A Turbulence-Resolving Numerical Investigation of the Wave-Supported Gravity Flow

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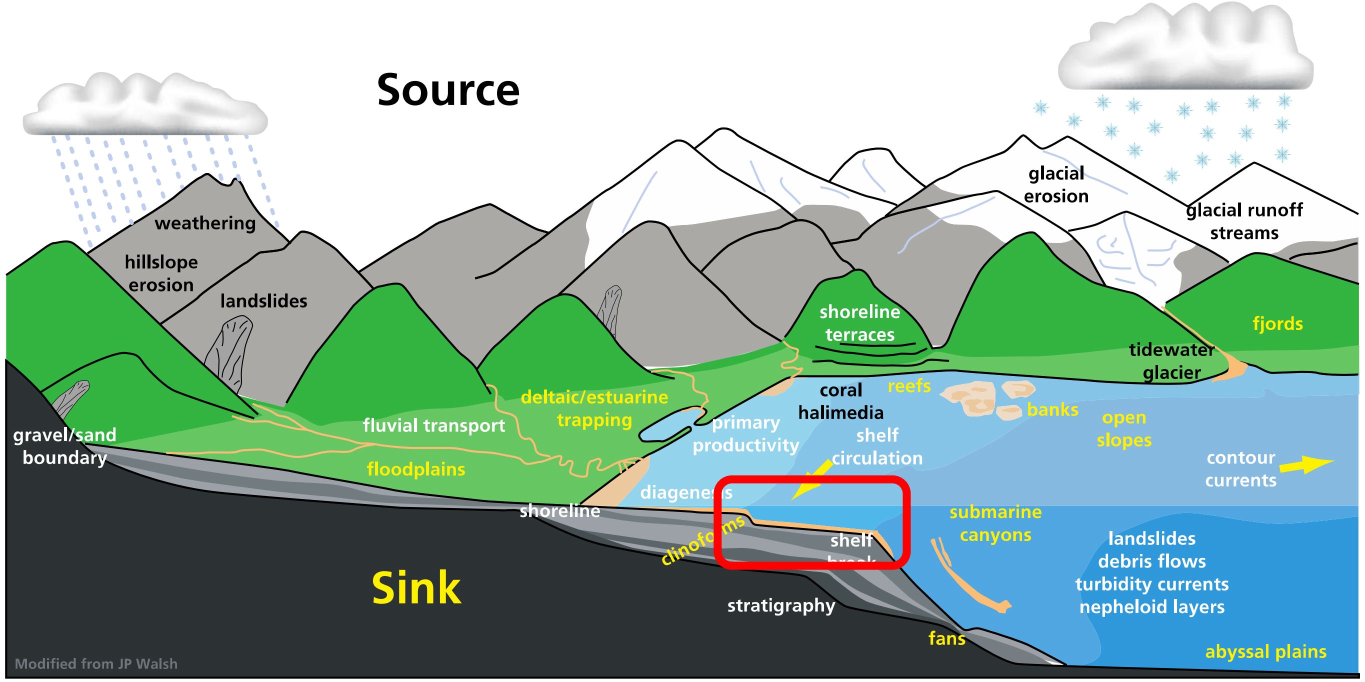
Sediment Transport in the Source to Sink System

- Erosion sculpts landscape, and the redistribution of sediment creates the alluvial plains, coasts, deltas, and deposits on continental shelves.
- Transfer of sediment plays a key role in cycling of elements when passing through a connected suite of environmental units.
- Current and **wave-supported gravity flows (WSGFs)** were identified as the main offshore delivery mechanism of fine terrestrial sediments in the source to sink system (e.g., Wright et al. 1988; Traykovski et al. 2000; Hale and Ogston 2015).



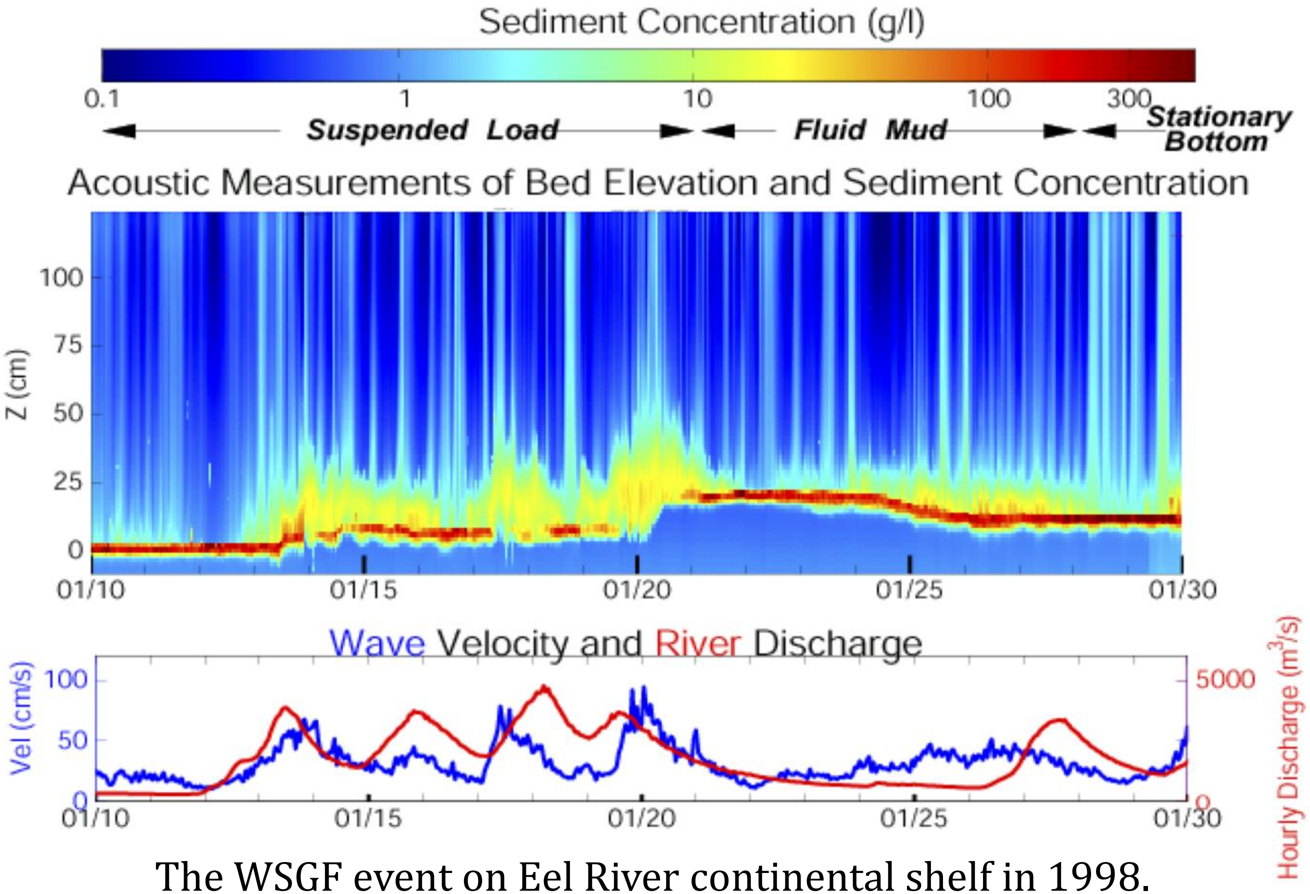
The source to sink system.
Adapted from MARGINS Science Plans (2003).

Field Observation of the Wave-Supported Gravity Flows

Direct field evidences (Traykovski et al. 2000 Cont. Shelf Res.; Hale and Ogston 2015) indicate that WSGFs are one of the most important processes driving the cross continental shelf fine sediment transport, and following understandings have been achieved:

1. **Wave resuspension** plays a key role in the generation of WSGFs.
2. There is a **high concentration sediment layer** in the resulting wave bottom boundary layer.

Limited by the sensors, it is difficult to measure concentration and velocity accurately in the thin and concentrated turbid layers.

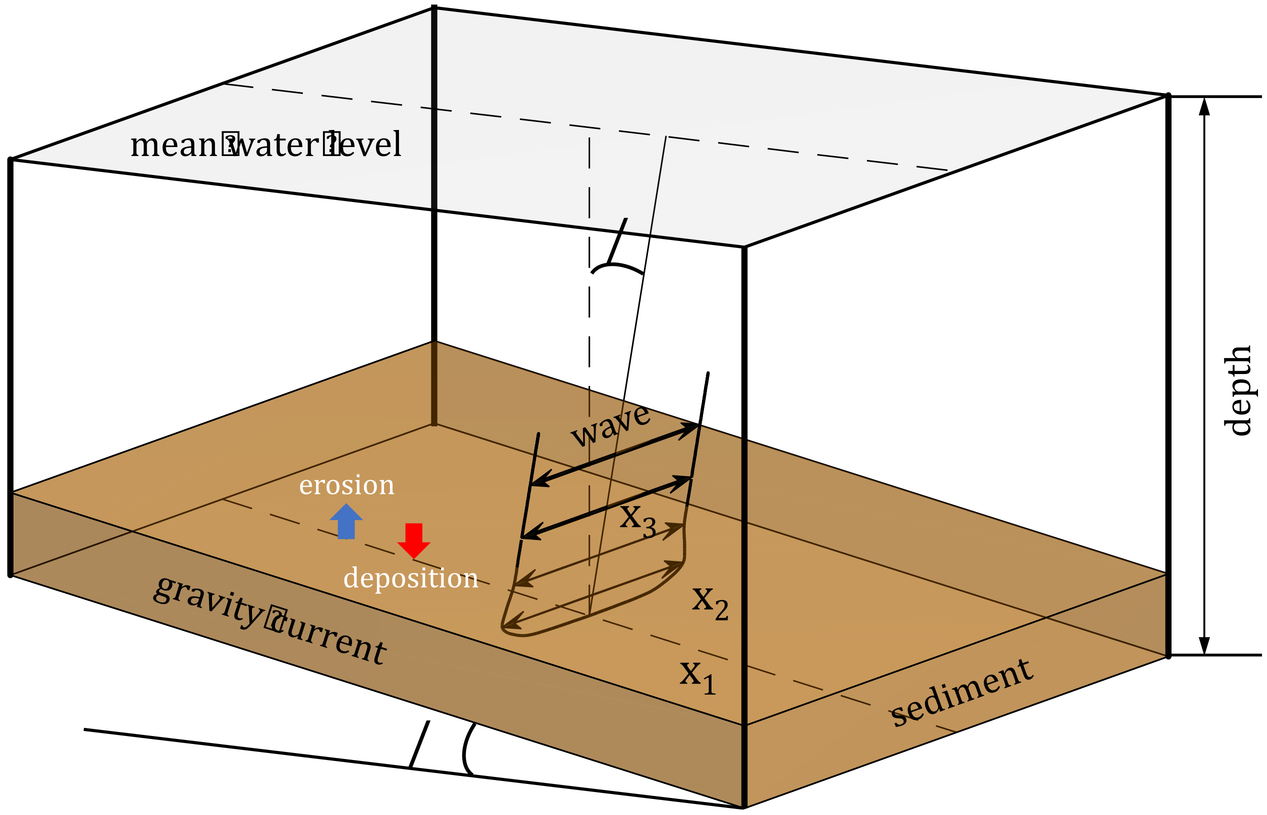


The WSGF event on Eel River continental shelf in 1998.
Adapted from Traykovski et al. (2000) Cont. Shelf Res.

Model Formulation for the Wave-Supported Gravity Flows (I)

Illustration of the physical model:

1. Since the continental shelf is an open field, there is **no net pressure gradient** acting on the flow. Namely, without any sediment suspension to cause baroclinic pressure gradient in the water column, there will be no downslope current.
2. To isolate the effects of slope, waves are specified as transverse (x_2) to the downslope direction (x_1).
3. Erosion and deposition of sediment are taken into account.
4. In the figure, the slope angle θ (about $\mathbf{0.5^\circ}$) is exaggerated while the water depth (about **10~100 meters**) is minified.



Physical setting of the problem: the flow is driven only by the excess density of the water-sediment mixture. Cantero et al. (2009) J. Geophys. Res.

Wave bottom boundary layer is only about 10 cm!

Model Formulation for the Wave-Supported Gravity Flows (II)

Based on **the equilibrium Eulerian approach** (Balachandar and Eaton (2010) Annu. Rev. Fluid Mech.), the model system with erosion and deposition is governed by

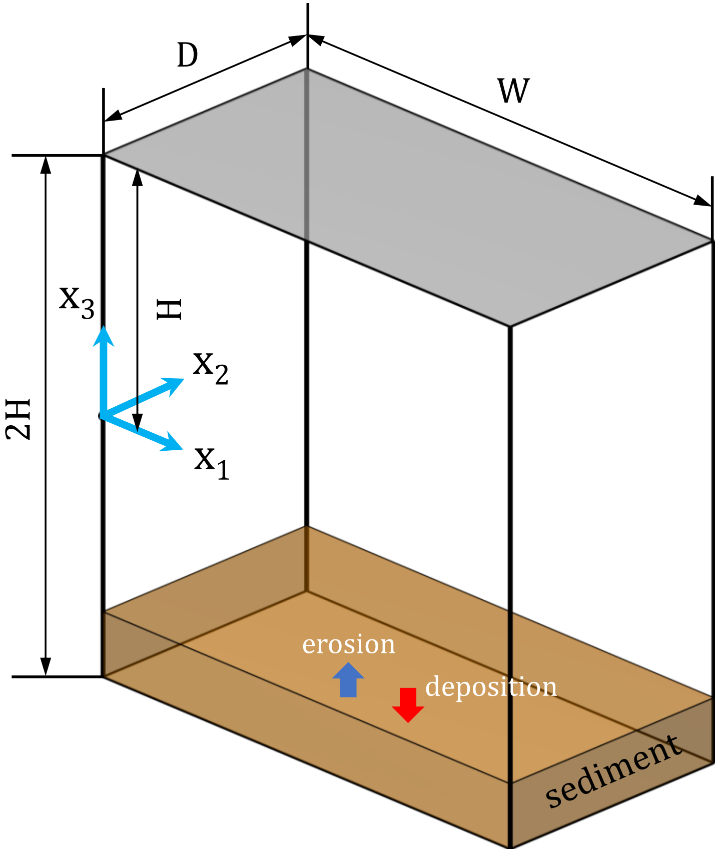
$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}} \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i + \frac{\mathbf{1}}{\mathbf{Fr}^{\mathbf{2}}} \boldsymbol{\Phi \phi n_i}$$

$$\frac{\partial \phi}{\partial t} + \frac{\partial \phi v_j}{\partial x_j} = \frac{1}{\mathrm{ReSc}} \frac{\partial^2 \phi}{\partial x_j \partial x_j}$$

where $n_i = [\sin(\theta) \quad 0 \quad -\cos(\theta)]$ is the unit direction of gravitational acceleration and $v_i = u_i + \boldsymbol{w} n_i$ is the velocity of sediment.

The **pseudo-spectral method** (e.g., Ozdemir et al. 2010, JFM) is used to solve the above governing equations accurately with suitable boundary conditions. (Cheng et al. 2015, JGR).



Sketch of the computational domain.

Numerical Result | Fine Sediment Transport in Current Boundary Layer at Re_τ=180

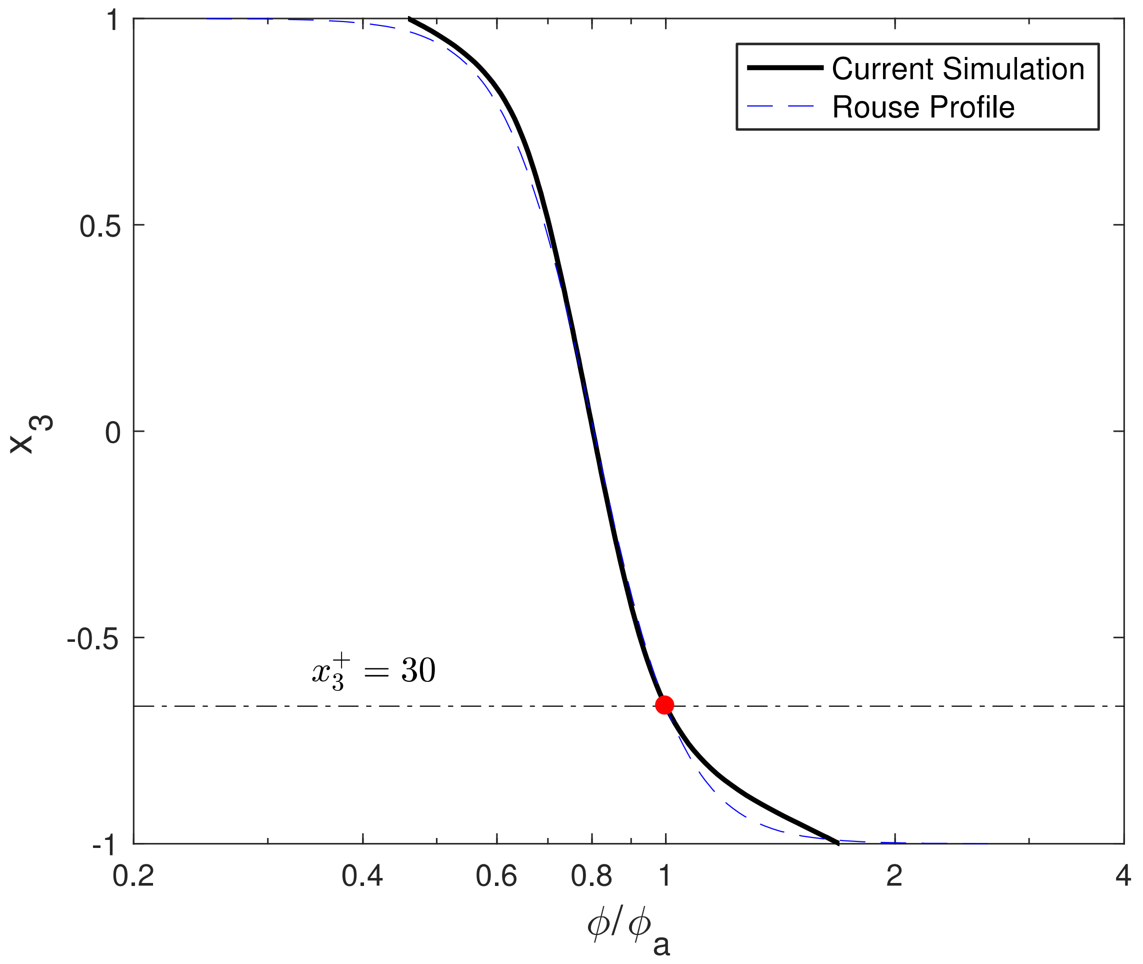
Numerical setup:

- Domain size: $4\pi \times 3\pi \times 2$
- Reynolds number: $Re_\tau = \frac{2u_* H}{\upsilon} = 180$
- Settling velocity: $w = 0.5$ mm/s
- Grid number: $128 \times 128 \times 129$ (2M)

From flux balance, the well-known Rouse formula for **dilute** suspension:

$$\phi = \phi_a \left(\frac{1 - x_3}{1 + x_3} \frac{a}{2 - a} \right)^{w/\kappa u_*}$$

where ϕ_a is a reference concentration at the reference height $x_3 = a$.



Comparison of concentration profile with Rouse formula.

$a = 0.33$ and $\boldsymbol{\phi_a = 5.78 \times 10^{-5}}$

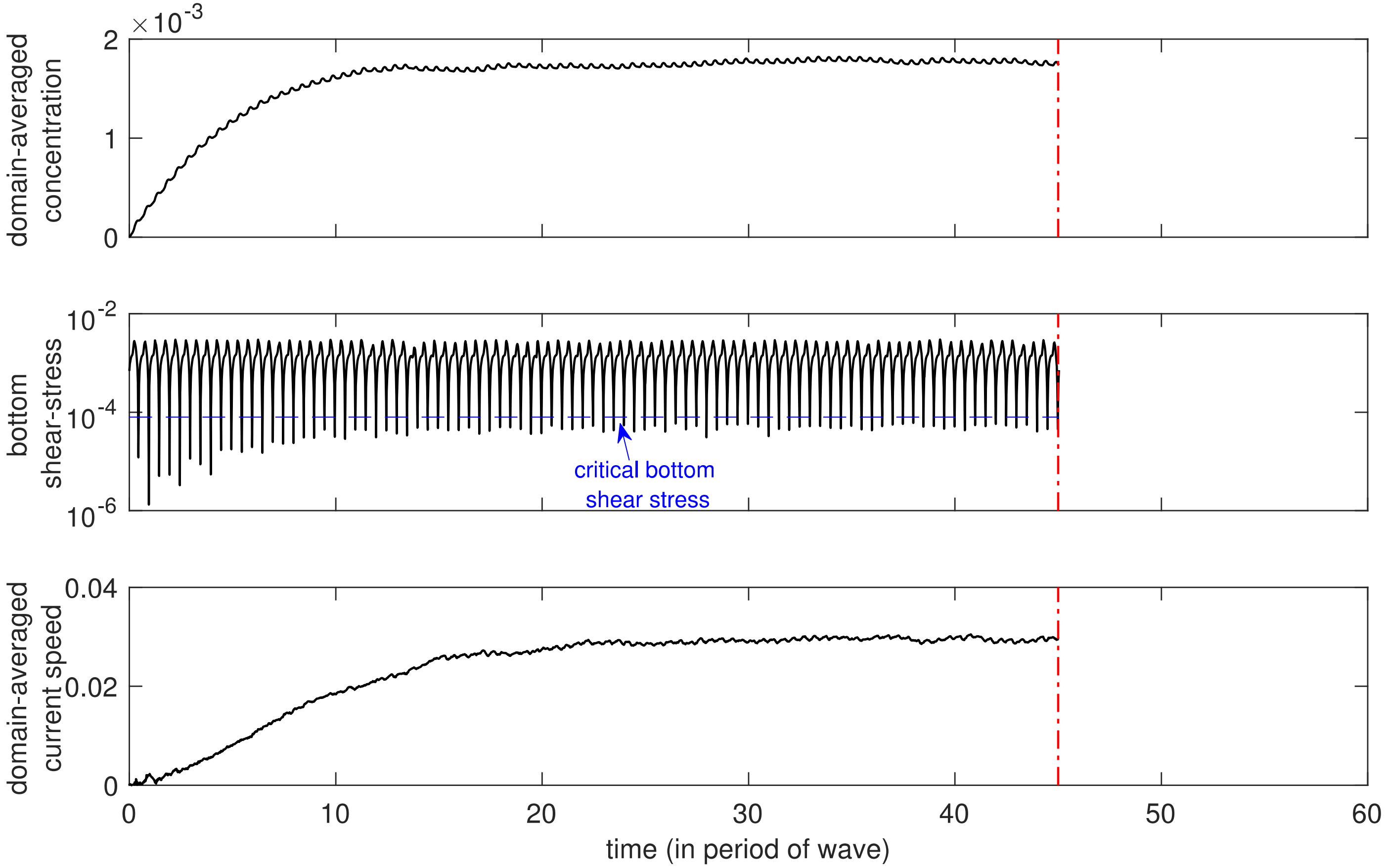
Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (I)

Numerical setup:

- Domain size: $60\delta \times 60\delta \times 60\delta$

  $(\delta = \sqrt{\frac{2\upsilon}{\omega}} = 1.78\text{ mm})$
- Bottom slope: $\boldsymbol{\theta = 0.29°}$
- Wave period: $T = \frac{2\pi}{\upsilon} = 10\text{ s}$
- Reynolds number: $Re_\delta = \frac{U\delta}{\upsilon} = 1000$

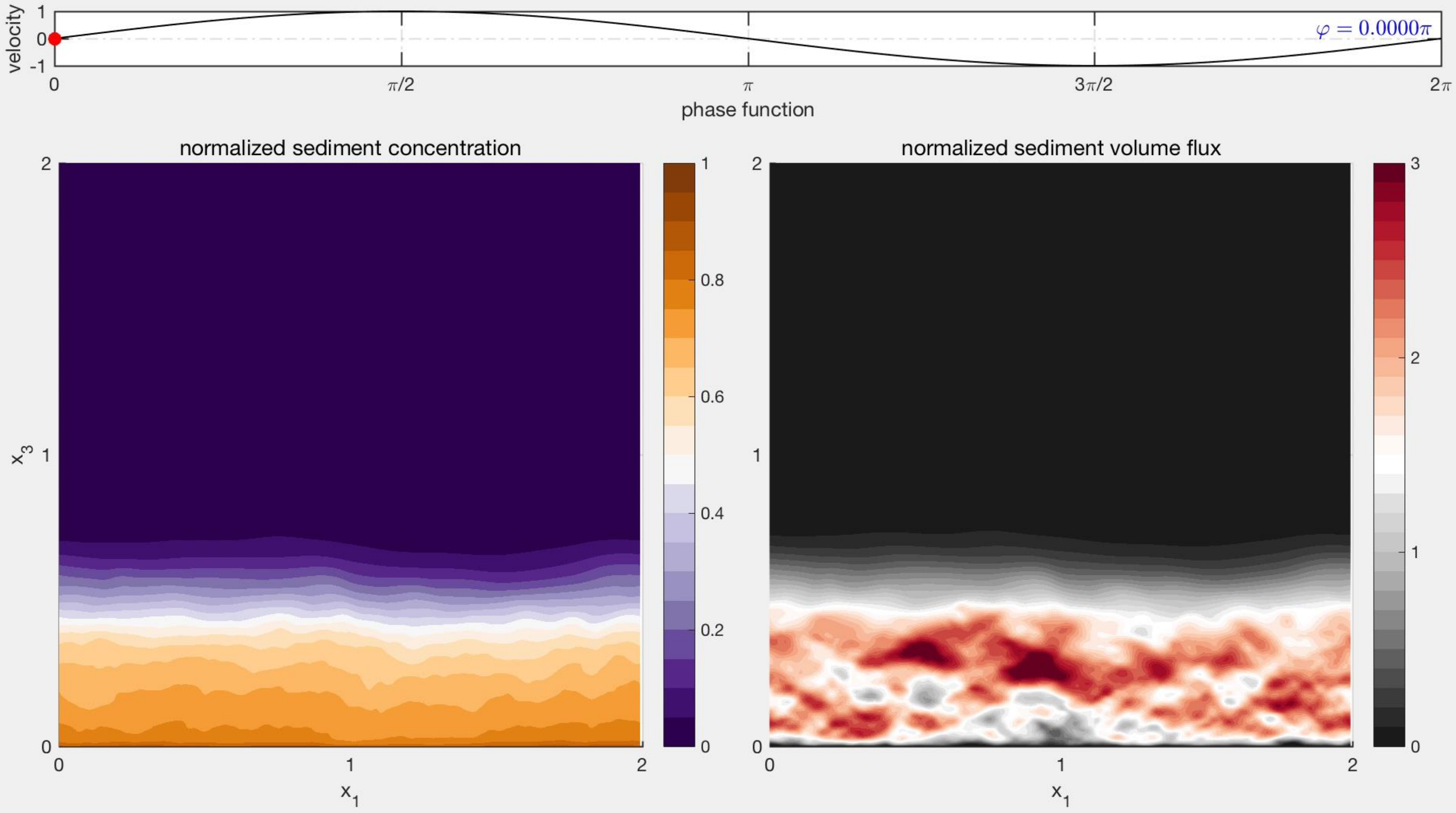
  $(U = 0.56\text{ m/s})$
- Settling velocity: $w = 0.5\text{ mm/s}$
- Critical shear stress: $\tau_c = 0.025\text{ Pa}$
- Grid number: $192 \times 192 \times 193$ (7M)



Time history of domain-averaged concentration, bottom shear stress and current speed.

Numerical Result

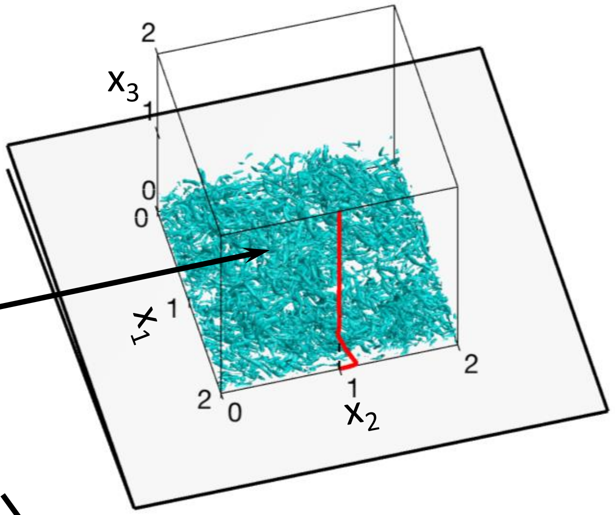
Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (II)



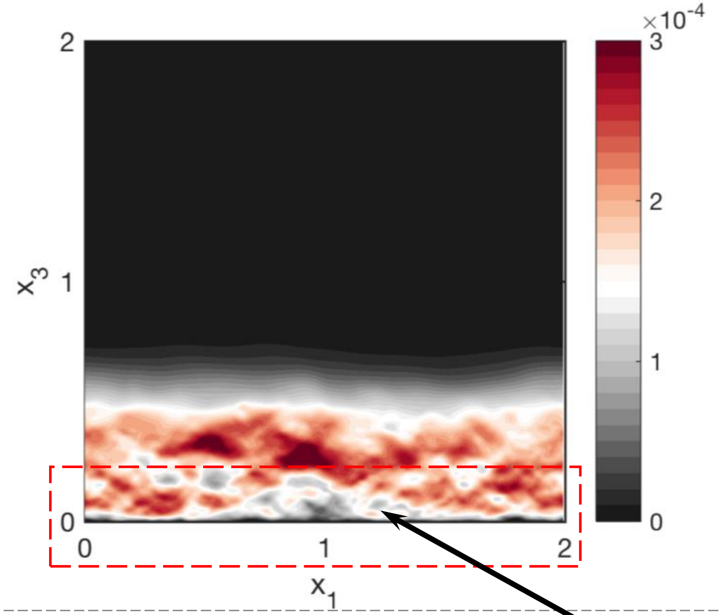
Numerical Result

Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (III)

Flow Reversal

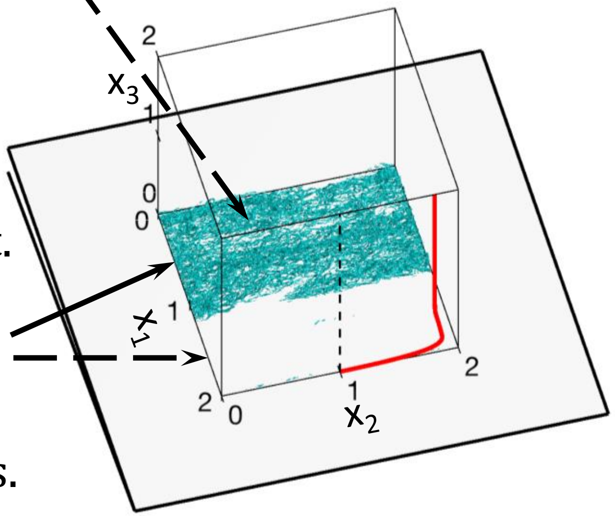


Relatively larger vortex structures

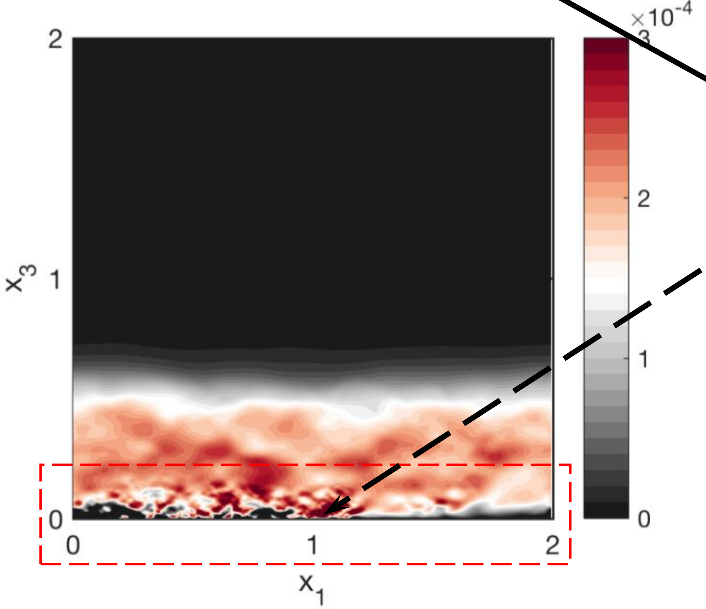


Significant near-bed feature

Flow Peak



Intermittent turbulent.
Ozdemir et al. (2010)
J. Fluid Mech.;
Cheng et al. (2015)
J. Geophys. Res. Oceans.



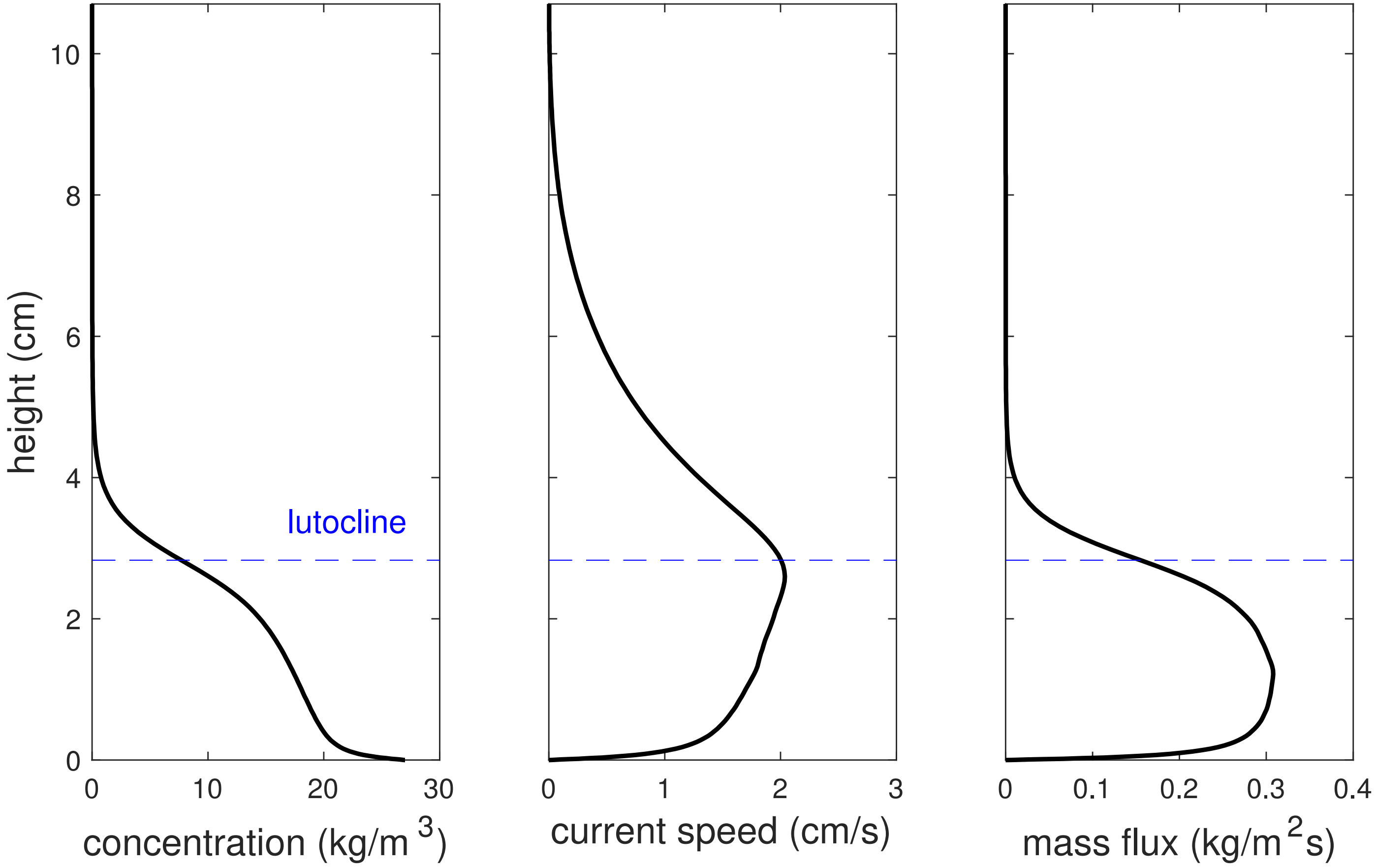
Vortex structure viewed by Q method

Dimensionless volumetric flux

Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (IV)

Several findings from the mean profiles:

1. Sediment is constrained below the lutocline (whose height is about 3 cm) and close to the bottom with a mass concentration about **20 kg/m^3** (Traykovski et al. 2000 Cont. Shelf Res.; Hale and Ogston 2015).
2. The mean downslope current has a maximum speed about **2 cm/s**. Other phenomena, e.g. the ambient current and hindered settling may enhance the gravity current.
3. A maximum mass flux of **0.3 kg/m^{2}s** is reached.



Time and plane-averaged concentration, streamwise (downslope direction) velocity and sediment mass flux.

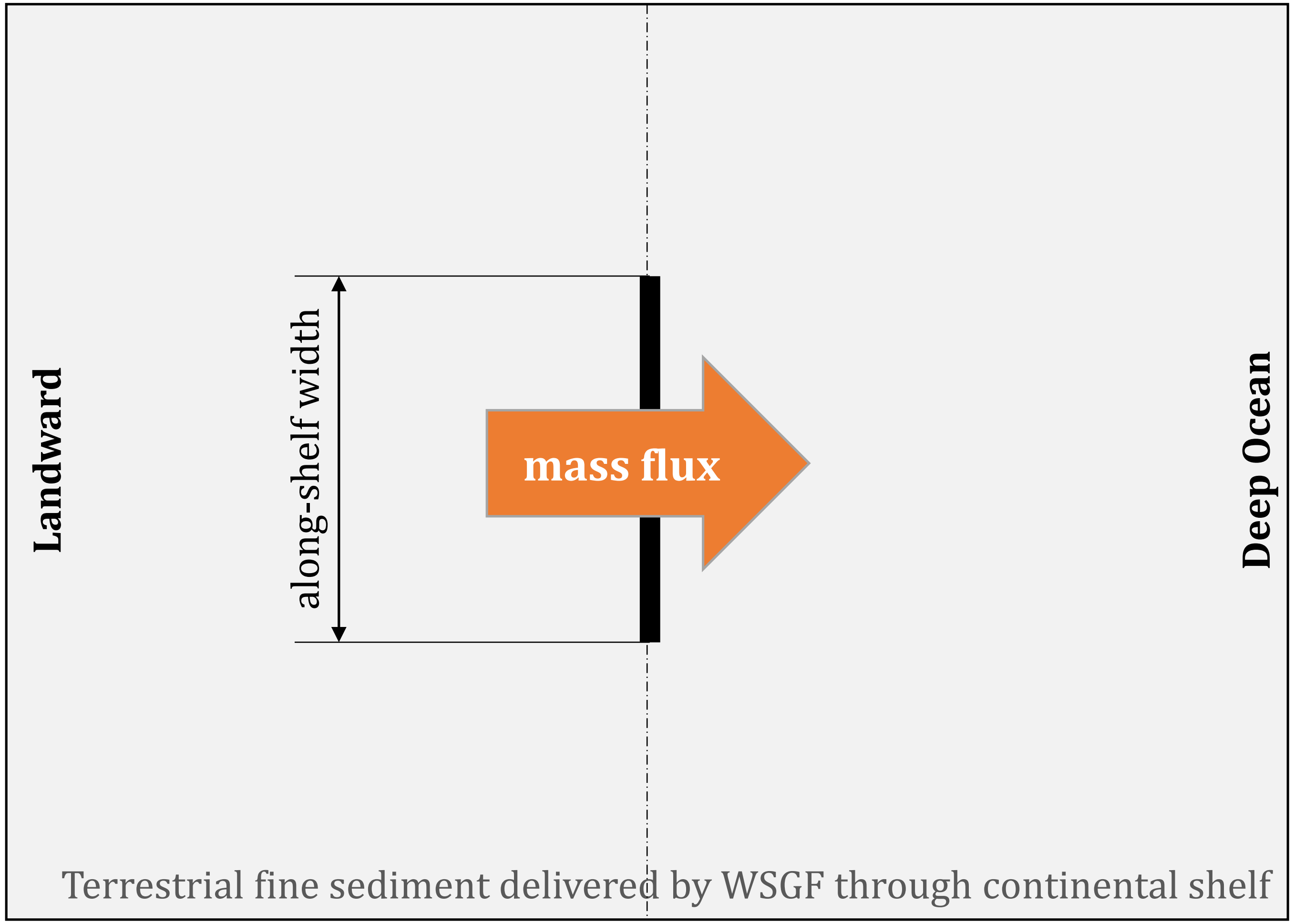
Numerical Result

Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (V)

How important is WSGF in the source to sink system? A simple calculation:

- Along-shelf unit width: 1 km
- Event (storm) duration: 1 h
- Mean mass flux: 0.25 kg/m^2s
- Lutocline height: 3 cm

The resulting sediment transport rate from landward to deep ocean is **27 ton/(km•h)**, through the thin and turbid boundary layer.



Terrestrial fine sediment delivered by WSGF through continental shelf

Numerical Result

Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (VI)

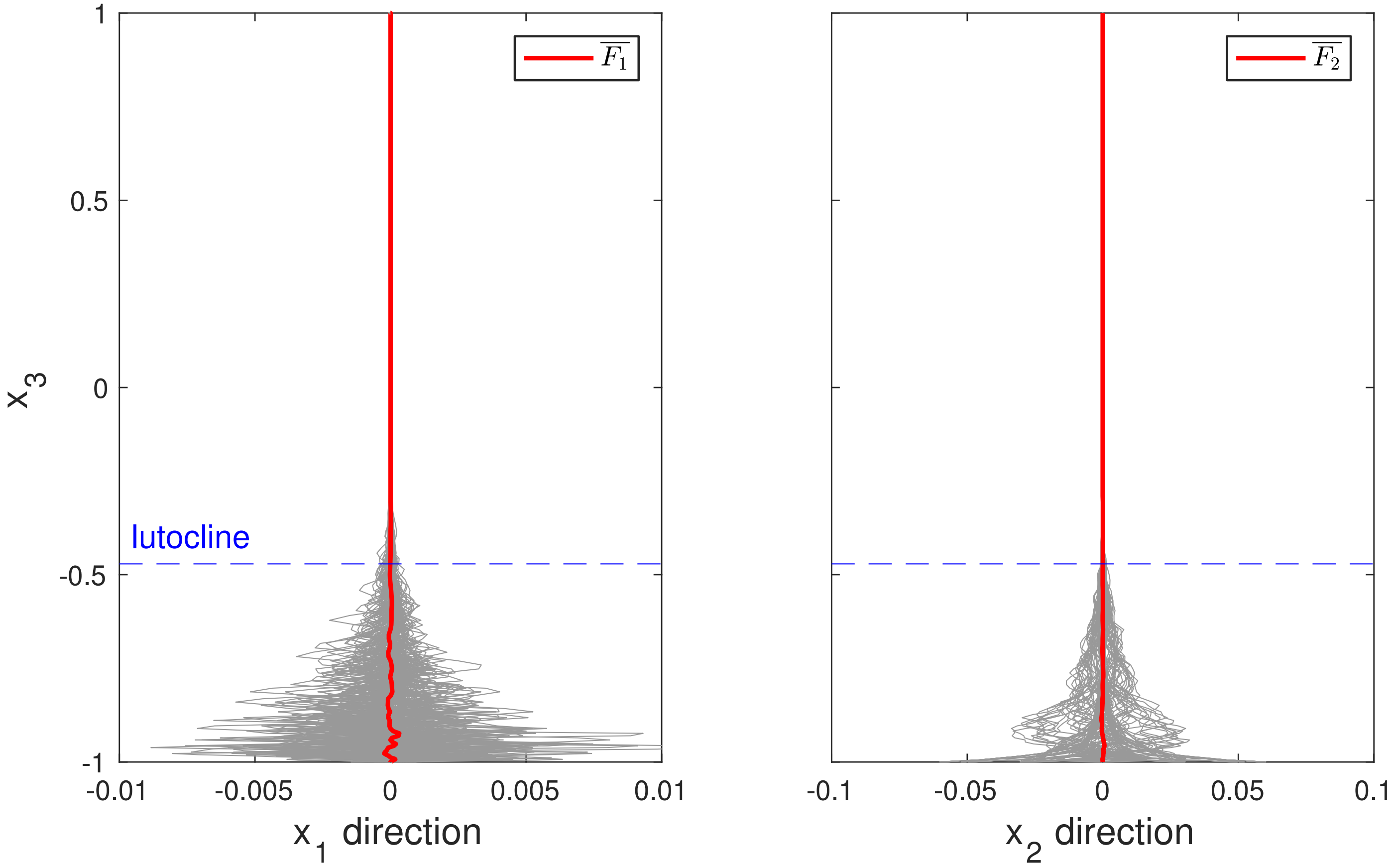
The force balance equations after time-averaging over the momentum equation in x_1 (downslope) and x_2 (wave) direction:

$$\overline{F_1} = \overline{\frac{\partial \tau_1}{\partial x_3}} + \overline{g'} \sin\theta = 0$$

$$\overline{F_2} = \overline{\frac{\partial \tau_2}{\partial x_3}} = 0$$

where τ_1 and τ_2 are the total shear stress, g' is reduced gravitational acceleration.

The force balance in downslope direction demonstrates that the gravity flow is driven by the suspended sediment. As a result, the **buoyancy** (Parsons et al. 2009) is balanced by drag force, which is important in future parameterization.



Force balance in downslope (x_1) and wave (x_2) direction.
Gray lines are instantaneous profiles.

Wave-Supported Gravity Flow at Re_δ=1000 and Slope=0.005 (VII)

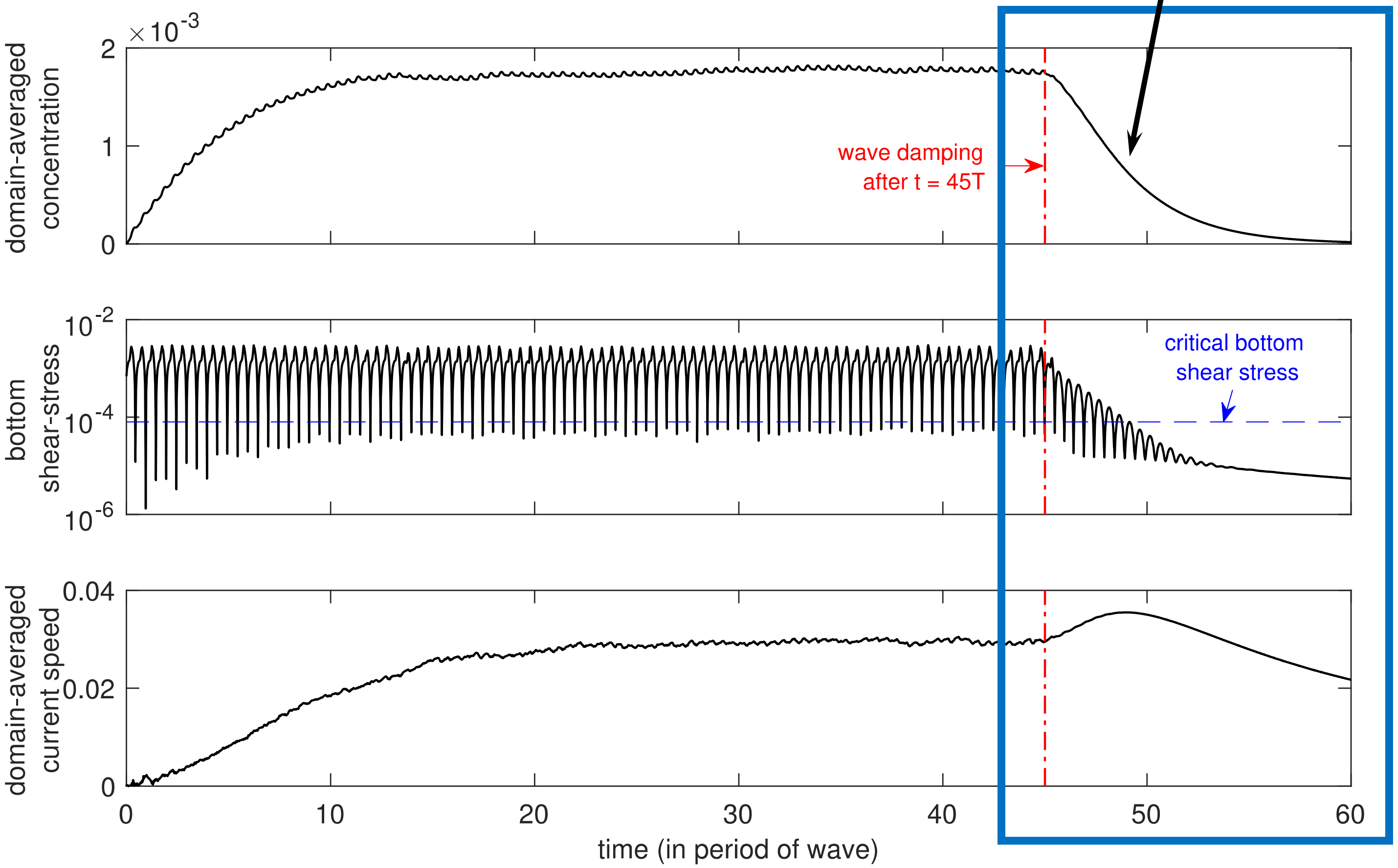
The simulated flow is the **wave-supported gravity flow**, not self-sustaining turbidity current. A widely accepted auto-suspension criterion (Parker 1982, Marine Geology):

$$k = \frac{w}{U_c \theta} \leq 1$$

where U_c is the velocity of current. In the present simulation, $\boldsymbol{k = 5 > 1}$.

To confirm this conclusion, the waves are **damped exponentially** in three wave periods after $t = 45T$, followed by a rapid decay of the sediment-induced gravity current.

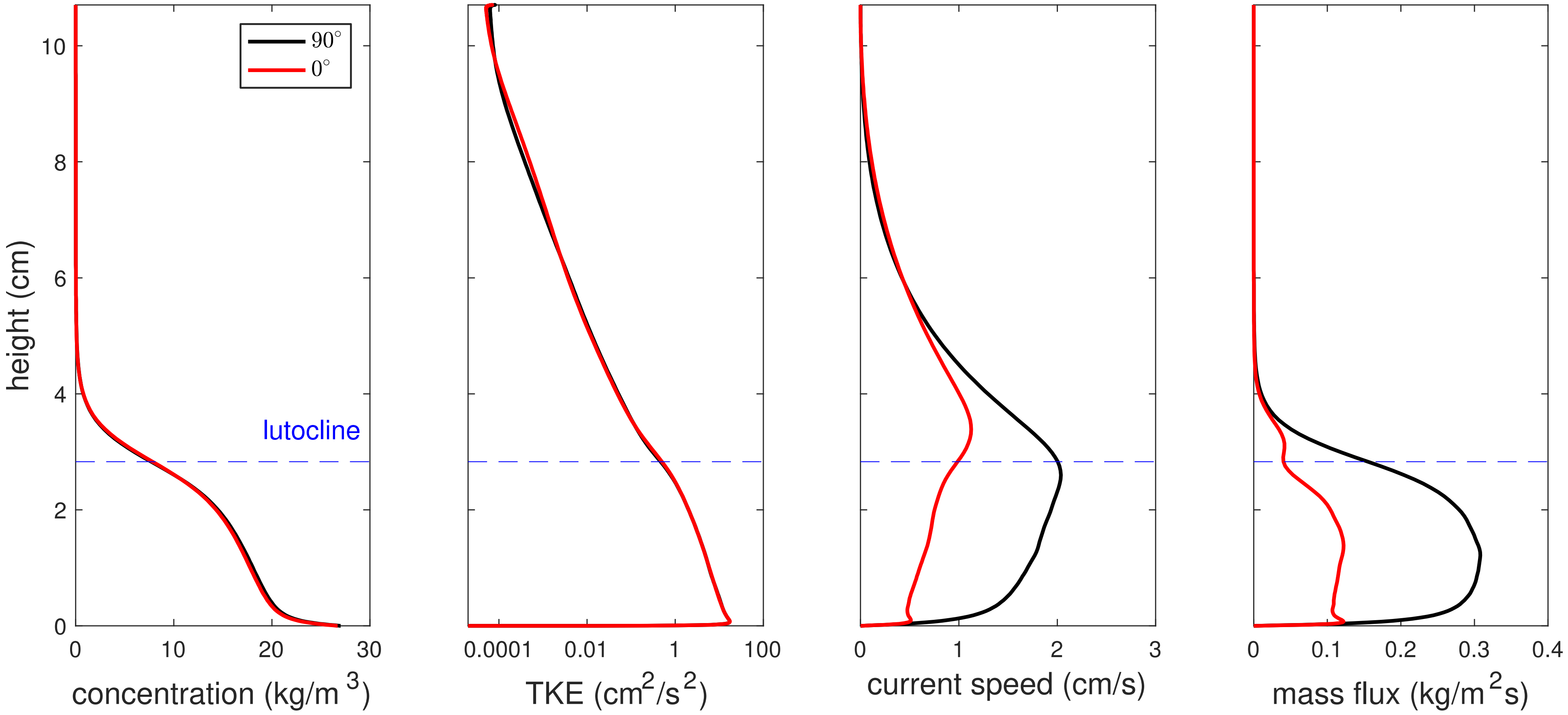
Rapid loss of sediment



Time history of domain-averaged concentration, bottom shear stress and current speed.

Numerical Result

Wave-Supported Gravity Flow and the Role of Wave Direction



Time and plane-averaged concentration, turbulence kinetic energy,
gravity current speed and sediment mass flux.

Summary

- Wave-supported gravity flow is studied here through a turbulence-resolving numerical simulation.
- The near-bed sediment concentration is about 20 kg/m^3 which is close to field measurement.
- The buoyancy force from dilute sediment suspension is demonstrated to be strong enough for the generation of WSGF even over a very gentle slope (0.29°).
- Larger current speed (>2 cm/s) may be expected due to the co-existence of ambient current and hindered settling.
- Wave direction plays a role in the generation of WSGF.

Future Work

a) Study the mechanism behind WSGFs (e.g. the role of slope versus waves, energy transfer in the event).

b) The magnitude of gravity current vs. the suspended load, which is a function of the Reynolds number (wave intensity), critical shear stress (sediment availability), hindered settling, ambient current.

c) Multi-class of fine sediment (very fine sand and mud; Hooshmand et al. 2015, JGR) and flocculation.

Acknowledgement

Thanks for your attention!

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