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Understanding wave-driven fine sediment transport through 3D turbulence resolving simulations – Implications to offshore delivery of fine sediment

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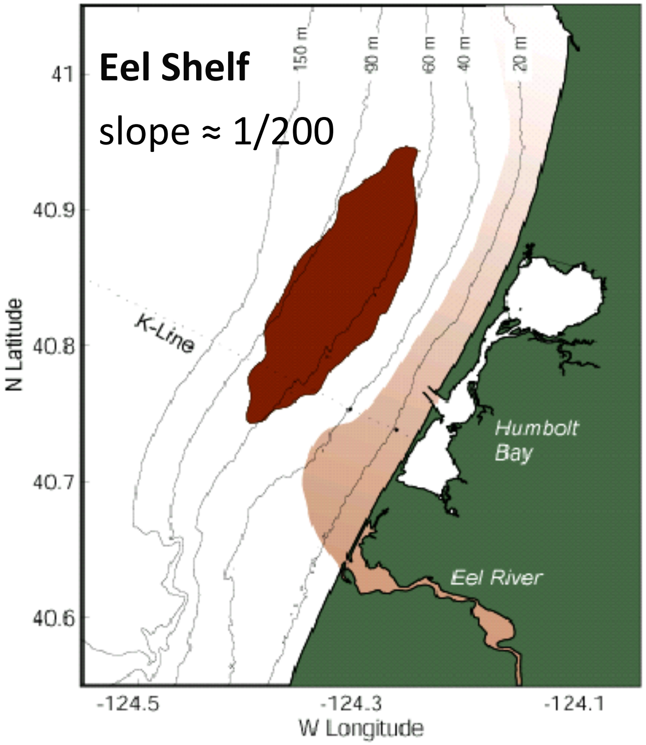
ichael Lamb, California Institute of Technology (Caltech).

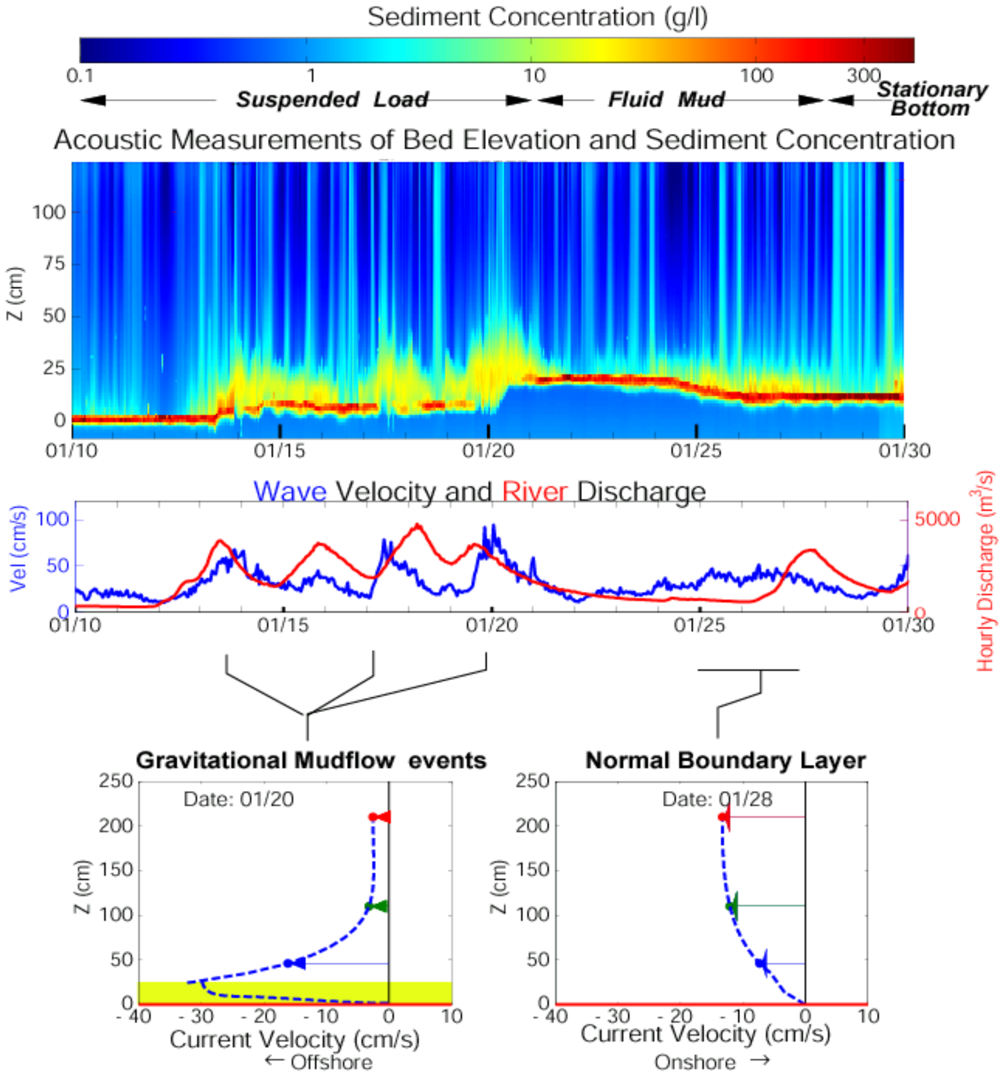
ificance – offshore delivery of fine sediment

e-driven fine sediment transport is a critical mechanism in sediment source to sink (Wheatcroft &
geld 2000, CSR; Warrick 2014, MG): Wave-supported gravity-driven mudflows (Traykovski et al. 2000;
on et al. 2000, CSR).

STRATAFORM PROGRAM



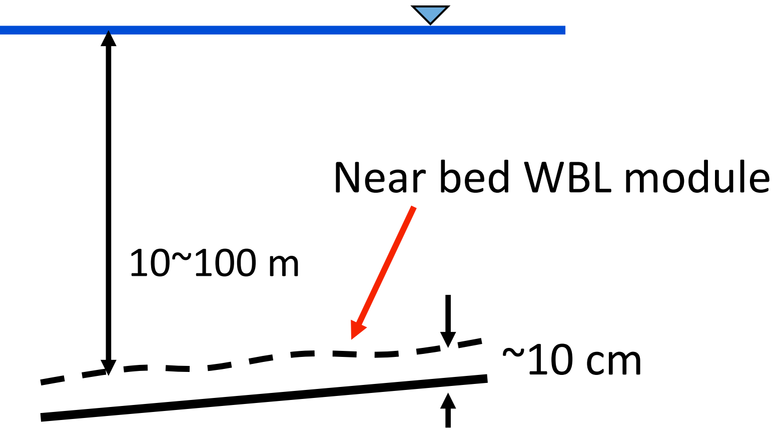
Traykovski et al. 2000; Cont. Shelf Res.



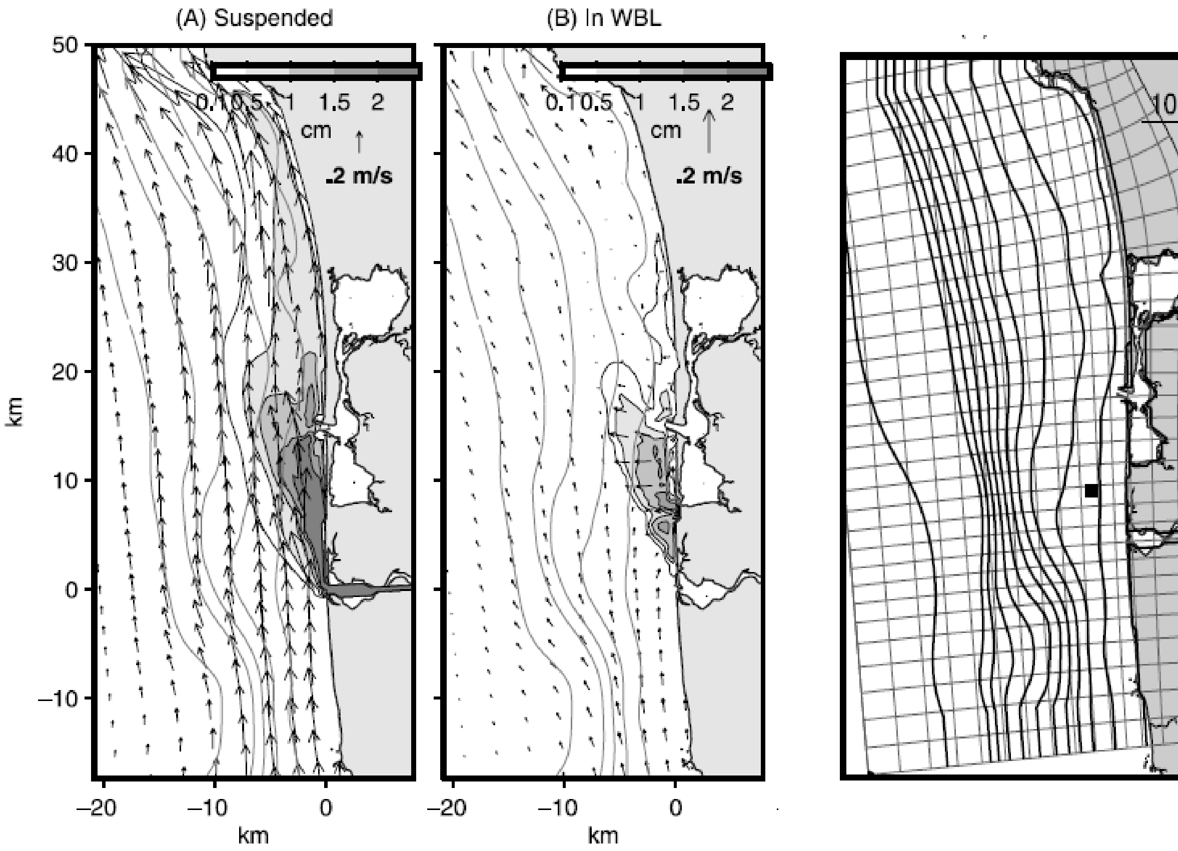
lenges in source to sink modeling:

ight et al. (2001), Mar. Geo.; Scully et al.
001), JGR. Use a bulk Richardson
mber control.

rris et al. (2004), Est., Coast. Mod.
rameterization of a near-bed turbid layer

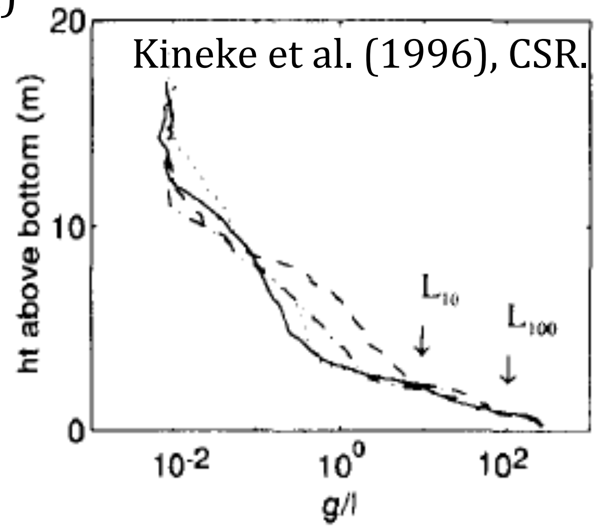


Harris et al. (2005), JGR: Flood dispersal and deposition b
near-bed gravitational sediment flows and oceanographi
transport: A numerical modeling study of the Eel River sh
northern California.



gnificance – hydrodynamic dissipation over muddy seabed

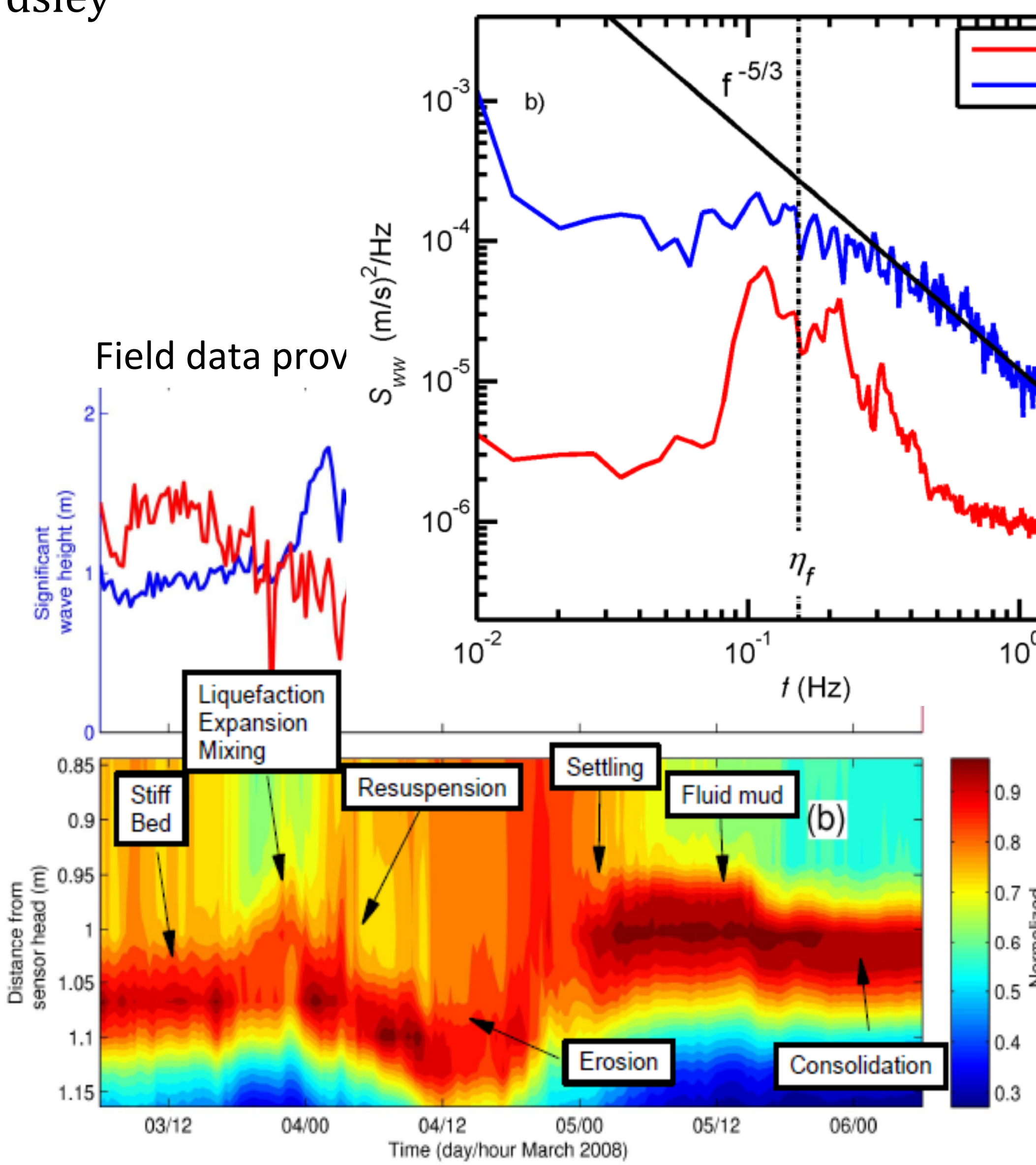
Tidal currents experience drag reduction (Beardsley et al. 1995, JGR)


Kineke et al. (1996), CSR.

Waves experience significant attenuation over muddy seabed (e.g., Sheremet & Stone 2003, JGR). Modeled as enhanced viscosity due to mud: Dalrymple & Liu (1978), JPO.

Question: How suspended sediment can modulate turbulence and causes ransition of these diverse seabed states?

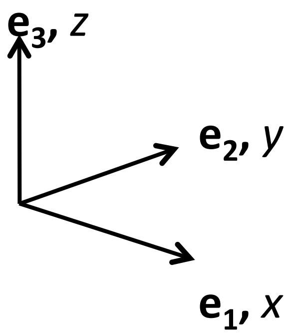
Field data provided by P. Traykovski (W


Field data prov

del Formulation & Governing Equations:

1) Turbulence-resolving approach is needed to resolve turbulence-sediment interaction.
2) For typical cohesive sediments, settling velocity is 0.1~1 mm/s. The inertia of particle is assume negligible (Stokes number is St<<1). Equilibrium approximation (Balachandar & Eaton 2010):

Sediment velocity: $v_i = u_i - W_s \boldsymbol{\delta}_{i3} - \cancel{St(1-\boldsymbol{\beta})\frac{Du_i}{Dt}}$



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

$$\frac{Du_i}{Dt} = -\delta_{i1}\frac{2}{\mathrm{Re}_\Delta}\sin\frac{2t}{\mathrm{Re}_\Delta} - \frac{\partial p}{\partial x_i} - \boxed{Ri\phi\delta_{i3}} + \frac{1}{\mathrm{Re}_\Delta}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\frac{\partial \phi}{\partial t} + \frac{\partial (u_i - W_s\delta_{i3})\phi}{\partial x_i} = \frac{1}{\mathrm{Re}_\Delta\, Sc}\frac{\partial^2 \phi}{\partial x_i \partial x_i}$$

merical Implementation:

Model is solved by a high accuracy pseudo-spectral scheme (Cortese & Balachandar 1995). Validated extensively by earlier DNS study for steady and oscillatory channel flows (Kim & Moin 1987; Spalart & Baldwin 1988) .

Non-dimensional Parameters:

Stokes Reynolds number (wave intensity):

$$\mathrm{Re}_{\Delta} = \frac{\widetilde{U}_0 \Delta}{\nu}$$

For Eel shelf: U=0.55 m/s; T=10 sec; Re_{Δ}<=1000 (Traykovski et al. 2000)
⇒ Wave boundary layer is "intermittently turbulent" (Jensen et al. 1989, JFM)

Nondimensional settling velocity

$$W_s = \frac{\widetilde{W}_s}{\widetilde{U}_0}$$

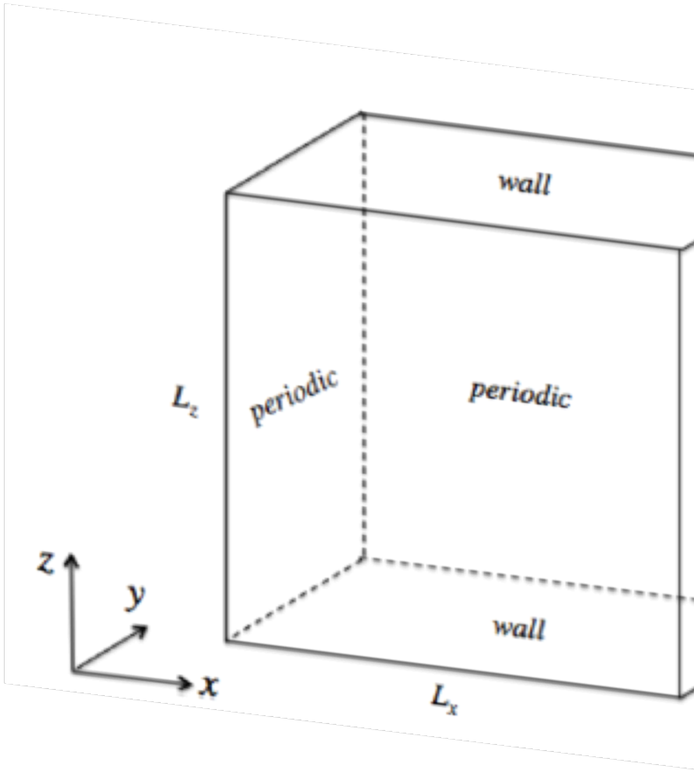
For fine sediment $\widetilde{W}_s = 0.1 \sim 1.5\,\mathrm{mm/s}$ (e.g., Hill et al. 2000, CSR)
(flocculation/floc dynamics is not considered)

Sediment availability

(a) Prescribe sediment initially and set no-flux in the bottom and top wall (Ozdemir et al. 2010; 2011; Yu et al. 2013, 2014).
i.e., Φ=constant, *Ri* is fixed in a given case.
⇒ simple; similar to field condition when sediment supply is determined by river flooding

$$Ri = \frac{(s-1) g \Delta \Phi}{\widetilde{U}_0^2}$$

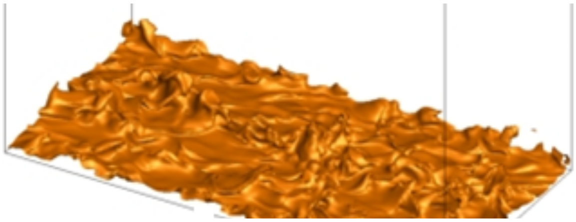
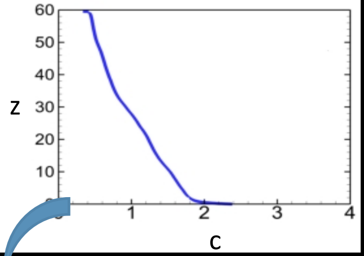
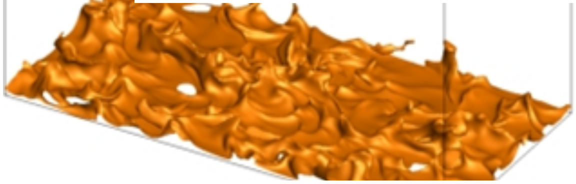
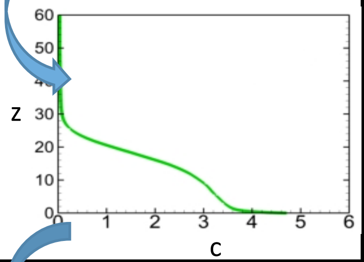
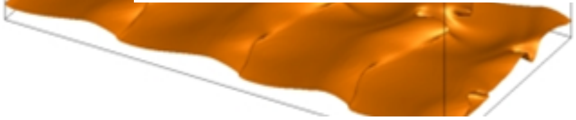
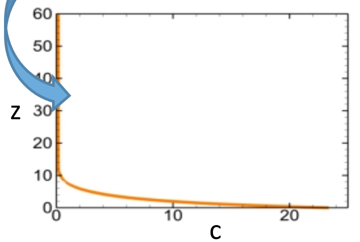
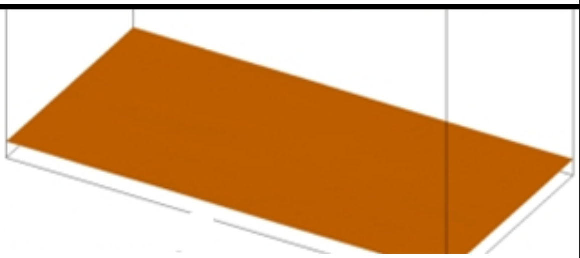
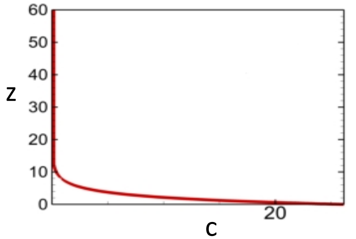
(b) Erosional/depositional boundary condition at bottom wall (this talk). *Ri* is part of the solution of model due to resuspension.



ence modulation due to sediment-induced density stratification:

Ozdemir et al. (2010) JFM; Re_Δ=1000, **$Ri=0 \sim 6\times10^{-4}$**, $\tilde{W}_s = 0.5$ mm/s

Ozdemir et al. (2011), JGR: Re_Δ=1000, $Ri=1\times10^{-4}$, $\tilde{W}_s = 0.25 \sim 1.5$ mm/s

I			Sediment is well-mixed in the WBL; passive to flow turbulence; Mode I exists when sed. conc. is below O(1) g/L
II			Formation of lutocline; turbulence is damped above lutocline; Mode II exists when sed. conc. is O(10) g/L.
III			Collapses of turbulence except during flow reversal; Mode III exist when sed. conc. is several tens of g/L
IV			Complete collapses of turbulence; saturation; laminarization; Mode IV exist when sed. conc. is O(100) g/L

wave-supported gravity flow (offshore transport).

Onset of laminarization – large wave dissipation termination of WSGF?

Increasing settling velocity (W_s)

Carrying capacity conce
Winterwerp (2001), JG

$$C_s = K_s \frac{1}{(s-1)} \frac{U_*^3}{gh\tilde{W}_s}$$

Non-dime
general fo

$W_s \cdot Ri = f(Re_\Delta)$

Ozdemir et al. (2011

What happen when sediment supply is constraint by botto resuspension?

revision to the numerical scheme

id Spectral-compact finite difference scheme: Yu et al. (2013, Computer & Geosciences)
easy implementation of variable viscosity (rheology; LES) and nonlinear boundary conditions.

sion/deposition bottom

., Sanford and Maa (2001), MG:

$$E(t)=m(\tau_b(t)/\tau_c-1) \qquad D(t)=W_s\,\phi_b(t)$$

ivation - At equilibrium (in wave-averaged "<>" sense):

$$<E>=<D> \qquad \langle\tau_b(t)\rangle=\boldsymbol{\tau_{eq}} \qquad \langle\phi_b(t)\rangle=\boldsymbol{\phi_{beq}}$$

$$\boldsymbol{\tau_{eq}}=(W_s\,\boldsymbol{\phi_{beq}}/m+1)\tau_c=\alpha\tau_c \qquad \Phi\sim f(\boldsymbol{\tau_{clear}}-\boldsymbol{\tau_{eq}})$$

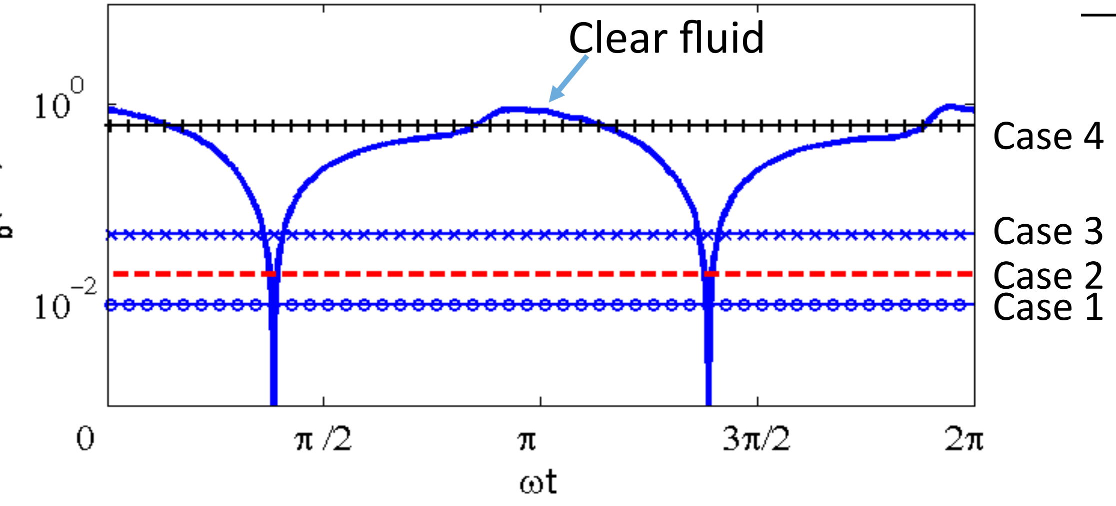
or example, if τ_c is small, $\boldsymbol{\tau_{eq}}=\alpha\tau_c$ is small comparing to $\boldsymbol{\tau_{clear}}$ and Φ **is larger.**

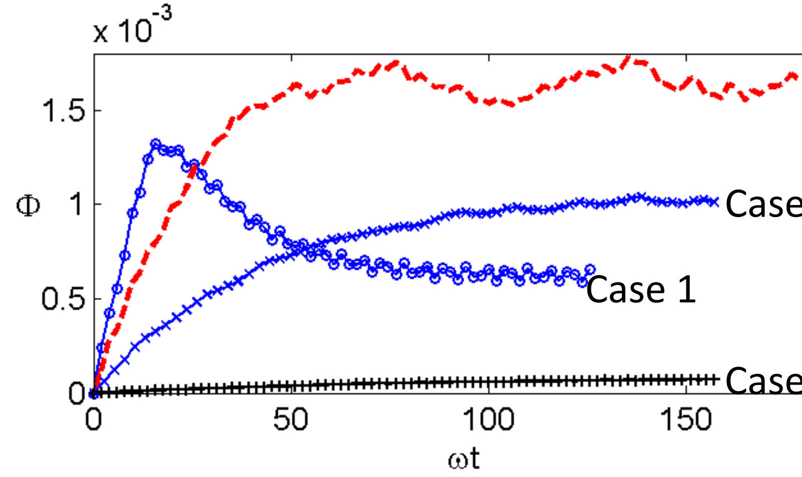
The resulting flow modes may be dictated by erodibility parameters, e.g., τ_c and m.
Settling velocity is also involved bottom erosion/deposition balance, i.e., α.
The relationship $W_s\cdot Ri=f(Re_\Delta)$ is not sufficient to parameterize the transport process.

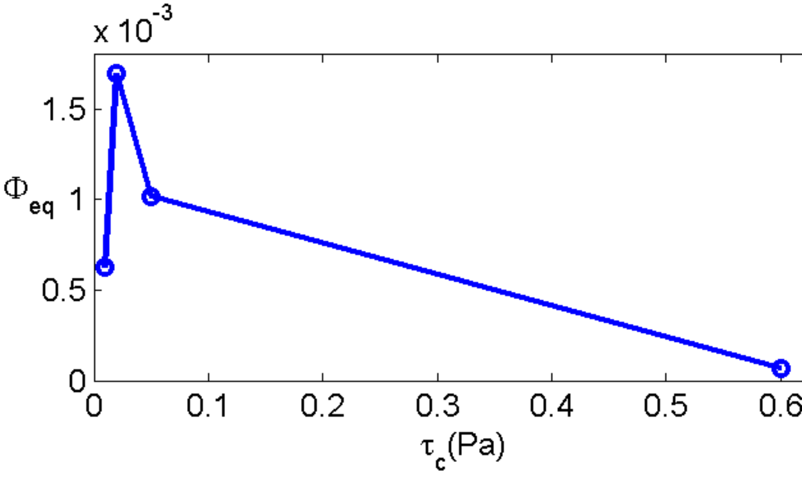
role of critical shear stress

=1000; $W\downarrow s$ =0.5 mm/s

	$W\downarrow s$ (mm/s)	$\tau\downarrow c$ (Pa)	$\tau_{eq}=\alpha\tau\downarrow c$	Φ_{eq}	**Flow Mode**
e 1	0.5	0.01	0.28	6.1×10^{-4}	IV
e 2	0.5	0.02	0.38	1.7×10^{-3}	II
e 3	0.5	0.05	0.43	1.0×10^{-3}	II
					I





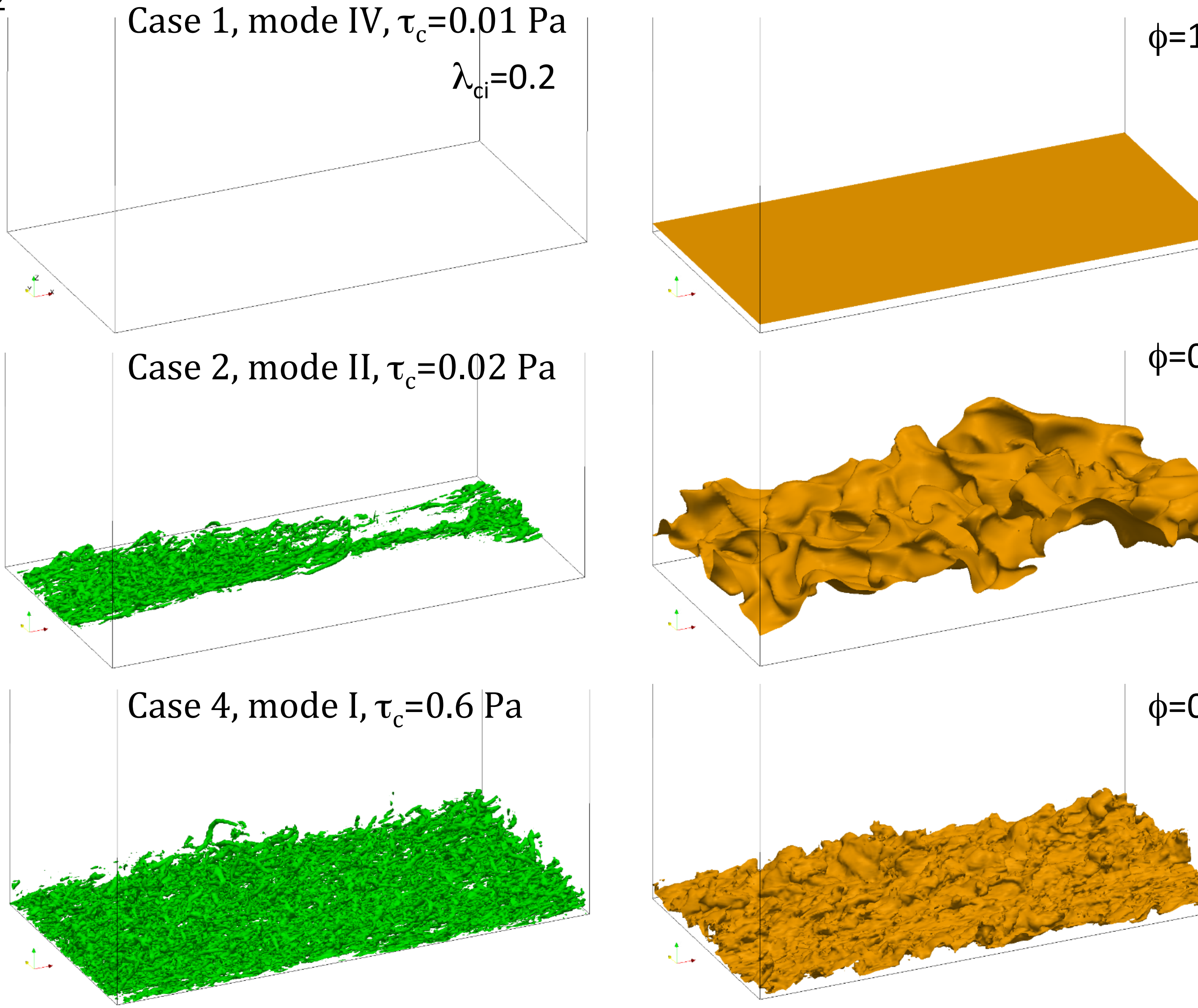


- Lower τ_c generally gives larger suspended sediment load but when τ_c is too low suspended load reduces again! How?

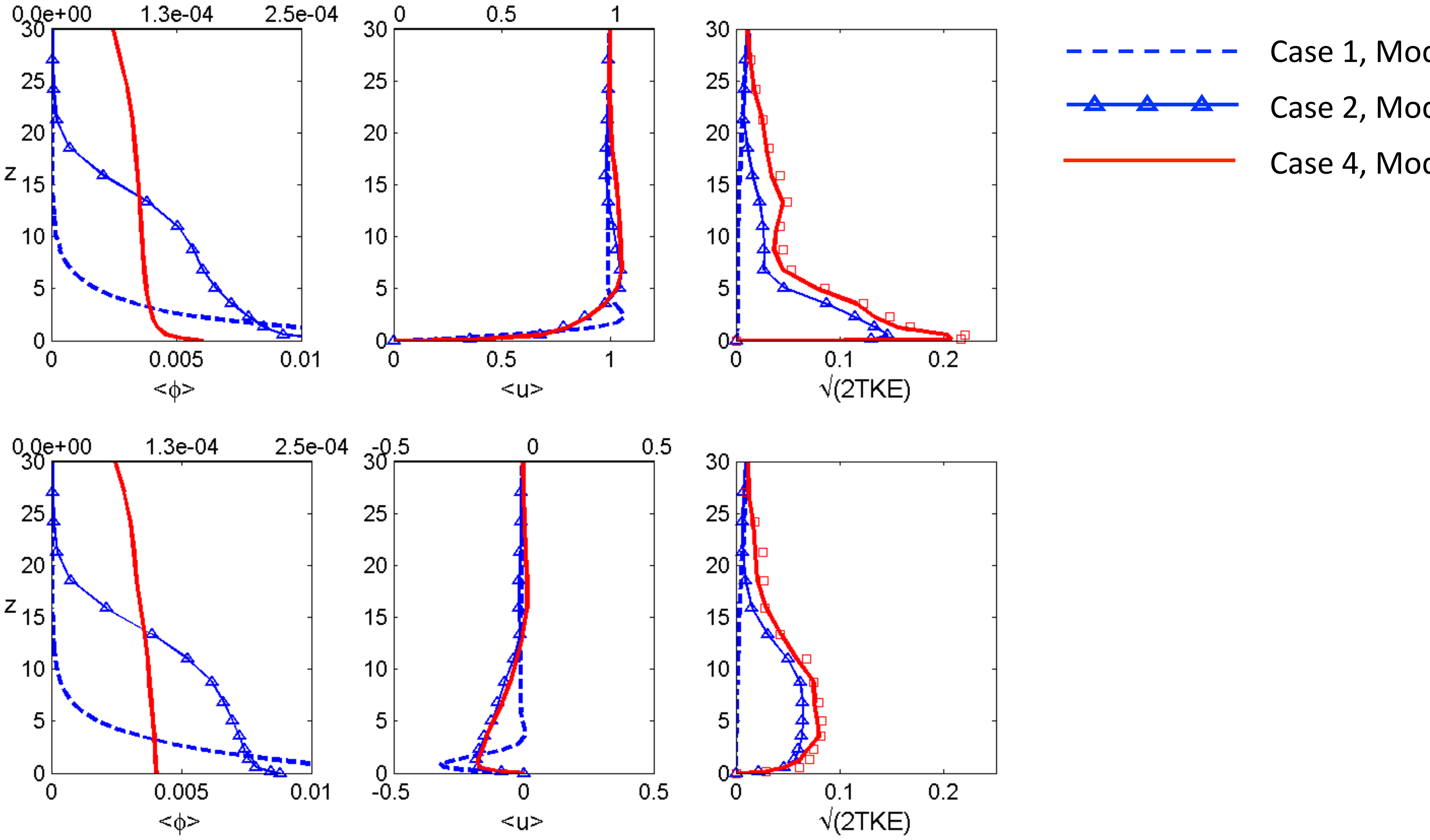
ole of critical shear stress

ent flow modes, i.e., well-
l (I), formation of lutocline
nd laminarization (IV) can
tained via different critical
stress of erosion τ_c.

ent structure is visualized
method (Zhou et al. 1999,



role of critical shear stress



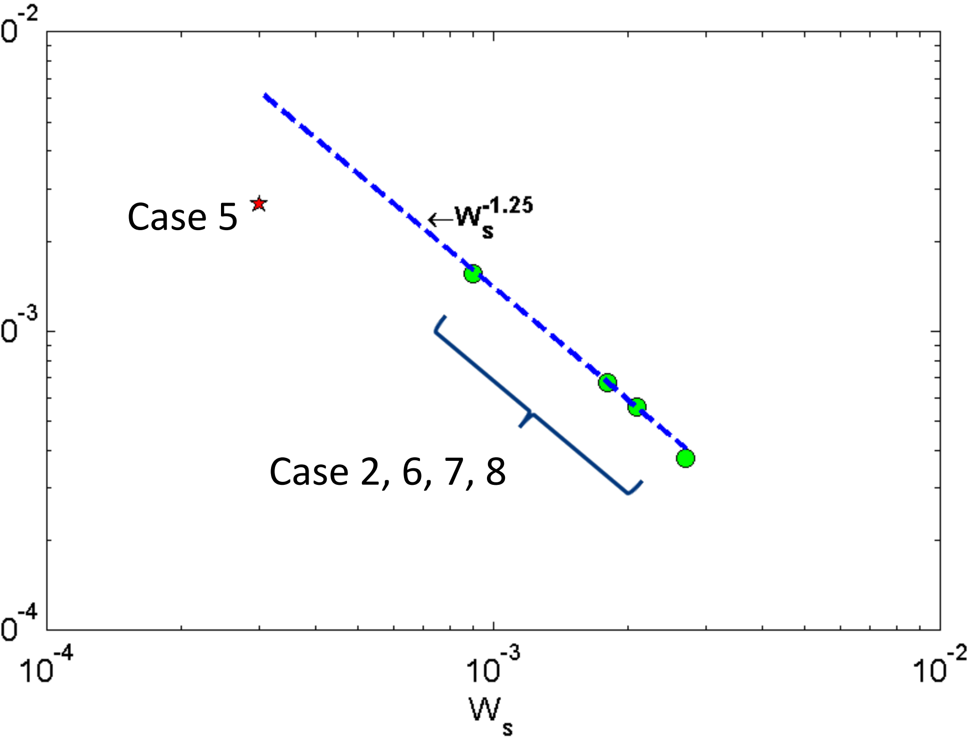
Flow peak:

low reversal:

le of settling velocity

$Re_{\Delta}=1000$; $\tau_c=0.02$ (Pa)

	W_s (mm/s)	ϕ_{beq}	τ_c (Pa)	$\tau_{eq}=\alpha\,\tau_c$	Flow Mode
5	0.17	2.4×10^{-2}	0.02	0.28	IV
2	0.5	1.1×10^{-2}	0.02	0.38	II
6	1.0	6.0×10^{-3}	0.02	0.42	II
7	1.17	5.2×10^{-3}	0.02	0.42	II
8	1.5	4.0×10^{-3}	0.02	0.43	II



- **Laminarization (model IV) can be triggered by very small settling velo**

$$\tau_{eq}=(W_s\ \phi_{beq}/m+1)\tau_c=$$

$$\Phi\sim f(\tau_{clear}-\tau_{eq})$$

- Within flow mode II,

simulation results suggest: $\Phi\sim W_s^{-}$

carry capacity concept suggest: $\Phi\sim W_s$

Carrying capacity works in flow mod

$$Ri=f(Re_{\Delta})/\ W_s$$

neterization (1)

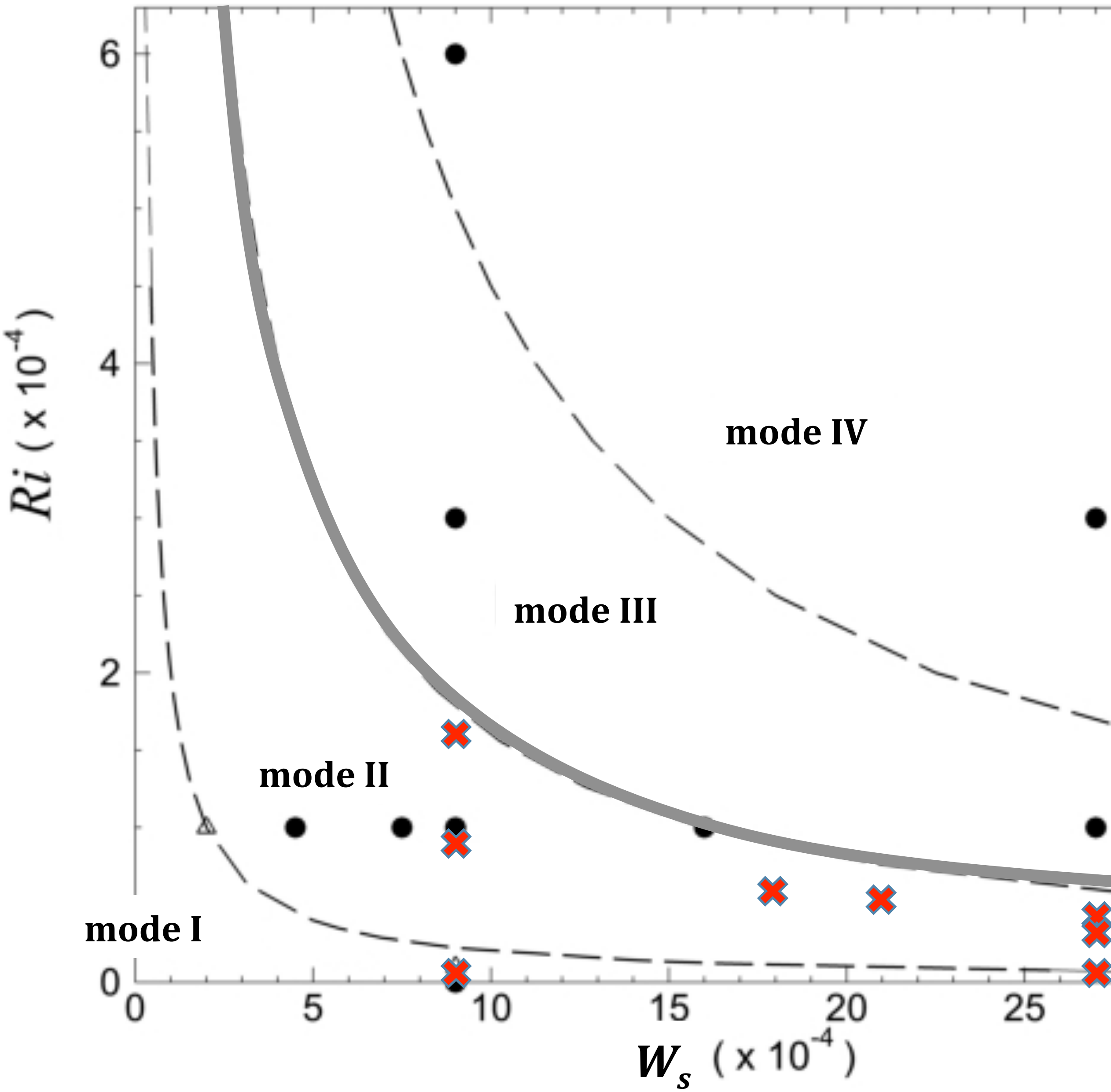
emir et al. (2011) prescribe fixed ment availability (Ri) and suggested se the carry capacity to describe the sition of flow modes:

$$Ri=f(Re_{\Delta})/ W_s$$

e Ri is determined by resuspension. vever, mode 1 and mode 2 where flow remains turbulent, the unt of suspended sediment can still arameterized by carrying capacity.

further need a parameterization he onset of laminarization nsition to flow mode IV).

Adopted from Ozdemir et al. (2011



eterization (2)

ll sediment flux balance in equilibrium:

$$\boldsymbol{\tau_{eq}} = (W_s\ \boldsymbol{\phi_{beq}} / m + 1)\tau_c$$

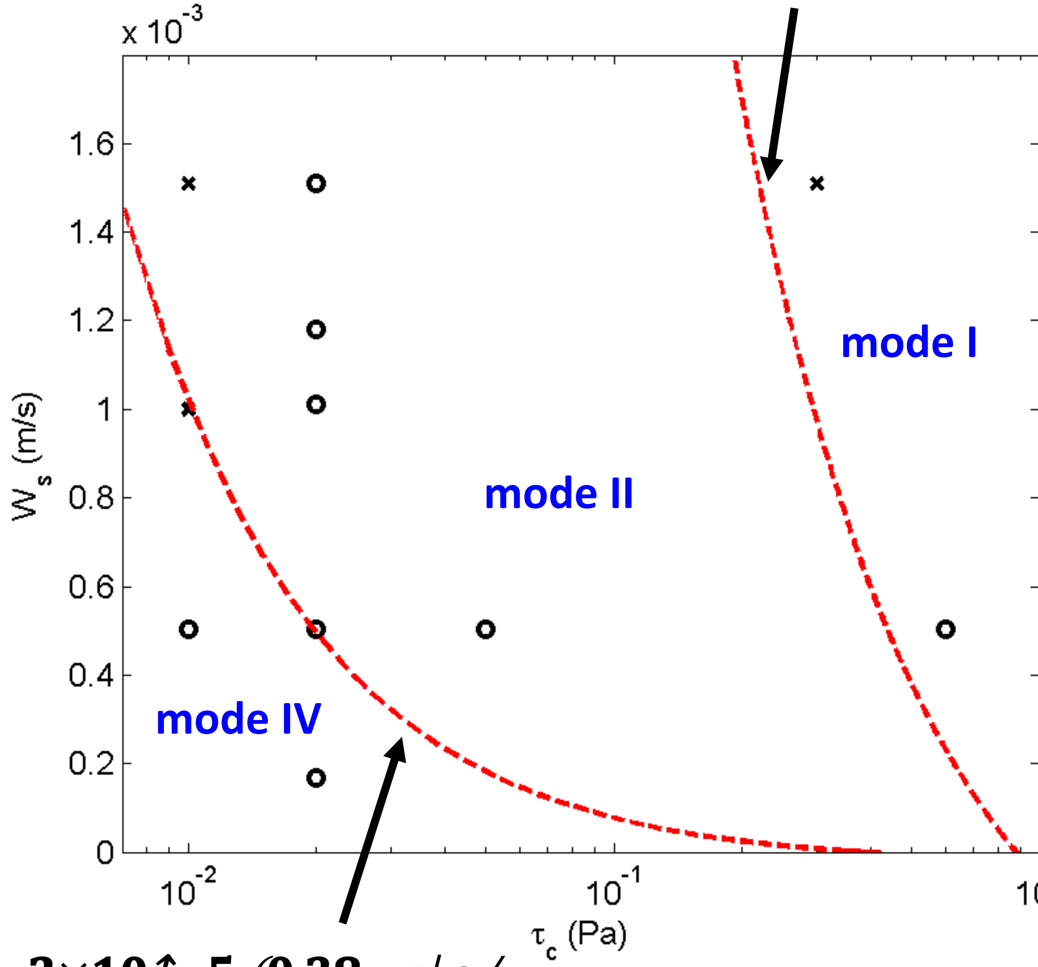
$$\Rightarrow \quad W_s = K(\tau_{ceq} - \tau_c / \tau_c\ )$$

$\tau_{ceq} \sim$ Characteristic stress at equilibrium
0.88 (Pa) for mode I-II;
0.38 (Pa) for mode II-IV.

$K \sim m/\boldsymbol{\phi_{beq}}$ ⇒ via empirical fit

At Re_Δ=1000:

$W_s = \mathbf{5\times10^{-4}}\ (\mathbf{0.88} - \tau_c$



$W_s = \mathbf{2\times10^{-5}}\ (\mathbf{0.38} - \tau_c /$
$\tau_c\ )$

ary

Erodibility parameters, i.e., critical shear stress, can dictate the transition of flow modes.

Suspended sediment can reduce bed stress via density stratification (drag reduction); laminarization occurs when equilibrium bed stress is reduced to about 0.38 (Pa).

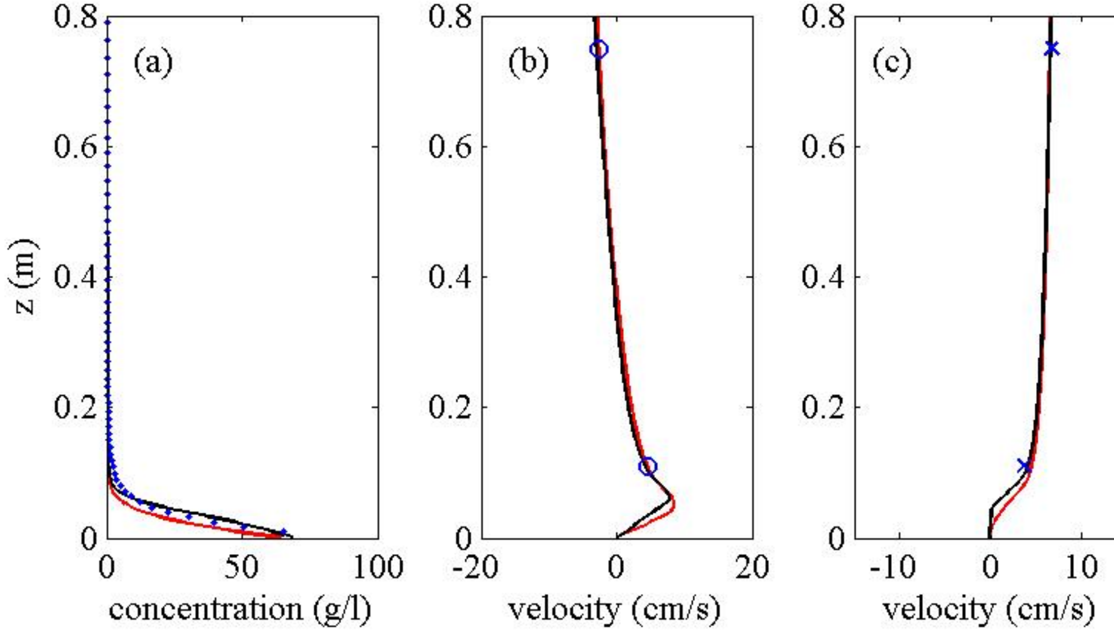
Suspended sediment load can be parameterized by carry capacity in flow mode I and II.

Semi-empirical formulae ($W{\downarrow}s$ vs $\tau{\downarrow}c$) describing the borders between mode I & II and mode II & IV.

ng and Future Work

The transition of flow modes on dynamics of wave-supported gravity-driven mudflow.

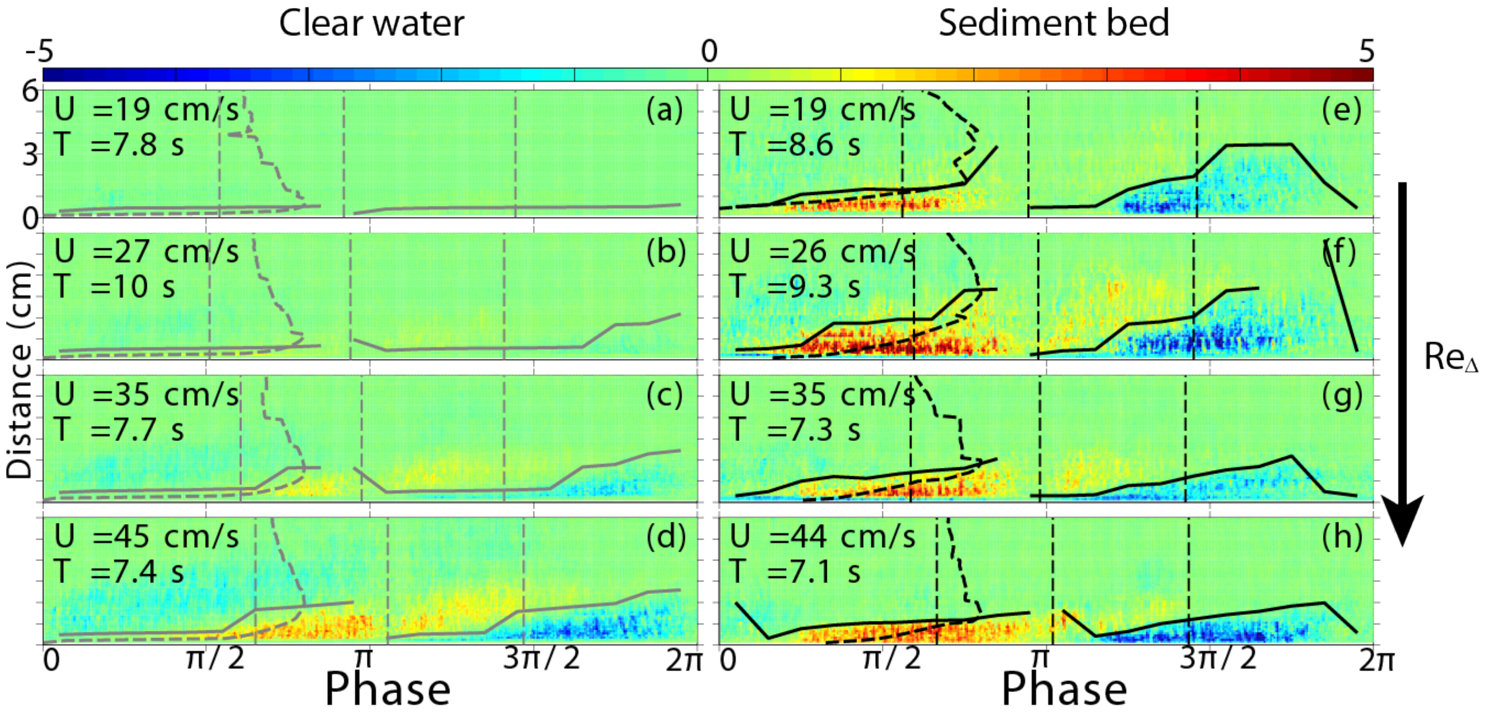
Question: Wave-supported gravity-driven mudflows only exist in flow mode II?



RANS modeling of wave-supported gravity-driven mudflov
Hsu, Ozdemir, Traykovski (2009), JGR.

- **understand how the sand fraction can dictate the flow mode and hence the initiation, transport and termination of wave-supported gravity currents**

A small amount of sand (13%) can armor the bed and generate bedforms at the surface layer and modify fine sediment transport (Liang, Lamb, Parsons 2007). Active layer approach (e.g., Harris & Wiberg 1997, CSR; Reed et al. 1997, MG)



Hooshman, Horner-Devine, Lamb (2014) manuscript in preparation

Laboratory data is obtained in collaboration with A. Horner-Devine (U. Washington)