Earth-surface Dynamics Modeling & Model Coupling

A short course

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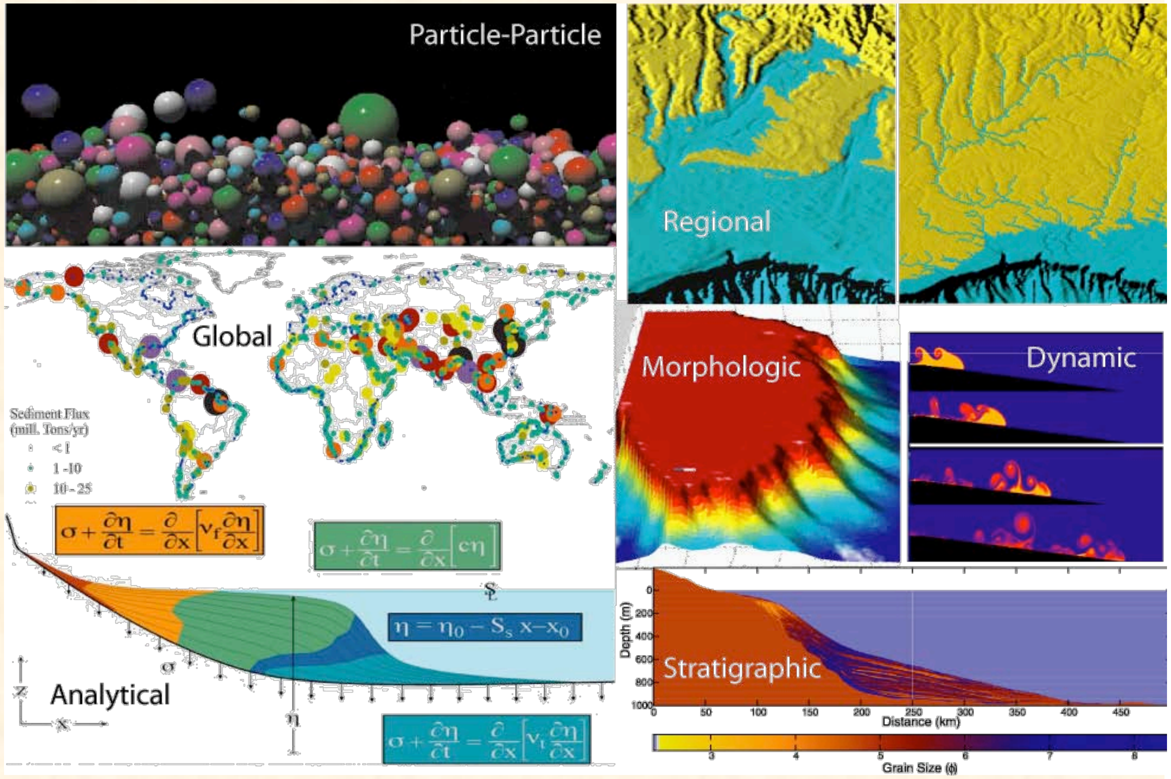
Module 1: Process-response modeling principals

ref: Syvitski, J.P.M. et al., 2007. Prediction of margin stratigraphy. In: C.A. Nittrouer, et al. (Eds.) Continental-Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy. IAS Spec. Publ. No. 37: 459-530.

Modelers checklist,
  definitions (2)
From Concept to Model (6)
Constraints, Sensitivity &
  Scaling (7)
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
    - Forcing functions: are they Periodic? Episodic? Deterministic? Probabilistic? Chaotic?
- 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,

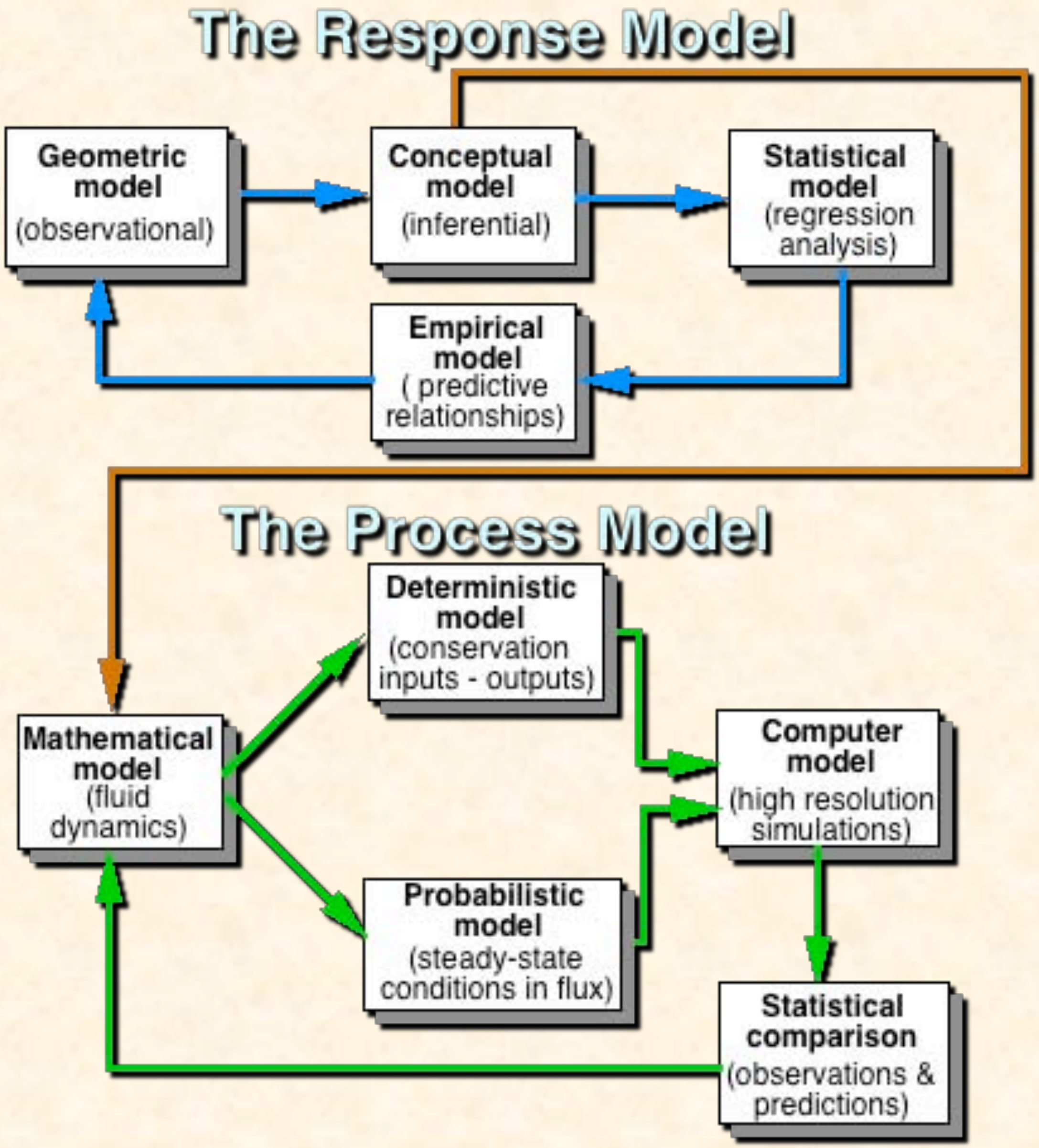
VALIDATION: testing the applied model for compliance with nature (measurements or standards): involves calibration and verification

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

Mathematical model (fluid dynamics)

Deterministic model (conservation inputs - outputs)

Probabilistic model (steady-state conditions in flux)

Computer model (high resolution simulations)

Statistical comparison (observations & predictions)

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

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{1}{h}\frac{\partial}{\partial x}\left(hK_x\frac{\partial C}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(hK_y\frac{\partial C}{\partial y}\right) + \frac{S}{h}$$

Advection-
Diffusion

$$\frac{\partial}{\partial t^*}(\rho^* u^*) + \frac{\partial}{\partial x^*}(\rho^* u^{*2} + p^*) + \frac{\partial}{\partial y^*}(\rho^* u^* v^*) + \frac{\partial}{\partial z^*}(\rho^* u^* w^*) = \frac{\partial \tau^*{}_{xx}}{\partial x^*} + \frac{\partial \tau^*{}_{xy}}{\partial y^*} + \frac{\partial \tau^*{}_{xz}}{\partial z^*}$$

Navier-Stokes
Momentum

$$\frac{\partial}{\partial t^*}(\rho^* e_t{}^*) + \frac{\partial}{\partial x^*}(\rho^* u^* e_t{}^* + p^* u^*) + \frac{\partial}{\partial y^*}(\rho^* v^* e_t{}^* + p^* v^*) +$$

$$\frac{\partial}{\partial y^*}(\rho^* w^* e_t{}^* + p^* w^*) = \frac{\partial}{\partial x^*}(u^* \tau_{xx}{}^* + v^* \tau_{xy}{}^* + w^* \tau_{xz}{}^* - q_x{}^*)$$

$$\frac{\partial}{\partial y^*}(u^* \tau_{yx}{}^* + v^* \tau_{yy}{}^* + w^* \tau_{yz}{}^* - q_y{}^*) + \frac{\partial}{\partial z^*}(u^* \tau_{zx}{}^* + v^* \tau_{zy}{}^* + w^* \tau_{zz}{}^* - q_z{}^*)$$

Navier-Stokes
Energy

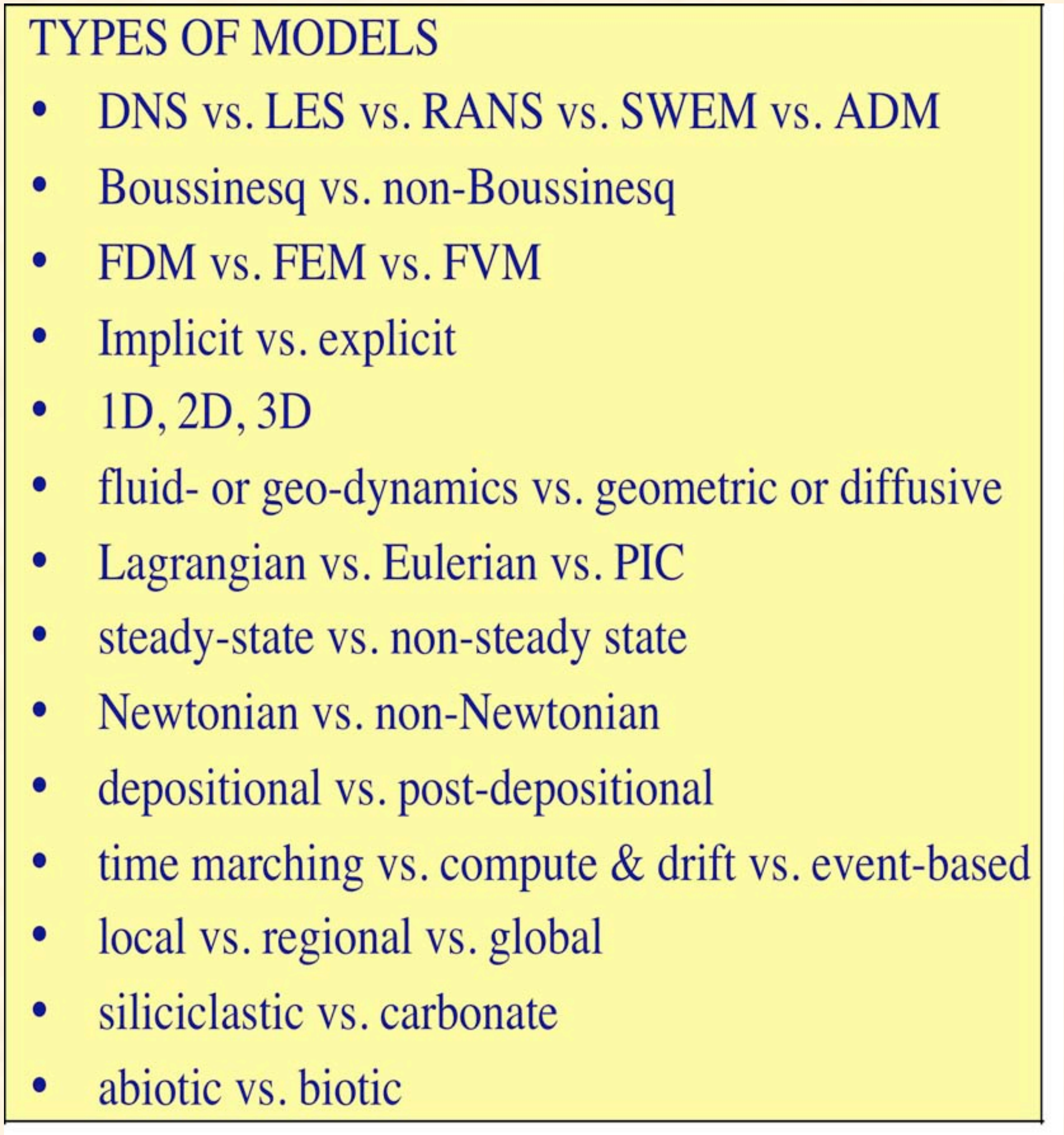
Parker & Imran et al., formulation of the debris flow momentum

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

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

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).

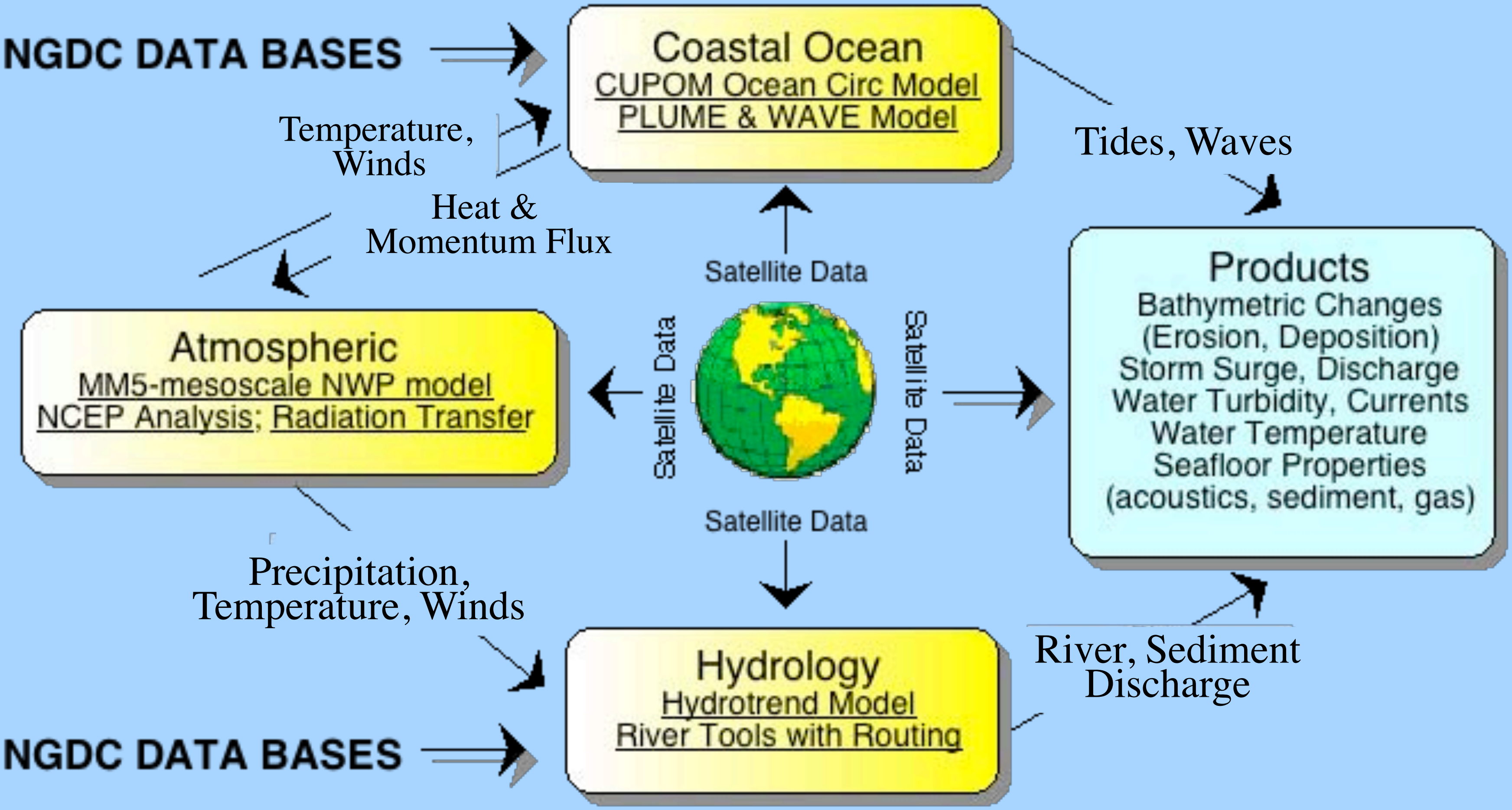


TYPES OF MODELS

- 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

Temperature, Winds

Heat & Momentum Flux

Tides, Waves

Satellite Data

Atmospheric
MM5-mesoscale NWP model
NCEP Analysis; Radiation Transfer

Satellite Data

Satellite Data

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

Satellite Data

Precipitation, Temperature, Winds

Hydrology
Hydrotrend Model
River Tools with Routing

River, Sediment Discharge

NGDC DATA BASES

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.

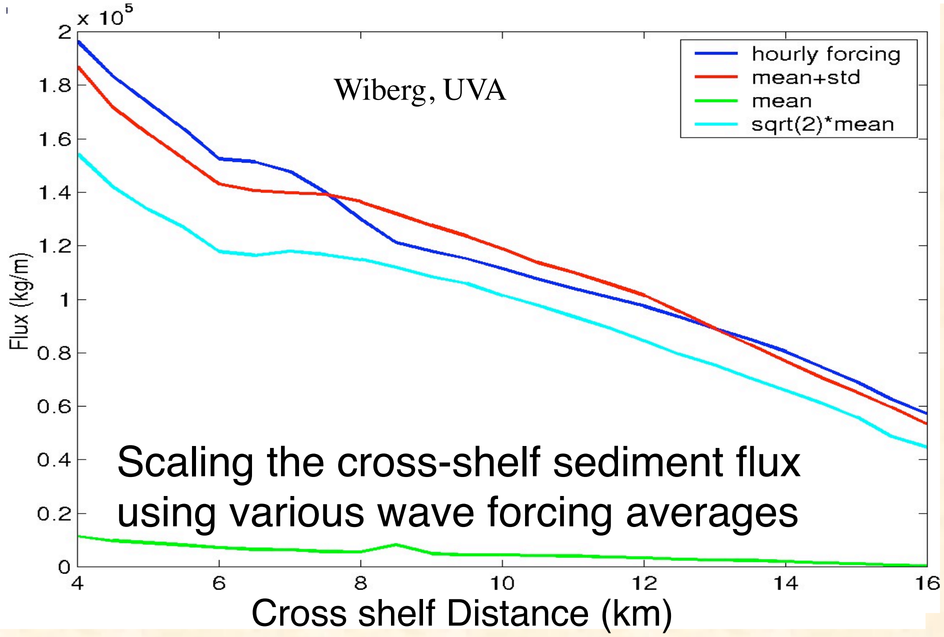
(4) Use realistic inputs from the external world, i.e. outside the immediate area

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 parameters 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 TIME



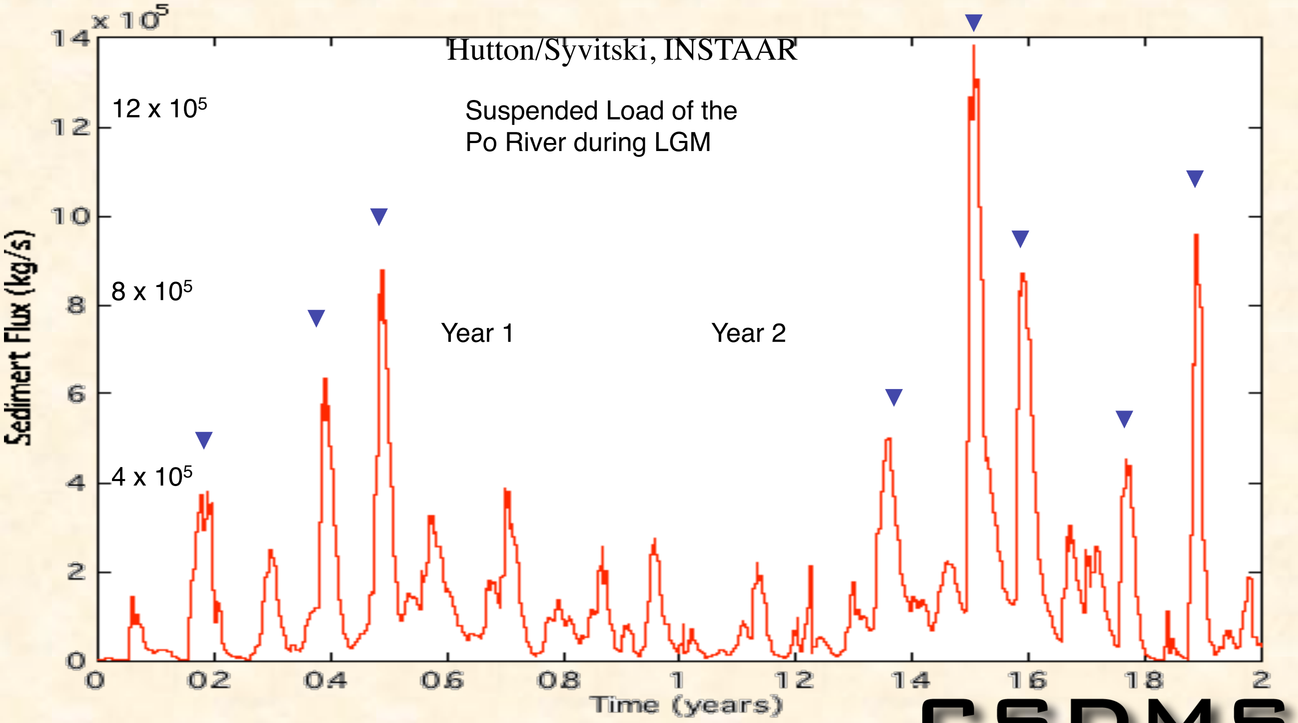
Wiberg, UVA

Scaling the cross-shelf sediment flux using various wave forcing averages

Low Frequency, High Magnitude Events (PDF-CDF approach)

Scaling Analysis:

- Scaling Time;
- Scaling Space;
- Scaling Dynamics;
- Scaling Variability;
- Upscaling;
- Downscaling



Hutton/Syvitski, INSTAAR

Suspended Load of the Po River during LGM

Earth-surface Dynamic Modeling & Model Coupling, 2009

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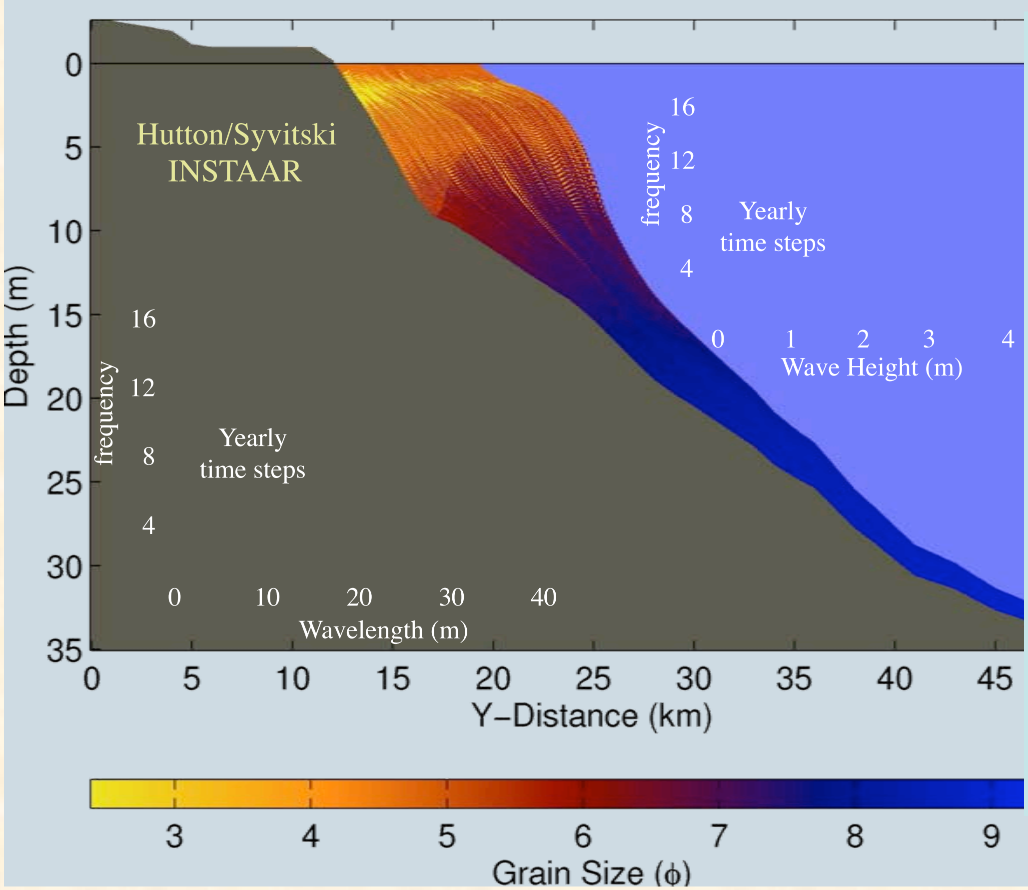
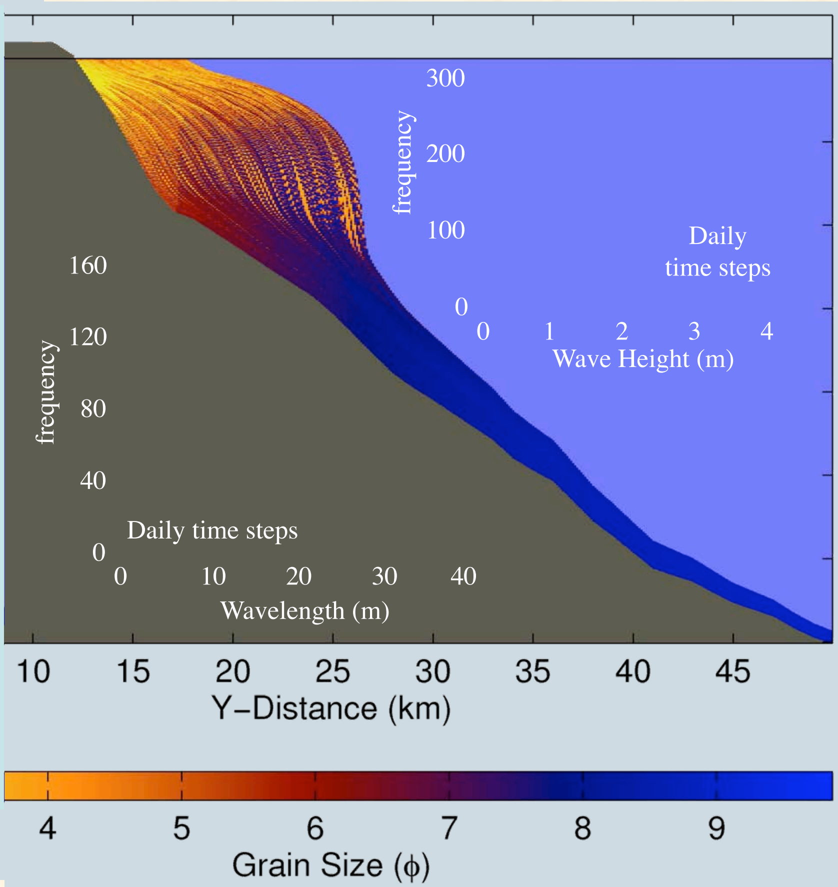
Experiments with Time Steps

Yearly Time Step

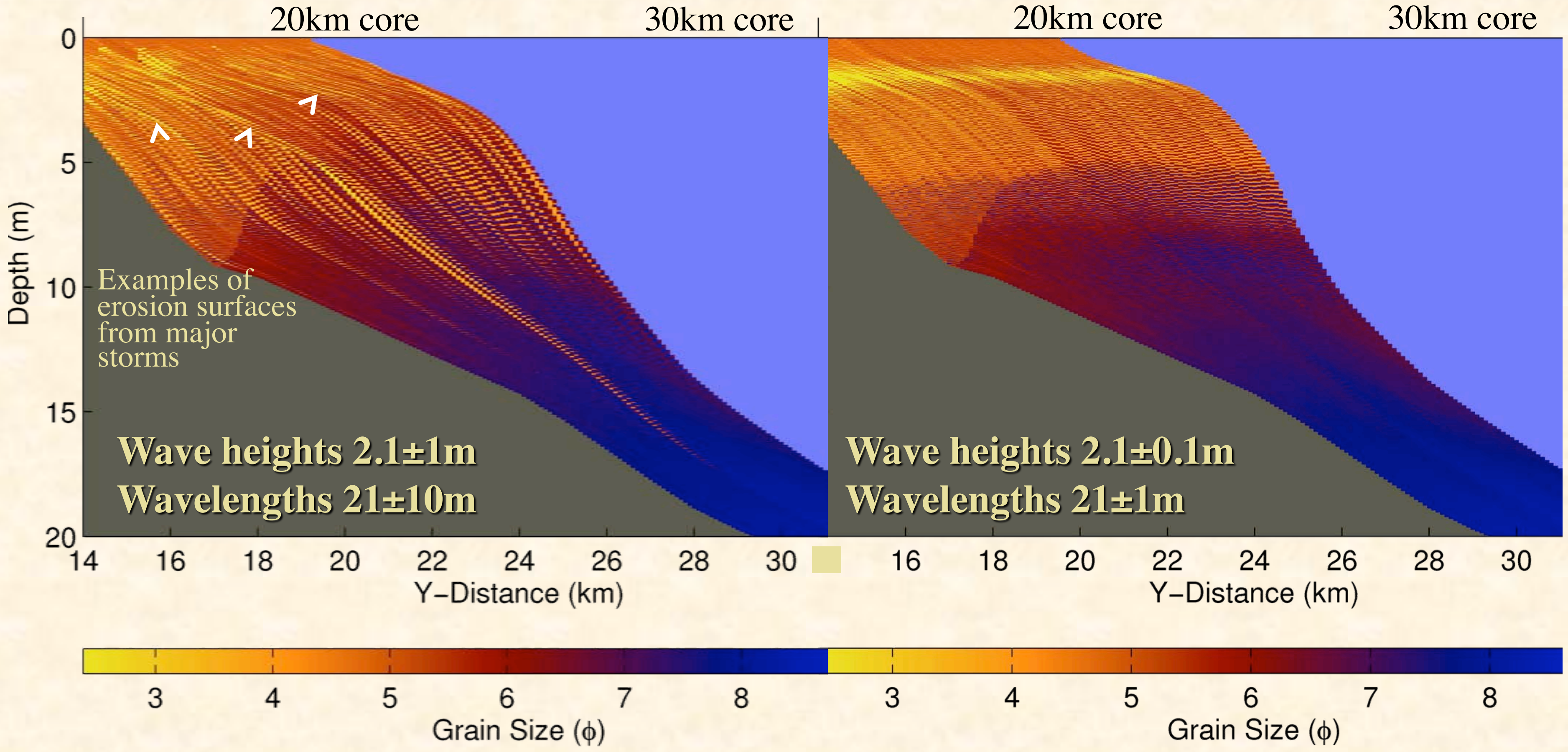


Daily Time Step



For long time steps, only model the large events

Experiments on Wave Variability



High Wave Variability

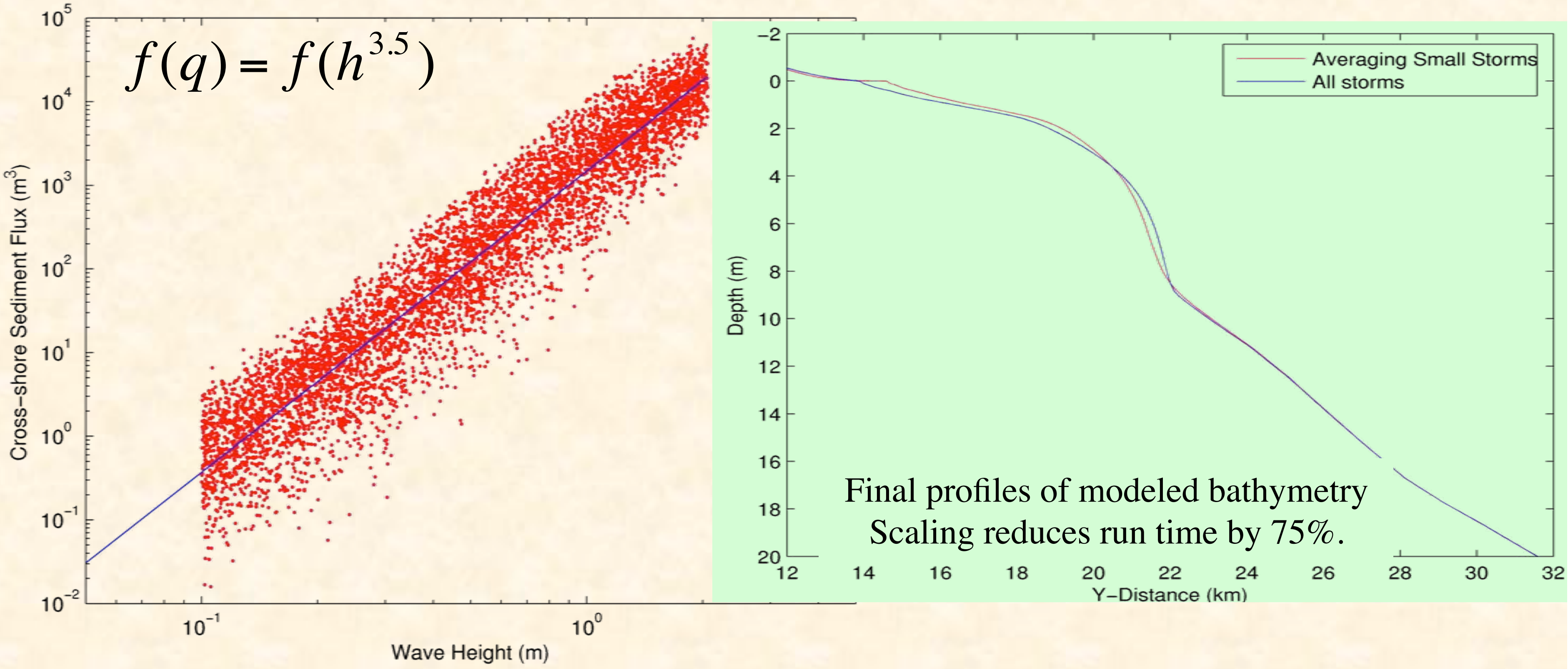
Low Wave Variability

Examples of erosion surfaces from major storms

Wave heights 2.1±1m
Wavelengths 21±10m

Wave heights 2.1±0.1m
Wavelengths 21±1m

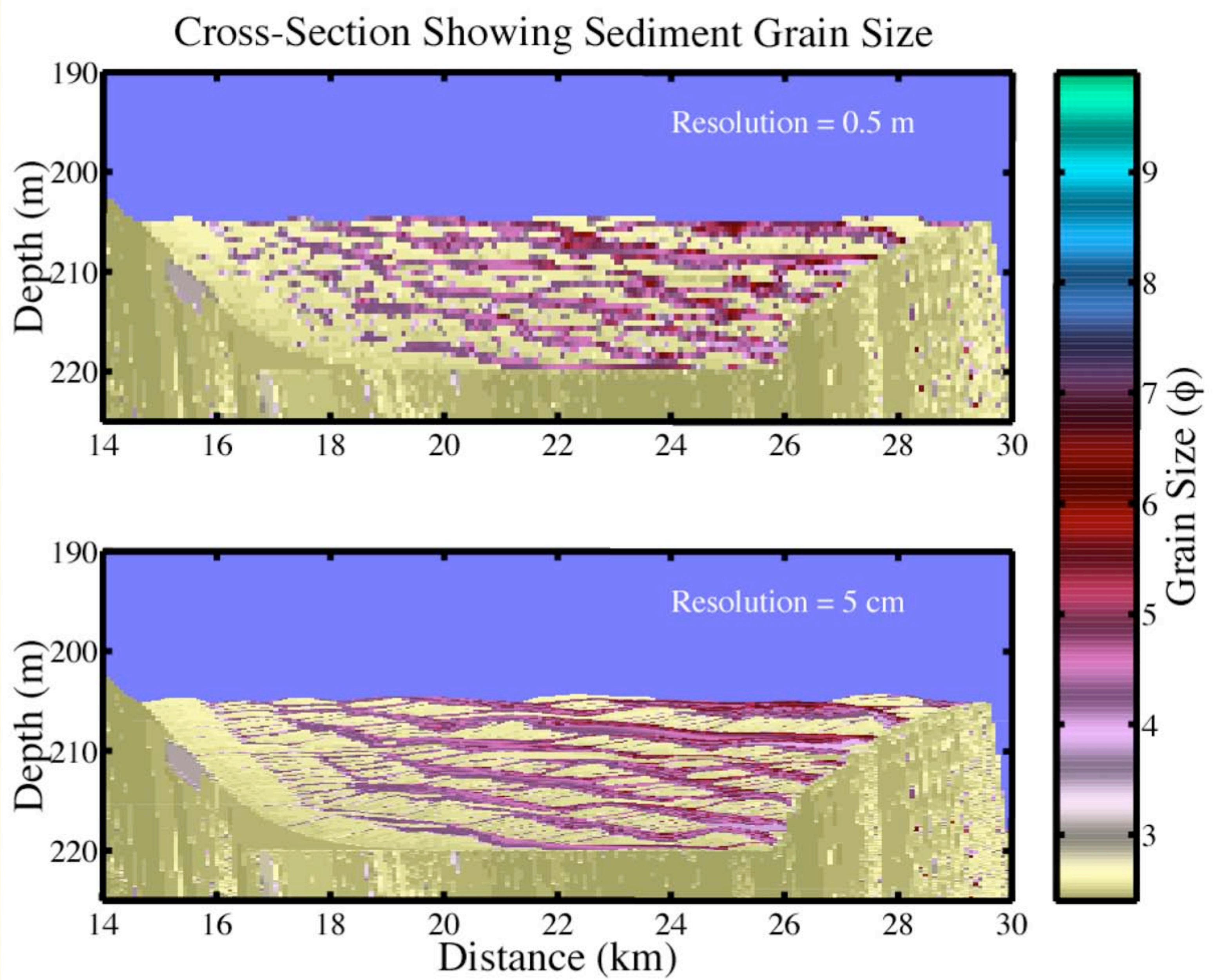
Resuspended sediment volume per day as a function of wave height

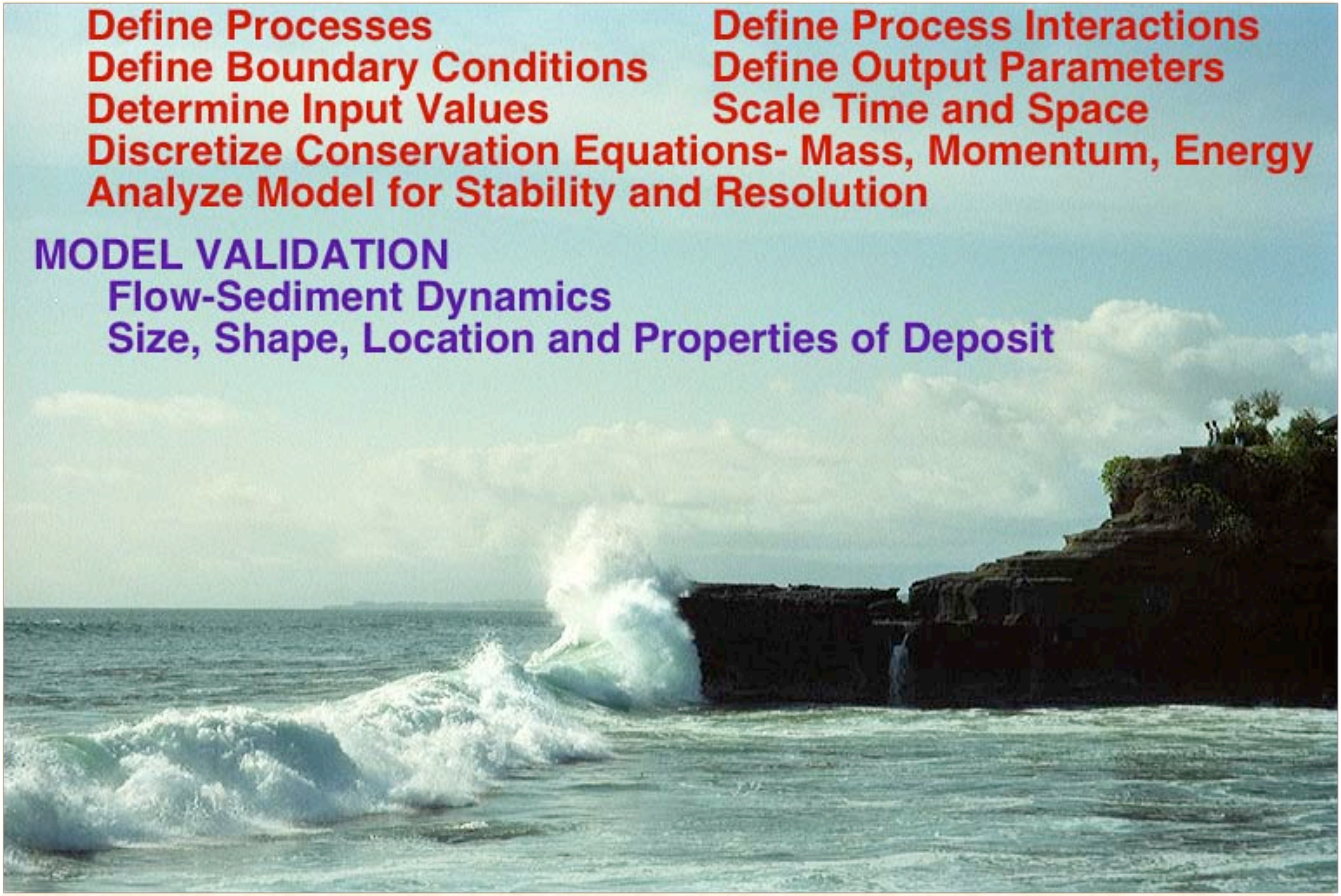


$$f(q) = f(h^{3.5})$$

Final profiles of modeled bathymetry
Scaling reduces run time by 75%.

Resolution


Cross-Section Showing Sediment Grain Size
Resolution = 0.5 m
Resolution = 5 cm
Depth (m)
190
200
210
220
14
16
18
20
22
24
26
28
30
Distance (km)
Grain Size (ϕ)
3
4
5
6
7
8
9



Define Processes
Define Boundary Conditions
Determine Input Values
Define Process Interactions
Define Output Parameters
Scale Time and Space
Discretize Conservation Equations- Mass, Momentum, Energy
Analyze Model for Stability and Resolution

MODEL VALIDATION

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

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