River, Coastal and Estuarine Morphodynamics: RCEM 2009 – Vionnet et al. (eds)

Morphodynamic models: An overview

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ABSTRACT: Morphodynamic modeling involves fluid dynamics, geodynamics and ecodynamics with and without human interaction. Scales are immense, whether the dimensions are time or space. Morphodynamic models are ever increasing in the processes they incorporate, and in their dimensionality. Challenges facing the morphodynamic modeling community include: upscaling, process coupling, model coupling, data systems, high-performance computing, and model testing.

1 INTRODUCTION

The science of morphodynamics involves the response of bathymetry to fluid dynamical processes, and the interaction that each has on the other (Wright & Thom 1977). Since this early definition, the morphology portion of the term has correctly expanded to include topography or any earth-surface elevation change; the dynamics portion has expanded beyond fluid interactions to include ecodynamics and geodynamics, and even human dimensions. Morphodynamics in other scientific realms has other meanings; for example developmental morphodynamics involves the physical and geometrical principles that underlie biological processes during development. This article presents an overview of earth-surface morphodynamics from a modeler's perspective, with contributions from the scientific chairs of the Community Surface Dynamic Modeling System (csdms.colorado.edu/wiki/). The article is not a review of the literature, which is vast (Syvitski et al. 2007). Rather the paper focuses on general trends and areas for future developments. We begin with modeling aspects concerning the terrestrial environment, then move into coastal and estuarine environments, the open marine environment including carbonate morphodynamics, and end with a limited discussion on high performance computing in relationship to turbidity currents.

2 TERRESTRIAL MORPHODYNAMIC MODELS

2.1 *Introduction*

Morphodynamic processes and phenomena on land range vastly in scale, from eolian ripples to mountain chains. Terrestrial morphodynamic models have been developed to address a correspondingly wide range of research problems, from the shape of a sand dune to potential feedbacks between climate and tectonics in a continent-continent plate collision.

Terrestrial morphodynamic models share the common elements of describing evolving forms as a function of physical and/or chemical transport processes. Thus a critical challenge has been the formulation, testing, and refinement of mathematical functions that describe the rate of mass transport by a particular process, either from point-to-point in space (as in sand transport by a river) or from one form into another (as in the conversion of rock into sediment and solutes by erosion and weathering processes). The development of transport laws has been accompanied by the creation of time-evolving numerical models of landform evolution, which combine one or more transport laws with a continuity of mass framework to describe the morphodynamics that emerge from various combinations of processes, materials, and driving forces. Models of this type cover a broad range of time and space scales, but in nearly all cases the data necessary to test these models have lagged behind the models themselves. This is particularly true for longer-term models.

2.2 *Geomorphic transport laws*

Dietrich et al. (2003) define a geomorphic transport law as "a mathematical expression of mass flux or erosion caused by one or more processes acting over geomorphically significant spatial and temporal scales." Geomorphic transport laws include expressions for physical transport of mass from place to place, and expressions for transformation of mass between one form and another (such as the conversion of rock to soil or vice versa). A hallmark of geomorphic transport laws is that they describe time-integrated mass fluxes, rather than transport during a particular event such as an individual landslide or debris flow. When geomorphic transport laws are combined with a continuity of mass equation, the result is a mathematical expression of morphodynamic evolution (e.g. Kirkby 1971).

Geomorphic transport laws can be grouped into those that deal with (1) physical alteration of rock by weathering to form soils or regolith, produce solutes, and generate solutional landforms, (2) transport of sediment mass by primarily gravitational processes, (3) erosion and transport by moving liquid water, (4) transport and erosion by flowing ice, and (5) transport and erosion by wind. Since the 1960s, many geomorphic transport laws have been proposed for hillslope sediment transport processes (e.g. Carson & Kirkby 1972), and to a lesser extent for transport in streams and other environments. However, relatively few of these transport laws have been properly tested, as the time scales involved make testing difficult.

Dietrich et al. (2003) provide a perspective on the current status of geomorphic transport laws for hillslope and channel processes. Recent work has provided empirical support, for example, for the hypothesis that the rate of bedrock transformation into regolith tends to decline with increasing soil-mantle thickness (e.g. Heimsath et al. 1997, Small et al. 1999), with evidence for a maximum production rate under a finite cover thickness in some environments (Anderson 2002). However, at present the rate coefficients must be calibrated in the field, and their dependence on factors such as climate, materials, and biota is poorly known. Hillslope soil creep has received considerable attention, leading to linear and nonlinear slope-dependent transport laws that are supported by observational and experimental data (e.g. Roering 2008). However, much work remains to be done to develop well-tested transport laws for other forms of gravitational mass movement, such as slump-style mass wasting and debris flows (e.g. Stock & Dietrich 2006). Transport laws for sediment movement by rivers are well developed, in the sense that there are many formulas for bed-load and suspended-load sediment transport. Development of models for river incision into bedrock has been an area of particularly active research recently. Several different models have been proposed (e.g. Whipple 2004), and there has been a significant ongoing effort to compile data sets to test current models and distinguish between alternative formulations (e.g. Stock & Montgomery 1999, Snyder et al. 2003, Tomkin et al. 2003, van der Beek & Bishop 2003, Whittaker et al. 2007). Progress is also ongoing for transport and erosion by ice (e.g. Hallet 1996, MacGregor et al. 2000) and wind (e.g. Werner 1995).

2.3 *Coupled modeling of landform evolution*

Numerical models of landform evolution combine one or more geomorphic transport laws with a continuity of mass equation in order to simulate the time evolution of landforms. Models of three-dimensional hillslope and drainage basin evolution were introduced in the 1970s (Ahnert 1976, Armstrong 1976). The number and sophistication of models have since increased tremendously. Figure 1 shows an example of a landscape evolution model in a configuration that combines an eroding source terrain on a rising fault block with a depocenter on a subsiding block. This type of model typically represents terrain using either a regular grid or an unstructured polygonal mesh (Braun & Sambridge 1997, Tucker et al. 2001), and routes water across the surface using either a cellular algorithm or a numerical solution to an approximate form of the shallow-water equations. Water fluxes drive erosion and transport, and cell elevations evolve through time in response to the resulting mass flux.

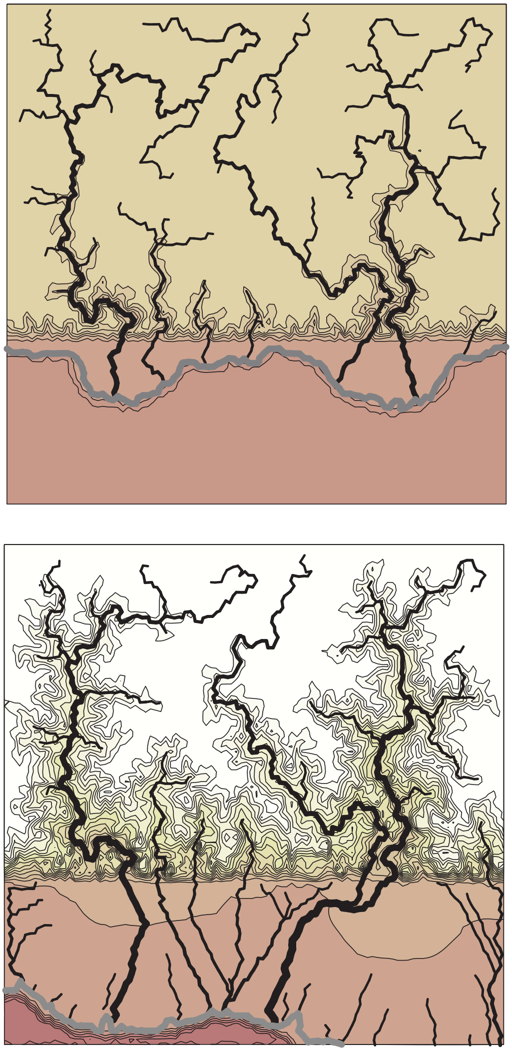

Figure 1. Example simulation using the CHILD landscape evolution model (Tucker et al. 2001), showing erosion of a rising source terrain and growth of fan delta complexes on a subsiding fault block. Domain size is 10 × 10 km.

Among current landscape evolution models, some have targeted small-catchment scales and relatively short time periods, ranging from the late Quaternary to the Anthropocene (e.g. Willgoose et al. 1991, Coulthard et al. 1998). Others address regional to subcontinental scales associated with problems such as orogenesis and flexural isostasy (e.g. Beaumont et al. 1992, Tucker & Slingerland 1996, van der Beek & Braun 1999). Commonly the models address fundamental theoretical issues such as the initiation and growth of channels (Smith et al. 1995), the regular spacing of drainage basins (Perron et al. 2008), and location-specific applications.

The majority of landscape evolution models have focused on terrain formed around hillslopes and channel networks. The most basic form of such models combines a diffusion equation for hillslope transport with either an erosion law or a sediment transport formula that is a function of local slope and drainage area (as a surrogate for water discharge) (Willgoose et al. 1991, Moglen & Bras, 1995, Simpson & Schlunegger 2003). Many models have since grown to include additional phenomena and capabilities. For example, some models have addressed transport of multiple grain-size fractions in river networks (Coulthard et al. 1998, Gasparini et al. 1999, 2004, Clevis et al. 2003, 2006, Sharmeen & Willgoose 2006). Although many models have been developed to explore the genesis of erosional topography, there has been increasing attention to coupled erosional and depositional systems (e.g. Johnson & Beaumont 1995, Clevis et al. 2003, Shennan et al. 2003, Fagherazzi et al. 2004).

Stratigraphically oriented applications range from the orogen scale (Johnson & Beaumont 1995) to the scale of individual alluvial fans and river valleys (Coulthard & Macklin 2003, Clevis et al. 2006, Nicholas & Quine 2007). In this example from Clevis et al. (2006), the model domain is a segment of a meandering river valley (Fig. 2). A river meandering sub-model (Lancaster & Bras 2001) is used to compute the evolution of the channel planform through

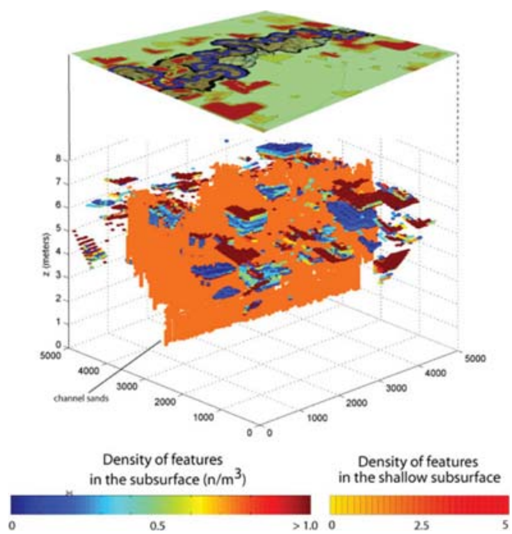

Figure 2. Cut away image from a high-resolution CHILD simulation of stratigraphy beneath a meandering-river valley, showing distribution of channel sands (orange) and density of associated archaeological features. Meandering channel is shown in blue on surface image. From Clevis et al. (2006).

time, while overbank deposition rate in response to a stochastic sequence of floods depends on local flood depth and distance from the main channel. Such simulations enable one to visualize the relationships between depositional processes and the resulting stratigraphic patterns.

The past ten years have seen a rapid proliferation of applications and capabilities of landscape evolution models. Although a comprehensive review is beyond the scope of this paper, there have been several excellent papers in recent years that review various aspects of models and their application (Beaumont et al. 2000, Coulthard 2001, Wilcock & Iverson 2003, Martin & Church 2004, Willgoose 2005, Codilean et al. 2006, Bishop 2007, Coulthard & Van de Weil 2007).

2.4 *Testing landscape evolution models*

The development of data sets for testing landscape evolution models has tended to lag behind the development of the models themselves. For obvious reasons, this is particularly true for longer-term applications. To date, quantitative tests of models have focused on the use of terrain statistics. G. Willgoose and G. Hancock of U. Newcastle in Australia have, together with colleagues, contributed significantly to developing methods for testing of landscape evolution models using terrain statistics such as the slope-area relationship, as well as experimental data (Willgoose 1994, Willgoose et al. 2003, Hancock & Willgoose 2001, Hancock et al. 2002).

For fluvial process laws, it has been recognized that cases of transient response are generally more diagnostic than steady cases (Whipple & Tucker 2002). This has motivated the search for natural experiments in transient landscape evolution, such as the case of accelerated fault motion studied by Whittaker et al. (2007) and Attal et al. (2008). In general, there remains a pressing need to identify and develop natural experiments in that provide strong constraints on terrain evolution, whether through preserved sediment volumes, cosmogenic isotope data, thermochronology, preserved remnants of past land surfaces, or (ideally) a combination of several of these sources.

2.5 *Outlook*

A large and growing number of models have been developed to compute the morphodynamic evolution of land surfaces. These span a range of process combinations, scales, and levels of detail. In many cases, the geomorphic transport laws in these models remain relatively poorly tested, and one of the most pressing needs is to identify data sets that can provide meaningful tests of terrestrial morphodynamic models at the proper time and space scales. As with many types of environmental model, scaling presents a challenge, and thus an additional research imperative is analysis of how the rules governing surface mass fluxes change at different levels in the scale hierarchy.

3 COASTAL MODELS

Gaps in knowledge and modeling capabilities that apply across the coastal environments include:

- Different models are required to address different questions at different scales, yet the processes at different scales interact. Thus we need to better 'up-scale' or parameterize the effects that smaller- and faster-scale processes collectively have on larger-scale processes. For example, ripples and small-scale bedforms affect—and are in turn affected by—currents and sediment transport patterns on scales much larger than those of the small bedforms.
- Limited techniques for including the processes involved in cohesive and mixed sediments.
- Better methods to include the two-way communication between coastal change, and those of land use and direct human manipulation (such as beach stabilization). The two-way coupling likely plays a first-order role in steering the evolution of many coastal landscapes, but our ability to model these couplings, and the resulting feedbacks, remains in its infancy.
- Coupling of models of different sub-environments, e.g. beaches, marshes, estuaries and rivers, represents a ubiquitous challenge—one of the central challenges of CSDMS.

3.1 *Tidal marshes and lagoons*

A number of new models explore interactions between sediment transport and vegetation growth in tidal environments (e.g. Fagherazzi et al. 2006, D'Alpaos et al. 2007, Kirwan & Murray 2007; Marani et al. 2007, Temmerman et al. 2007). These models find that feedbacks between vegetation growth and the depth of water inundating an intertidal surface strongly influence the morphology of these environments and their resilience to changes in rates of sea level rise and sediment delivery. Many models consider the effect of vegetation on channel flow, wave erosion, and sediment settling, resulting in potentially complex interactions and multiple stable equilibria. An increase in inundation associated with increased rates of sea level rise has been shown to increase the stability of salt marsh ecosystems by increasing vegetation productivity, sediment trapping efficiency, and contributions of organic matter. Increases in inundation on the marsh tend to increase the efficacy of wave erosion, the volume of water contributed to the channel network (leading to channel erosion), and in some cases the reduction of vegetation biomass.

Interactions between these components lead to the common model observation that vegetated intertidal surfaces and unvegetated subtidal mudflats can occur as alternative stable equilibrium states for a single combination of sea level rise rate and sediment supply (Kirwan & Murray 2007, Marani et al. 2007).

Several knowledge gaps require these types of models to be primarily used for exploring interactions between biotic and abiotic components, rather than for predictive purposes. In particular, vegetation treatments are in their infancy. Vegetation biomass typically increases with inundation duration in these models (Morris et al. 2002, Kirwan & Murray 2007), though some (D'Alpaos et al. 2007, Marani et al. 2007) also consider the opposite scenario. It remains unclear whether these types of relationships are generally applicable to a variety of regions and vegetation types, or if they should be determined locally and for each type of vegetation. While research has focused to date on tidal surfaces covered by salt marsh vegetation, similar modeling approaches may provide useful insight into the morphology and evolution of surfaces covered by mangroves, freshwater marshes, sea grasses, and macrophytobenthos.

Because intertidal environments occur at the interface of marine and terrestrial environments, they provide an exceptional opportunity to explore interactions between terrestrial, coastal, and marine systems. For example, terrestrial land use change can lead to dramatic changes in the morphology and stability of salt marshes by altering sediment delivery rates to the estuary. Characteristics of the adjoining coastal and marine systems are also important. Direct wave erosion may exceed rates of marsh loss due to sea level rise, and tidal amplitude is widely considered an important variable controlling the ability of marshes to maintain elevation relative to rising sea level. Barrier islands and marshland may represent a system that evolves co-dependently, and whose survival depends directly on interactions between its components. Characteristics of barrier islands (e.g. morphology, rate of retreat) depend directly on the topography of the surface over which they retreat, and the elevation of marshes depends on barrier characteristics (e.g. sediment deposition due to overwash events, exposure to wave erosion, tidal amplitude). In areas with depleted sediment sources and high sea level rise rates, survival of marshland may depend on overwash events, and the survival of barrier islands may depend on the presence of high elevation marsh to retreat over.

3.2 *Deltas*

State of the art models for deltaic systems are highly scale dependent. Engineering models such as Delft3D (Lessera et al. 2004) couple detailed hydrodynamics with morphologic change, and can simulate evolution of a single delta lobe over tens of km and decades, capturing fine-scale plume and bar dynamics within one or a few channels (Storms et al. 2007; Edmonds & Slingerland 2007, 2008). Geomorphologic models using simplified hydrodynamics and sediment transport simulate landscape-scale delta evolution over millenia, capturing planform shoreline and distributary-network dynamics, including avulsion (Sun et al. 2002) and alongshore transport (Ashton & Murray 2005). As in landscape evolution, most geomorphic delta models treat channels using a sub-grid approach, but the recent model by Seybold et al. (2007) resolve channels and levees.

Deltas house large populations and valuable biological and economic resources which are threatened by coastal and riverine flooding, exacerbated by subsidence and sea level rise (Ericson et al. 2006). While current delta models are able to capture self-organized dynamics under a constant forcing regime, effective management of deltaic environments will require understanding of response to changing natural and anthropogenic forcings. CSDMS provides the opportunity to address these issues by coupling delta dynamics to upstream sediment and water supply, downstream waves and sea level, and coastal plain subsidence, using models for each of these components. Deltas with documented millenial-scale changes resulting from anthropogenic forcing (e.g. Ebro, Mississippi) can serve as a useful testing ground for these new coupled delta models.

3.3 *Coastlines*

The majority of existing large-scale coastline models address sandy coastline evolution. The spatial scales addressed in these models range from meters to kilometers while temporal scales range from hours to millennia. The smaller space and time scale models typically employ explicitly reductionist methodologies where conservation of momentum forms the explicit means for evolving the system. Often these models are used to simulate specific locations or response from individual event scale forcing. As an example, XBEACH (Roelvink et al. 2007) uses conservation of momentum and advection diffusion equations for sediment transport to simulate the response of the coast and dune to individual storm events. Larger scale models use a range of approaches to evolve system characteristics. In some cases, model dynamics represent abstractions of fine scale processes. An example of this methodology is the Ashton/Murray (2006) coastline model, in which the dynamics are based on abstracted parameterizations that represent the collective effects of smaller-scale details of sediment transport and on a series of rules for wave shadowing around complex coastlines. In other large-scale models, morphological evolution occurs in response to changes in geometric relationships. An example of this approach is the morphological-behavior model, GEOMBEST (Moore et al. 2007, Stopler et al. 2005).

Large-scale coastal modeling efforts have not yet incorporated some of the processes that are important in the evolution of many sandy coastlines. The role of biology and geochemistry remains an open question, and the role of heterogeneous underlying lithology is only recently being incorporated in numerical models. The role of humans in altering coastlines has only recently been investigated (e.g. McNamara & Werner 2008) and considerable effort remains to augment and explore the impact of coupling humans in varying coastal systems. There is also currently a lack of modeling efforts addressing the evolution of other coastal environments including arctic coastlines and rocky coastlines.

An array of processes contributes to long-term evolution of rocky coasts. During sea level highstands, sea cliffs retreat in response to an incoming wave field through the processes of abrasion, block failure, and microcracking by cyclical wave loading (Adams et al., 2005). Sea cliff retreat rate is also strongly influenced by lithology. Long-term (several kyr) generation and degradation of marine terraces has been simulated by Anderson et al. (1999). Most recently, numerical models of sea cliff evolution have been developed to investigate the response of cliffed coasts to climate change over the 21st century (Dickson et al. 2007, Hall et al. 2006, Walkden & Hall 2005). Links should be developed between a sea cliff retreat model and models simulating other geomorphic systems in the coastal environment. How does wave transformation over a continental shelf influence the alongshore transport and redistribution of sediment, a.k.a. exposure of the sea cliff toe? Over timescales of thousands to millions of years, and spatial scales of 10's to 100's of km, how does an evolving plan-view pattern of sea cliff retreat and alongshore transport pathways evolve and interact with a growing shelf and nearshore-connected submarine canyons that serve as sediment sinks?

4 INTEGRATED ESTUARINE MODELING: CHESAPEAKE BAY CASE

The Chesapeake Bay is the largest estuary in the United States and one of the largest estuaries in the World. The Bay has enjoyed a long history of attention and funding for research, monitoring, and modeling. It is special because it has been under increasing pressure from the growing population on the watershed and the associated economic infrastructure that has been developing. Among other large estuaries, it is probably the most populated and impacted. It also has a remarkably large watershed to waterbody area ratio or about 15, which only adds to the loading that the Bay receives from the land.

4.1 *The CBP models*

Chesapeake Bay modeling has historically evolved around water quality issues. The Chesapeake Bay Program (CBP) was charged to develop the tools needed to support decision making for the Bay, to help establish the Total Daily Maximum Loads (TMDL) and identify the quotas for loading from the five states in the watershed. The CBP modeling suite consists of:

1. The Community Multi-Scale Air Quality modeling system (CMAQ) that produces atmospheric deposition data for nutrients and other constituents;
2. The watershed model (HSPF) that produces loadings that come from the land into the estuaries;
3. The Water Quality and Sediment Transport Model (WQSTM), a 3D model of the tidal Bay, that incorporates a full sediment transport simulation that supports PCB and other toxic modeling efforts. Living resource models of filter feeders and underwater grasses are embedded within the WQSTM.

The modeling system has developed over the past 25 years. The models are linked only loosely. Output from one model is sent as input into the other model as a data file (Fig. 3). Decisions are mostly based on the predictions for the future state of the Chesapeake Bay in terms of such indicators as the area of hypoxia, or suitability of habitat for oysters, while most of the decisions are made for the watershed, where the nutrient load is generated. The estuary model is very much dependent upon the loadings that it receives from the watershed model. Whenever the watershed model gets updated, it produces different output. As a result, every time the watershed model is changed, the estuary model needs to be re-calibrated.

By linking the models together, the overall modeling effort is simplified. However the overall complexity increases every time a new component is linked, making calibration more difficult, and reducing one's ability to understand the whole model suite. While the CBP modeling suite has been criticized

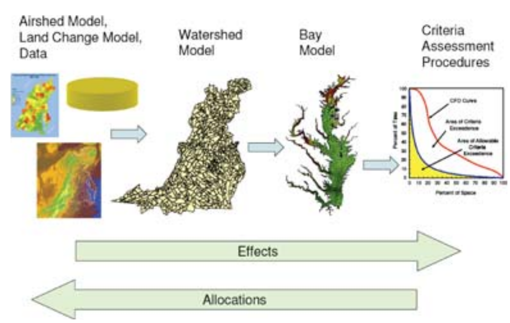

Figure 3. The CBP suite of models. The Airshed model generates nutrient deposition for the watershed model that then calculates the loads that go into the Estuary model.

on several occasions for lacking flexibility, being over-parameterized, and lacking uncertainty analysis, it remains the main decision support tool used for the Bay.

4.2 *Chesapeake bay forecast system*

The Chesapeake Bay Forecast System (CBFS, http:// www.climateneeds.umd.edu/chesapeake/index.html) consists of regional atmosphere, ocean, biogeochemical and land dynamical models that are coupled together to provide comprehensive forecasts of the environmental behavior of the Chesapeake Bay region (Fig. 4). CBFS dynamically downscales global climate forecasts at time scales from sub-daily to interannual and decadal. The CBFS provides 16-day forecasts for the state of the Bay ecosystem. The Weather Research and Forecast (WRF) model, coupled to the NOAH land-surface model at 7.5 km resolution, provides the atmospheric component of CBFS. At present the NOAA/NCEP Global Forecast System model provides lateral boundary forcing for WRF 16-day forecasts. In the future, the Global ENsemble System (GENS) will produce the 16-day WRF forecasts for the Chesapeake Bay and its watershed.

The watershed component of the CBFS is the Soil and Water Assessment Tool (SWAT), which is integrated with NOAH and coupled to the WRF atmosphere. When fully implemented, SWAT will be run for each tributary of the Chesapeake watershed. The land use types, crop types for agricultural lands, point and distributed sources of pollution and nutrients, management data, and other details have been gathered for the Chesapeake watershed starting from 1995 with some future scenario projections of land use.

The Regional Ocean Modeling System (ChesROMS) is used for the marine component of Chesapeake Bay, employing a marine ecosystem model and an Ensemble Kalman filter assimilation system. Freshwater forcing in forecast mode from all the tributaries is prescribed in the demonstration phase from regression relations between historical runoff data and the NARR precipitation over the catchment area. Atmospheric flux forcing for the ROMS is obtained from WRF model forecasts. In the current demonstration phase, the atmospheric component of the CBFS provides forecasts of 16-day long hourly time series of temperature, moisture and winds at the surface and a number of levels in the free atmosphere, as well as precipitation, evaporation and radiation budget components at the surface on a regular grid with a spacing of 7.5 km for the entire Chesapeake Bay watershed region.

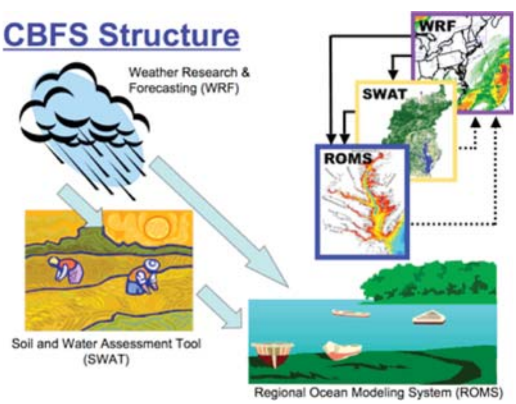

Figure 4. The Chesapeake Bay Forecasting System (CDFS) is made of components models.

SWAT predicts quantities related to surface runoff, including stream flow, sediment load and concentrations, nitrogen load, phosphorus load, algal biomass, carbonaceous biochemical demand, dissolved oxygen, soluble and absorbed pesticide output, bacteria, and metal transported out of the tributaries. The ocean component of the CBFS provides forecasts of currents, temperatures and salinities at a number of levels in the vertical on a regular grid with a spacing of about 3 km. Coupled biogeochemical models provide forecasts of dissolved oxygen, chlorophyll, nitrate, and tidal and non-tidal water levels. Digital elevation models are used in conjunction with water level forecasts to provide predictions of inundation and storm surge at street-level resolution. The goal of the CBFS is to transition to seasonal to inter-annual forecasts, which will be issued once the NCEP Climate Forecast System forecasts for the longer lead-times are available routinely and operationally.

4.3 *Chesapeake inundation prediction system*

The initial prototype uses advanced modeling and visualization techniques to depict expected inundation at a spatial resolution of less than a city block ($\approx$50 m, Fig. 5) and a vertical resolution of $\approx$30 cm in a time-step display of one hour or less (Stamey et al. 2007). The system is driven by the coupled WRF—regional atmospheric modeling system, coupled with LIDAR data and the ROMS hydrodynamic models. NOAA's Middle Atlantic River Forecast Center will provide river discharge forecasts from the Advanced Hydrologic Prediction Service.

4.4 *Chesapeake community modeling program*

The CCMP (ches.communitymodeling.org/index.php) is developing an open-source shared modeling effort driven primarily by researchers from Universities collaborating within the Chesapeake Research Consortium (CRC). The CCMP is soliciting various open source components that can be then rearranged depending upon the needs of particular applications and

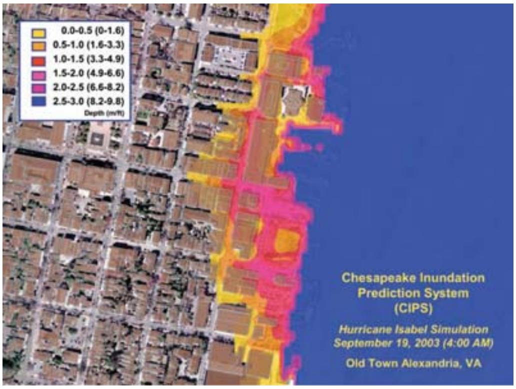

Figure 5. The visualization that the CIPS framework is going to provide to emergency managers.

projects. CCMP, and its CSDMS partner, takes advantage of the wealth of data accumulated over the many years of monitoring and measurements throughout the Bay, providing a unique test bed for models, and effort supported by the Chesapeake Bay Environmental Observatory (CBEO, cbeo.communitymodeling.org/testbed_data.php) team, which seeks innovative ways to explore, present, analyze and disseminate data related to the Chesapeake Bay (CBEO 2008). As more CCMP research is merged with the CSDMS development, outreach to stakeholder is likely to emerge as the major focus of the program.

5 MARINE MORPHODYNAMIC MODELING

Over the last 30 years or so, the development and application of numerical models for marine environments has produced significant advances in our understanding of and ability to predict short-term sediment processes on shelves and slopes and long-term stratigraphic evolutions of continental margins (Syvitski et al. 2007); ongoing and future modeling efforts on these problems will continue to be important. Advances in model capabilities, concomitant with our growing understanding of marine surface dynamics, have poised the marine modeling community to move in several new directions. These include models that integrate hydrodynamics, sediment dynamics, morphological response and, in some cases, biological and biogeochemical processes to better represent the complex coupled dynamics and feedbacks present in marine systems; models that bridge the coastal divide and couple terrestrial and marine environments ("source-to-sink"); and models that more directly relate short-term processes to long-term morphological and stratigraphic response. This section will briefly describe an example or two from each of these 3 directions in marine modeling.

5.1 *Models that integrate processes within the marine environment*

Surface dynamics in the marine environment is critically tied to ocean hydrodynamics. Recent advances in computer hardware and software have paved the way for a number of efforts to develop the next generation of hydrodynamic models for the ocean, including ROMS (the Regional Ocean Modeling System; www.myroms.org), FVCOM (The Unstructured Grid Finite Volume Coastal Ocean Model; fvcom.smast.umassd.edu/FVCOM) and Delft3D (delftsoftware.wldelft.nl). In addition to resolving 3D flow fields, modules for calculating sediment transport, water quality, sea ice, and biogeochemical and biological processes are available or are being developed for these models, making them valuable tools for exploring complex surface dynamics and transport problems in the marine environment.

The NOPP Coastal Sediment Transport Modeling System (CSTMS; www.cstms.org; Warner et al., 2008) project is building on ROMS, adding additional hydrodynamic, sediment transport and morphodynamic algorithms to enable realistic and useful simulations of processes that influence sediment transport in the coastal ocean (e.g. Fig. 6), including estuaries, nearshore regions, and the continental shelf over regional length scales (10's of meters to 100's of kilometers) and time scales ranging from transport events to decades. Sediment process modules being added to ROMS through CSTMS include ones for fluid mud, sediment gravity flows and flocculation, each of which has the potential to affect the hydrodynamics, creating feedbacks that the coupled model will be able to capture.

5.2 *Models that couple source to sink*

The problem of linking terrestrial processes to coastal and marine processes has begun to receive considerable attention during the last 15 years. Programs including the ONR STRATAFORM (Nittrouer et al. 2007) and EuroSTRATAFORM (Milligan & Cattaneo, 2007; Wiberg et al., 2008) programs, the NSF MARGINS Source-to-Sink program and now the CSDMS program are contributing critical observations and models to address these linkages. A recent example of the use of models and observations to study the phasing and dispersal of river sediment delivery to the coastal ocean comes from a MARGINS study by Bever et al. (2009) in the Waipaoa Sedimentary System (WSS), New Zealand, part of a larger effort to study transport pathways and sediment dynamics within a system that spans source areas in the headlands to marine depositional sinks.

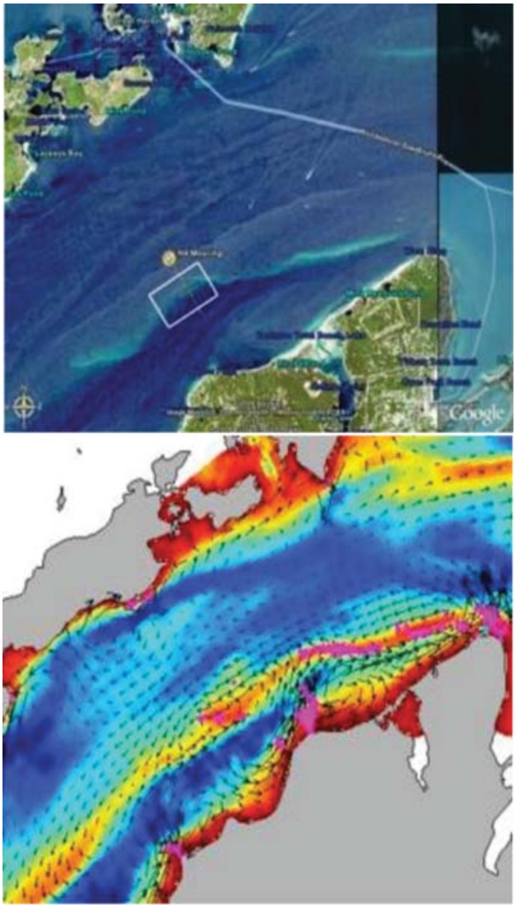

Figure 6. Example application of the CSTMS to shoal formation at Middle Ground, Vineyard Sound, MA. Middle Ground is apparent in the air photo (left panel; Google Earth with IKONOS imagery). The tidal-residual circulation (arrows, right panel) in the CSTM simulations generates sediment transport consistent with observed bedform migration patterns. Modeled long-term deposition (magenta symbols) occurs on the crest of the shoal (bathymetry is shown in color) (Courtesy of R.P. Signell; www.cstms.org).

Poverty Bay, the shallow marine portion of the WSS, has displayed shoreline progradation over the past 7 ky, but currently seems to deliver most of its fluvial load to the continental shelf, offshore. Bever et al. (2009) used ROMS to estimate hydrodynamics and sediment transport during a winter storm and flood season that overlaps observed water column currents, turbidity, and wave properties and seafloor mapping. Tides, waves, winds and freshwater input were accounted for in the hydrodynamic modeling. An estuarine-like pattern of circulation emerged from the ROMS model, where surface waters were directed seaward and nearshore flows were landward, likely in response to baroclinic pressure gradients combined with offshore directed winds. Depositional patterns reflected counterclockwise circulation, with sediment deposited in the middle and towards the southern side of the bay (Fig. 7A). Sediment deposition during storms occurred offshore of the river mouth (Fig. 7C), but this material was subsequently resuspended and transported out of the bay towards the shelf (Fig. 7B). Model results indicated that sediment dispersal from the bay during floods might take a different pathway than material that is resuspended after a period of ephemeral deposition.

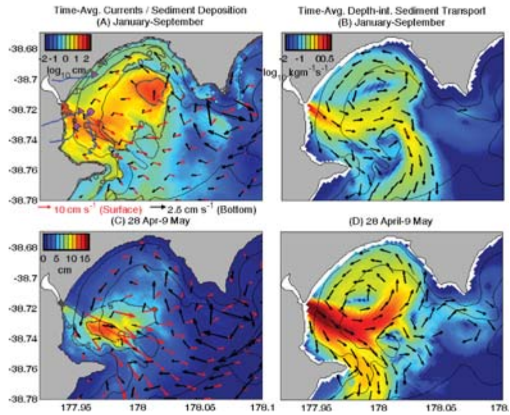

Figure 7. (A, C) Time-averaged currents (arrows) and sediment deposition (colors) over the time frame in the titles. (C, D) Depth-integrated and time-averaged sediment transport direction (arrows) and magnitude (colors), showing the estimated direction and magnitude of sediment transport from the Waipaoa River mouth during 2006. April–9 May encompasses a moderate storm (from Bever et al., 2009).

5.3 *Models that relate short-term processes to longer-term evolution of morphology*

The problem of upscaling from event time scales (storms, floods, slope failures) to morphologically or stratigraphically relevant time scales (usually 1000's of years or more), is one of the most challenging problems in surface dynamics modeling. Several approaches are possible, including the use of simplified models that attempt to capture the dominant short-term process responsible for long-term change and the use of more detailed models to parameterize relationships that can be applied over longer time scales. An example of each is provided here.

Friedrichs & Scully (2007) developed The Wave and Current Supported Sediment Gravity Flow Analytical Model (WSGFAM), a 2-D discretization of depth-integrated analytical equations for the gravity-driven transport of fine sediment, to simulate annual cycles of flood-induced sedimentation on several riverine shelves around the globe (Fig. 8). The governing equations of WSGFAM are (i) a Chezy-type balance between the sediment-induced down-slope pressure gradient and bed friction, (ii) a bulk Richardson-number criteria which limits to total suspended load, and (iii) the Exner equation for bed change in response to flux convergence or divergence. External forcings/boundary conditions include initial shelf bathymetry, wave height and period and a line-source of riverine sediment input along the coastline. Results for predicted deposition patterns are most sensitive to (in order of decreasing importance) (i) shelf bathymetry (both depth and slope), (ii) strength and time-history of ambient waves and currents, (iii) sediment supply along the coast, and (iv) model coefficients.

Slingerland et al. (2008a; 2008b) have been investigating the structure and evolution of clinoforms on the inner shelf of the Gulf of Papua (GoP) off the Fly River to determine how clinoform morphology and internal geometry vary as a function of relative sea level fluctuations, changes in sediment flux to the shelf, and oceanographic processes dispersing sediment across the shelf as part of the MARGINS Source-to-Sink program. To derive causal relationships between oceanographic processes and clinoform characteristics, they hindcast a year of tidal, oceanic, and wind- and thermohaline-driven currents in the Gulf of Papua using NCOM, the US Navy Coastal Ocean Model embedded inside EAS16 NFS, an experimental real-time 1/16th degree ocean nowcast/forecast System developed by the U.S. Navy for the East Asian Seas (Barron *et al*. 2004).

The upper 100 m of the Gulf of Papua Shelf comprises two stacked clinothems—an older deeply eroded clinothem forming the middle and outer shelf, and a superjacent younger clinothem extending from the coast offshore, forming the inner shelf. Computed annual circulation of the GoP in response to trade wind and monsoon conditions shows that the flow fields are significantly more complex than previously understood (Fig. 9). During trade winds sediment particle paths on the clinoform top are obliquely offshore to the east. A zone of convergence lies near the 25 m isobath along the clinoform face, where offshore-directed waters on the shelf meet onshore-directed bottom waters climbing the clinoform face, possibly localizing sediment deposition there. This could be a mechanism for clinoform formation and explain the dearth of modern sediment offshore. During monsoon conditions, average bottom flow is landward on the modern clinoform top and minimal over much of the slipface, suggesting that variations in sediment type at the bed level may be circulation related and seasonal.

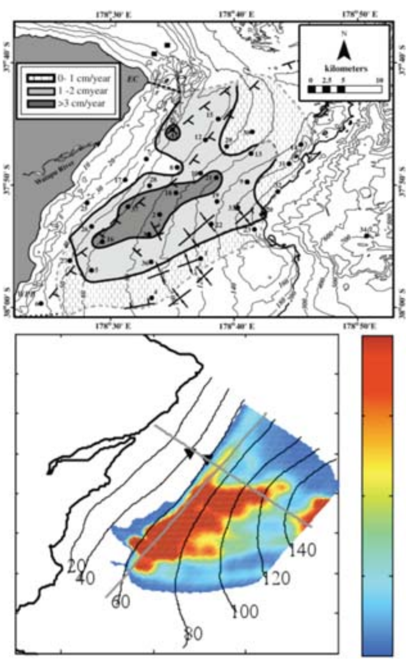

Figure 8. Comparison of observed shelf mud deposits with those predicted by the WSFAM model for the Waiapu shelf, northeastern New Zealand, for (a) observed 210-Pb sediment accumulation rate (Kniskern et al., in press) and (b) modeled deposit thickness from winter 2004 floods (Courtesy of C.T. Friedrichs).

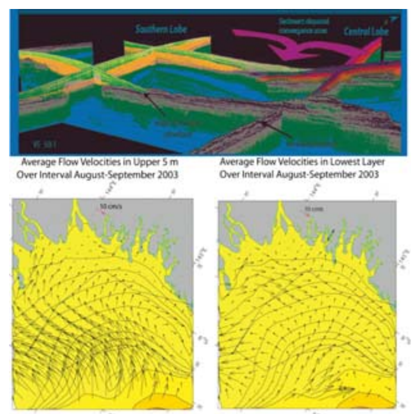

Figure 9. A) Chirp fence diagrams of the GoP clinothems showing a southern lobe downlapping the central lobe. The downlapping stratal geometry of the southern lobe onto the central lobe suggests an abrupt shift in the loci of deposition away from the central lobe. Sediment rerouting due to oceanographic changes accounts for this dramatic shift in the depositional lobes (from Johnstone et al. unpub.). B) Surface and C) bottom currents predicted by the EAS16NFS during the 2003 trade wind period in the Gulf of Papua (Courtesy of R.L. Slingerland).

The overall potential transport pathways presumably indicate that the majority of sediment will be deposited on the inner shelf between the Fly and Kikori Rivers, although the disparity between fluvial sediment input and total post-LGM sediment volume within the modern clinoform, on the other hand, suggests a major escape, perhaps to the west.

6 CARBONATE MORPHODYNAMIC MODELS

A key difference between siliciclastic and carbonate morphodynamic forward models is inclusion of chemo-biological elements in the later to calculate in-situ production of carbonate sediment. In carbonate systems, unlike in siliciclastic systems, much material that accumulates and is preserved as strata was produced in-situ by living organisms that precipitated calcium carbonate from solution in sea-water to form their skeletal elements. These skeletal elements are then disarticulated and broken down to create carbonate sediment. Sediment transport is also a key process in carbonate systems, but before any sediment can be transported, it must be produced. Carbonate sediment production is typically modeled as a water-depth dependent process using a depth production profile, either based on measured levels of light in the water column (Bosscher & Schalger 1992) or inferred from modern or ancient carbonate accumulations (Pomar 2001).

6.1 *Modeling large-scale platform architecture*

Many carbonate morphodynamic models focus either on replicating one of the types of carbonate platform system (e.g. flat-top attached platforms), or on replicating a sub-system within a particular platform type (platform interior strata). Production-depth profiles play a key role in determining carbonate platform architectures. Some of the earliest carbonate forward models successfully reproduced basic progradation geometries in two-dimensions (e.g. Bice 1988). Bosence & Waltham (1990) followed with an illustration from a 2D model of how relative sea-level oscillations could control platform geometry.

More recent morphodynamic modeling to recreate basic platform geometries has demonstrated, for platforms generally (Warrlich et al. 2002), the Oligocene to Recent of the Bahamas (Eberli et al. 1994), the Miocene and Pliocene in Mallroca (Bosence et al. 1994, Huessner et al. 2001) and the Triassic of the northern margin of Tethys (Emmerich et al. 2003), details of their depositional history and the factors that might control their development, including early diagenesis (Whitaker et al. 1997; Whitaker et al. 1999). Carbonate ramp platforms remain relatively poorly understood in terms of their formative processes, and modeling helps illustrate how sea level control (Read et al. 1991) and interactions of sediment production and transport (Aurell et al. 1998, Warrlich et al. 2008) may contribute to their formation. This work illustrates the power of morphodynamic models to generate concepts and hypotheses that can then be tested with outcrop and subsurface data, but care must be taken not to over-interpret the model results, particularly when geometries are dominated by the initial model conditions (e.g. Schlager & Warrlich, in press).

6.2 *Modeling platform interior stacking patterns*

Cyclicity in carbonate strata, particularly platform interior strata, has been a fruitful topic for morphodynamic modeling since the earliest models were developed to investigate it (Read et al. 1986, Spencer & Demicco 1989). Goldhammer et al. (1990) used a 1D model to investigate the influence of composite eustasy, and found, perhaps unsurprisingly in the absence of many other processes, that simple, hierarchical oscillations in relative sea-level produced ordered, hierarchical allocyclic strata, though they noted that accumulation is modulated by varying subsidence regime. Barnett et al. (2002) used two different models, one 2D allocyclic model and one autocyclic 3D model to conclude that Visean strata were most likely controlled by combined third and forth order eustatic oscillations, and Paterson et al. (2006) reached a similar conclusion about ice house platforms generally using a 3D model, but also made some interesting observations about unfilled accommodation and bucket-morphologies on ice-house platform tops.

Morphodynamic modeling has investigated the influence of autocyclic processes on stacking and facies partitioning in platform interiors. Ginsburg (1971) first proposed a simple and elegant process of autocycle generation based on observations from modern carbonate shorelines, and led to the development of an autocycle model based on migrating islands on a platform top (Pratt & James, 1986). A 2D model reproduced the Ginsburg model, generating unforced cyclicity via shoreline and tidal flat progradation (Demicco 1998), and subsequence 3D modeling studies explored the Ginsburg process more fully showing how it could be an important contribution to cyclicity in platform-top strata (Burgess et al. 2001, Burgess & Emery 2005, Burgess 2006). Burgess (2001) showed how parasequence thicknesses and stacking patterns commonly attributed to forcing by relative sea-level changes could also be attributed to autocycles influenced by variations in production and transport rates, perhaps related to climatic fluctuations. Burgess & Wright (2003) used a hybrid deterministic and stochastic 3D model to show how autocyclic platform interior strata may be highly discontinuous, with low stratigraphic completeness. Results from these morphodynamic models suggests that development of platform interior strata may be considerably more complicated than previous generations of numerical model suggested, and more complicated than most sequence stratigraphic models currently used to interpret outcrop data.

6.3 *What next?*

Despite significant effort in formulating, testing and inverting forward morphometric models, significant issues remain with applications aiming to reproduce and predict specific stratal geometries from outcrop or subsurface data because of issues like sensitive dependence that place severe limits on deterministic predictive power (Burgess & Emery 2004, Tetzlaff 2004). Warrlich et al. (2008) claimed progress in this area with a 3D carbonate model, but typically best-fit modeling approaches have tended to suffer from issues of an overly-simple objective function and potentially circular reasoning whereby parameters derived from interpretations of data were input into the model, which then rather unsurprisingly reproduced the same interpreted geometries; it remains unclear what this actually demonstrates, or what predictive power a single best-bit model of this type actually has.

More experimental approaches constructing models to formulate hypotheses of the form "what strata geometries would result if a carbonate system worked as follows" represent a possibly more useful application of carbonate morphometric modeling. Recent examples include Drummond and Dugan (1999) who used cellular automata to reproduce negative exponential thickness-frequency relationships observed in outcrop successions. Given our still incomplete understanding of the origins of these basic thickness-frequency relationships (Burgess, 2008) this seems like a very fruitful avenue of investigation for the next-generation of carbonate morphodynamic models.

7 HIGH-PERFORMANCE COMPUTING: TURBIDITY CURRENTS

Turbidity currents can be maintained for hours or even days, transport many km^3 of sediment each, and they can propagate along the ocean floor over distances up to 1,000 km. The sediment deposits generated by these currents, known as turbidites, extend over tens or even hundreds of kilometers along the bottom of the ocean. They frequently are hundreds of meters deep and exhibit pronounced, self-organizing topographical features such as channels and gullies, levees and sediment waves. These individual features, with horizontal length scales ranging from O(100 m) to several kilometers, and depths from a few to hundreds of meters, may subsequently become charged with oil and/or gas. Hence they play an important role in determining the spatial extent and geometry of individual oil and gas reservoirs (Syvitski et al. 1996).

Physics-based computational modeling of the sediment transport and deposition by turbidity currents has the potential of playing an important role in producing reliable reservoir models of turbidite deposits. To date, efforts in this regard have been based almost exclusively on simplified sets of equations such as depth-averaged models (see Huppert 2000, Syvitski et al. 2007). While this approach requires only moderate computational resources, it invokes drastic, physically questionable simplifications and requires a number of empirical assumptions that make it unsuitable for predictive purposes. In contrast, the capability to perform high-resolution simulations based on physically realistic models allows for the detailed reproduction of the processes leading to the formation of sediment deposits in the form of levees, channels and sediment waves, including the spatial distributions of grain sizes, porosity and permeability. Over the last decade, high-fidelity computer simulation models for these complex processes of sediment transport and deposition by turbidity currents have been developed (e.g. Necker et al. 2002, Blanchette et al. 2005, Necker et al. 2005). These models are based upon the fundamental physics of the flows, utilizing direct numerical simulations (DNS) to solve the Navier-Stokes equations; they are not dependent upon empirical or arbitrary rule sets to generate geologically plausible results. The simulations are fully three-dimensional, incorporate erosion as well as deposition, respond dynamically to pre-existing and evolving bed topography, account for high-density effects in the flows, and explicitly describe the thickness and grain-size distribution of the resulting deposits.

7.1 *Progress to date and future challenges*

Figure 10 shows a snapshot of one of the largest simulations carried out to date (from Gonzalez-Juez, pers. comm.). These simulations employ $O(10^8)$ computational grid points, and they typically run for several weeks on O(100) processors of midsize or larger clusters. The CPU effort required for such simulations is largely a function of the Reynolds number of the flow. Today, we can carry out direct numerical simulations (DNS) for Reynolds numbers of $O(10^3–10^4)$ and large eddy simulations for $O(10^4–10^5)$, which corresponds to typical laboratory size flows. In contrast, large scale turbidity currents in the ocean are characterized by Reynolds numbers of $O(10^9–10^{10})$. From basic scaling considerations for turbulent flows (Tennekes & Lumley 1972), we know that the ratio of the largest to the smallest scales in the flow increases as $Re^{3/4}$. For three-dimensional simulations this implies that the number of required grid points scales as $Re^{9/4}$.

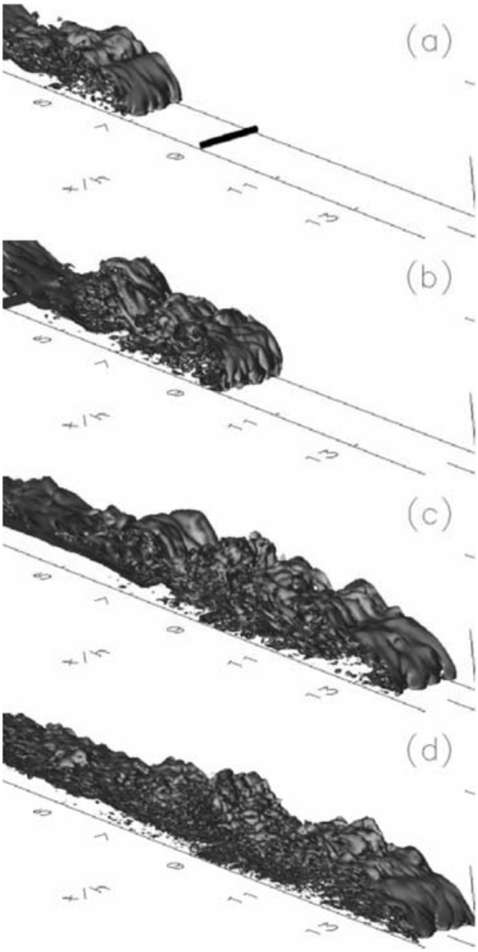

Figure 10. Temporal evolution of a gravity current flow over a cylindrical obstacle such as a submarine pipeline (from Gonzalez-Juez et al. 2009).

Since the number of required time steps typically increases as $Re^{3/4}$ as well, the overall computational effort can be estimated to scale as Re^3.Note that this estimate is based on the (optimistic) assumption that the computational effort scales linearly with the number of grid points. Based on the above scaling argument, the overall computational effort required for a DNS simulation of a geophysical turbidity current with $Re = 10^{10}$ is $O(10^{18})$ larger than for the case shown in Figure 8, so that DNS simulations of geophysical turbidity currents will be out of reach in the foreseeable future even on the largest computing facilities. Some progress can be accomplished with advanced turbulence modeling approaches. However, for complex, variable density two-phase flows such as turbidity currents, with the additional complication of a bottom topography evolving as a result of sedimentation and erosion, this approach is fraught with its own uncertainties, so that other advances should be exploited to the maximum extent possible, in order to perform simulations of the highest possible fidelity.

Advanced adaptive meshing approaches offer some promise in this regard. As can be seen in Figure 8, turbidity currents are characterized by steep velocity and concentration gradients (fronts) that are limited to a small portion of the overall flow field. In addition, the accurate representation of the current's thin bottom boundary layer is crucially important, since it governs the dynamics of sedimentation and erosion. On the other hand, much of the flow outside the turbidity current remains relatively unperturbed, and hence does not give rise to small-scale motion. This indicates that large savings can be realized by employing a variable mesh size. One needs to keep in mind, however, that the turbidity current front is continuously moving through the flow field in an unsteady fashion, so that a static mesh will be inadequate. Instead, adaptive meshes are needed that will automatically refine the resolution where required. Novel concepts for the accurate solution of the Navier-Stokes equations on adaptive meshes, are based on recursive data structures of the quadtree and octree type (Samet 1989, Samet 1990). Recently, new approaches have been developed that allow for second order accuracy on such meshes, e.g. (Losasso et al. 2006). Their efficient implementation on massively parallel computer architectures with $O(10^4–10^6)$ processors, however, represents a challenging task. Here it is important to keep the discretization local, in order to minimize the need for communication among the processors (Gibou et al. 2006).

The chief bottleneck that determines how far Navier-Stokes simulations can be scaled on massively parallel computers lies in the size of the Poisson system that can be solved. For problems of even modest size, the Poisson solver dominates computational time. The fraction devoted to the Poisson solver grows with problem size (Aggarwal 2008). For very large-scale simulations, the Poisson solver will account for nearly all of the computational work. It also represents the most communication-intensive part of the computation due to global data dependencies. Nevertheless, promising developments are currently taking place in this field.

In order to develop efficient simulation codes for future facilities with $O(10^6)$ processors as envisioned by the National Science Foundation and other organizations, there is a need for a scalable development environment. This will allow for the implementation and testing of the various components of the simulation code on virtual facilities. Towards this end, novel approaches such as the open-source cloud computing infrastructure 'Eucalyptus' (cf. eucalyptus.cs.ucsb.edu/) offer new opportunities, as they enable the simulation of systems that are larger in scale than the underlying hardware on which they run.

Many of the above mentioned developments are in a state of flux, and subject to revision, due to the fact that high-performance computer architectures in general are rapidly evolving as a result of such developments as many core chips, heterogeneous processors such as GPUs, massively multithreaded architectures and high-speed interconnect technology. Hence the development of simulation tools for future machines whose specifications are presently unknown has to involve components of modeling, validation, and simulation.

8 CONCLUSIONS

This overview of earth-surface morphodynamic models summarizes some of the challenges facing the community: upscaling, coupling, data systems, computing, and testing. The community is presently self-organizing and rallying behind efforts such as CSDMS, to rapidly advance the field of morphodynamic modeling. The challenging problems facing CSDMS scientists relate to: self-organization, localization, thresholds, strong linkages, scale invariance, and interwoven biology and geochemistry. These lead to the following fundamental scientific questions that form the foundation and motivation for the CSDMS effort:

1. What are the fluxes, reservoirs, and flow paths associated with the physical, biological, and chemical transport processes across and through the earth's surface? How do these depend on substrate properties like morphology, geology, and ecology, and on human activities?
2. What processes lead to self-organization and pattern formation in surface systems? How do self-organized patterns mediate surface fluxes and evolution?
3. How do material fluxes and surface evolution vary across time and space scales?
4. How are physical and biological processes coupled in surface systems?
5. How is the history of surface evolution recorded in surface morphology and physical, chemical, and biological stratigraphic records?
6. How do linked surface environments communicate with each other across their dynamic boundaries? How do changes in one part of the global surface system affect other parts?
7. How does the Critical Zone couple to the tectosphere, atmosphere, hydrosphere, cryosphere, and biosphere and serve as the dynamic interface among them?

ACKNOWLEDGEMENTS

The National Science Foundation under the Cooperative Agreement 0621695 supports this work. The authors express their appreciation of the efforts of the 275 members of CSDMS. In particular, Peter Adams, Matt Kirwan, Dylan McNamara, Laura Moore, and Matt Wolinsky contributed to the writing of this paper.

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