A COUPLED COHESIVE SEDIMENT ENTRAINMENT AND BIOTURBATION MODEL

Timothy Keen and Yoko Furukawa

Naval Research Laboratory, Stennis Space Center, Mississippi

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Objectives

- **Project Goal:** To understand the dynamics of sediment transport in heterogeneous sedimentary environments

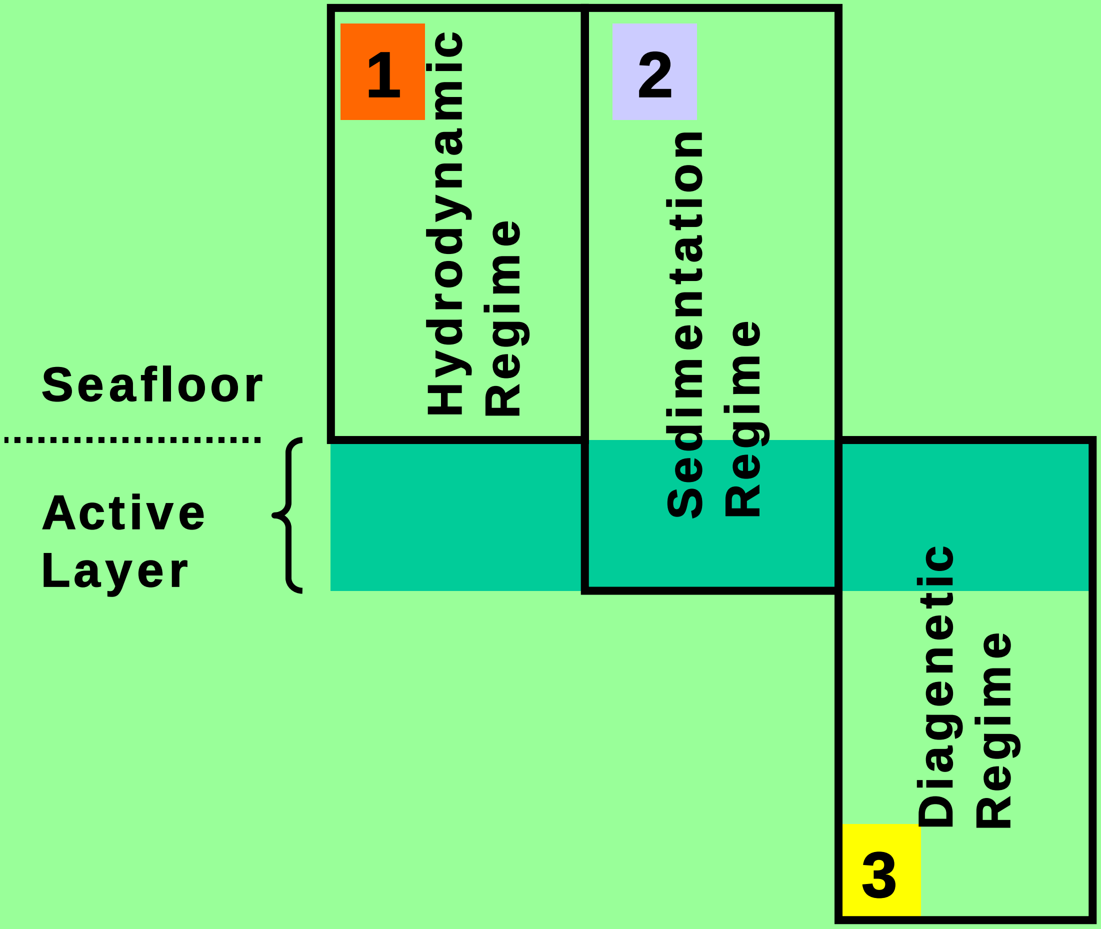
- **Task Goal:** Investigate biological, chemical, and physical factors that determine cohesive sediment properties (e.g., entrainment, flocculation, settling velocity)

Outline

- 1D Model overview
- Wave-current hydrodynamic model
- Sediment entrainment model
- Reaction-transport diagenetic model
- Feedback loops
- Tidal channel example

1D Model Overview

1. Wave-current interaction model
2. Sediment entrainment model
3. Reaction-transport geochemical and bioturbation model



1. Hydrodynamic Regime

- 1D wave-current interaction model (Keen and Glenn, 1994)
- Calculated or fixed bottom roughness z_0
- Mean wave field (H_S, T_M, θ)
- Steady currents
- Calculate shear stress and current profile for boundary layers with both wave and steady currents

2. Sedimentation Regime

- 1D vertical
- Sandy or muddy beds
- Multiple sizes of noncohesive sediment
- Uses active layer
- Advection neglected

Sand/Mud Entrainment

- **Sand:** Reference concentration C_{z0} based on excess shear stress and resuspension coefficient γ_0
  - Rouse-like profile
  - Computed bed roughness
- **Mud:** $E_B = A_0 A_B A_C(\tau/\tau_c - 1)^m$
  - A_B and A_C are bioturbation and consolidation parameters determined from fitting entrainment data for natural sediments. A_0 and m are adjustable.
  - Profiles use dynamically computed floc size and settling velocity
  - Fixed bed roughness

3. Reaction-Transport Regime

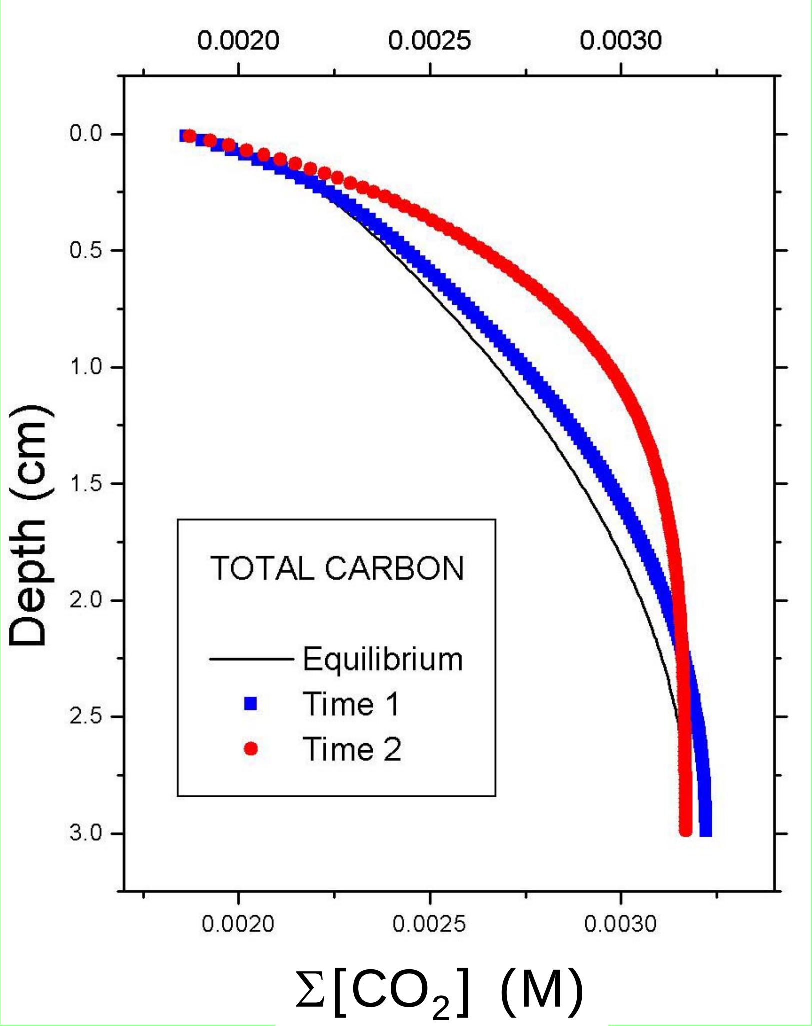
- Reaction and diffusion model from Berner (1980)
- 1D conservation equation:

$$\varphi \frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(\varphi \frac{D}{\theta^2} \frac{\partial C}{\partial x} \right) + R$$

- φ = porosity; *C* = concentration; *D* = diffusion coefficient; θ = diffusive tortuosity; *R* = net reaction rate
- Species: O_2, NO_3^-,SO_4^{2-}, NH_4^+, ΣS (H_2S+HS^-), ΣCO_2 ($CO_2+H_2CO_3^-+HCO_3^-+CO_3^{2-}$) and titration alkalinity ($HCO_3^-+2CO_3^-+HS^-$)
- BC's: Constant at seafloor; no gradient at depth

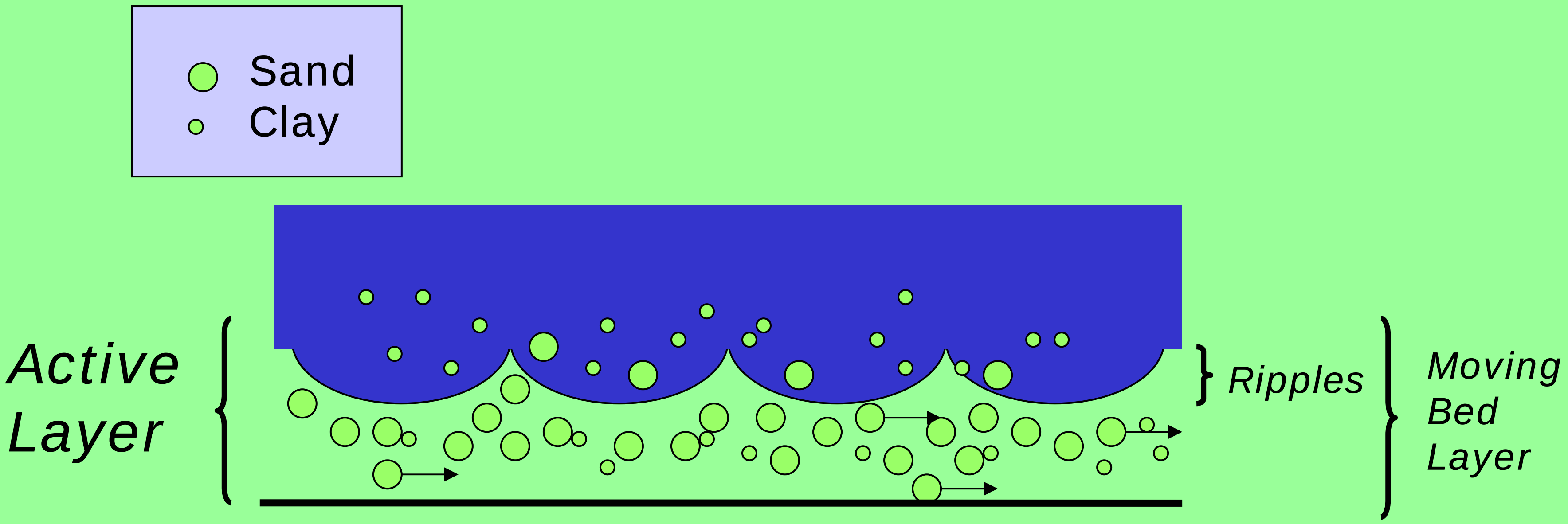
Equilibrium Profiles

- Model grid = 0.3 m; DZ = 200 μm; DT = 1 s
- Conservation equations integrated for external time step imposed by hydrodynamic and sedimentation regimes
- Plot shows profiles of ΣCO_2 ($CO_2 + H_2CO_3 + HCO_3^- + CO_3^{2-}$) as they move towards equilibrium
- Equilibrium profiles require varying times, which are much greater than the external time step (1 hour) without changes in bottom sediment.



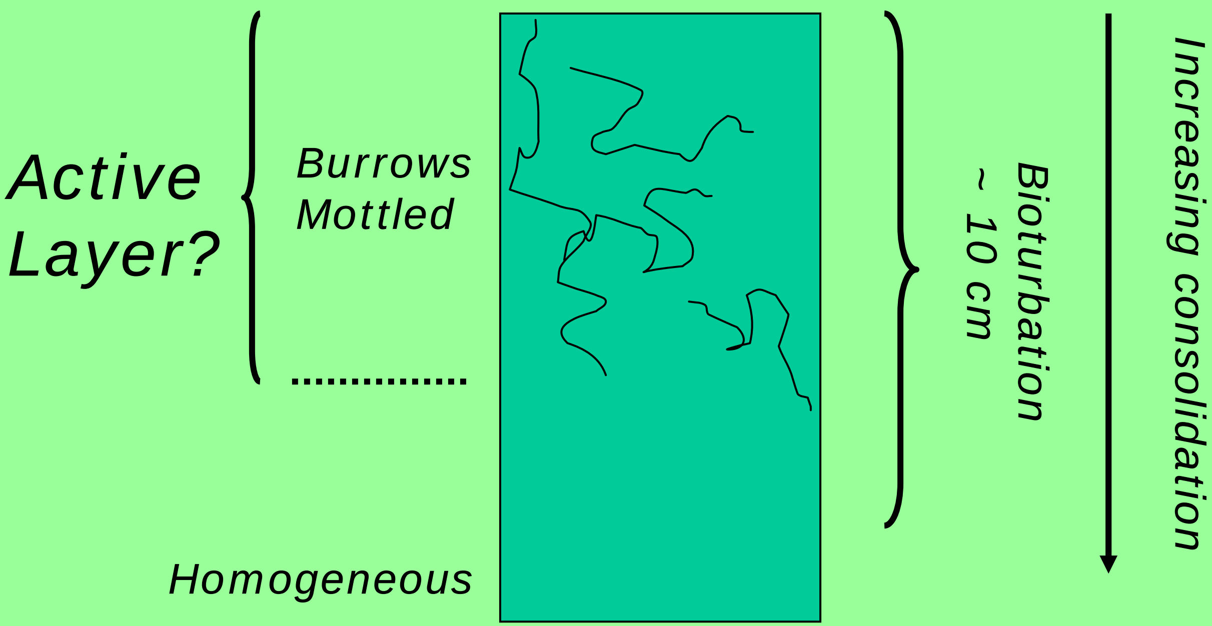
Feedback in the Active Layer: Sandy Sediment

- Active Layer: the thickness of bed that interacts with the flow during a time scale of interest
- The active layer for sandy sediments is computed from the *moving bed layer* and *ripple* properties.
- Clay particles are winnowed from this layer.



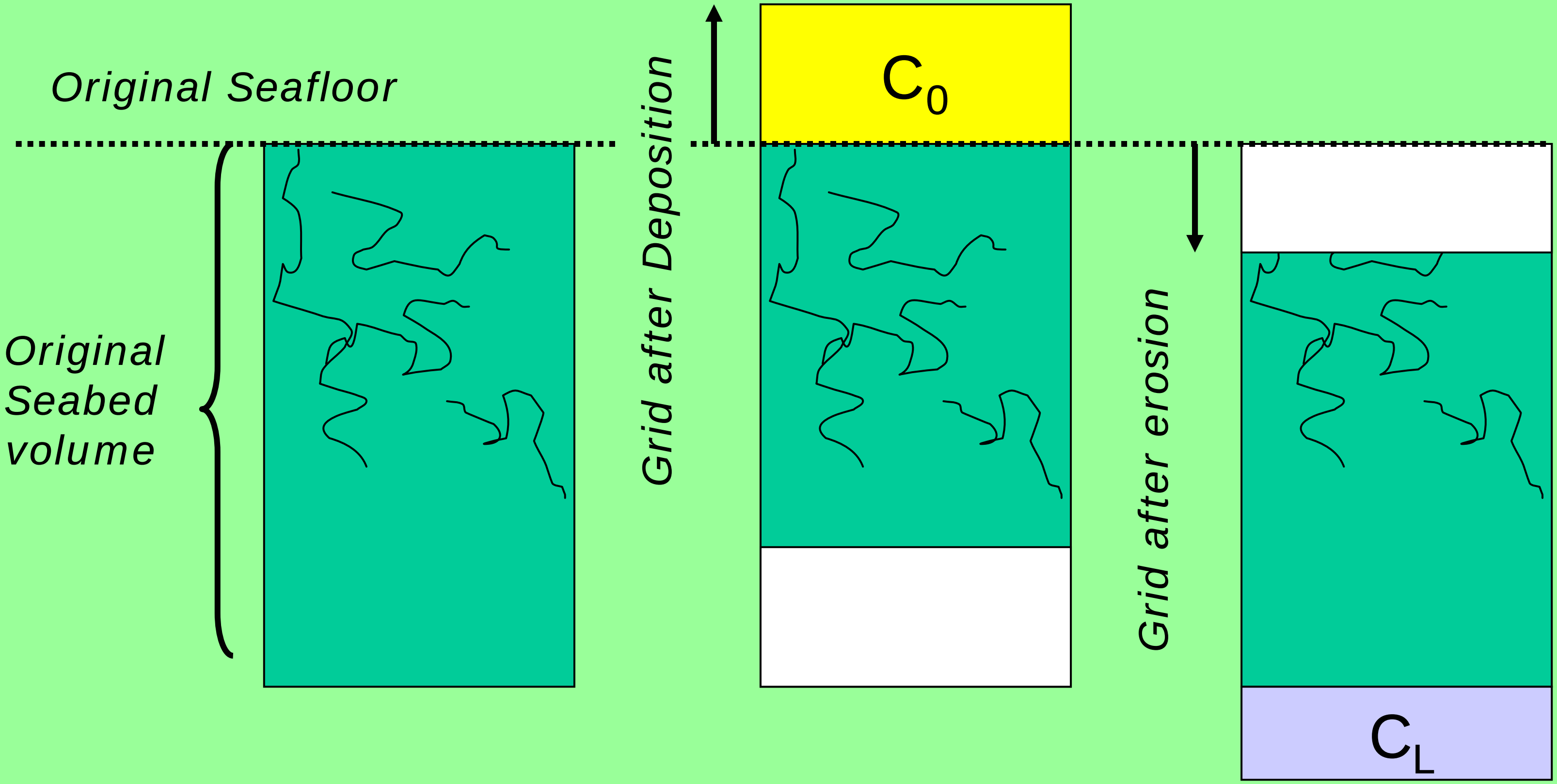
Feedback in the Active Layer: Muddy Sediment

- The active layer for muddy sediments is estimated from laboratory measurements of seafloor core properties (e.g., critical shear stress, bulk density).
- There is no deterministic basis for predicting the active layer depth in these sediments.



Feedback in the Active Layer : Deposition and Erosion

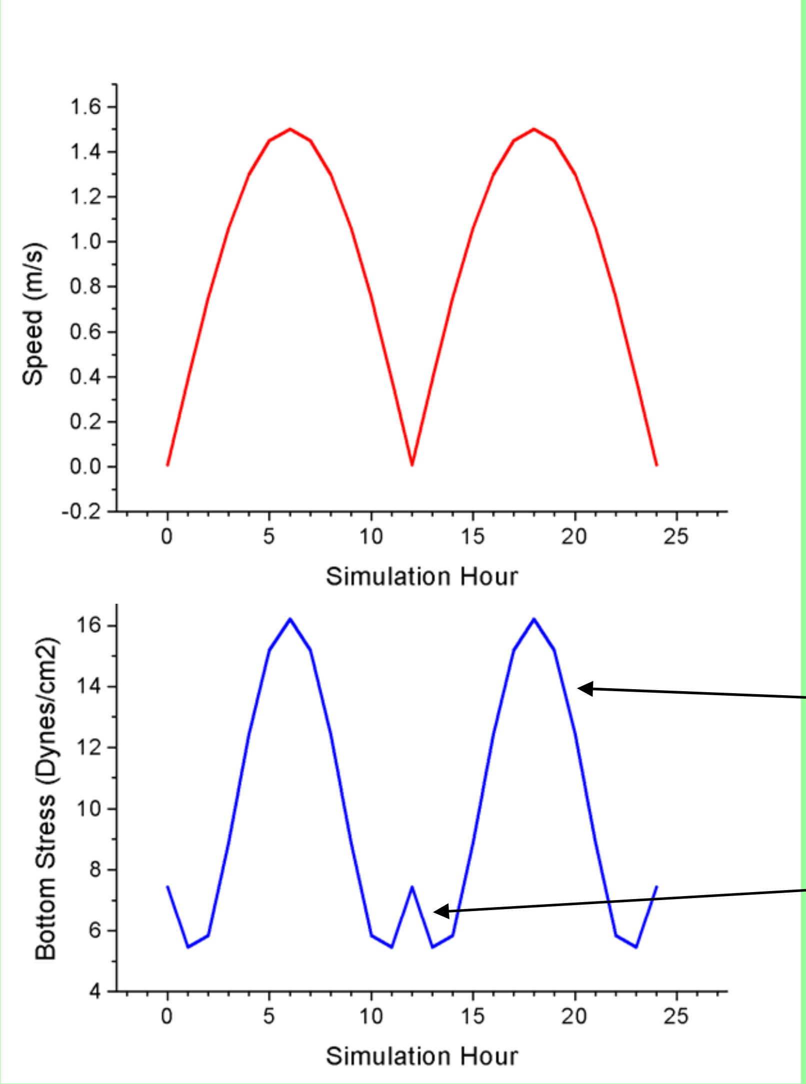
- **Deposition:** Sediment is added to geochemical model grid with upper BC concentrations (C_0).
- **Erosion:** Sediment is eroded, and deepest sediment assumes concentrations resulting from lower BC (C_L).



Example: Tidal Channel

- Environmental Conditions:
  - Water Depth = 5 m
  - Variable currents (max = 1.5 m/s)
  - Steady waves: H_s = 0.5 m; T_M = 6 s
  - Sandy bottom (60% sand)
    - median diameter = 0.1 mm (100 microns)
    - interstitial mud
  - Muddy bottom (100% cohesive)
    - Variable floc size (~ 10 micron)
    - Variable floc settling speed (~ 60 micron/sec)
- Compute sediment and chemical profiles
  - IC for geochemcial species = C_0.

Example: Time-Variable Forcing



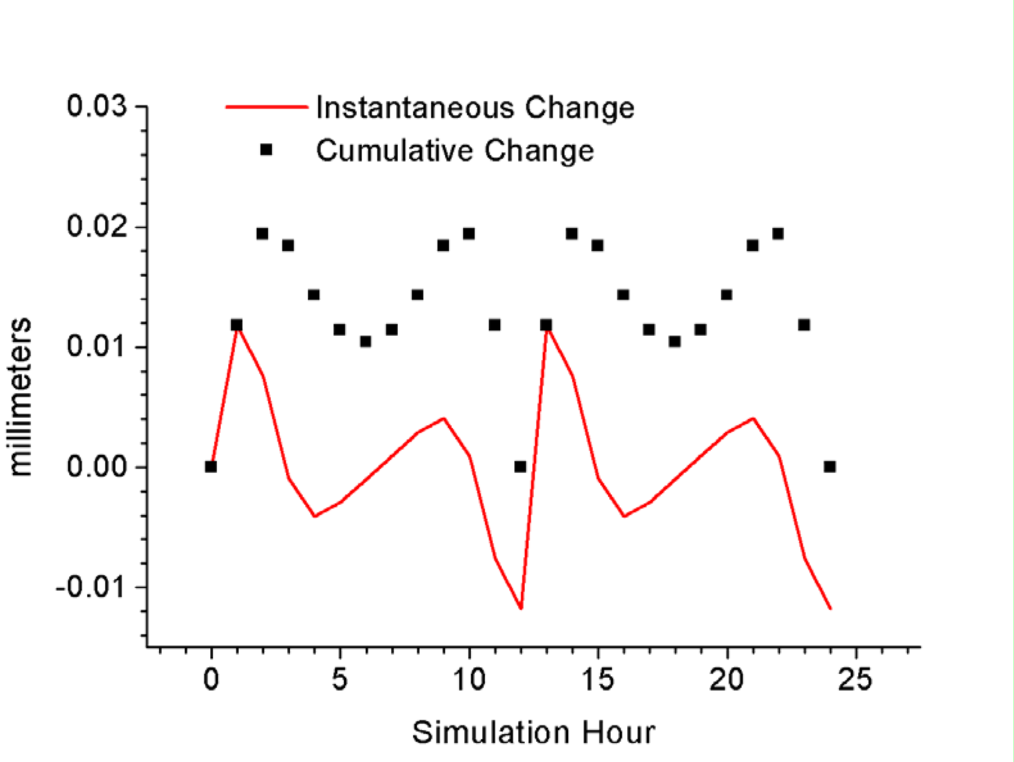
- Variable steady current
- Diurnal period (24 h) with max speed of 1.5 m/s
- The shear stress shows 2 peaks
  - a large peak, resulting from wave-current interaction
  - A small peak from waves alone at slack tide

Example: 1D Bed Elevation Changes

- Bed elevation change:

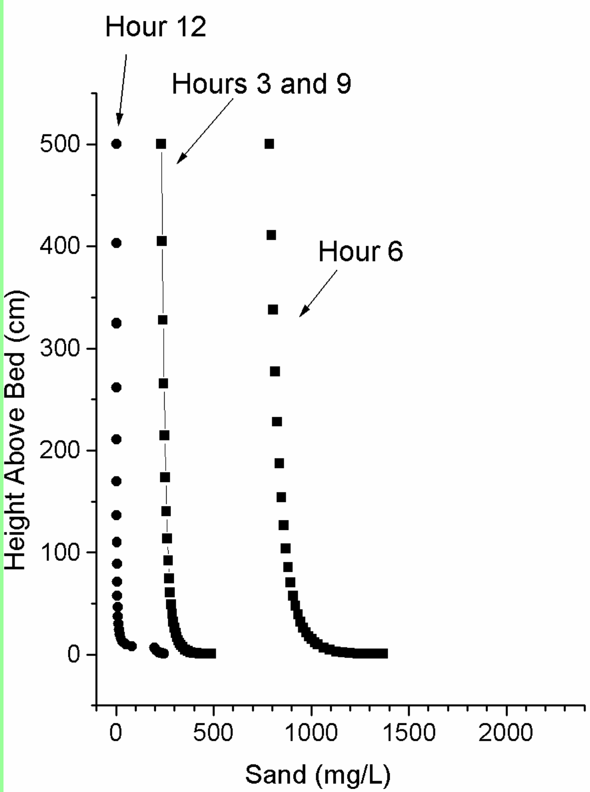
$$\frac{\partial h}{\partial t} \approx \frac{dh_R}{dt}$$

- h = bed elevation; h_R = entrainment depth
- Changes in entrainment depth produce deposition or erosion
- Cumulative change = 0 over a tidal cycle

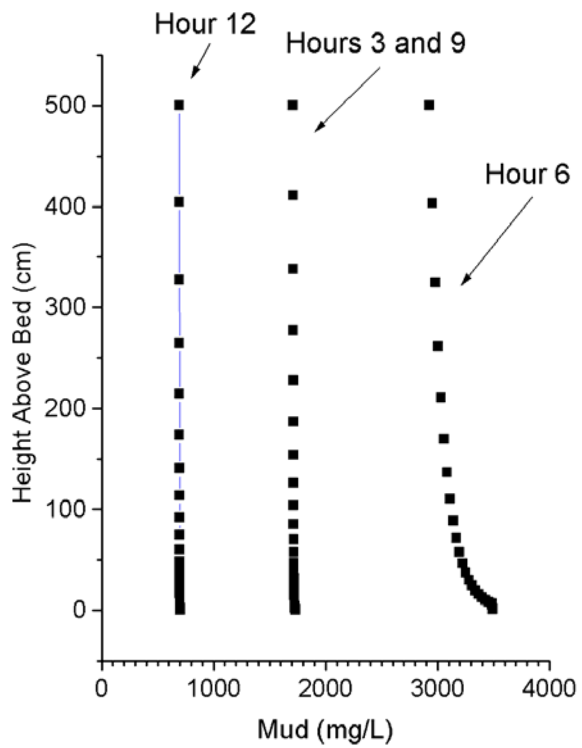


Example: Suspended Sediment Profiles

For a sandy bed, interstitial mud is entrained in larger quantities than sand, producing a sandy layer.



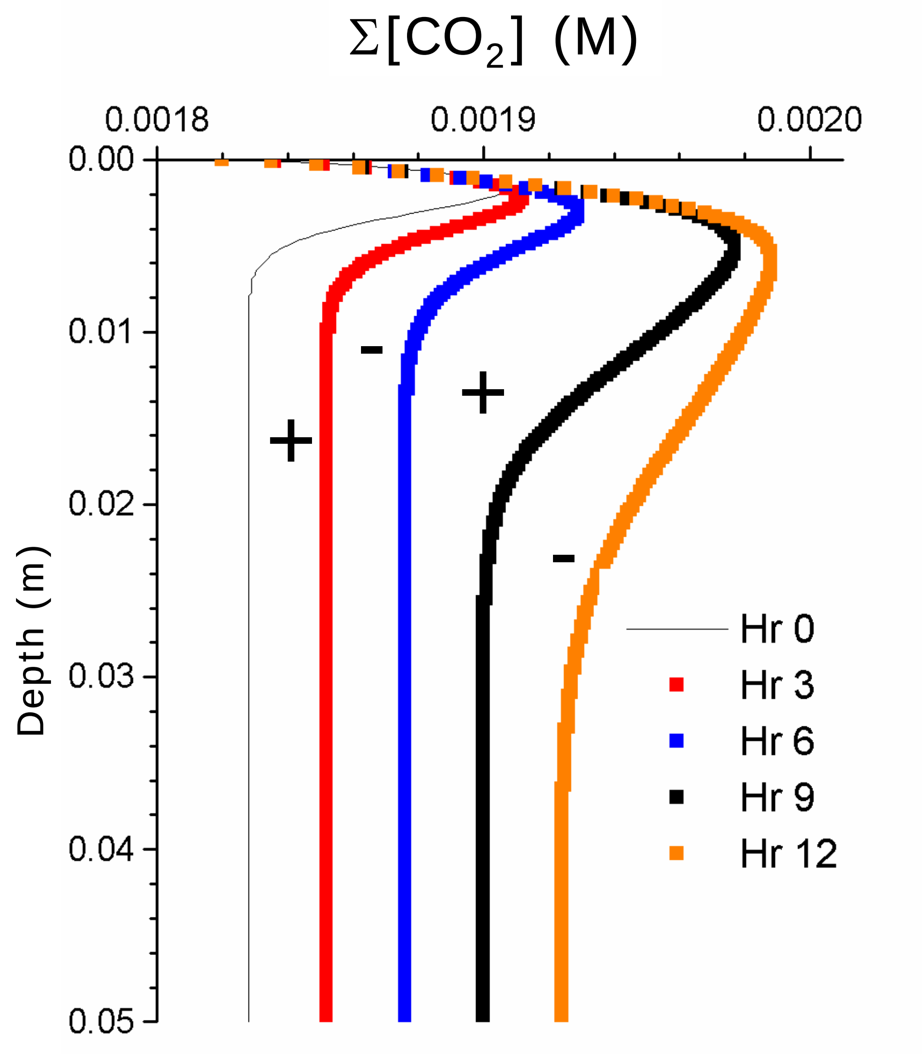
Sand concentration during the flood/ebb tide



Mud concentration during the flood/ebb tide

Example: $\Sigma[CO_2]$ Profiles

- Nonequilibrium profiles result from rapid changes in deposition and erosion.
- Initial $CO_2 = C_0$
- The profile is moving toward equilibrium.
- Note: (+) denotes deposition and (-) is for erosion
- The coordinate system is moving with seabed elevation



Future Work

- Relate active layer/critical shear stress in cohesive sediments to geochemical properties and bioturbation
- Develop time-dependent BC for geochemical model
- Expand model to 2D and 3D to include advection effects

Summary

- Hydrodynamic, sediment entrainment, and geochemical processes in the seabed have been coupled in a 1D model
- The 1D model shows realistic chemical response to variations in the physical environment (e.g., currents, sediment type, etc.)