.htm

GOOS: The Global Ocean Observing System: is intended to be a permanent global system for observations, modeling and analysis of marine and ocean variables needed to support operational ocean services worldwide. GOOS will provide: (i) accurate descriptions of the present state of the oceans, including living resources; (ii) continuous forecasts of the future conditions of the sea for as far ahead as possible; and (iii) the basis for forecasts of climate change. GOOS is coordinated by the Intergovernmental Oceanographic Commission (IOC), World Meteorological Organization (WMO), United Nations Environment Programme (UNEP) and the International Council for Science (ICSU) and is being implemented by national and international facilities and services, including the Met Office. GOOS consists of an international GOOS Steering Committee, a number of regional programs (e.g. EuroGOOS), national co-ordinating committees (e.g. in the UK the Inter-Agency Committee on Marine Science and Technology (IACMST) GOOS Action Group) and scientific and technical panels. GOOS has two main themes, (i) coastal and shelf monitoring and modeling, and (ii) global open-ocean monitoring and modeling.
http://www.metoffice.com/research/ocean/goos/goos.html

International Societies

ICSU-IAHS: International Association of Hydrological Sciences: promote the study of Hydrology as an aspect of the earth sciences and of water resources;

- to study the hydrological cycle on the Earth and the waters of the continents; the surface and groundwaters, snow and ice, including their physical, chemical and biological processes, their relation to climate and to other physical and geographical factors as well as the interrelations between them;
- to study erosion and sedimentation and their relation to the hydrological cycle;
- to examine the hydrological aspects of the use and management of water resources and their change under the influence of man's activities;
- to provide a firm scientific basis for the optimal utilization of water resources systems, including the transfer of knowledge on planning, engineering, management and economic aspects of applied hydrology.

http://www.cig.ensmp.fr/~iahs/

IUGS-IAS: International Association of Sedimentologists: Objectives of the Association are to promote the study of Sedimentology by publication, discussion and comparison of research results, encouraging the interchange of research, particularly where international cooperation is desirable, and promoting integration with other disciplines.
http://www.iasnet.org/

IUGS/AAPG-IAMG: International Association of Mathematical Geologists: Promotes international cooperation in the application and use of mathematics in geological research and technology. IAMG has historical specialties in quantitative stratigraphy and global databases.
http://www.geomorph.org/

IUGS-IAG: International Association of Geomorphologists: A scientific, non-governmental and non-profit organization, whose principal objectives are to promote an international understanding of the science and nature of geomorphology.
http://www.iamg.org/

AGU: American Geophysical Union: Advances the geophysical sciences and serves the public good by:

- Informing and educating the public and by demonstrating the relevance of geophysical research to society,
- Fostering a strong and diverse Earth and space science workforce by educating students and teachers and supporting professionals at all stages of their scientific careers,
- Providing a basis for the development of public policy activities worldwide.

http://www.agu.org/