Modeling of Particle Flows in Aquatic Environments

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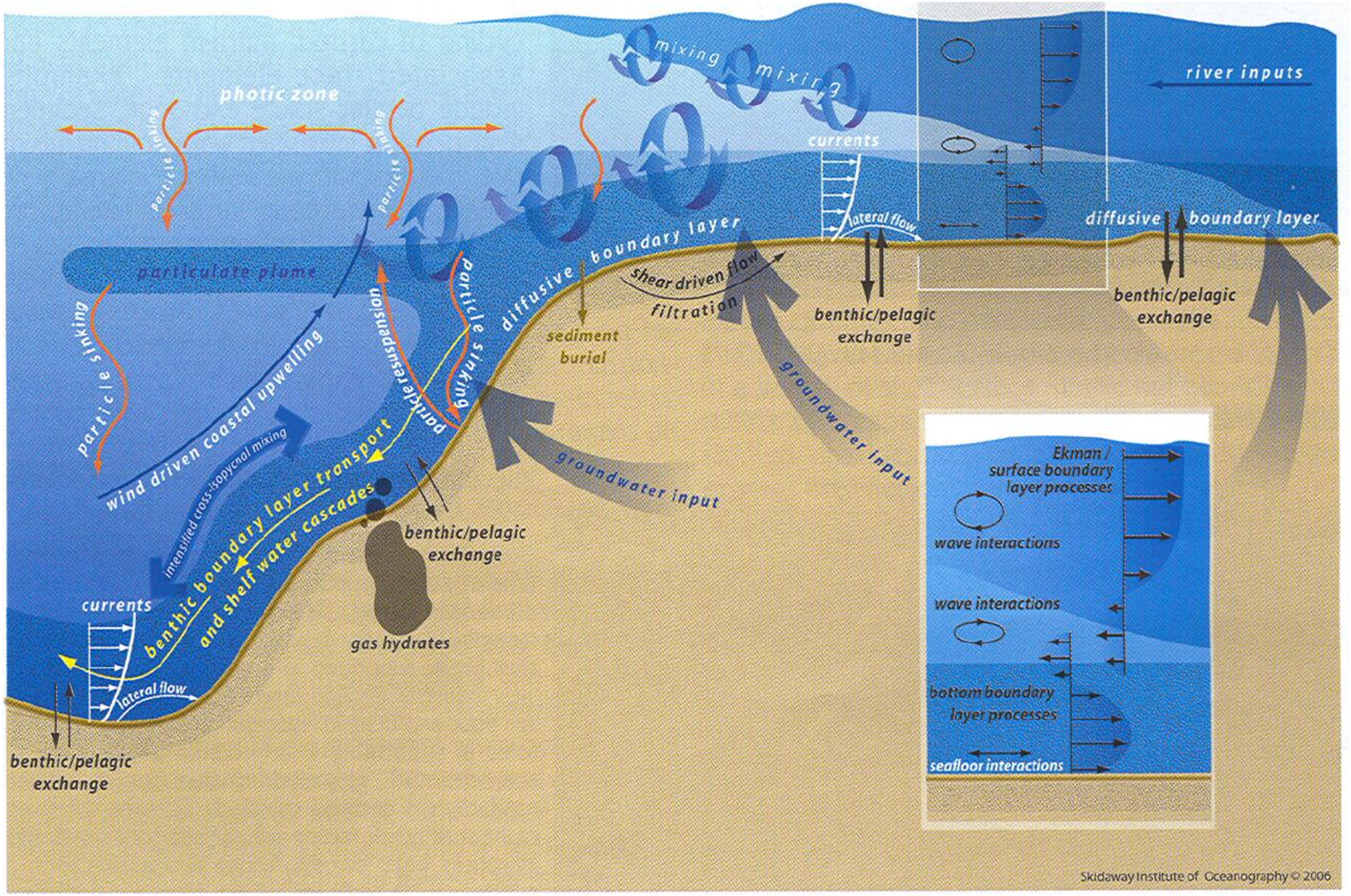
- *Continuum approach*
  - *'single-fluid' approach*
  - *extension from lab scales to field scales*
- *Grain-scale approach*
  - *erosion, deposition, segregation*
  - *concentration-dependent rheology / upscaling*
- *Summary*
- *Outlook*

Coastal margin processes



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Framework: Dilute flows

Assumptions:

- *volume fraction of particles* $< O(10^{-2} - 10^{-3})$
- *particle radius « particle separation*
- *small particles with negligible inertia*

Dynamics:

- *effects of particles on fluid continuity equation negligible*
- *coupling of fluid and particle motion primarily through momentum exchange, not through volumetric effects*
- *particle loading modifies effective fluid density*
- *particles follow fluid motion, with superimposed settling velocity*

→ *'single-fluid' approach*

Moderately dilute flows: Two-way coupling (cont'd)

$$\nabla \cdot \vec{u}_f = 0$$

$$\frac{\partial \vec{u}_f}{\partial t} + \left(\vec{u}_f \cdot \nabla\right) \vec{u}_f = -\nabla p + \frac{1}{Re} \nabla^2 \vec{u}_f + c\,\vec{e}_g$$

effective density

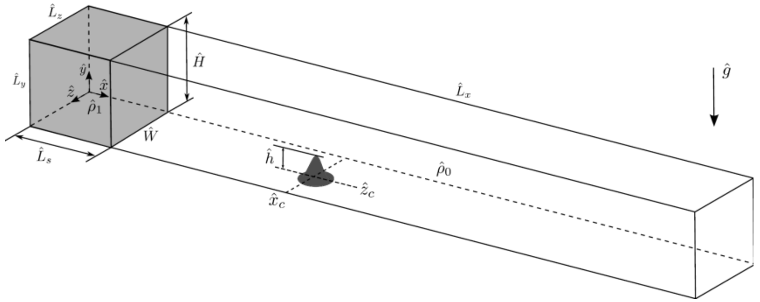
$$\frac{\partial c}{\partial t} + \left[\left(\vec{u}_f + \vec{U}_s\right) \nabla\right] c = \frac{1}{Sc\,Re} \nabla^2 c$$

settling velocity

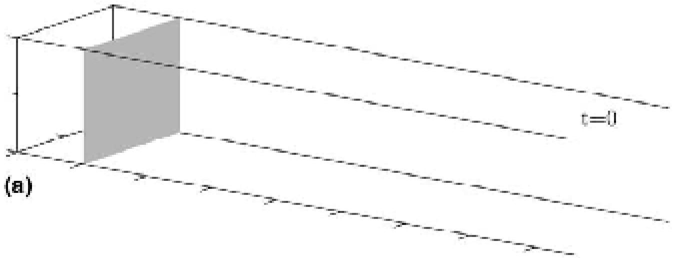
$$Re = \frac{u_b\,L}{\nu} \quad , \quad Sc = \frac{\nu}{D} \quad , \quad U_s = \frac{u_s}{u_b}$$

Model problem (with M. Nasr-Azadani)

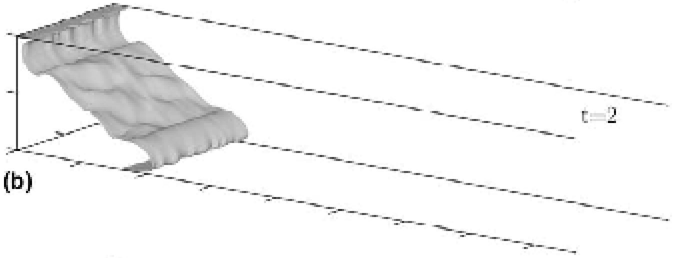
Lock exchange configuration



Dense front propagates
along bottom wall



Light front propagates
along top wall

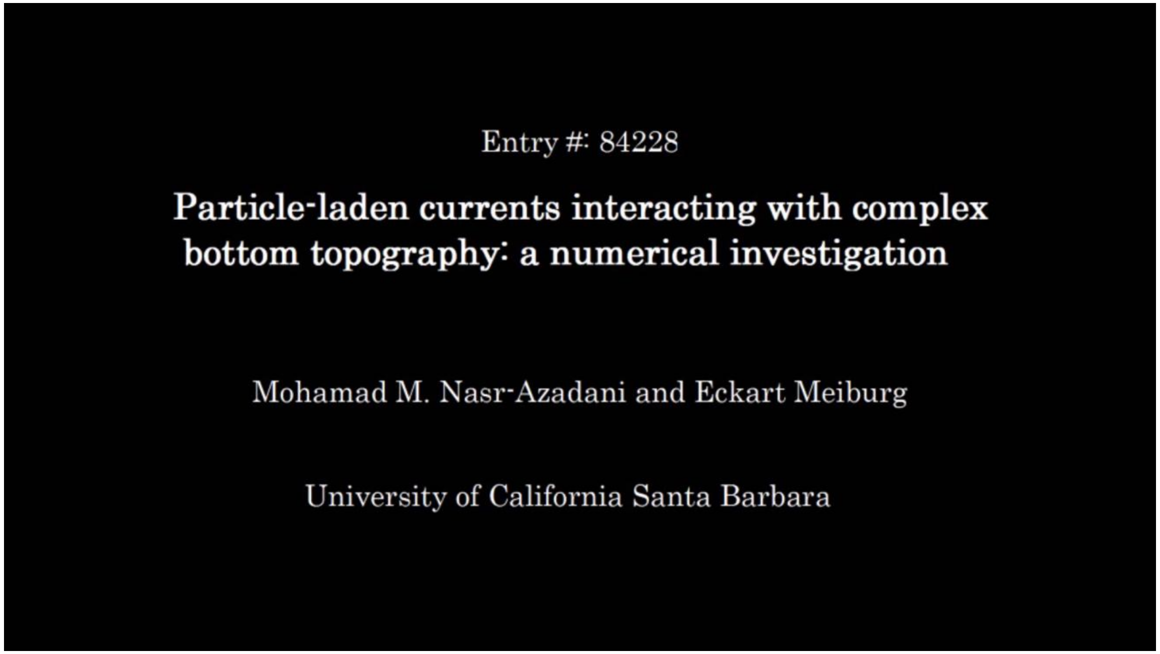


Computational approach for flow over complex geometry

- *second order central differencing for viscous terms*
- *third order ENO scheme for convective terms*
- *third order TVD Runge-Kutta time stepping*
- *projection method to enforce incompressibility*
- *domain decomposition, MPI*
- *employ PETSc (developed by Argonne Nat'l Labs) package*
- *non-uniform grids*
- *immersed boundary method for complex bottom topography*

Lock exchange configuration

Flow of turbidity current around localized seamount



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Particle-laden currents interacting with complex bottom topography: a numerical investigation

Mohamad M. Nasr-Azadani and Eckart Meiburg

University of California Santa Barbara

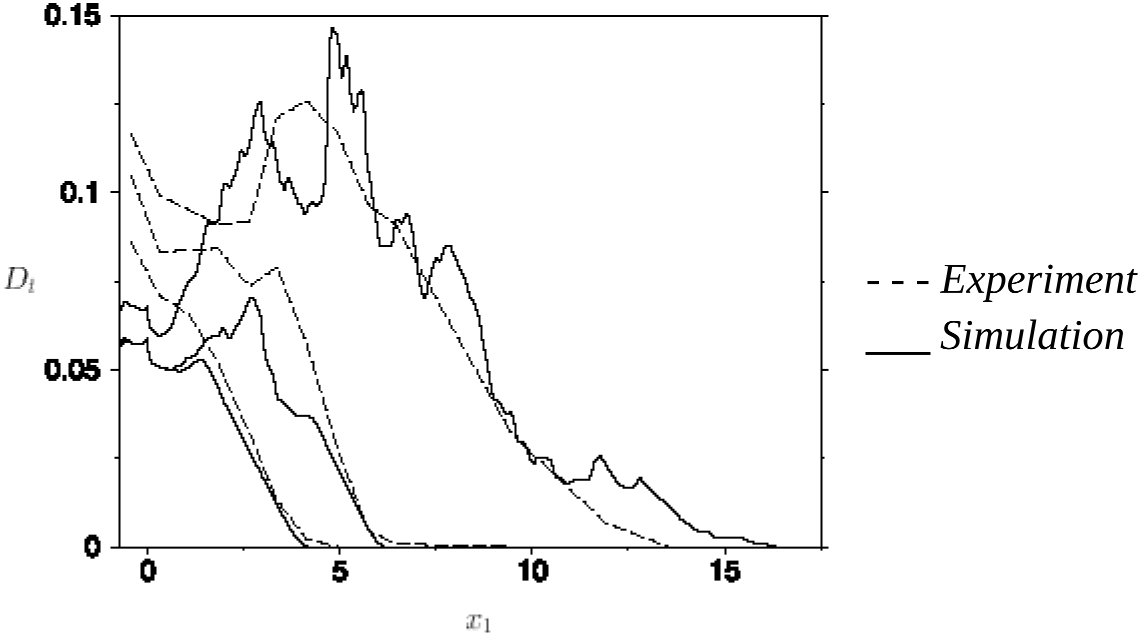
- *turbidity current develops lobe-and-cleft instability of the front*
- *current dynamics and depositional behavior are strongly affected by bottom topography*

$$Re_{sim} = 2,000 : \;\; u_b \approx 2cm/s \;,\;\; L \approx 10cm \;,\;\; \nu \approx 10^{-6} m^2/s$$

→ *simulation corresponds to a laboratory scale current, not field scale!*

Deposit profiles

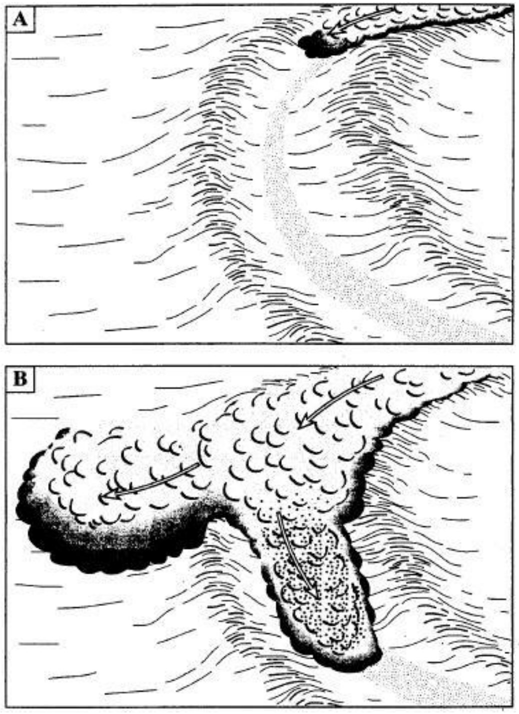
Comparison of transient deposit profiles with experimental data of de Rooij and Dalziel (1998)

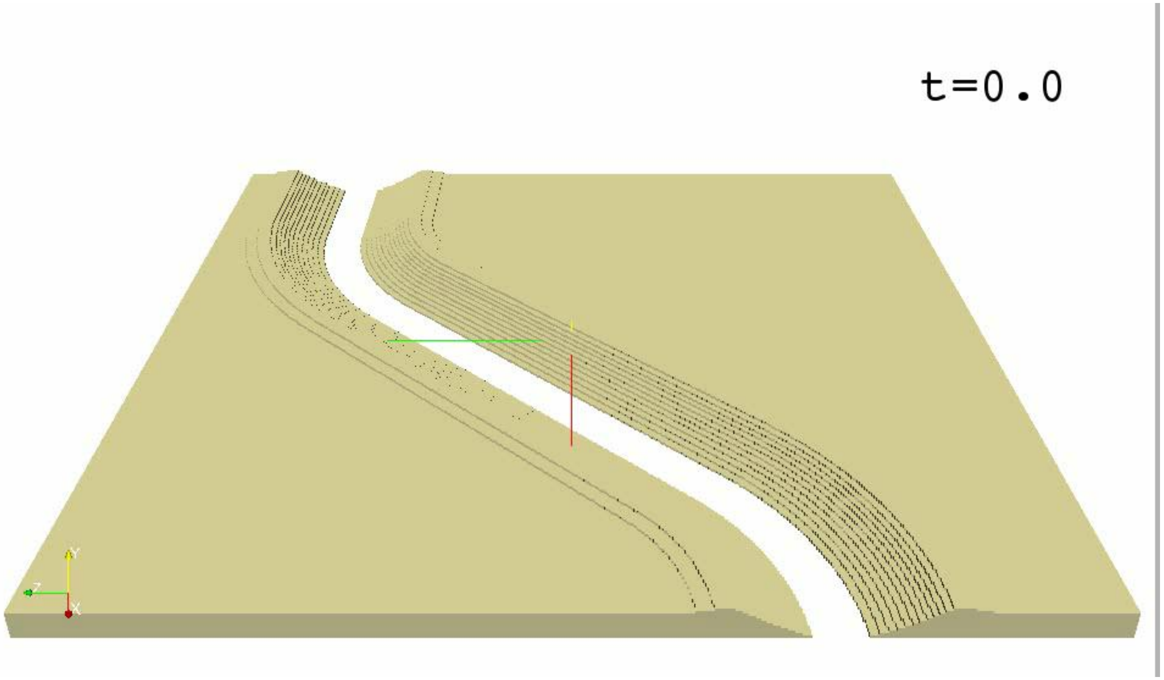


- *simulation reproduces experimentally observed sediment accumulation*

Turbidity current/sediment bed interaction

‘Flow stripping’ in channel turns: lateral overflows



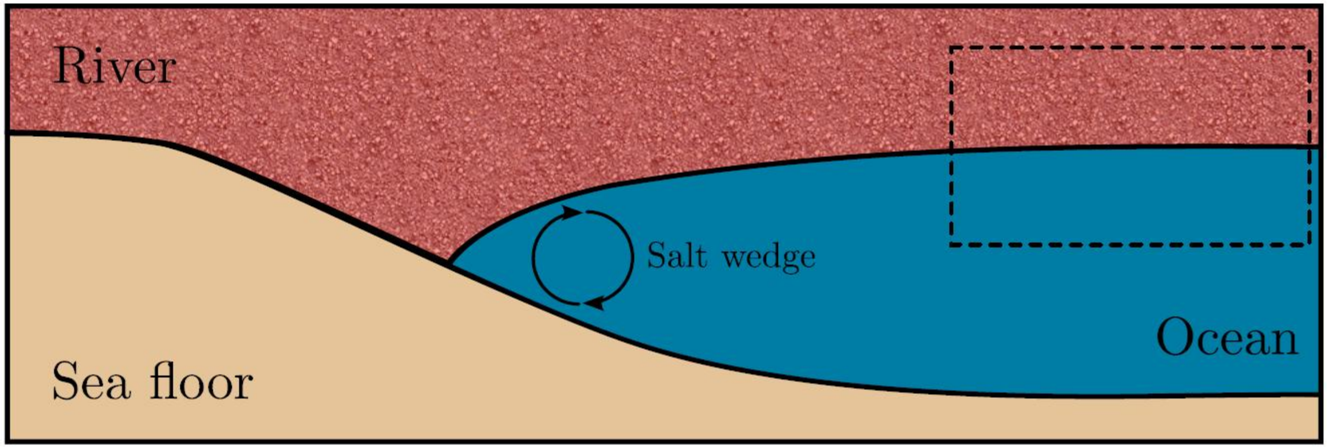


Sedimentation from river plumes (w. P. Burns)

Hypopycnal river plumes:

density of the river (fresh water + sediment) < density of ocean (water + salinity)

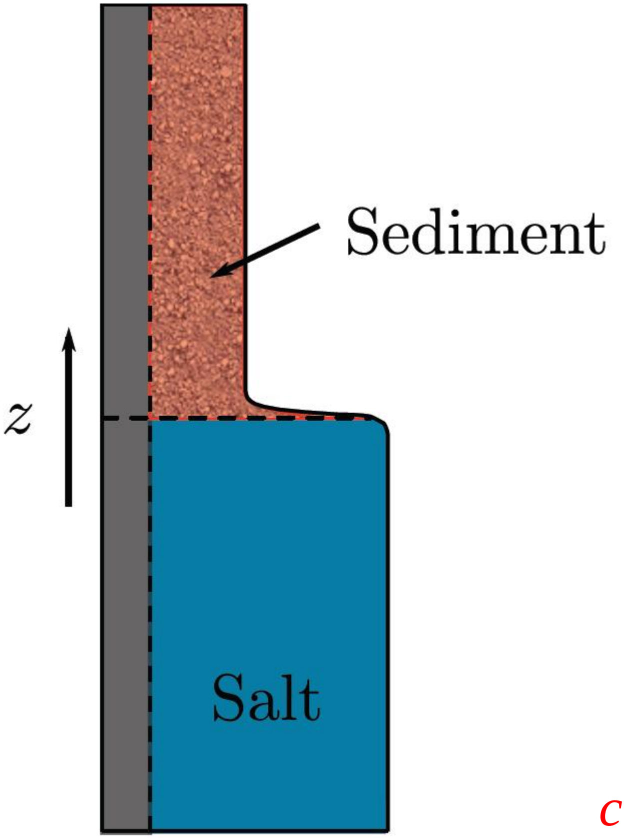
→ *river outflow propagates along the ocean surface*

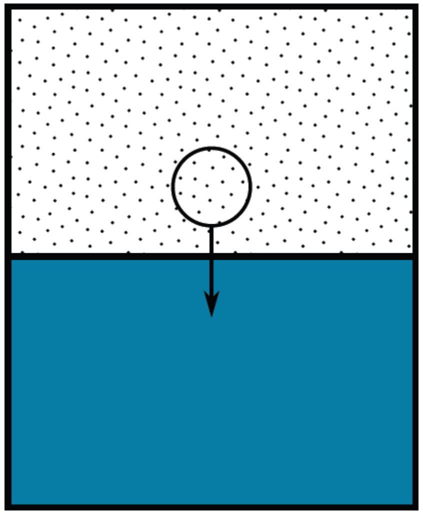


- *focus on the downstream density stratification*

Sedimentation from river plumes: Double-diffusion

Base density profile:

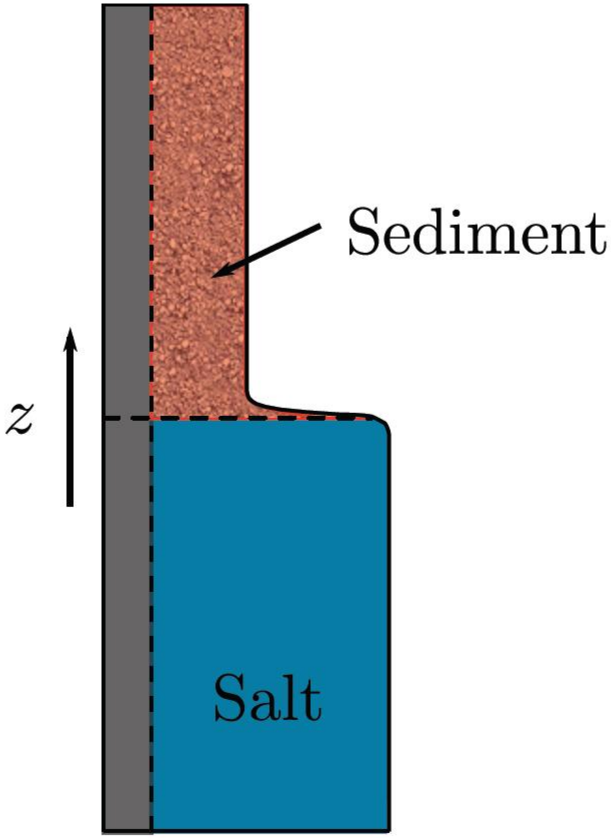


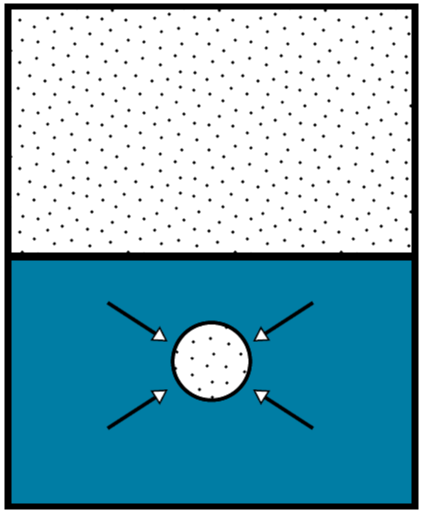


consider local downward perturbation of fluid element across opposing gradients

Sedimentation from river plumes: Double-diffusion

Base density profile:

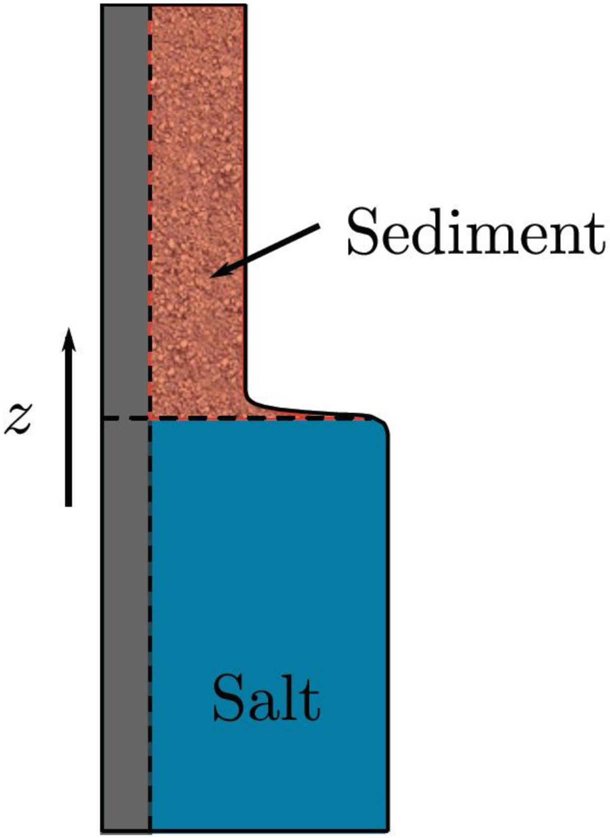


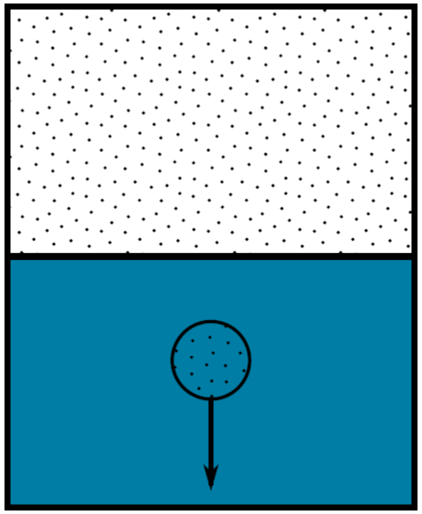


salinity diffuses inward more rapidly than particles diffuse outward

Sedimentation from river plumes: Double-diffusion

Base density profile:





→ *fluid element will continue to sink*

Sedimentation from river plumes: Numerical simulations

DNS simulations

Strengths:

- *accurately reproduce continuum-scale physics*
- *provide very detailed information on mixing, dissipation etc.*
- *require a minimum of empirical modeling assumptions*

Current challenges:

- *computationally very expensive*
- *limited to small Reynolds numbers, laboratory scale currents*
- *limited to dilute, depositional currents carrying small particles*
- *difficult to correctly capture erosion, bedload transport*
- *no direct particle/particle interactions (collisions)*
- *limited ability to reproduce segregation of different particle sizes*
- *no hindered settling, no concentration-dependent rheology*

Alternative approach:

- *two-fluid models: wider applicability, but require empirical closures*

Why can we not do a DNS simulation at $Re=10^9$?

- *Re is a measure of the ratio of the largest ("integral") length scale L of the flow to the smallest ("Kolmogorov") length scale η, at which kinetic energy is dissipated into heat*
- *turbulence theory shows that* $\frac{L}{\eta} = Re^{3/4}$
- *DNS, which resolves all scales, needs to have grid spacing $\Delta x \sim \eta$, and computational domain size $\sim L$ → number of grid points in each direction $N \sim Re^{3/4}$. For 3D simulation $N_x \cdot N_y \cdot N_z \sim Re^{9/4}$. Time step $\Delta t \sim \Delta x$ →*

Computational effort $E \sim N_x \cdot N_y \cdot N_z \cdot \Delta t^{-1} \sim Re^3$!!

- *field scale simulation would require 10^{18} times effort of lab scale simulation*

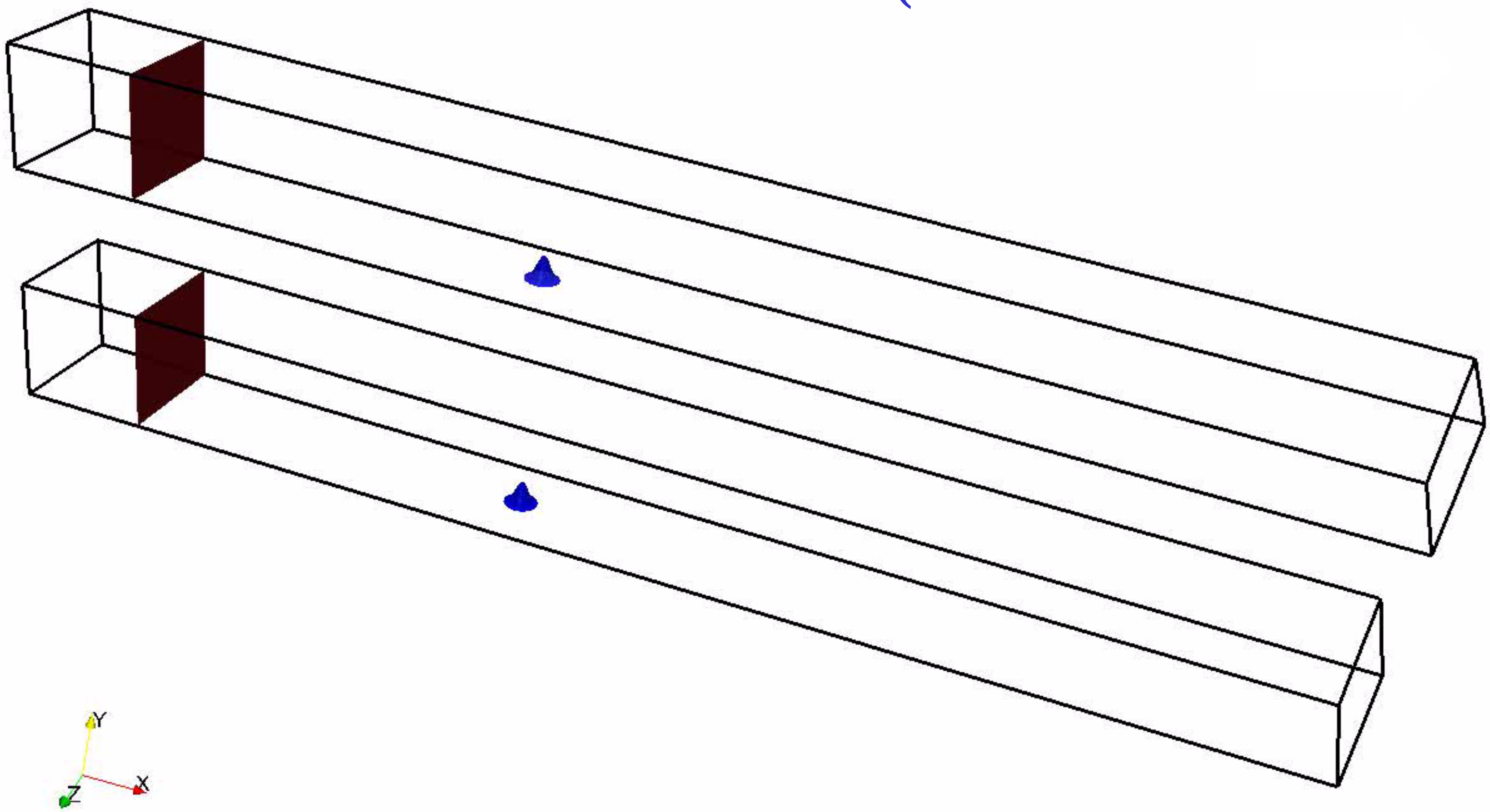
How can we perform simulations at field scale?

Key idea:

- *While the large scale flow features are unique for every flow, the smallest scale flow features are similar for all turbulent flows → we may not have to resolve them, but instead may be able to model their main effect (energy extraction from large scales) by means of a* ***turbulence model***

- *Two different approaches:*
  - *temporal averaging of governing equations →* ***Reynolds-averaged Navier-Stokes (RANS) simulations***
  - *spatial averaging of governing equations →* ***Large-eddy simulations (LES)***

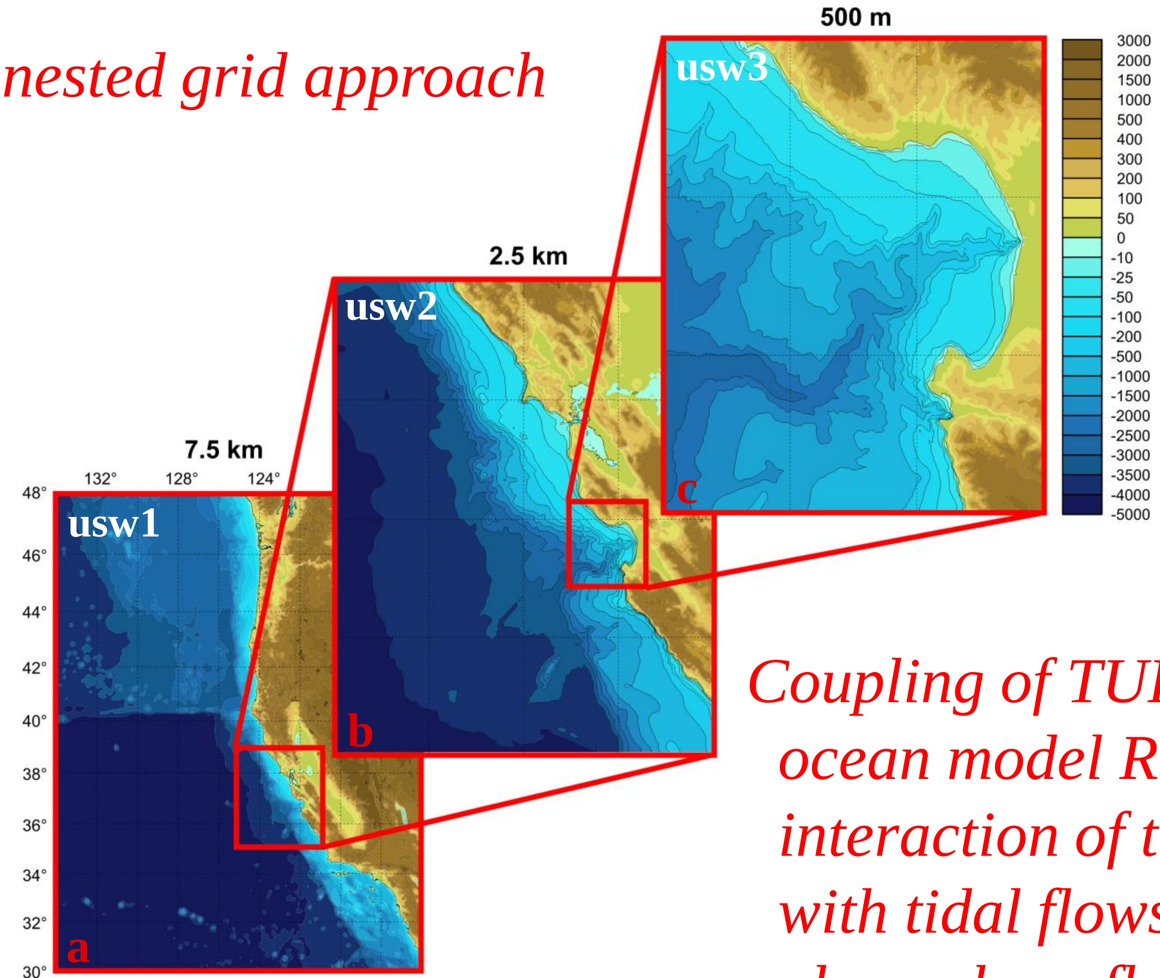
DNS simulation at Re=10^3 vs. LES simulation at Re= $2x10^5$
(with S. Radhakrishnan)



- *higher Re current propagates faster, has more fine-scale structure*
- *similar flow structure, but large difference in bottom shear stress*

Upscaling: Embedding high-resolution simulation within coarser resolution one (w. J. Syvitski, H. Arango, C. Harris)

- *nested grid approach*



Coupling of TURBINS with regional ocean model ROMS, to include interaction of turbidity currents with tidal flows, internal waves, along-shore flows, Coriolis effects...

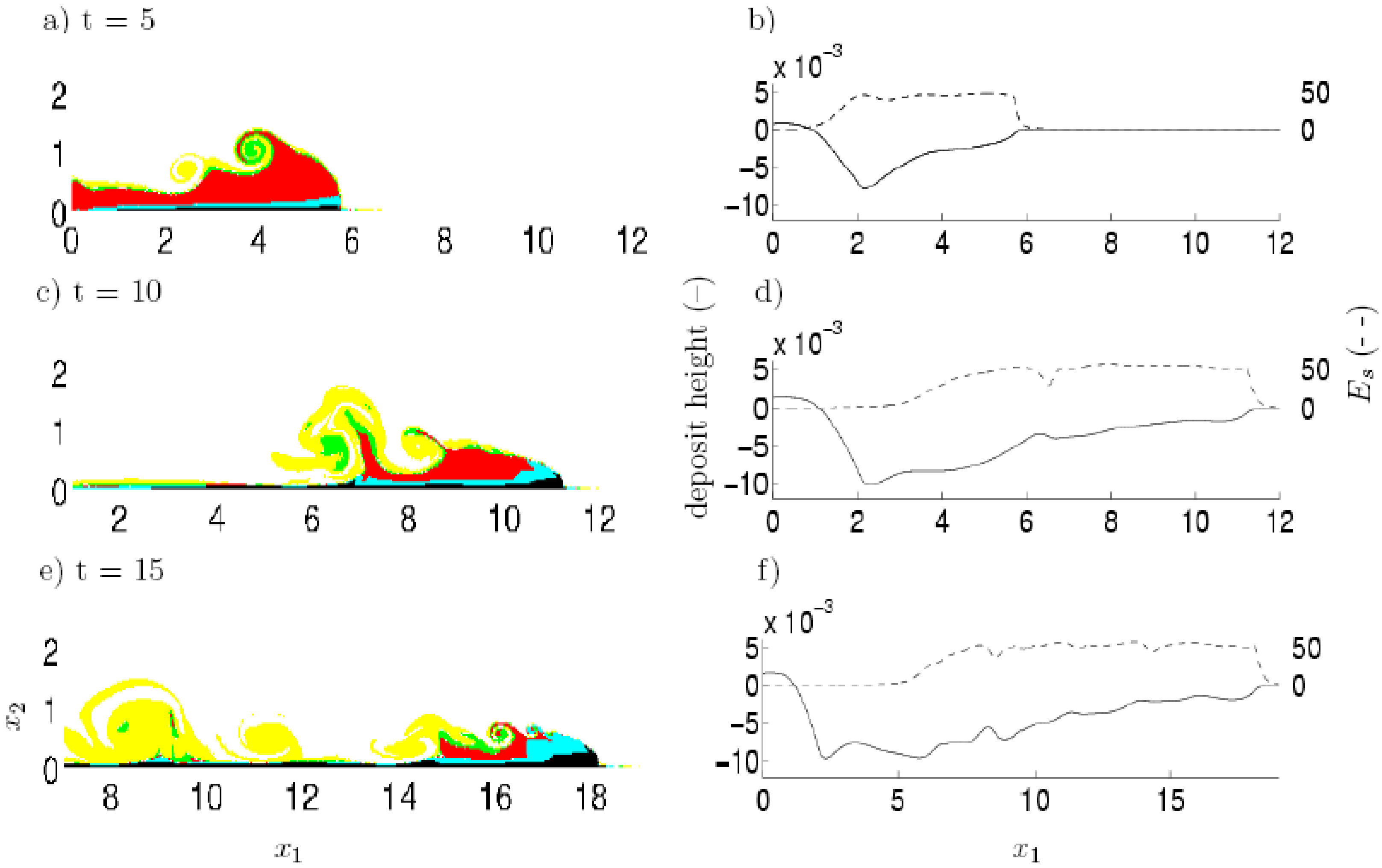
Erosion, resuspension of particle bed (with F. Blanchette, M. Strauss, B. Kneller, M. Glinsky)

Experimentally determined correlation by Garcia & Parker (1993) evaluates resuspension flux at the particle bed surface as function of:

- *bottom wall shear stress*
- *settling velocity*
- *particle Reynolds number*

Here we model this resuspension as diffusive flux from the particle bed surface into the flow

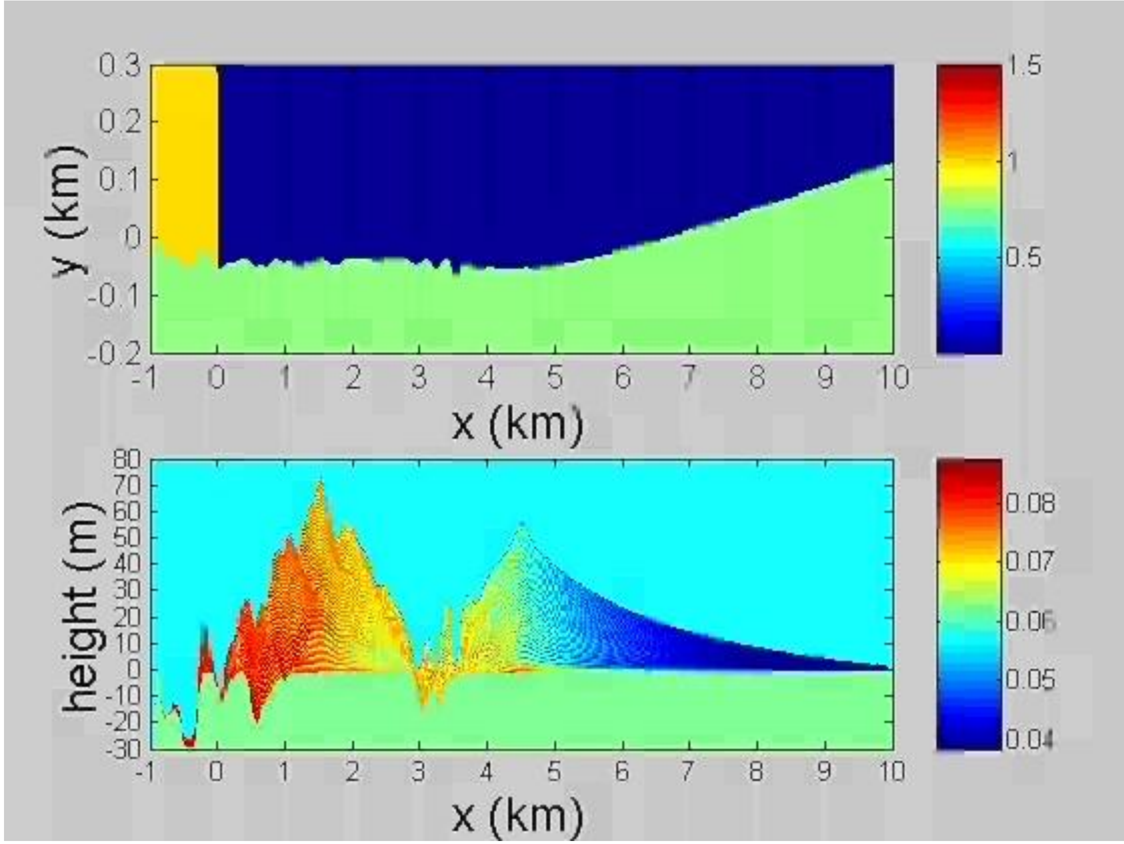
Erosion, resuspension of particle bed (cont'd)



- *based on experimentally measured correlation between shear stress at the surface of the bed and an effective resuspension flux*

Erosion, resuspension of particle bed (cont'd)

- *multiple, polydisperse flows*
- *feedback of deposit on subsequent flows*
- *formation of ripples, dunes etc.*

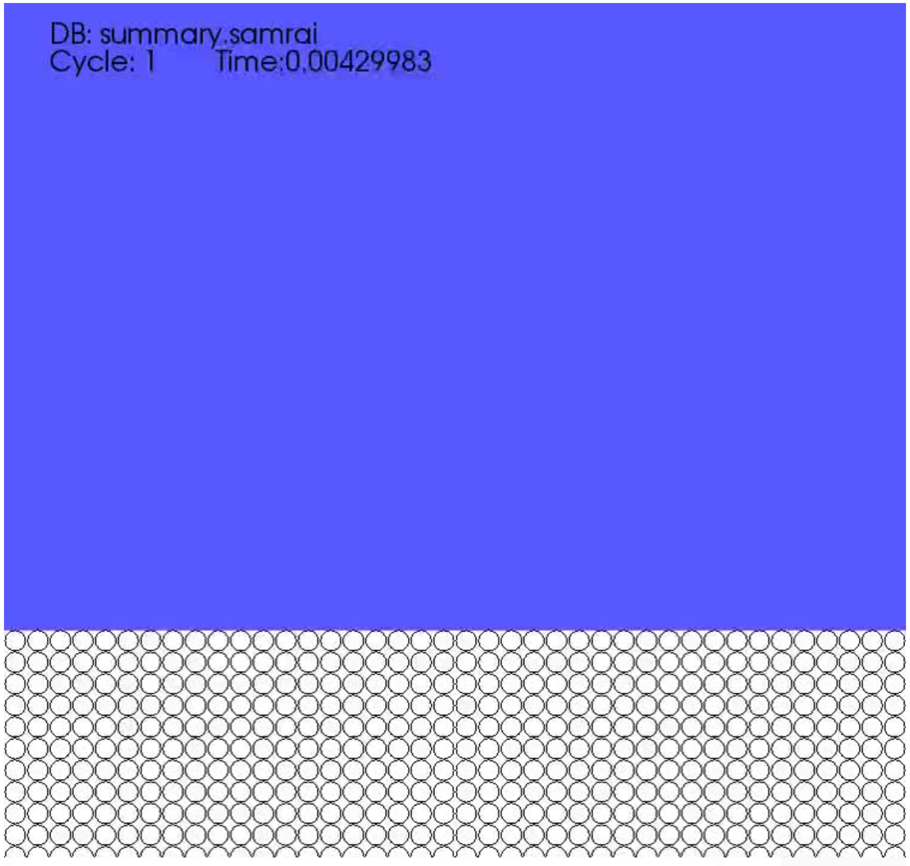


Erosion of sediment bed (Z. Borden, Y. Kanarska, M. Glinsky, E. Biegert)

- *erosion models to date are mainly empirical, e.g. Garcia and Parker (1993), limited validity, not based on first principles → research at the microscopic level is needed to develop improved erosion models*
- *perform many-particle simulations, with the flow around each particle resolved*
- *employ model flows (Couette), subject sediment bed to increasing shear stress until erosion occurs*
- *study mechanics of erosion from first principles*
- *derive scaling laws for improved macroscopic, continuum erosion models*

Erosion of particle bed: Couette flow (Z. Borden, L. Maurin)

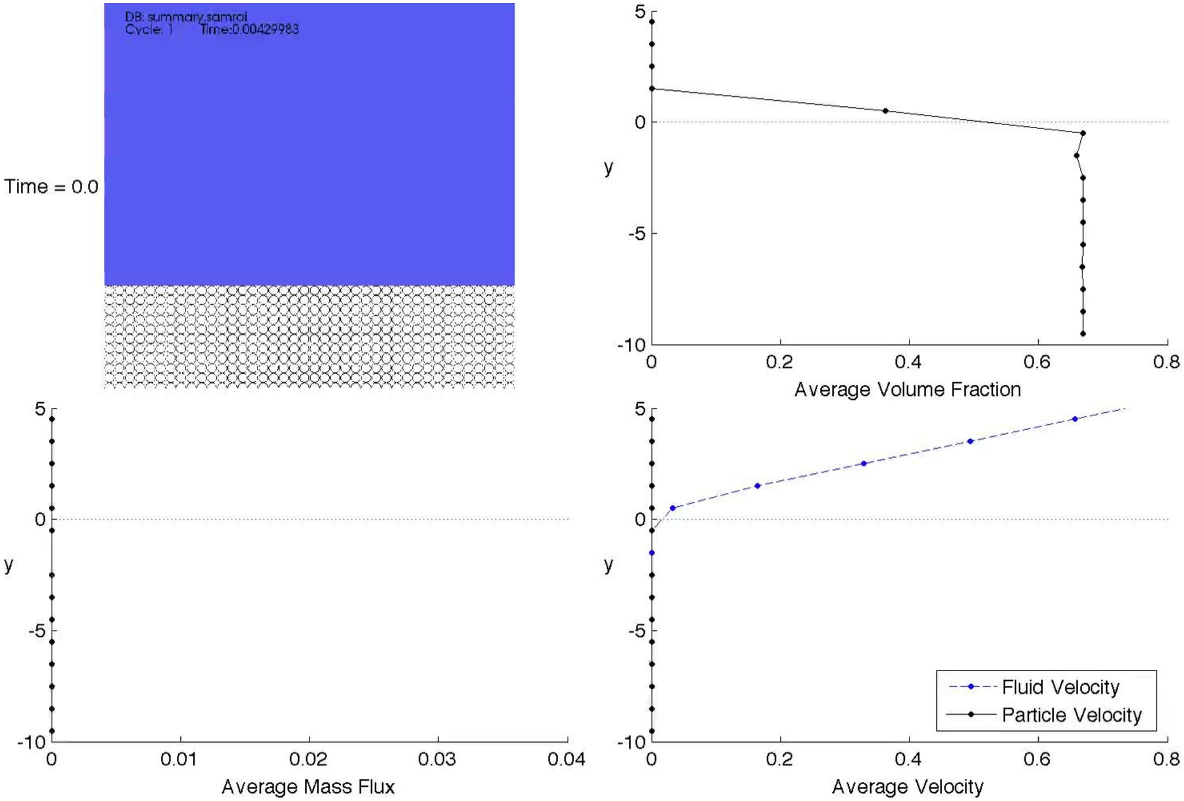
2D simulation, Shields number = 0.16:



Borden, Maurin and Meiburg (2012)

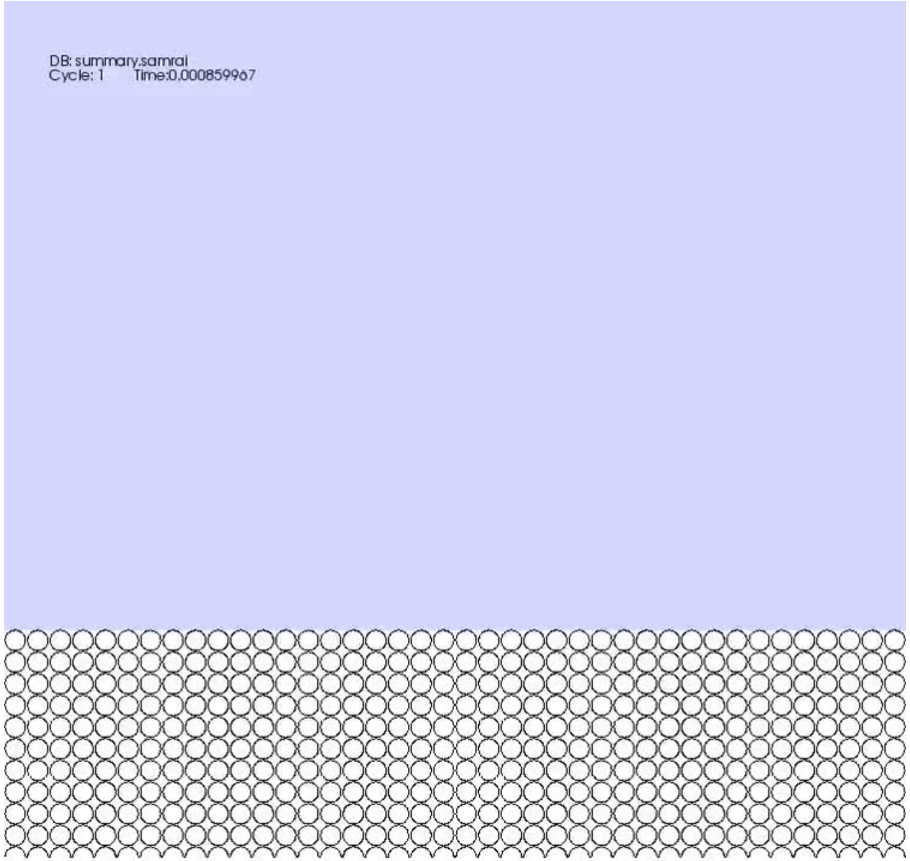
Erosion of particle bed (cont'd)

- *Extracting continuum information:*



Erosion of particle bed (cont'd)

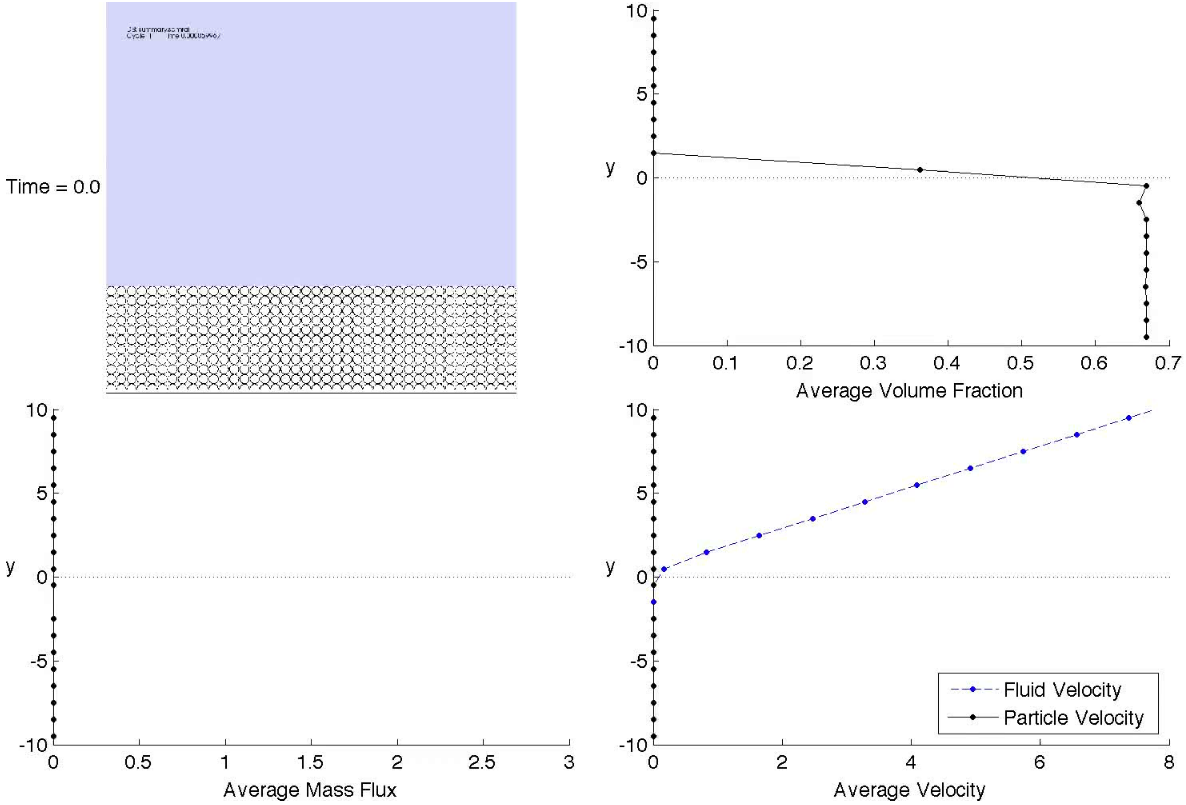
2D simulation, Shields number = 0.80:



Borden, Maurin and Meiburg (2012)

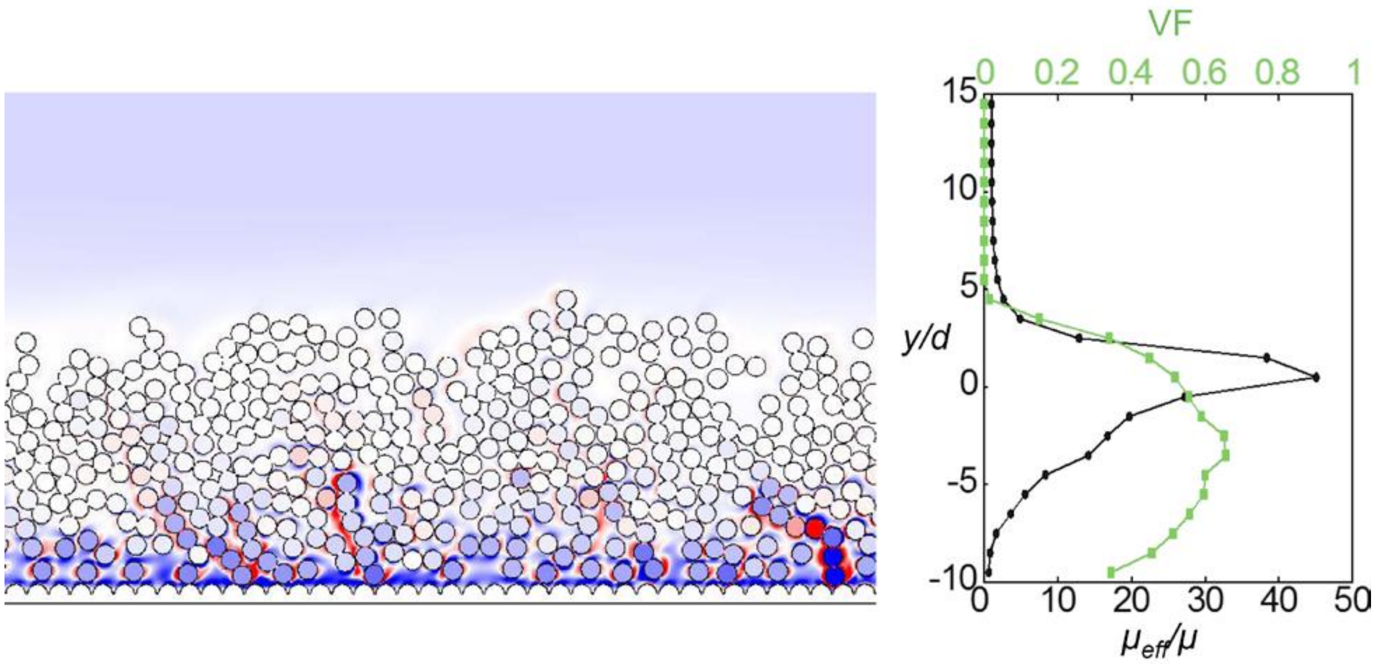
Erosion of particle bed (cont'd)

Towards effective continuum boundary conditions:



Erosion of particle bed (cont'd)

Towards effective rheology and continuum boundary conditions:



- *effective viscosity can increase by a factor of 50!*

Settling of particles, segregation (w. E. Biegert, D. van Vugt)

Particles of different sizes settling, interacting via collisions:

- *study segregation mechanisms, spatial properties of resulting sediment bed*

Grain-scale simulations

Advantages:

- *accurately capture dynamics of individual grains*
- *provide very detailed information on grain/grain interactions*
- *can clarify mechanisms governing size segregation*
- *potential to extract effective rheology, and to upscale*
- *potential to analyze erosion of compacted vs. non-compacted sand*
- *potential to study the coupling between flow above and inside bed*

Current challenges and questions:

- *computationally very expensive*
- *limited to small scales, O(1,000) particles*
- *how relevant are the dynamics at the grain scale, compared to erosion of large chunks of sediment by large-scale energetic eddies?*

Summary

- *simulation tools for laboratory–scale, dilute depositional currents carrying small particles have contributed to our understanding*
- *extension to field scale via LES/RANS models is underway*
- *beginning to understand the physics behind bedform formation: ripples, dunes, antidunes, sediment waves, levees …*
- *challenges: erosion, bedload transport, particle/particle collisions, hindered settling, concentration-dependent rheology*
- *alternative: two-fluid models, require empirical closure assumptions*
- *grain-scale simulations are beginning to contribute to our understanding of microscale phenomena*
- *limited to O(1,000) particles, but may provide information that will allow for progress with regard to upscaling*
- *importance of grain-scale phenomena for large-scale dynamics?*

Outlook

- *close gap between grain-scale and lab-scale (‘mesoscale’) → upscaling*
- *extend lab-scale modeling to field scales via LES/RANS models*
- *need better understanding of current/bed interaction, including erosion, bedload transport, coupling between flow above the bed and inside the bed …*
- *need better understanding of the influence of higher concentrations of particles: collisions, hindered settling, rheology*
- *progress will require coordinated advances in modeling (grain-scale, mesoscale, laboratory scale, field scale), laboratory measurements and field-scale observations*
- *it will be useful to define specific test cases to be analyzed from different perspectives*

Acknowledgments

- *B. Kneller, B. Hall, F. Blanchette, M. Glinsky, M. Strauss, M. Nasr-Azadani, S. Radhakrishnan, Z. Borden, E. Biegert*