Earth-surface Dynamics Modeling & Model Coupling

A short course

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Module 1: Process-response modeling principals


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Summary (2)
**Modelers checklist**

- Define goals of the modeling program
- Outline processes to be simulated
- Define assumptions behind each process and final model package
- Describe conditions governing the environment being modeled:
  - Domain boundary conditions
  - Timing & location of environmental forcing: in a day, season, millennium, geologic epoch
- Describe the data available vs. required to meet modeling goals
- Select the computational strategy and the governing equations
- Select the computational schema (single vs. multi-threading)
- Calibrate or verify modules
- Conduct numerical experiments
Definitions

SCHEMATIZATION: structure the computer uses to represent nature: discretization of space & time, boundary conditions & geometry, simplification of physical processes; i.e. how to represent wave climate or wind stress,

VALIDATION: testing the applied model for compliance with nature (measurements or standards): involves calibration and verification

CALIBRATION: adjustment of control parameters and boundary conditions: e.g. calibration of a 2DH tidal model with a number of water elevation and velocity data involves tuning the amplitudes and phases of the tidal constituents at the boundaries and assessing the mean water level slopes

VERIFICATION: correctness of the model without further tuning or adjustment: blind test, i.e. calibration of one part of tidal cycle and prediction for the other.

BENCHMARKING: Measure (speed, accuracy) of one model against another, given constrained inputs and boundary conditions
FROM CONCEPT TO MODEL

The Response Model

- Geometric model (observational)
- Conceptual model (inferential)
- Statistical model (regression analysis)
- Empirical model (predictive relationships)

The Process Model

- Deterministic model (conservation inputs - outputs)
- Mathematical model (fluid dynamics)
- Probabilistic model (steady-state conditions in flux)
- Computer model (high resolution simulations)
- Statistical comparison (observations & predictions)

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**Statistical model:** relationships amongst simultaneously-varying attributes are analyzed. Relationships not previously recognized may be indicated.

**Empirical model:** variables interrelated in a predictive algorithm. e.g. polynomial model to estimate the transport of suspended sediment to the ocean: variables include discharge, suspended sediment concentrations -based on observations and limited to environments with similar conditions

**Response model loop:**
1. predictions are made
2. new observations collected to test predictive model
3. conceptual model revised
4. statistical testing and generation of refined empirical model
The Process Model: e.g. based on fundamental theory.

• theoretical expressions of physical or biophysical laws (e.g. fluid mechanics), considered mathematical approximations of reality, that when linked together can describe a physical system.

• include conservation equations of mass, momentum, and energy.

• continuity equations keep track of volume or mass within the system being modeled: e.g. Exner (erosion – deposition)

• conservation of energy equation e.g. conversion of turbulence to work done (erosion, suspension)

• conservation of momentum equation: operating forces at a given location and boundary shear stresses.

• some parameters are determined fairly accurately and others are merely constrained estimates.

• untested theory is the weak link in a model
\[
\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \frac{1}{h} \frac{\partial}{\partial x} \left( h K_x \frac{\partial C}{\partial x} \right) + \frac{1}{h} \frac{\partial}{\partial y} \left( h K_y \frac{\partial C}{\partial y} \right) + \frac{S}{h}
\]

Advection-Diffusion

\[
\frac{\partial}{\partial t^*} \left( \rho^* u^* \right) + \frac{\partial}{\partial x^*} \left( \rho^* u^* u^* + p^* \right) + \frac{\partial}{\partial y^*} \left( \rho^* u^* v^* \right) + \frac{\partial}{\partial z^*} \left( \rho^* u^* w^* \right) = \frac{\partial \tau_{xx}^*}{\partial x^*} + \frac{\partial \tau_{xy}^*}{\partial y^*} + \frac{\partial \tau_{xz}^*}{\partial z^*}
\]

Navier-Stokes Momentum

\[
\frac{\partial}{\partial t^*} \left( \rho^* e_t^* \right) + \frac{\partial}{\partial x^*} \left( \rho^* u^* e_t^* + p^* u^* \right) + \frac{\partial}{\partial y^*} \left( \rho^* v^* e_t^* + p^* v^* \right) + \frac{\partial}{\partial y^*} \left( \rho^* w^* e_t^* + p^* w^* \right) = \frac{\partial}{\partial x^*} \left( u^* \tau_{xx}^* + v^* \tau_{xy}^* + w^* \tau_{xz}^* - q_x^* \right) + \frac{\partial}{\partial y^*} \left( u^* \tau_{yx}^* + v^* \tau_{yy}^* + w^* \tau_{yz}^* - q_y^* \right) + \frac{\partial}{\partial z^*} \left( u^* \tau_{zx}^* + v^* \tau_{zy}^* + w^* \tau_{zz}^* - q_z^* \right)
\]

Navier-Stokes Energy

Parker & Imran et al., formulation of the debris flow momentum

\[
\frac{2}{3} \frac{\partial}{\partial t^*} (U_p D_p) - U_p \frac{\partial D_s}{\partial t^*} + \frac{8}{15} \frac{\partial}{\partial x^*} \left( U_p^2 D_p \right) \frac{2}{3} U_p \frac{\partial}{\partial x^*} (U_p D_p) = D_s g \left( 1 - \frac{\rho_w}{\rho_m} \right) S - D_s g \frac{\partial D_s}{\partial x^*} - \frac{2}{3} \mu \frac{U_p}{D_s}
\]

\[
\frac{\partial}{\partial t^*} (U_p D_p) + \frac{\partial}{\partial x^*} \left( U_p^2 D_p \right) + U_p \frac{\partial D_s}{\partial t^*} + \frac{2}{3} U_p \frac{\partial}{\partial x^*} (U_p D_p) = D_p g \left( 1 - \frac{\rho_w}{\rho_m} \right) S - D_p g \frac{\partial D_p}{\partial x^*} - \frac{\tau_y}{\rho_m}
\]

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Numerical Simulation:

- Methods: finite difference (localized approximations) versus finite element (global constraints of the full domain).
- Solutions (explicit schemes, implicit schemes and method of characteristics) depend on form of the differential equation (elliptic, parabolic, or hyperbolic).

### TYPES OF MODELS

- DNS vs. LES vs. RANS vs. SWEM vs. ADM
- Boussinesq vs. non-Boussinesq
- FDM vs. FEM vs. FVM
- Implicit vs. explicit
- 1D, 2D, 3D
- fluid- or geo-dynamics vs. geometric or diffusive
- Lagrangian vs. Eulerian vs. PIC
- steady-state vs. non-steady state
- Newtonian vs. non-Newtonian
- depositional vs. post-depositional
- time marching vs. compute & drift vs. event-based
- local vs. regional vs. global
- siliciclastic vs. carbonate
- abiotic vs. biotic
Characterizing the Littoral Zone

Data Assimilation & Predictive Modeling

NGDC DATA BASES → Coastal Ocean
CUPOM Ocean Circ Model
PLUME & WAVE Model

Heat & Momentum Flux
Temperature, Winds

Atmospheric
MM5-mesoscale NWP model
NCEP Analysis; Radiation Transfer

Precipitation, Temperature, Winds

Satellite Data

Satellite Data

Hydrology
Hydrotrend Model
River Tools with Routing

Products
Bathymetric Changes
(Erosion, Deposition)
Storm Surge, Discharge
Water Turbidity, Currents
Water Temperature
Seafloor Properties
(acoustics, sediment, gas)

River, Sediment Discharge

Tides, Waves
CONSTRAINTS TO A PROCESS-RESPONSE MODEL

(1) **Principles of hydrodynamics must be observed.**
   e.g. critical stress governing the deposition of a particle from suspension
   must be less than the critical stress governing the erosion from the sea
   floor of that same particle

(2) **Laws of conservation must be adhered to**
   e.g. often governing equations can only be approximated ... numerical
   transport algorithms can lead to artificial diffusion when properties are
   considered constant throughout the cell

(3) **Boundary conditions must be realistic and not contribute to instabilities.**
   e.g. A diffusion equation relates bulk transport to concavity of the slope.
   Critical boundary state occurs when all sediment is removed by
   diffusion and rock basement is encountered.

(4) **Use realistic inputs from the external world, i.e. outside the immediate area**
   e.g. tides in the Bay of Fundy, the area where sediment transport was to be
   predicted, is based on a numerical grid that included the entire
   Gulf of Maine, an area nearly two orders-of-magnitude larger.
SENSITIVITY ANALYSIS

• used to determine the importance of various parameters in affecting the final result of a model's algorithms.

• allows the modeler to test both numerical stability and validity in boundary conditions, by choosing extreme values of input.

• a parameter's sensitivity depends on the magnitude of its exponential and the range of its variability.

• complex models often have many convoluted interactions that computer simulations are the only means to ascertain the sensitivity of a particular parameter.
Scaling Analysis:
• Scaling Time;
• Scaling Space;
• Scaling Dynamics;
• Scaling Variability;
• Upscaling;
• Downscaling
For long time steps, only model the large events
Experiments on Wave Variability

High Wave Variability

Wave heights 2.1±1m
Wavelengths 21±10m

Low Wave Variability

Wave heights 2.1±0.1m
Wavelengths 21±1m

Examples of erosion surfaces from major storms
Resuspended sediment volume per day as a function of wave height

\[ f(q) = f(h^{3.5}) \]

Final profiles of modeled bathymetry
Scaling reduces run time by 75%.
Define Processes
Define Boundary Conditions
Determine Input Values
Discretize Conservation Equations - Mass, Momentum, Energy
Analyze Model for Stability and Resolution

MODEL VALIDATION
Flow-Sediment Dynamics
Size, Shape, Location and Properties of Deposit

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Process-Response Modeling should push scientists to confront nature

- is one process coupled or uncoupled to another
- is a particular process deterministic or stochastic
- level of simplification (1D, 2D, 3D)
- has an analytical solution for a particular process been formulated yet
- how are processes scaled across time and space
- adequacy of databases on key parameters from field or laboratory measurements