# Cohesive Sediment Transport in COAWST

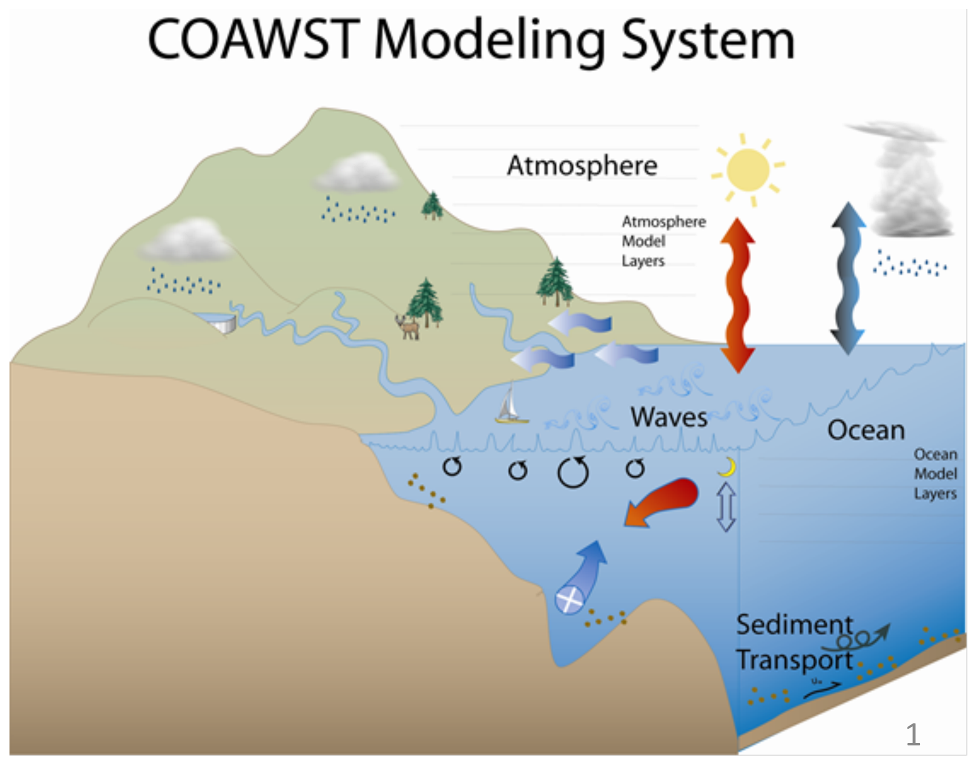
*Courtney Harris, Chris Sherwood,*
*Alfredo Aretxabaleta, Danielle Tarpley*

*CSDMS Webinar* *November 18, 2019*

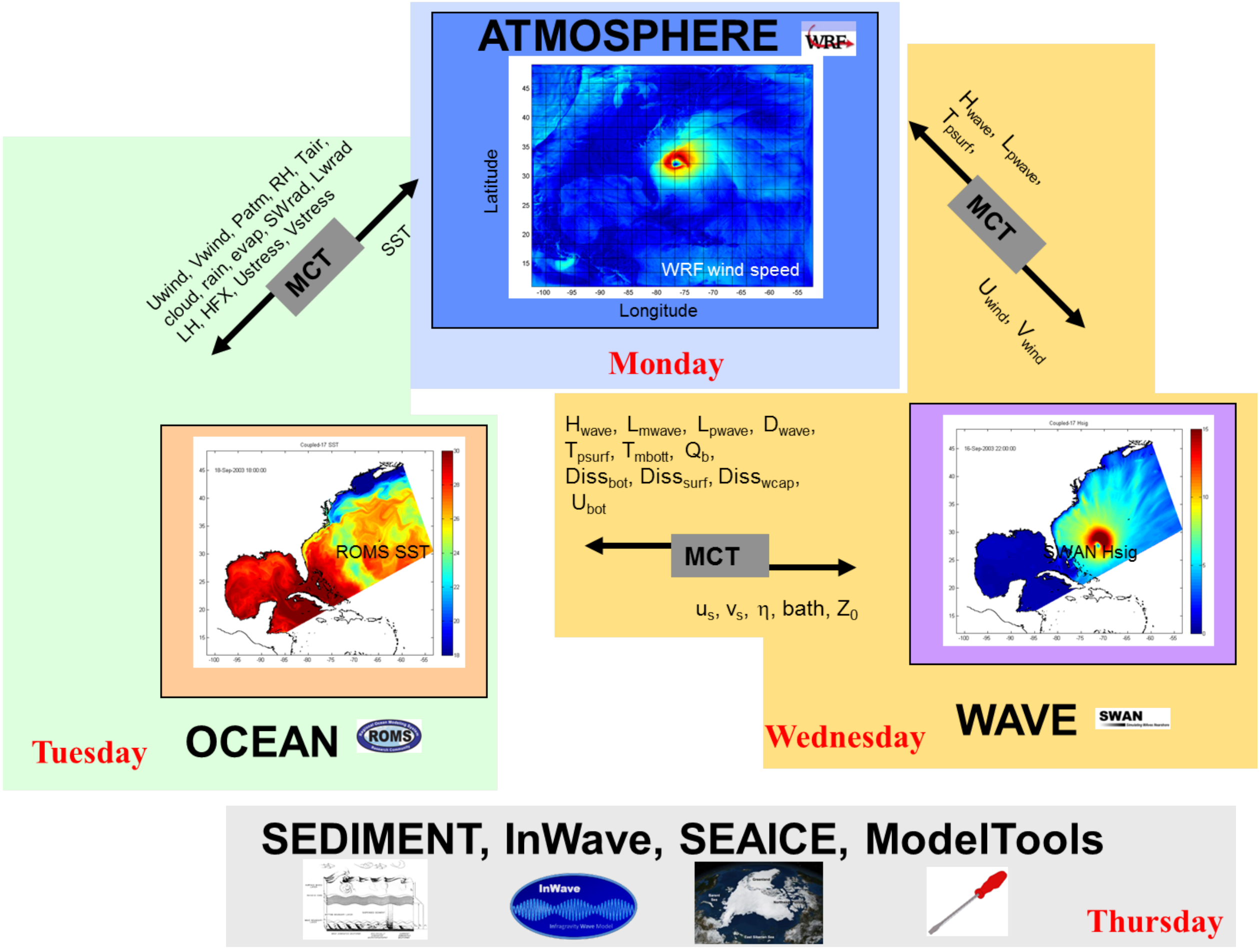
USGS science for a changing world

VIMS William & Mary Virginia Institute of Marine Science

CSDMS community surface dynamics modeling system



COAWST: Coupled-Ocean-Atmosphere-Wave- **Sediment Transport** Modeling System.



# Sediment Transport Components

- Erosion / deposition / bed model (sand, mud, or mixed)
- Settling
- Bedload transport and flux divergence
- Morphological evolution
- Flocculation/aggregation
- Sediment influence on density
- Positive-definite advection scheme (MPDATA, HSIND)
- Wave input (specified, or SWAN, 1- or 2-way coupled)
- Wave-current combined bottom stresses
- Wetting and drying

# Resuspension and Deposition

- Active layer thickness

$$\delta_{mix} = \max[\,k_1(\tau_b - \tau_{cr})/\tau_{cr}, 0] + k_2 D_{50}$$

$$k_1 = 0.007\text{mPa}^{-1}; \quad k_2 = 6$$

- Erosion

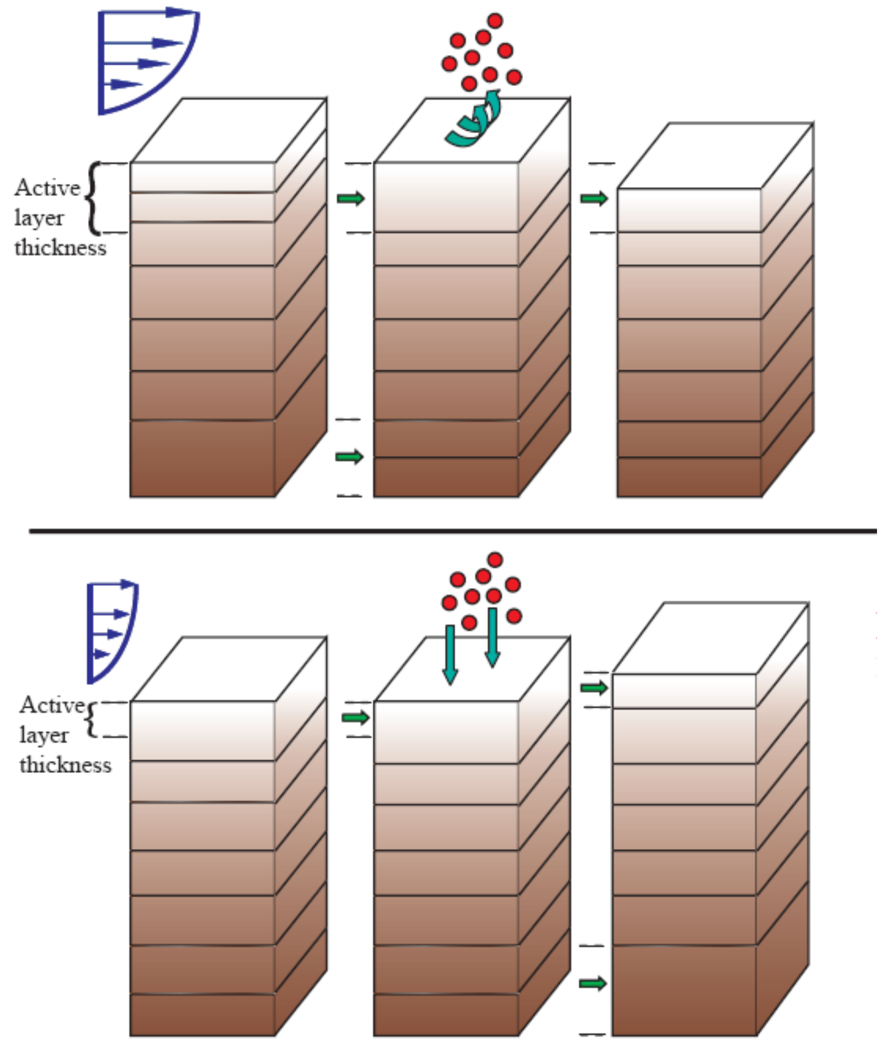
$$F_e = E(\tau_b - \tau_{cr})/\tau_{cr}$$

- Sedimentation

$$F_d = -w_s C$$

- Net deposition

$$\frac{\Delta C}{\Delta t} = F_d + \max\left[F_e, \frac{m_0}{\Delta t} - F_d\right]$$



# Bedload

- Meyer-Peter Müeller (1948) $\Phi = \max[\,8(\theta_{sf} - \theta_c)^{1.5},\ 0]$
- *Or* Soulsby and Damgaard (2005) $\vec{\Phi} = \max[A_2 \theta^{0.5}(\theta_{sf} - \theta_c)\frac{\vec{\theta}_{sf}}{\theta_{sf}}, 0]$

$\vec{\Phi} = (\Phi_{||}, \Phi_{\perp}), \quad \vec{\theta}_{sf} = (\theta_{sf||}, \theta_{sf\perp})$

- Accounts for net transport over a wave cycle of components parallel and perpendicular to mean currents
- Bed slope effect $q_{bl\_slope} = \frac{\tan\varphi_m}{(\tan\varphi_m - \tan\beta)\cos\beta}$

where $\beta = \tan^{-1}(dz/dx)$
$\varphi_m = \text{friction angle}$

- Upwind flux differencing

*...presently adding asymmetrical wave-driven bedload transport similar to SANTOSS formula*

# Bottom Boundary Layer

- Roughness ($z_0$): grains, saltation, ripples, biogenic features

$$z_0 = \max[\, z_{0N} + z_{0ST} + z_{0BF}, \quad z_{0MIN}]$$

- Law of the wall

$$|u| = \frac{u_{*wc}}{\kappa} \ln\left(\frac{z}{z_{0a}}\right)$$

where $|u|$ is current speed, $u_{*cw}$ is shear velocity, $z$ is elevation, $\kappa$ is von Kármán’s constant

- Apparent roughness ($z_{0a}$) is a function of $z_0$ and wave-current interaction

# Wave-Current Bottom Boundary Layer

- Orbital motions of waves near bottom creates more turbulence than currents alone
- More turbulence, better coupling of flow to bottom, more drag on mean flow ($u_{*cw}$, $z_{0a}$)
- Also, higher instantaneous bed stresses to mobilize sediment
- Madsen (1994) *or* Styles and Glenn (2000) *or* Soulsby (1997)

# Ripple Roughness

- Ripples increase roughness of seabed, adding drag and increasing stresses
- Ripple geometry (height, wavelength, maybe orientation) are computed from instantaneous equilibrium (Malarky and Davies, 2003 method of Wiberg and Harris, 1994)
- $z_{0BF}$ ~ height$^2$/wavelength
- Some of this is form drag; that portion does not contribute to the skin friction stresses that move sediment: corrected according to Smith and McLean (1997) and Wiberg and Nelson (1992)

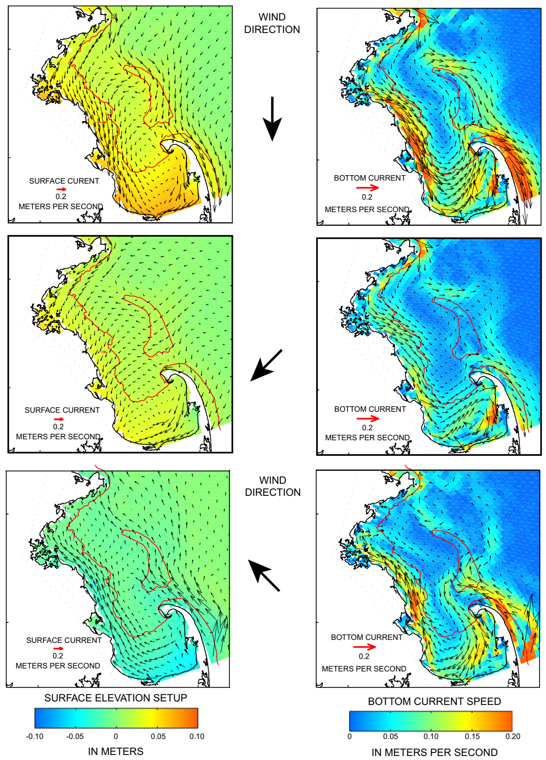
# COAWST/CSTMS Sediment

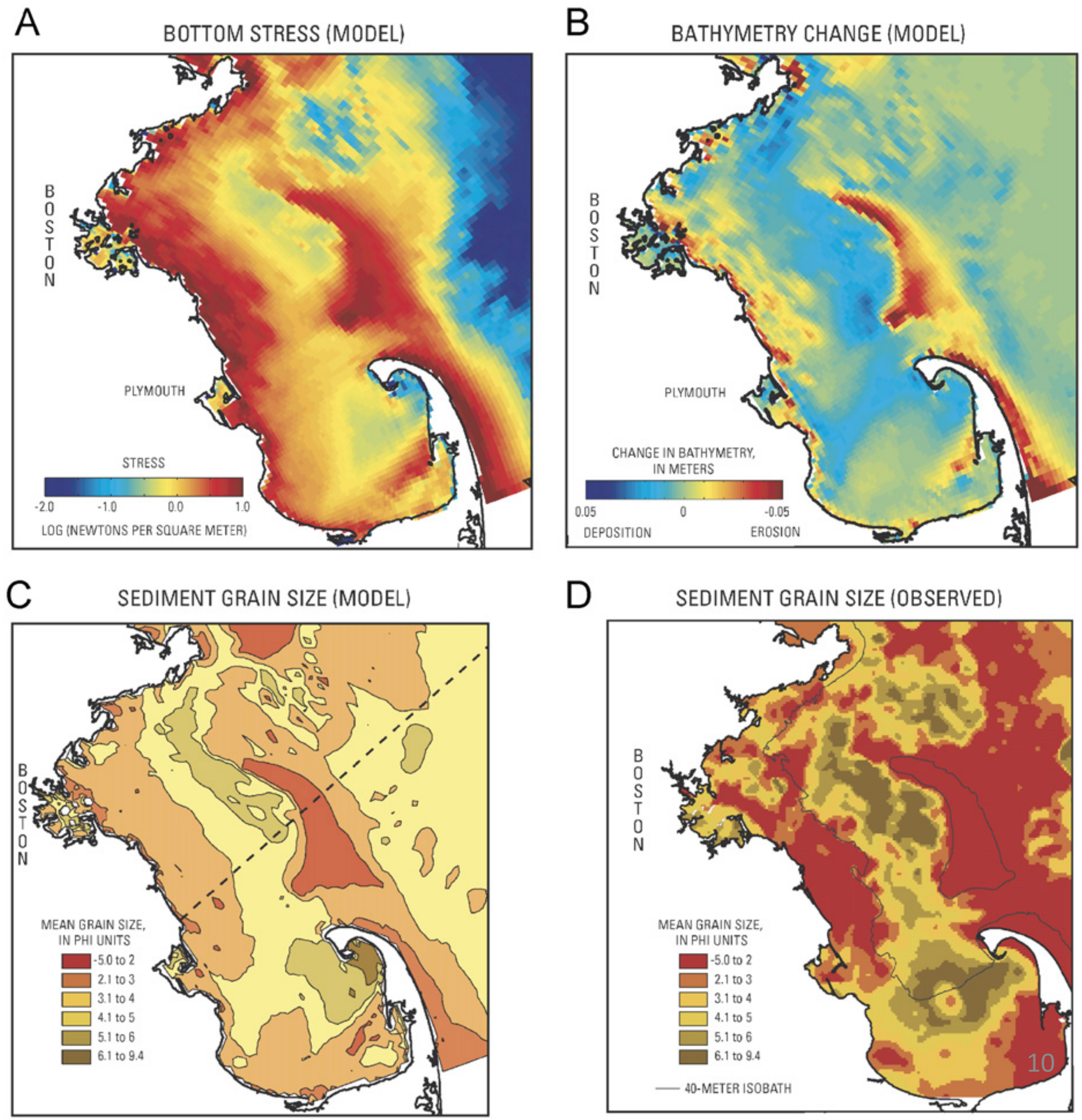
- Cohesive/mixed bed
- Biodiffusion
- Stratigraphy
- Flocs
- Biogeochemistry

Courtney Harris and students (Aaron Bever, J.P. Rinehimer, Kelsey Fall, Julia Moriarty, Danielle Tarpley)

```
if SEDIMENT
  sediment.F - Initiate sediment routines
  if BEDLOAD
    sed_bedload.F - Bedload transport
  endif
  if SUSPLOAD
    if SED_FLOCS
      sed_flocs.F - Floc dynamics
    endif
    sed_settling.F - Suspended sediment settling
    sed_fluxes.F - Erosion / Deposition
  endif
  if COHESIVE_BED or MIXED_BED
    sed_bed_cohesive.F *- Cohesive / mixed stratigraphy
    if SED_FLOCS and SED_DEFLOC
      sed_bed_cohesive.F *- Adjust floc distribution in bed
    endif
  elseif NONCOHESIVE_BED2
    sed_bed2.F *- Non-cohesive stratigraphy (revised)
  else
    sed_bed.F - Non-cohesive stratigraphy (original)
  endif
  if SED_BIODIFF
    sed_biodiff.F* - Biodiffusive mixing of bed
  endif
  sed_surface.F - Update surface properties
endif
```

# Example: non-cohesive bed

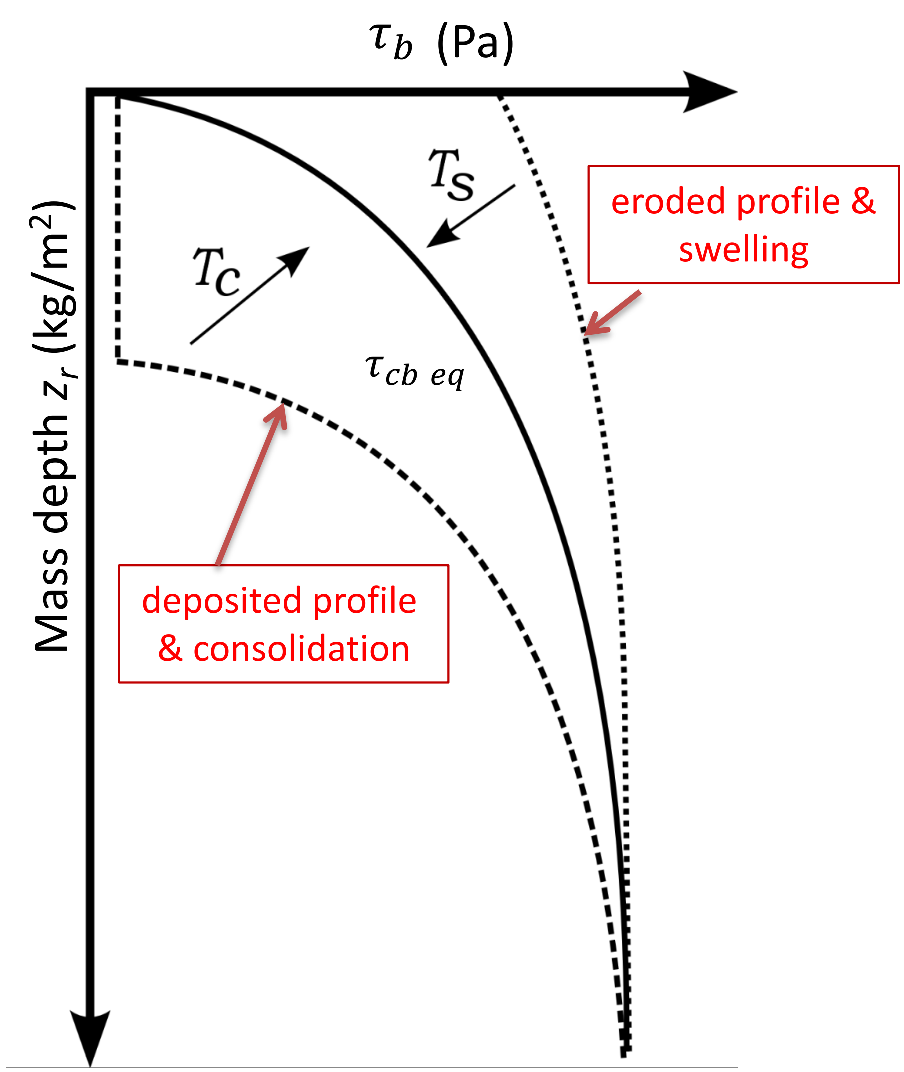



**Study the sediment size distribution (Mass Bay):**

**Warner et al., CSR, 2008**

# Cohesive behavior




$$\tau_{cb\ eq} = \exp\left(\ln(M) - offset\right) / slope$$

$$\frac{\Delta \tau_{cb}}{\Delta t} = \begin{cases} \frac{1}{T_c}\left(\tau_{cb\ eq} - \tau_{cb}\right) & , \quad \tau_{cb} < \tau_{cb\ eq} \\ 0 & , \quad \tau_{cb} = \tau_{cb\ eq} \\ -\frac{1}{T_s}\left(\tau_{cb\ eq} - \tau_{cb}\right) & , \quad \tau_{cb} > \tau_{cb\ eq} \end{cases}$$

$T_c$ = Time scale of consolidation

$T_s$= Swelling time scale (order 100 times slower)

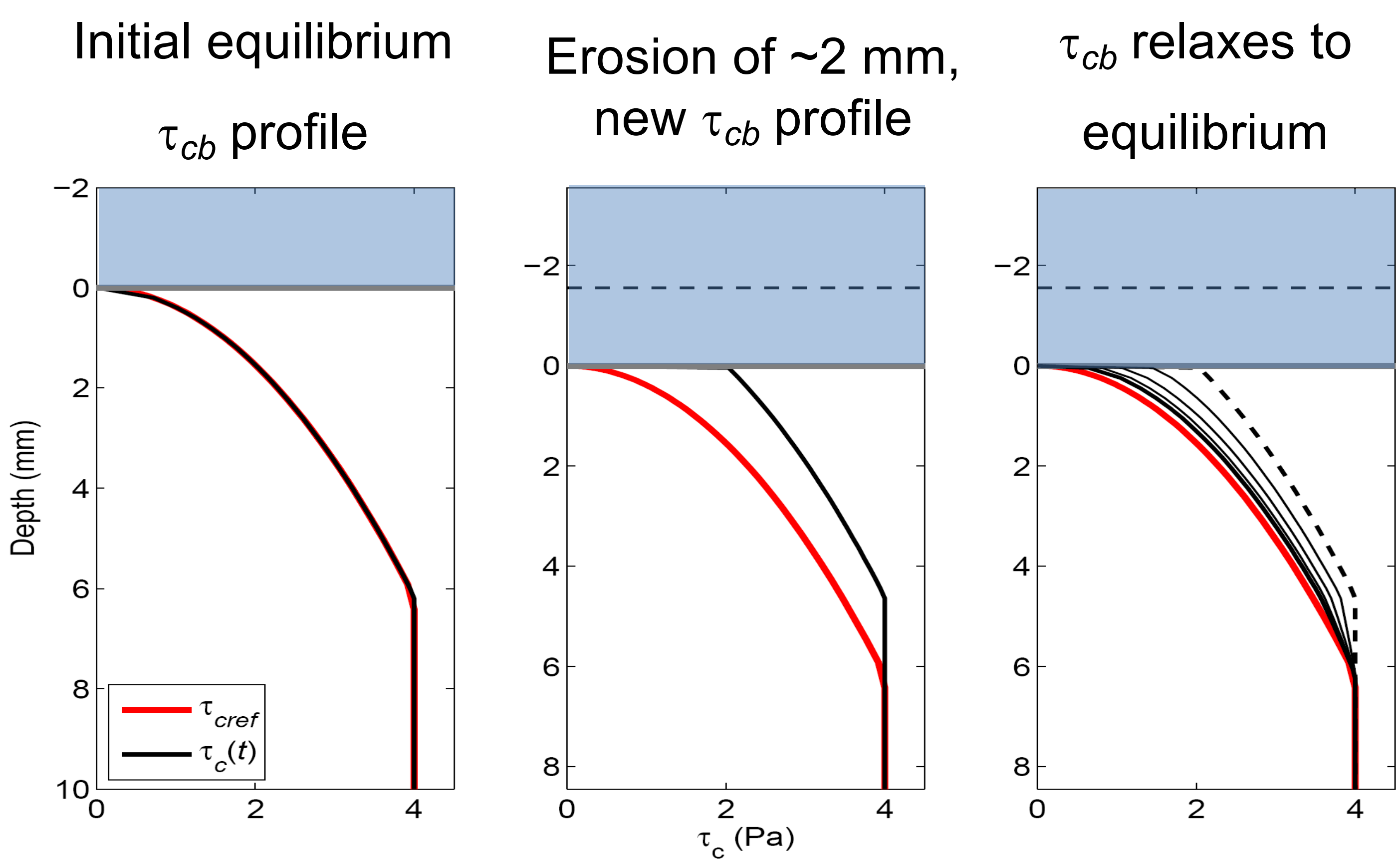
Development:

- Harris, Rinehimer + VIMS
- Sherwood, Ferré, Aretxabaleta + USGS

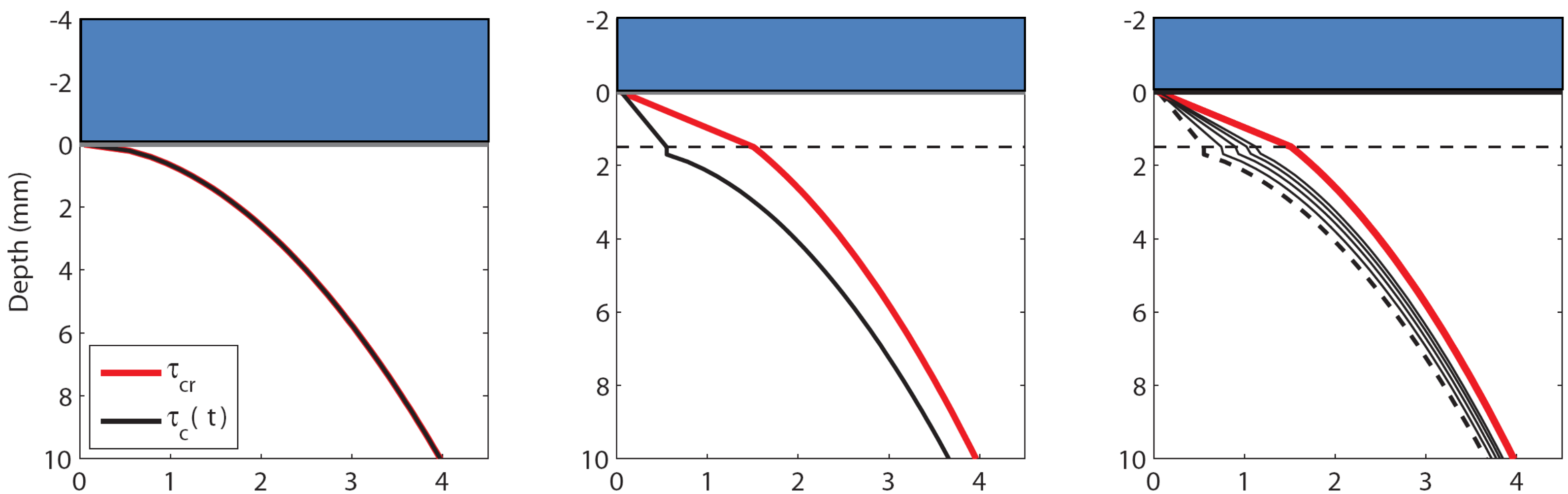
Rinehimer, 2008
Sherwood et al., 2018

# Erosion of a Cohesive Bed

- Key bed property: critical shear stress

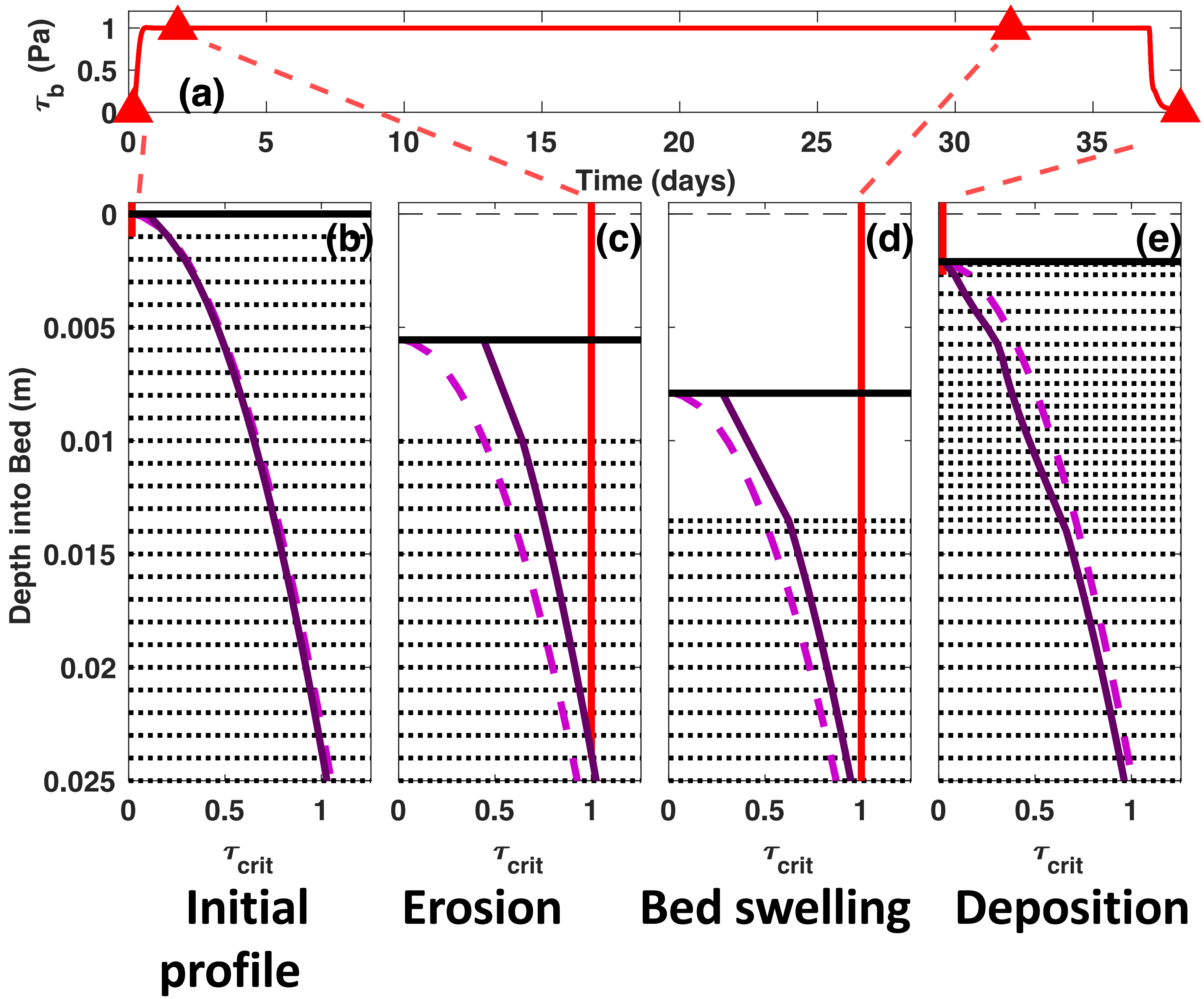


# Deposition on a Cohesive Bed




1) Initial profile.
2) Deposition of 2 mm. $\tau_c$ profile (black) is extended to new surface; sediment at surface is easier to erode.
3) In absence of further deposition or erosion, $\tau_c$ profile slowly reverts toward reference profile (red)

# Cohesive behavior

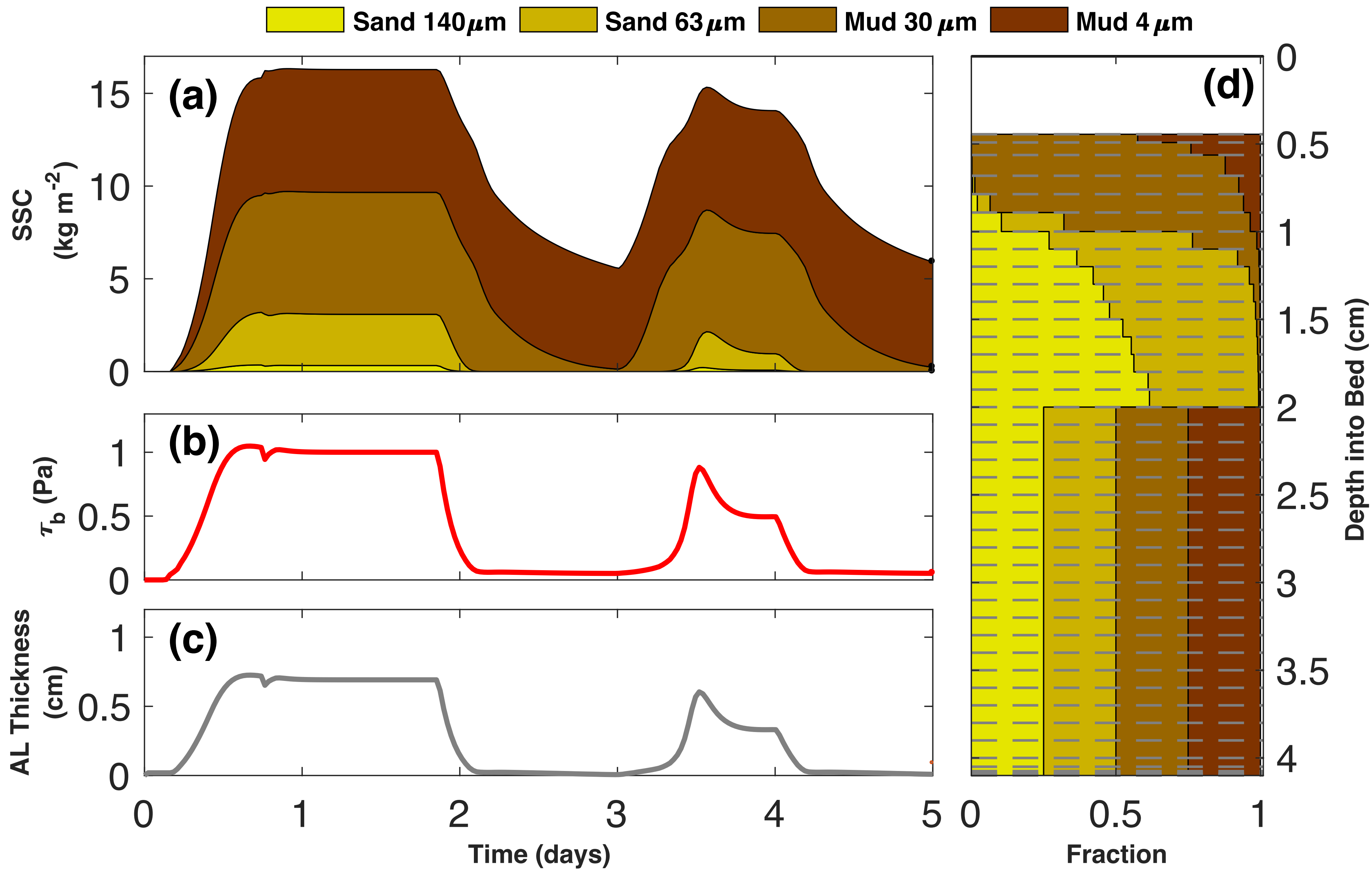



Equilibrium critical stress profile

Time-varying critical stress profile

Ambient Bottom Stress

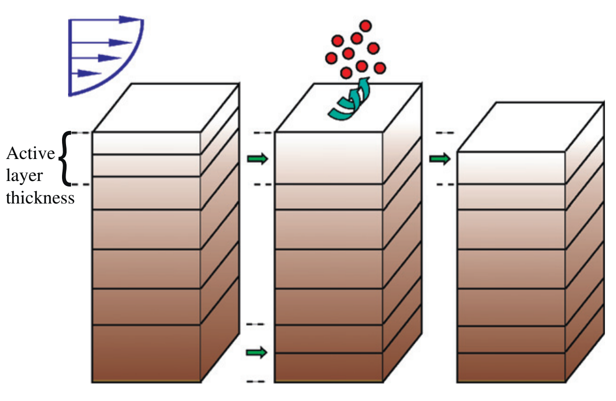
# 1-D case with 4 sediment classes

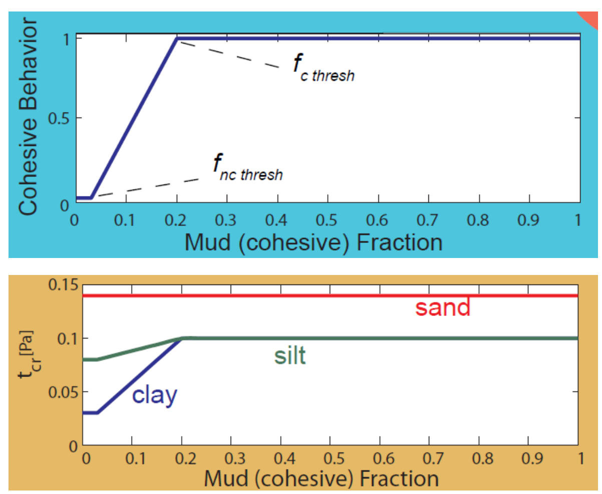


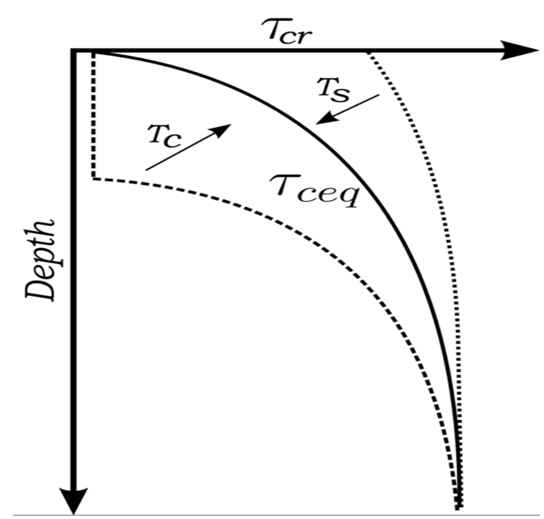
# Mixed bed behavior

Thresholds from Mitchener and Torfs, Coast.Engin., 1996

| Non-Cohesive Bed | Mixed Bed | Cohesive Bed |
|---|---|---|
| Erosion depends on each sed. class critical stress | Erosive behavior depends on mud/sand ratio | Erosion depends on entire bed critical stress |
| Mud fraction < 3-10% | 3-10% < Mud fraction < 20-30% | Mud fraction > 20-30% |



# Mixed bed behavior

## Determine how cohesive the bed is ($P_{coh}$)

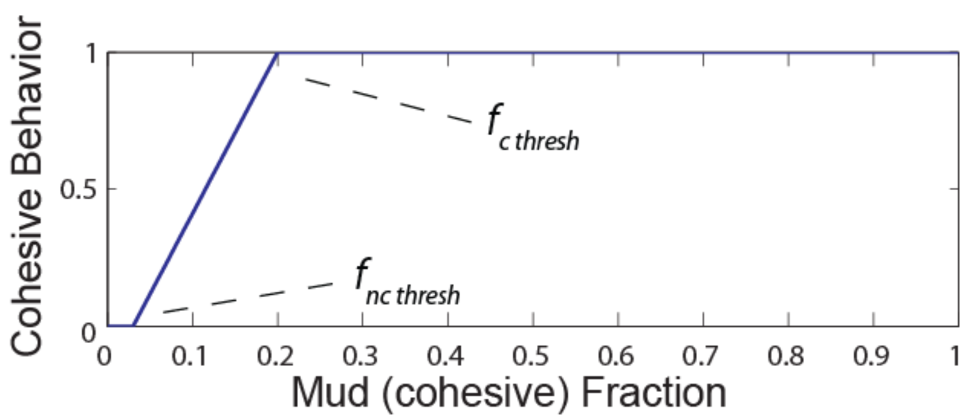
$f_c$ is the cohesive fraction:

$f_c < f_{nc\ thresh}$ (~0.03) -> fully non-cohesive behavior (Pcoh = 0)

$f_c > f_{c\ thresh}$ (~0.20) -> fully cohesive behavior ($P_{coh}$ = 1)

$f_{nc\ thresh} < f_c < f_{c\ thresh}$ -> intermediate behavior:

$$P_{coh} = \min\left[\max\left(\frac{f_c - f_{nc\ thresh}}{f_{c\ thresh} - f_{nc\ thresh}}, 0\right), 1\right]$$



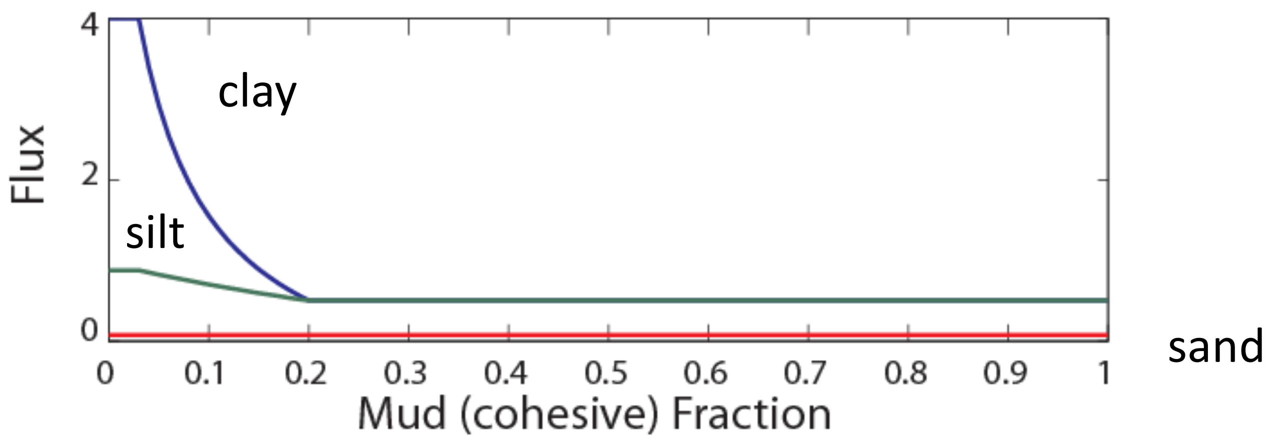

"Cohesive behavior" $P_{coh}$ is then applied to the critical shear stress and active - layer thickness.

# Mixed bed behavior

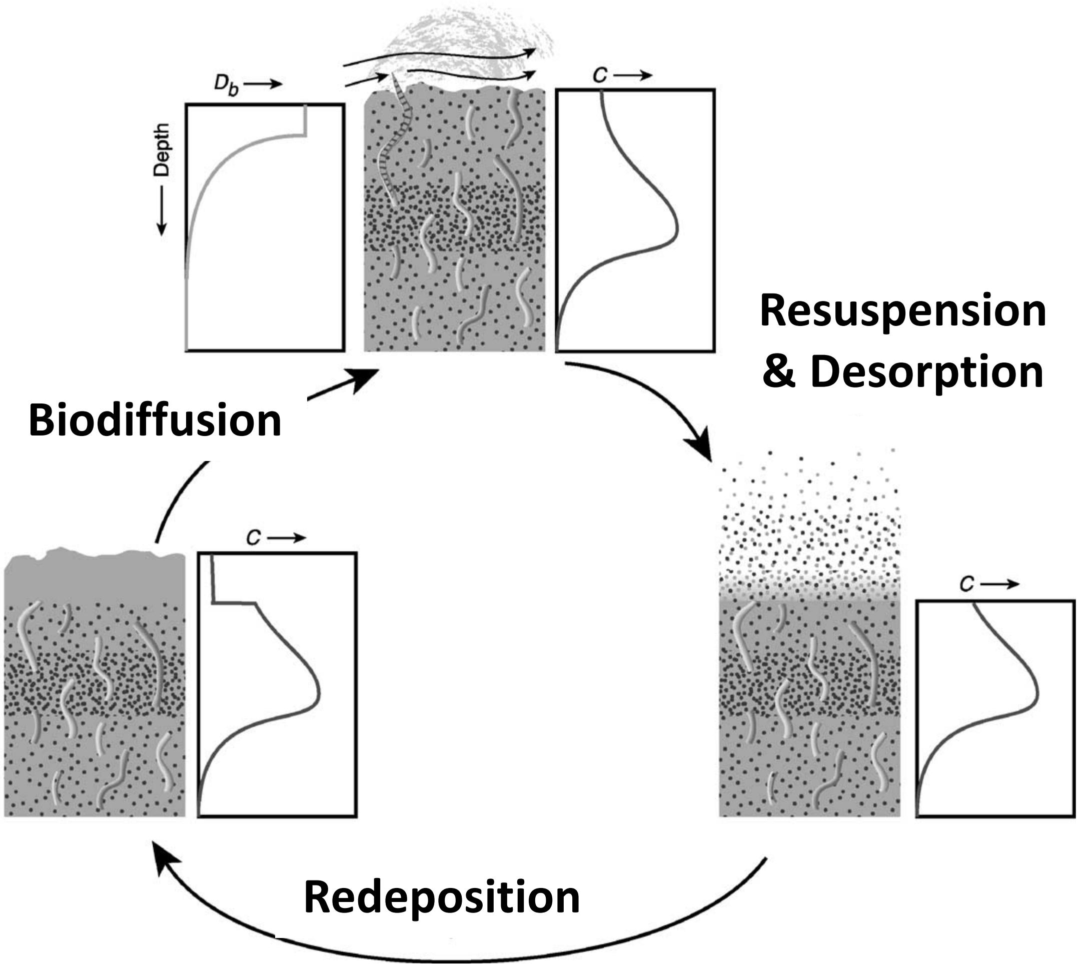
## Resuspension flux near bottom

If $dt$ is the time step, $E_0$ the surface erosion rate, $fr_i$ the fraction for each class, $\tau_w$ the maximum bottom shear stress and $\varphi$ the bed porosity:

$$flux_i = \max\left(0,\ dt\ E_0(1-\varphi)\ fr_i\ (\tau_w - \tau_{cr})\right)$$

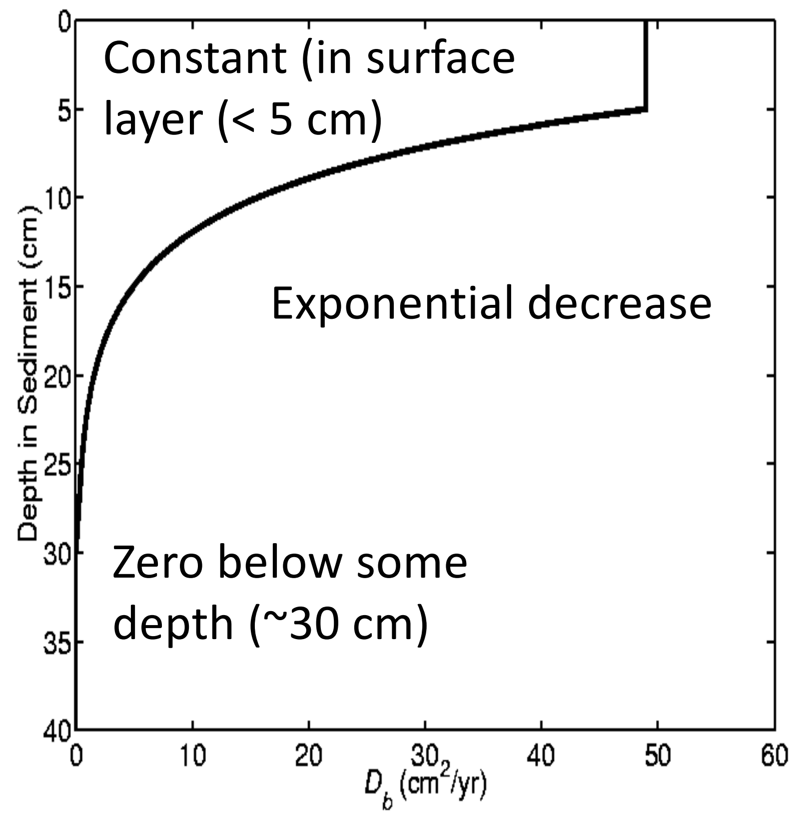


# Biodiffusion




Bioturbation causes mixing in the bed

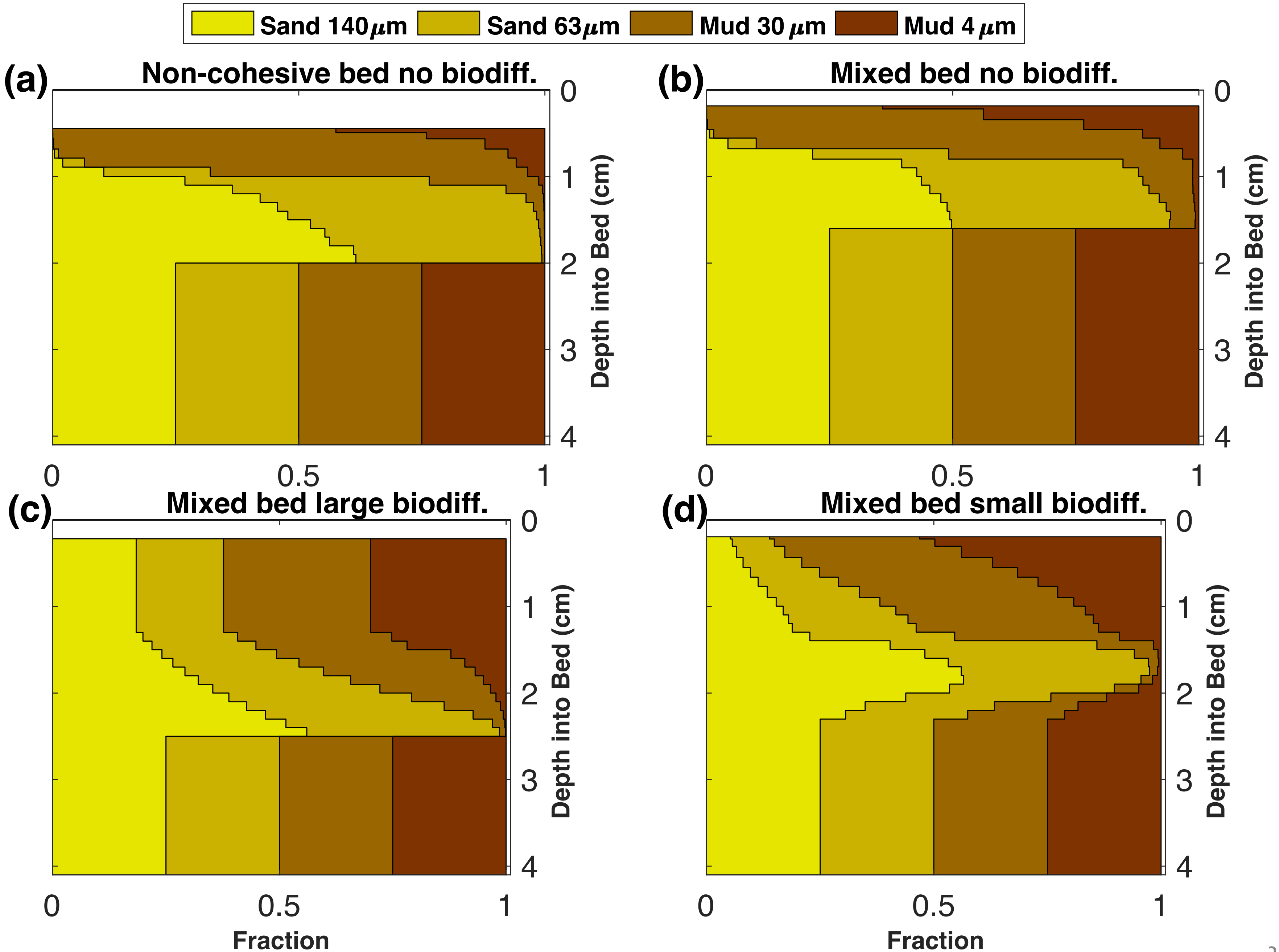
$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left( Db \frac{\partial C}{\partial z} \right)$$



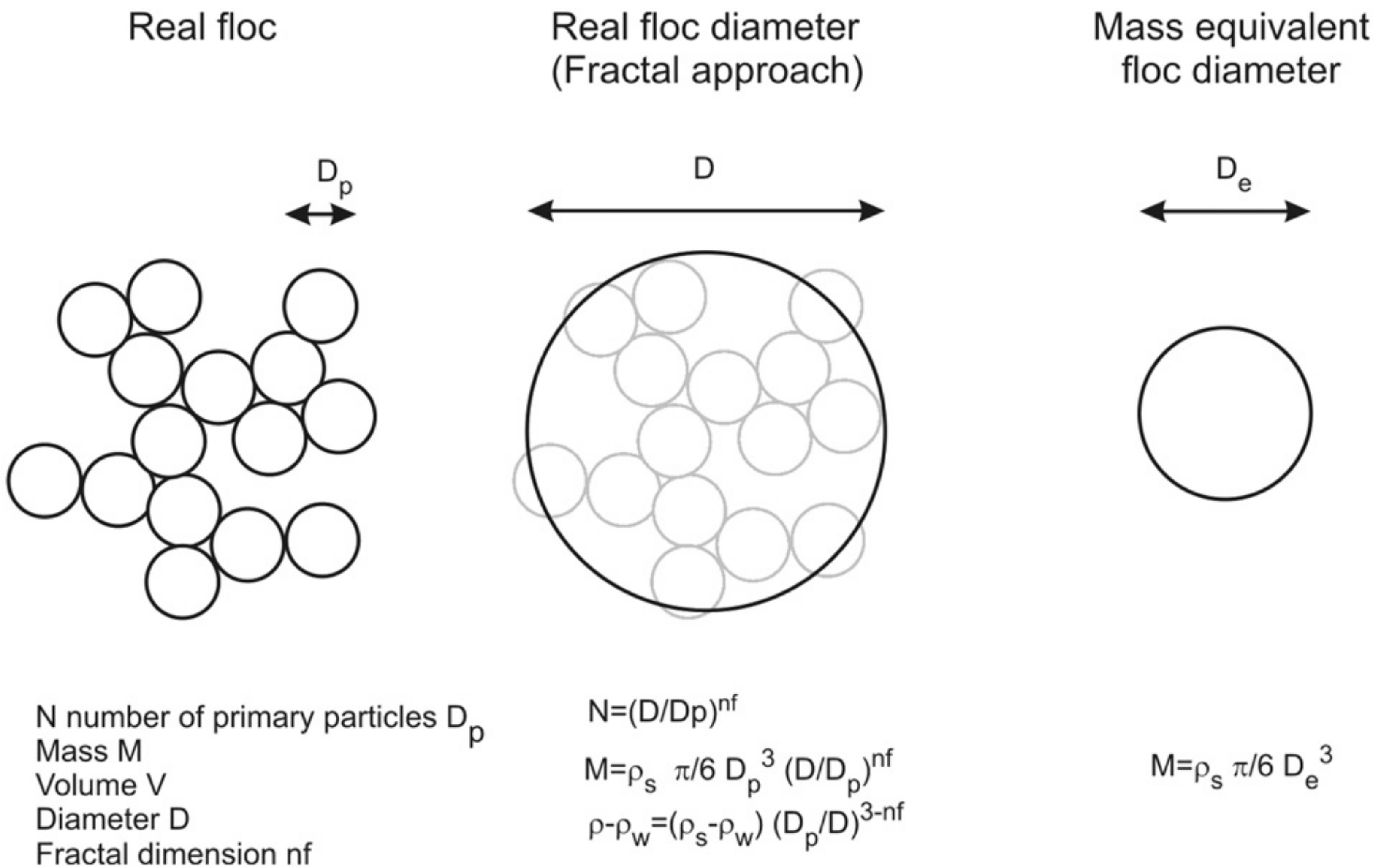

Typical values in top ~5-8 cm of the bed are 10 $cm^2/y$ (O $10^{-7}$ $m^2$ $s^{-1}$)

Sherwood et al., CSR, 2002

# Biodiffusion + Mixed bed



# Flocculation




Verney et al., 2011

# Flocculation

## Description of the SCB model – FLOCMOD

*Verney et al., 2011; Maerz et al., 2011; Mietta et al., 2011*

Based on the population equation proposed by Smoluchowski (1917) :

$$\frac{dn_k}{dt} = G_{aggr} + G_{break\_shear} + G_{break\_coll} - L_{aggr} - L_{break\_shear} - L_{break\_coll}$$

The floc population is described by *N* size classes, logarithmically distributed, e.g.:
*D* - 1: 50µm ; 2: 77µm ; 3: 118µm ; 4: 180µm ; 5: 275µm ; 6: 421µm ; 7: 643µm
*Ws* - 1: 0.13 ; 2: 0.19 ; 3: 0.28 ; 4: 0.41 ; 5: 0.61 ; 6: 0.89 ; 7: 1.30 mm/s

assuming a fractal dimension of *nf*=1.9. *nf* relates floc mass to volume through floc density. *nf* = 3 are solid spheres, lower *nf* = lower floc densities.

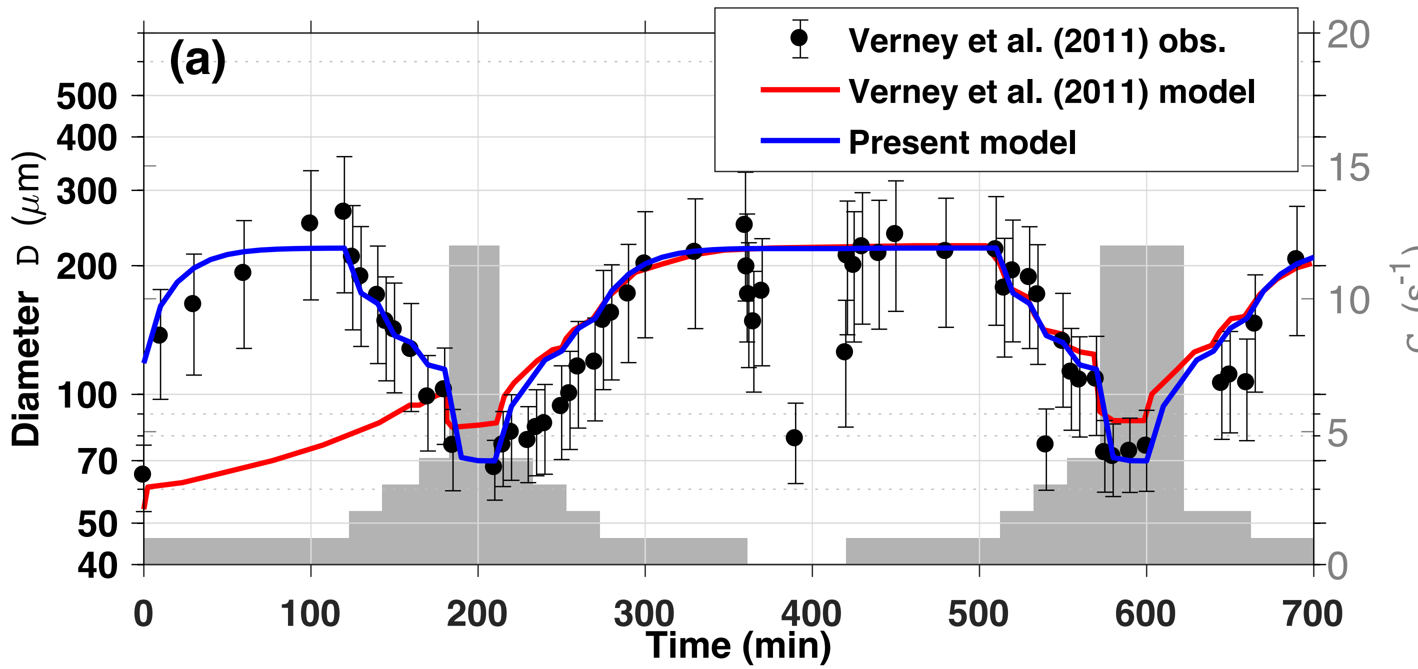
Mass moves among these classes through aggregation and fragmentation processes represented by kernel formulations.

# FLOCMOD in COAWST

- FLOCMOD computed at each *x*,*y*,*z*,*t*
  - $\Delta t$ = 1/4 to 1 s
  - 7 to 15 floc classes (4 – 1500 μm)
  - 1 to 3 sand classes (125 – 250 μm)
  - $D_p$ = 4 μm, $\rho_s$ = 2650 kg/m$^3$, $n_f$ = 2
  - Binary fragmentation
  - No floc deposition
  - Other parameters according to Verney et al., 2011

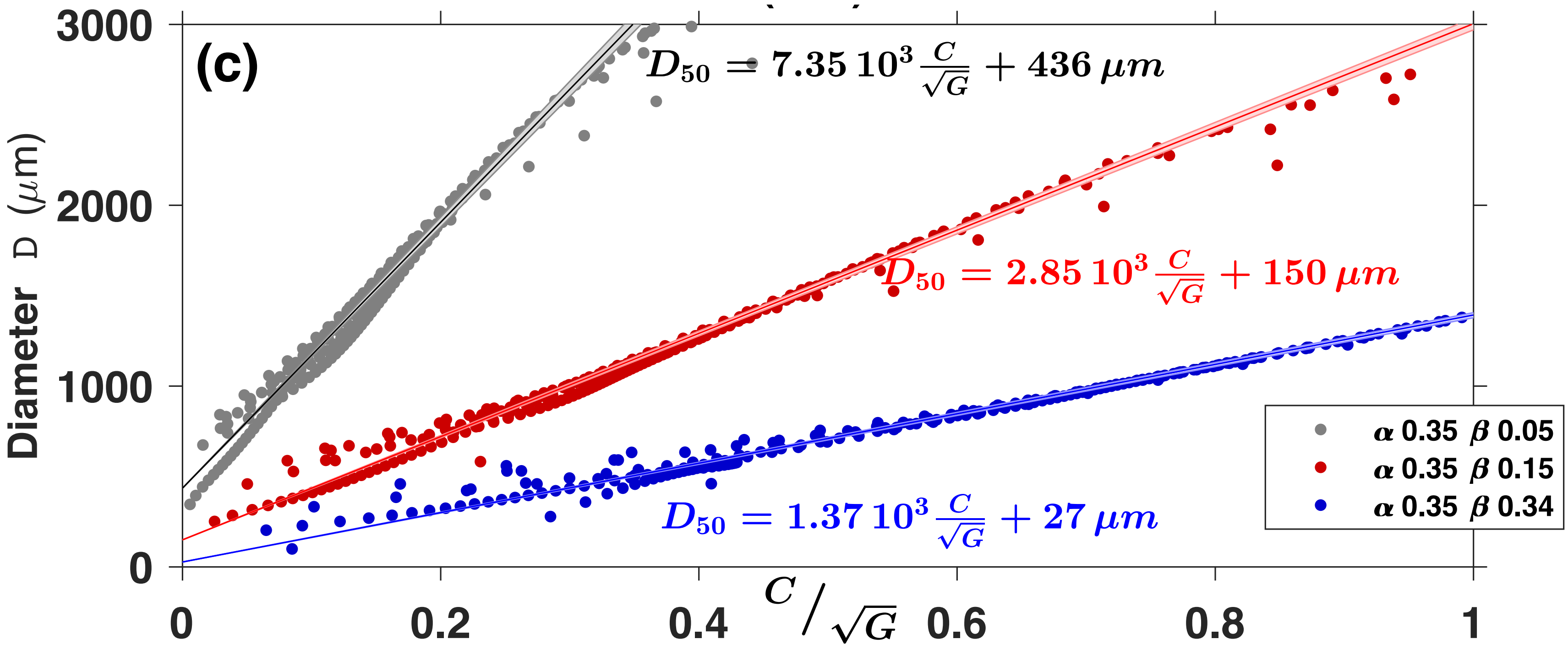
Verney Tank Experiment

Constant concentration = 0.093 kg/m$^3$




Sherwood et al., 2018

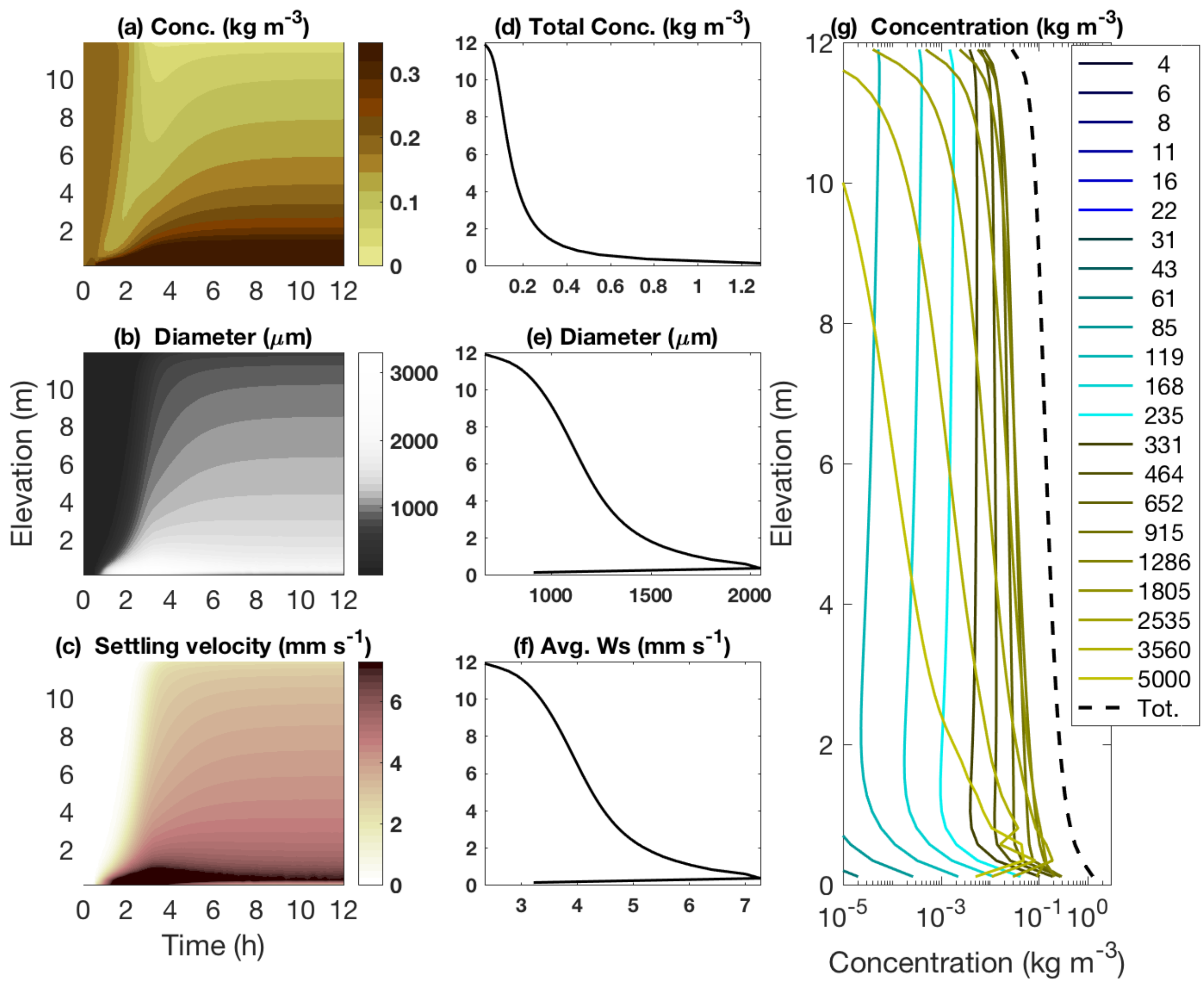
# FLOCS in COAWST
# Steady flow, no settling, no deposition




Sherwood et al., 2018

Winterwerp (equilibrium profile)
Study of different aggregation/disaggregation constants

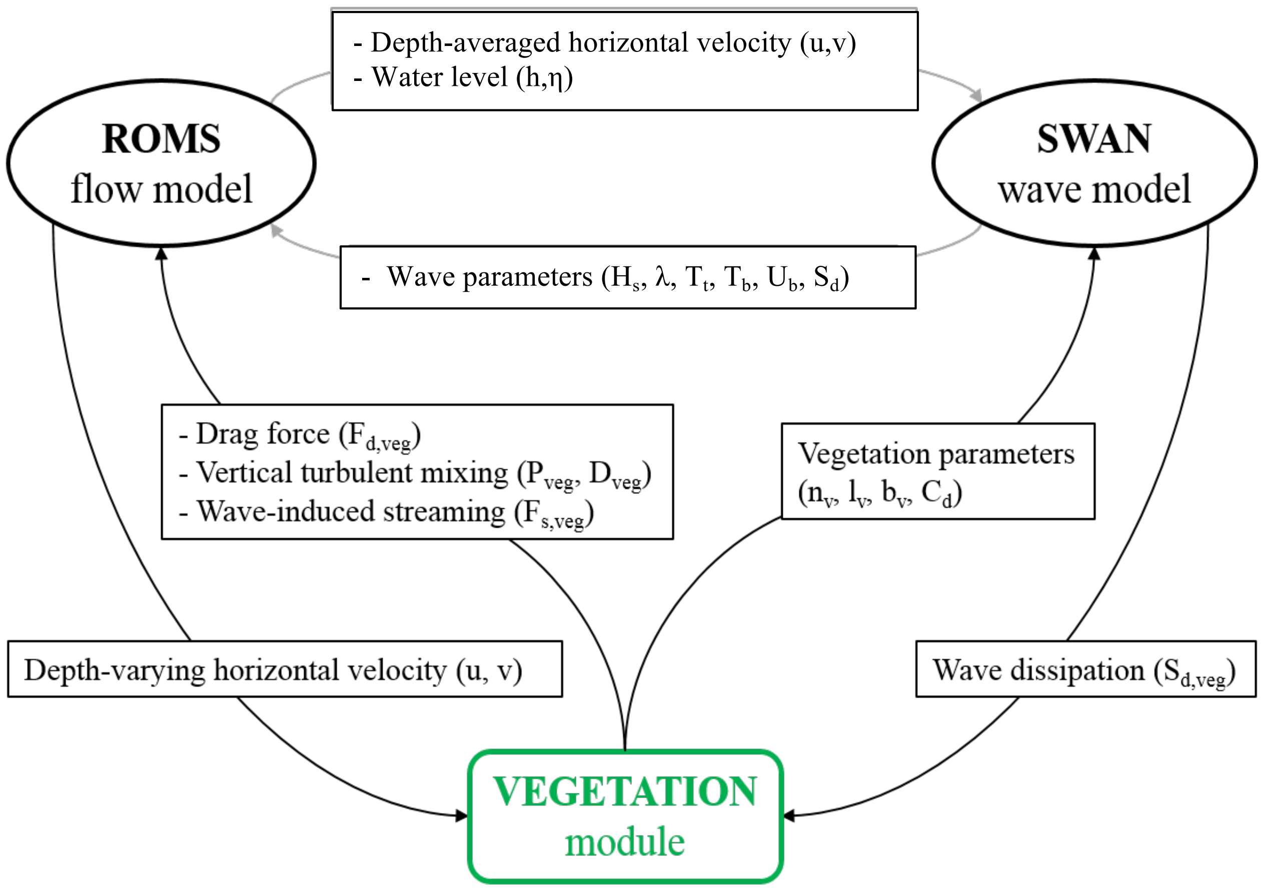
# FLOCS in COAWST
# Example: Steady flow




Sherwood et al., 2018

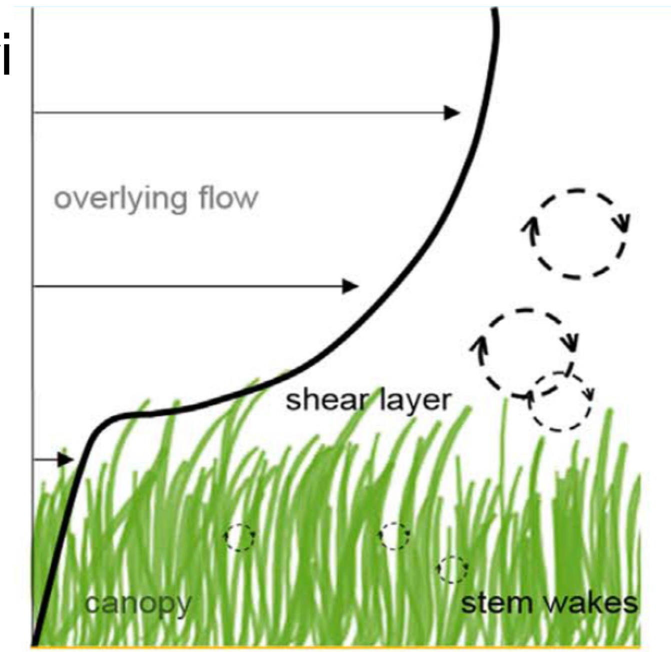
# Vegetation Module

Beudin et al., 2017, Comp. & Geosci.



# Effect of SAV on flow dynamics

- 3-D SAV represented by cylindri structures
- Modify mean and turbulent flow
- Local adjustment of water level
- Wave dissipation
- Within the canopy, reduced TKE
- Above the canopy, enhancing TKE




Schematic showing submerged vegetation canopy

# Modeling SAV effect on flow dynamics

| Process modeled | Additional terms in the model |
|---|---|
| 1. Momentum extraction | Drag force in momentum equation (ROMS) |
| 2. Turbulence production | Turbulent generation in the TKE equation (ROMS), Uittenbogaard (2003), |
| 3. Turbulence dissipation | Generic length scale (ROMS) |
| 4. Flexible SAV | Reduction of drag due to bending of flexible SAV (ROMS), Luhar and Nepf, 2011 |
| 5. Wave dissipation | Source term in wave action equation (SWAN), Dalrymple et al. (1984) and Mendez and Losada (2004) |
| 6. Wave streaming | Wave averaged forcing in momentum (SWAN+ROMS), Luhar et al., 2010; Luhar and Nepf, 2013 |

# What is different about sediment in COAWST? (external differences)

- Minimal
  - Switches in `.h` file
  - Changes in `.in` file
  - Need `sediment.in` file
  - Need to modify (a copy of) `ana_sediment.F`
  - …or provide more info in `init.nc` file
  - New output in `his.nc` file
- Many applications also need
  - More info in `init.nc` file (initial bed)
  - Wave input
  - River sediment input
  - Boundary conditions

# Cohesive Sediment Transport Models in an Idealized Estuary

**Danielle Tarpley (**Ph.D. Candidate)

**Courtney K. Harris*, Carl Friedrichs**
Department of Physical Sciences

**Chris Sherwood**
US Geological Survey

**presenting the webinar today*

CSDMS Webinar
November 18, 2019

# Community Sediment Transport Modeling System

- Described in Warner et al. (2008).
- Implemented in ROMS.
- Versions have also been ported to SCHISM, FVCOM, and other models.
- **Noncohesive sediment model.**
- **Treats particulate tracers as inert.**


Computers & Geosciences 34 (2008) 1284–1306

COMPUTERS & GEOSCIENCES

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ELSEVIER

Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model☆

John C. Warner[a,*], Christopher R. Sherwood[a], Richard P. Signell[a], Courtney K. Harris[b], Hernan G. Arango[c]

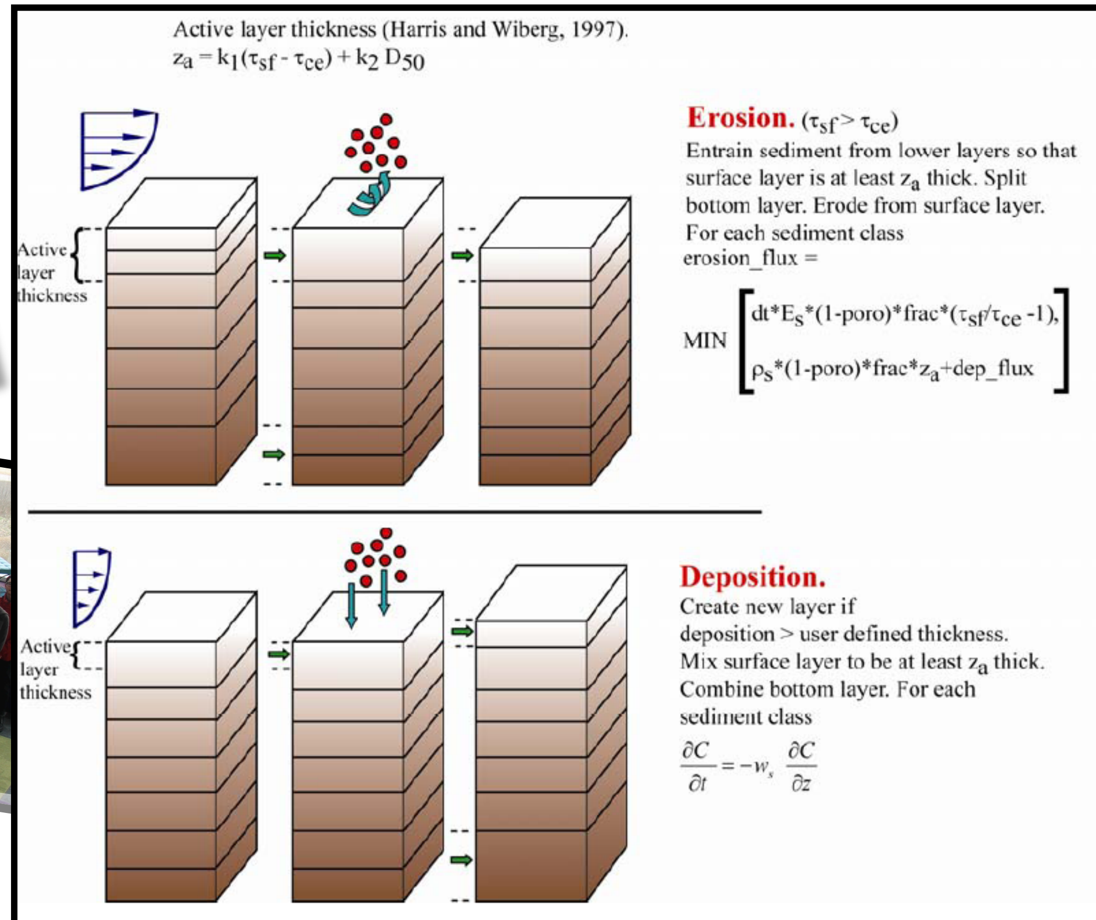
[a] US Geological Survey, Coastal and Marine Geology Program, Woods Hole, MA 02543, USA
[b] Virginia Institute of Marine Science, Gloucester Point, VA 23062, USA
[c] Institute for Marine and Coastal Sciences, Rutgers-The State University of New Jersey, New Brunswick, NJ 08901, USA

Received 5 September 2006

**Abstract**

We are developing a three-dimensional numerical model that implements algorithms for sediment transport and evolution of bottom morphology in the coastal-circulation model Regional Ocean Modeling System (ROMS v3.0), and provides a two-way link between ROMS and the wave model Simulating Waves in the Nearshore (SWAN) via the Model-
pling Toolkit. The coupled model is applicable for fluvial, estuarine, shelf, and nearshore (surfzone) environments.
ensional radiation-stress terms have been included in the momentum equations, along with effects of a surface
l. The sediment-transport algorithms are implemented for an unlimited number of user-defined non-
. Each class has attributes of grain diameter, density, settling velocity, critical stress threshold for
tant. Suspended-sediment transport in the water column is computed with the same
for all passive tracers and an additional algorithm for vertical settling that is not
deposition are based on flux formulations. A multi-level bed framework tracks
d stores bulk properties including layer thickness, porosity, and mass,
hy. Also tracked are bed-surface properties including active-layer
t is calculated for mobile sediment classes in the top layer.
nctions that enhance bottom stresses and thereby
the circulation. The model is demonstrated


COAWST user group meeting, February 2019



# CSTMS Now Includes Flocculation and Bed Consolidation

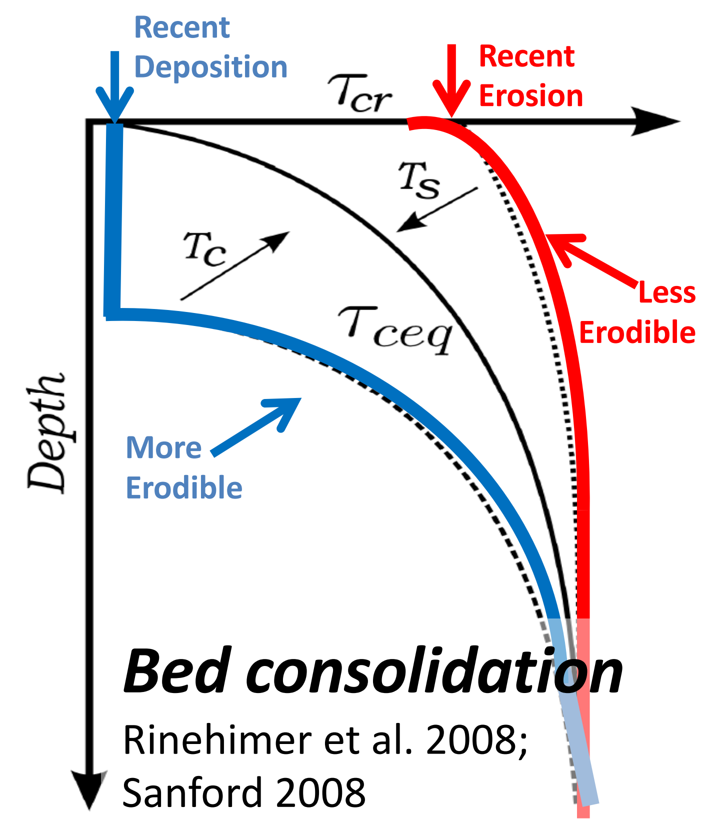
Geosci. Model Dev., 11, 1849–1871, 2018
https://doi.org/10.5194/gmd-11-1849-2018


Geoscientific Model Development
Open Access

## Cohesive and mixed sediment in the Regional Ocean Modeling System (ROMS v3.6) implemented in the Coupled Ocean–Atmosphere–Wave–Sediment Transport Modeling System (COAWST r1234)

Christopher R. Sherwood[1], Alfredo L. Aretxabaleta[1], Courtney K. Harris[2], J. Paul Rinehimer[2,a], Romaric Ver
and Bénédicte Ferré[1,b]

[1]U.S. Geological Survey, 384 Woods Hole Road, Woods Hole, MA 02543-1598, USA
[2]Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA 23062, USA
[3]IFREMER, Plouzane, France
[a]currently at: WEST Consultants, Bellevue, W
[b]currently at: CAGE-Centre for Arctic Gas Hy
UiT The Arctic University of Norway, 9037 T




***Bed consolidation***

Rinehimer et al. 2008;
Sanford 2008

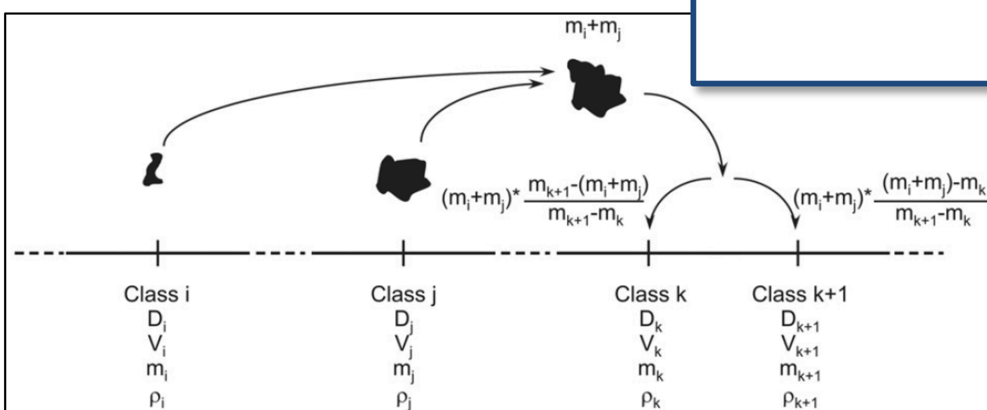
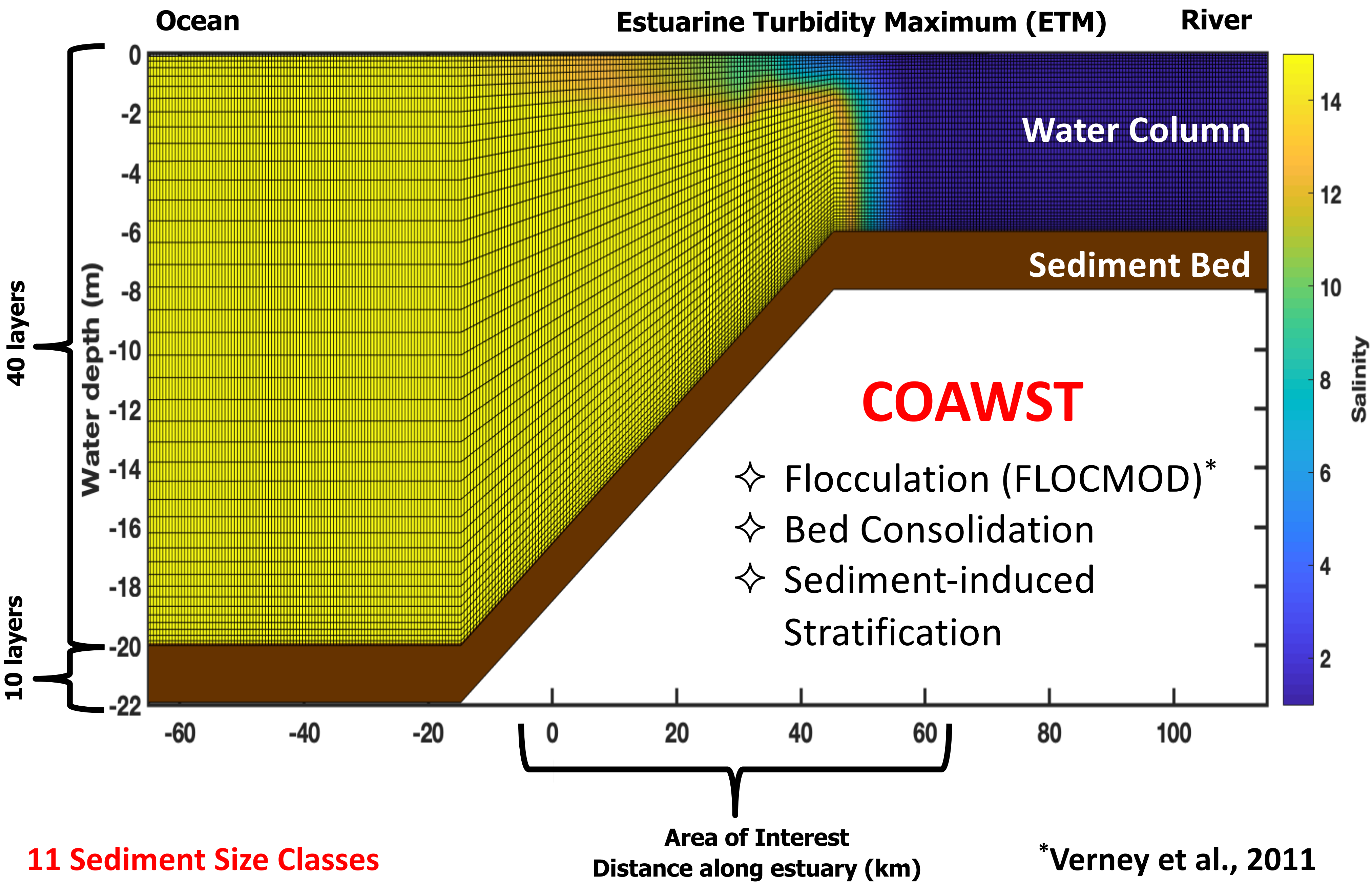



**Fig. 3.** Management of the newly formed flocs in the size class distribution: concept of continuous flocculation.

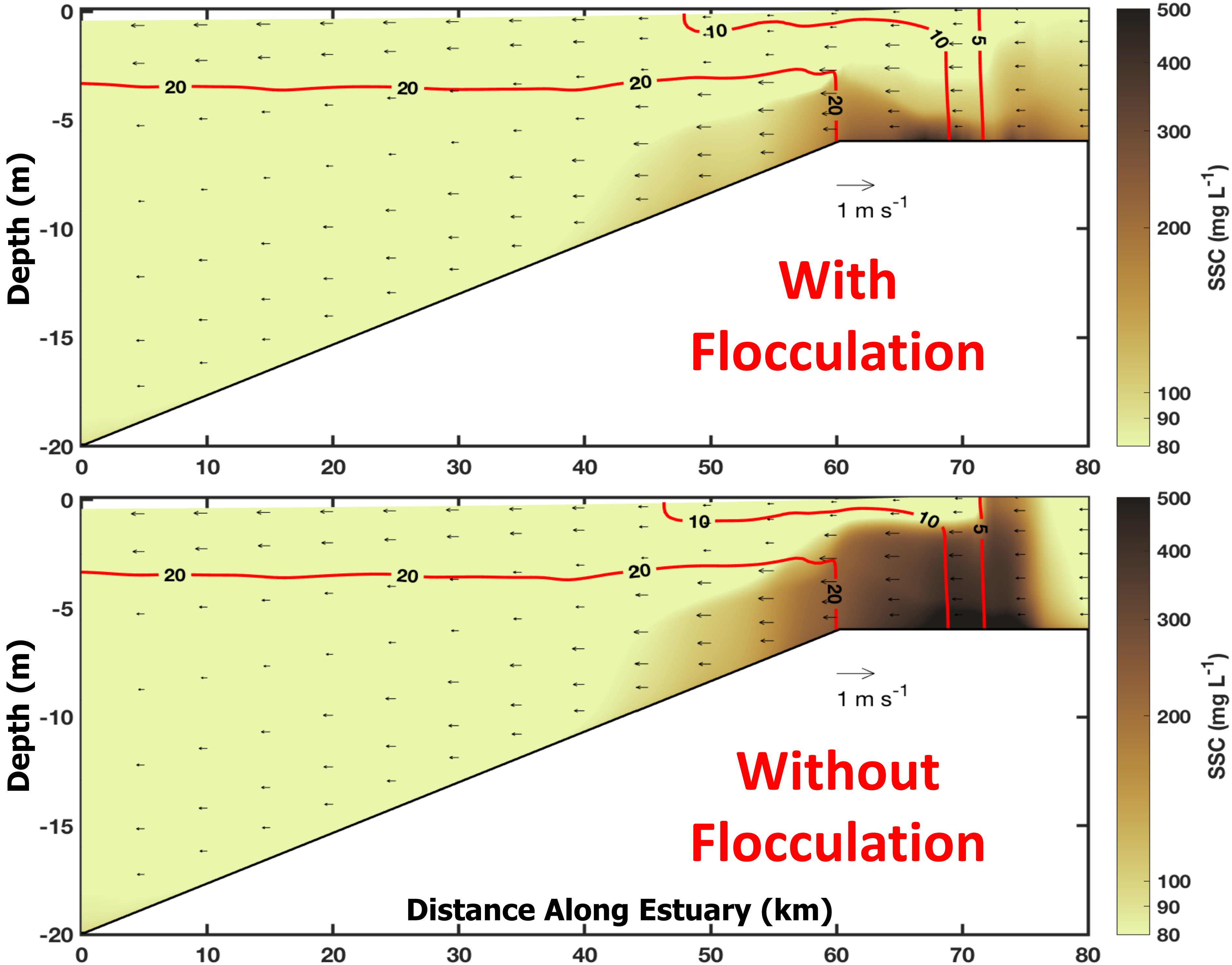
***FLOCMOD***

*Figure from Verney et al. 2011.*

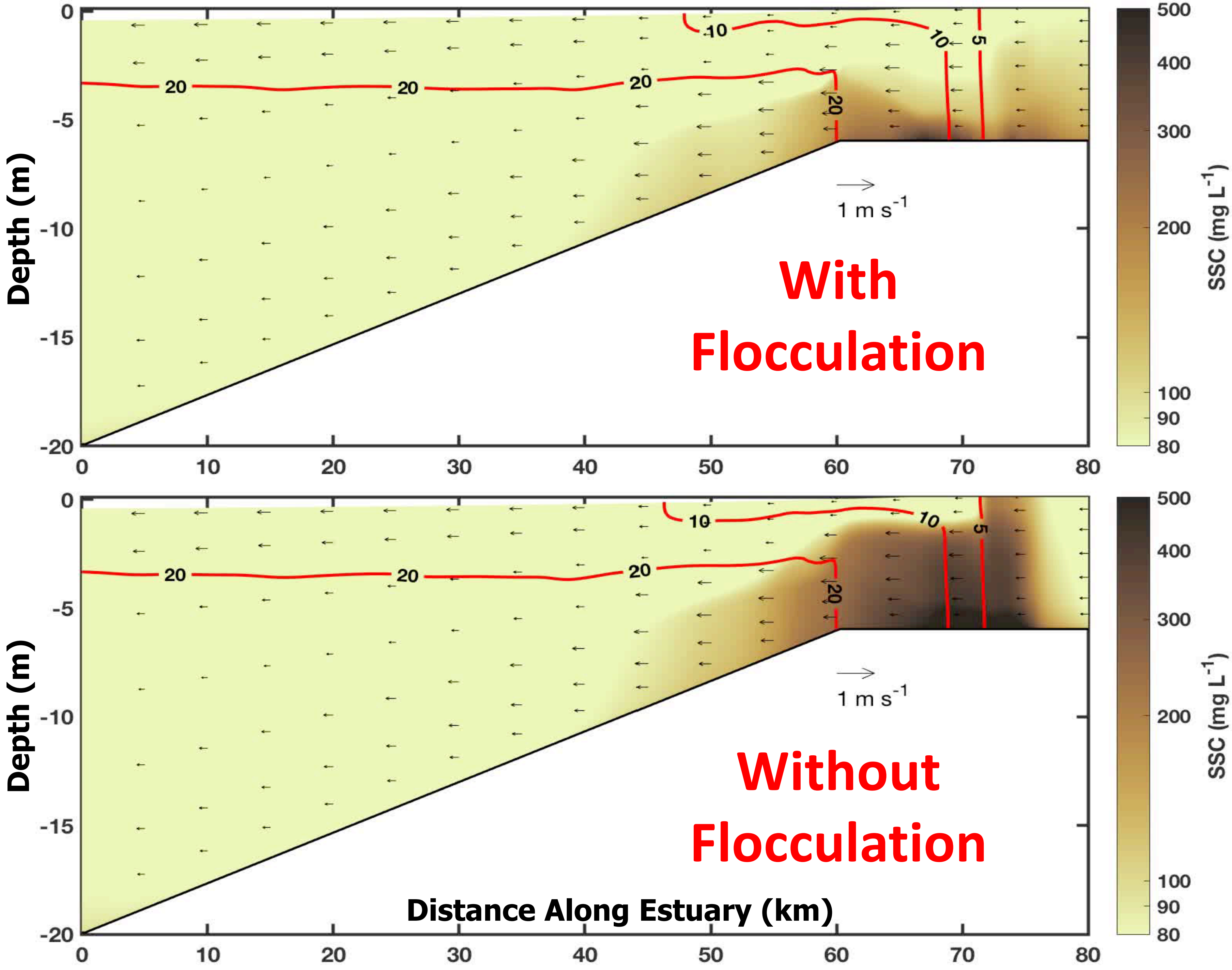

Danielle R.N. Tarpley[1]
K. Harris[1], Carl T.



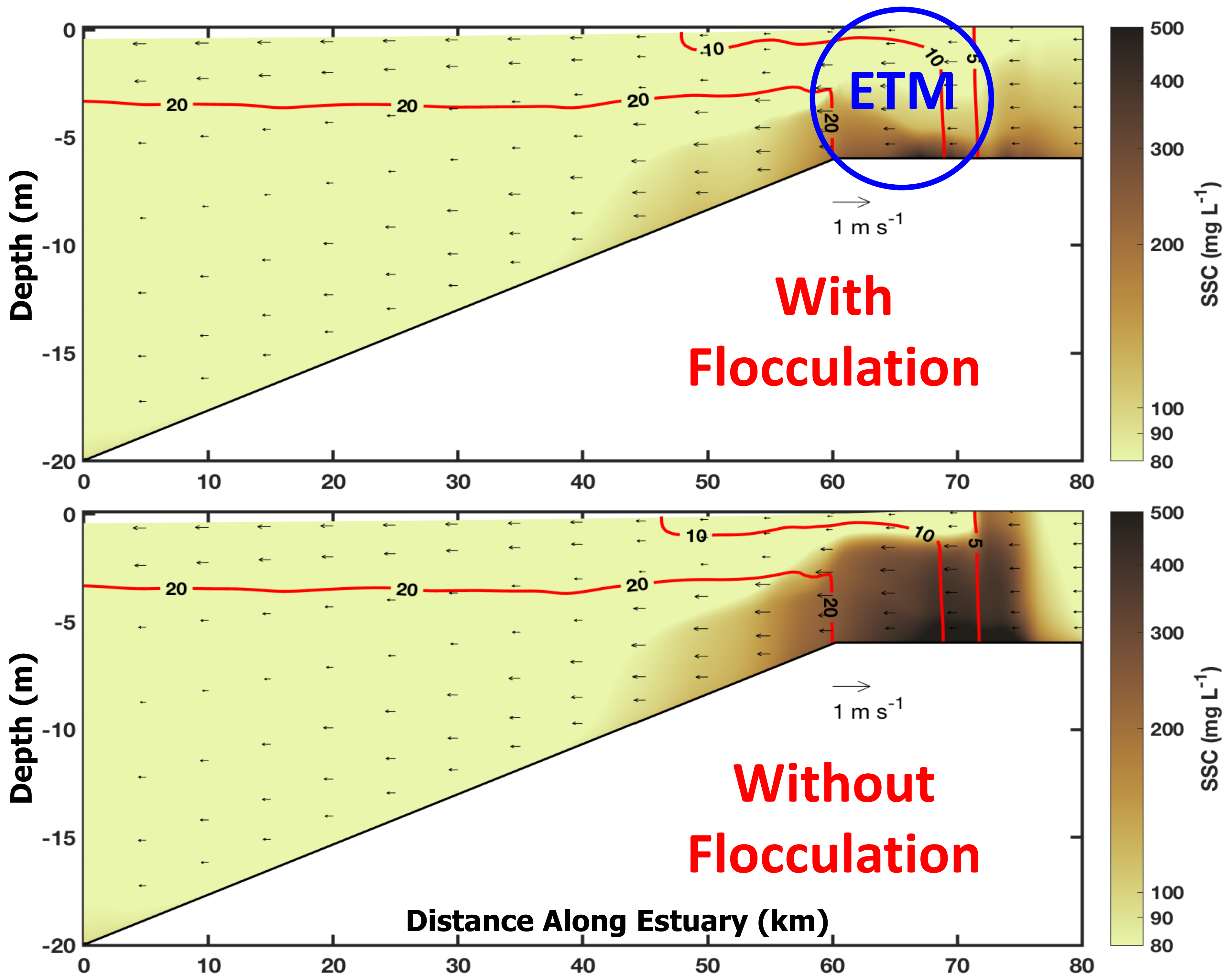

Tarpley et al. 2019. Tidal variation in cohesive sediment distribution and sensitivity to flocculation, bed consolidation in an idealized, partially mixed estuary. *JMSE*



With Flocculation
Without Flocculation
Depth (m)
Distance Along Estuary (km)
SSC (mg L-1)
1 m s-1
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
500
400
300
200
100
90
80
20
10
5

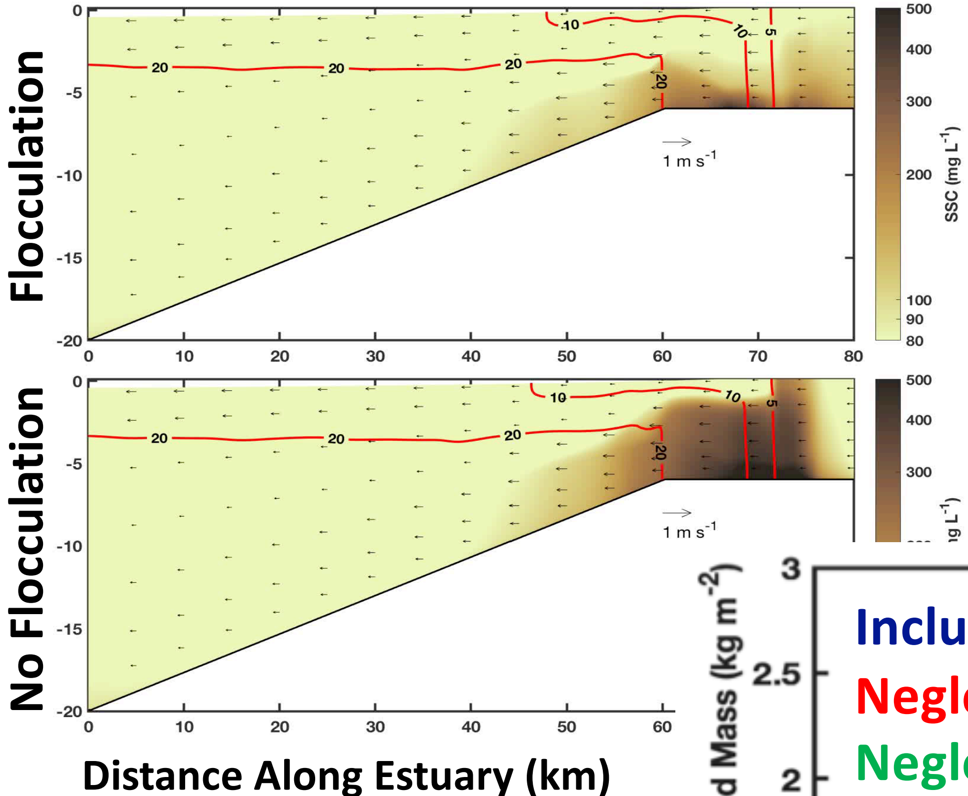


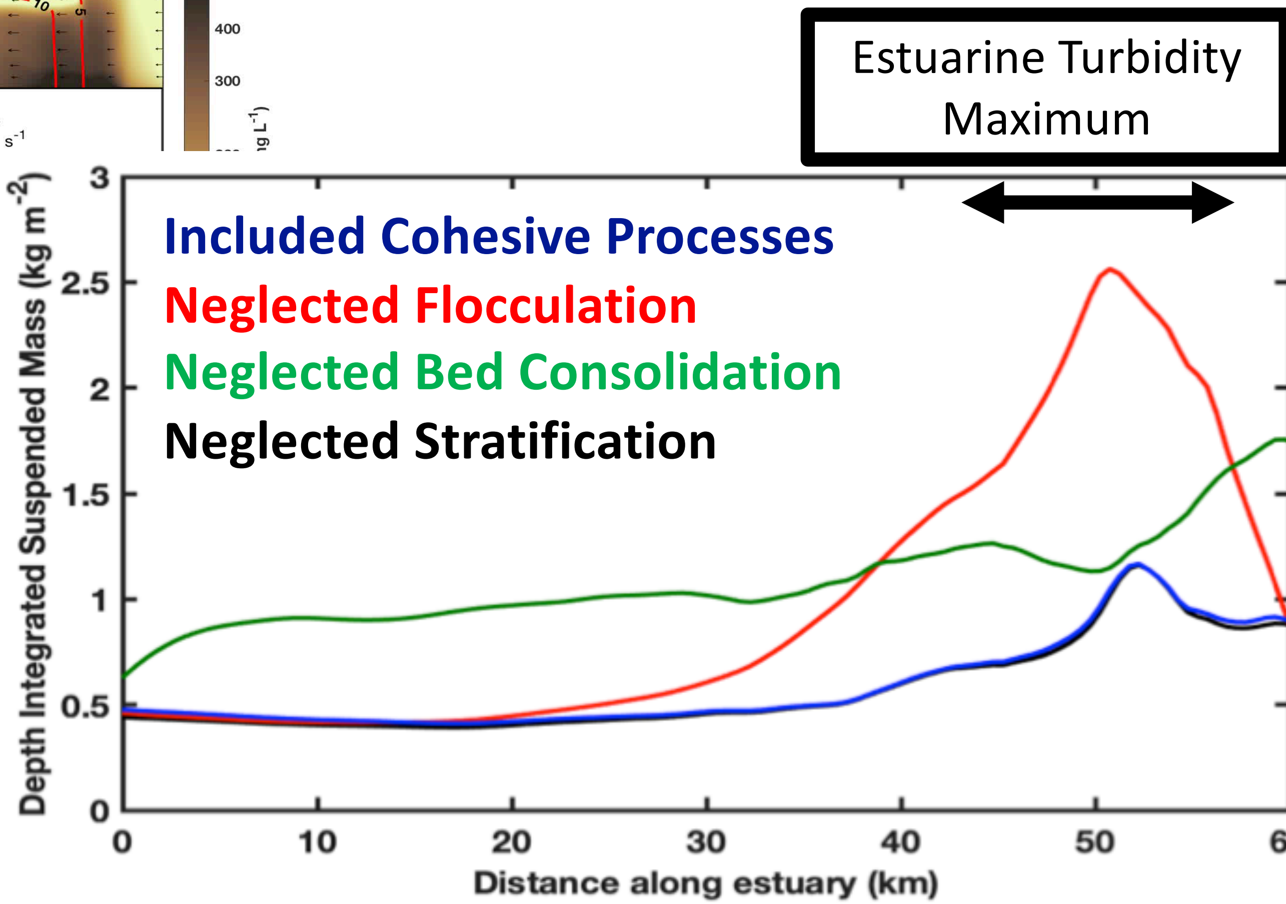
Depth (m)
SSC (mg L-1)
1 m s-1
With Flocculation
Without Flocculation
Distance Along Estuary (km)



ETM
With Flocculation
Without Flocculation
Depth (m)
Distance Along Estuary (km)
SSC (mg L-1)
1 m s-1
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
500
400
300
200
100
90
80
20
10
5

# Including Cohesive Processes in an Idealized Estuary

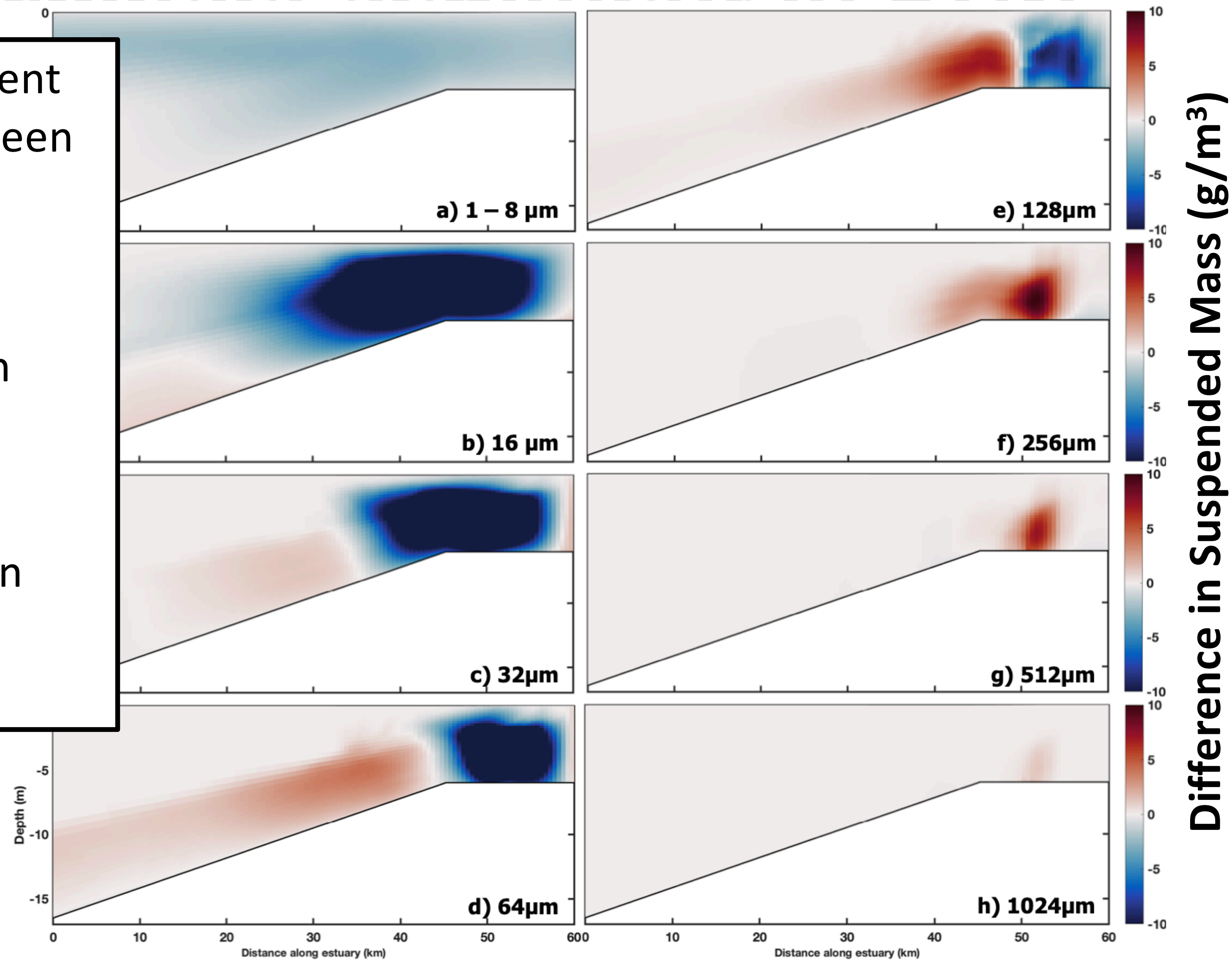



*Tarpley, Harris, Friedrichs and Sherwood, 2019.*

# Flocculation shifted distribution toward coarser sediment in ETM

- ❑ Difference in sediment concentration between two model runs.
- ❑ For each size class:
  - Red -> Flocculation **increased** concentration
  - Blue -> Flocculation **decreased** concentration



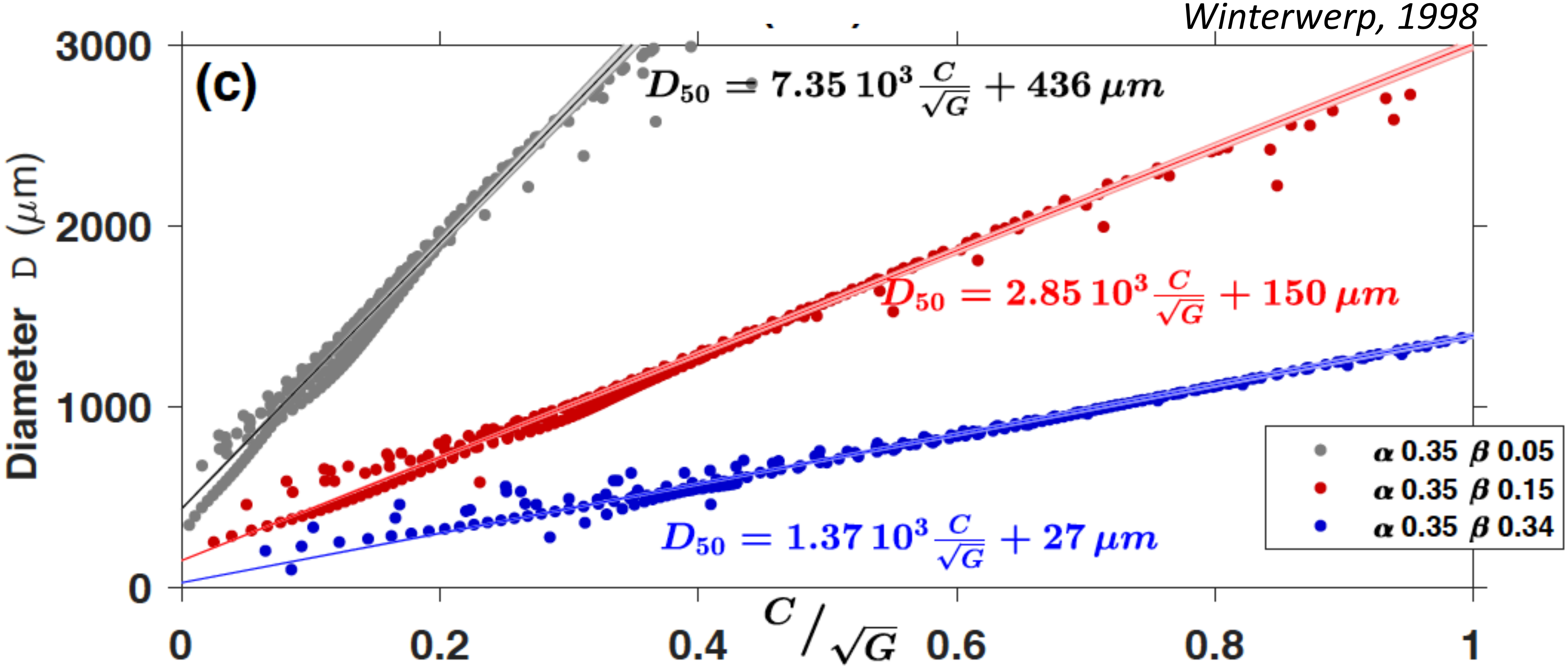

*Tarpley, Harris, Friedrichs and Sherwood, 2019.*

Question: Do floc sizes reach equilibrium in the idealized estuary?

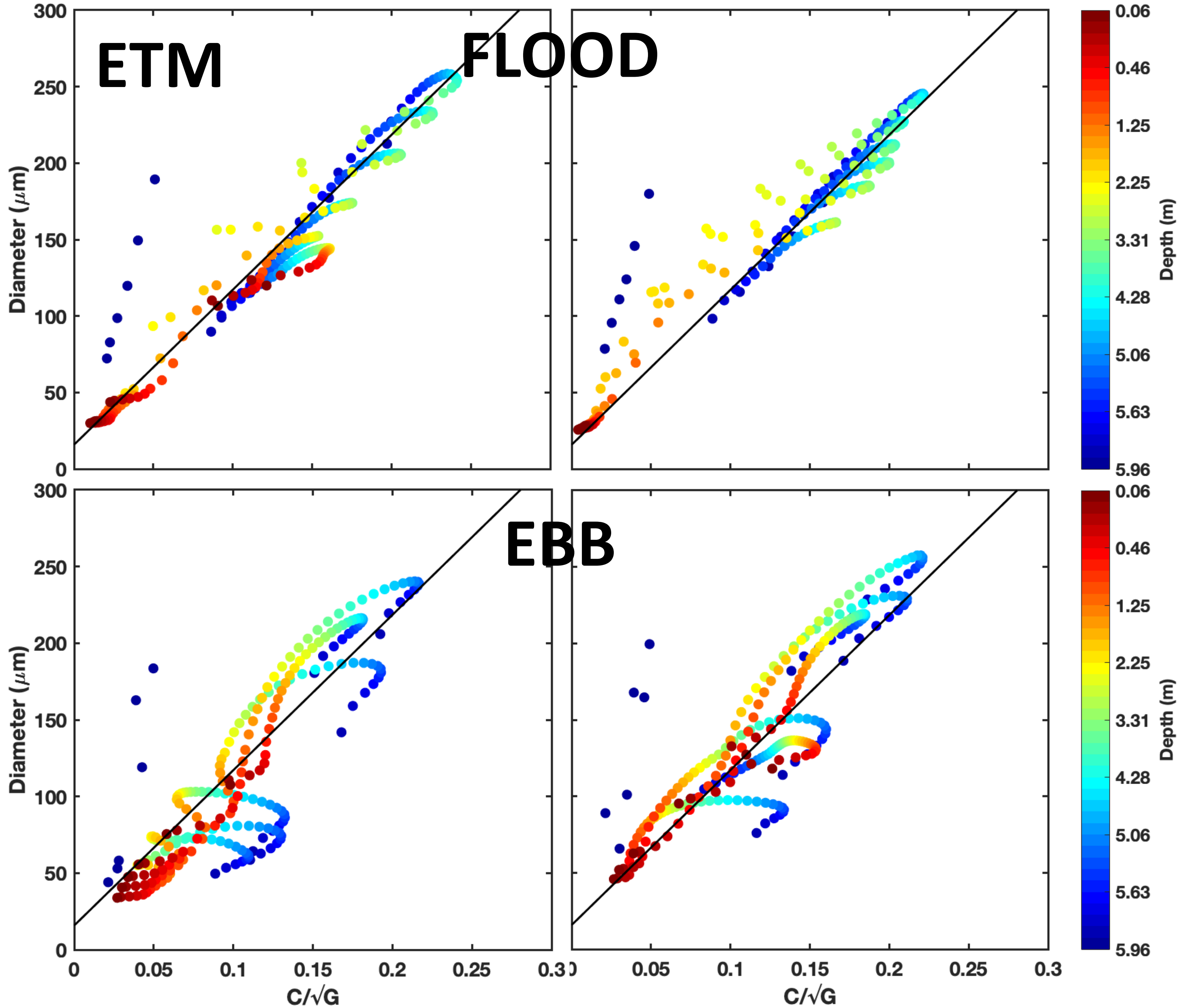
*Answer: Sometimes.*

$$D_e = D_p + \frac{k_A c}{k_b \sqrt{G}}$$

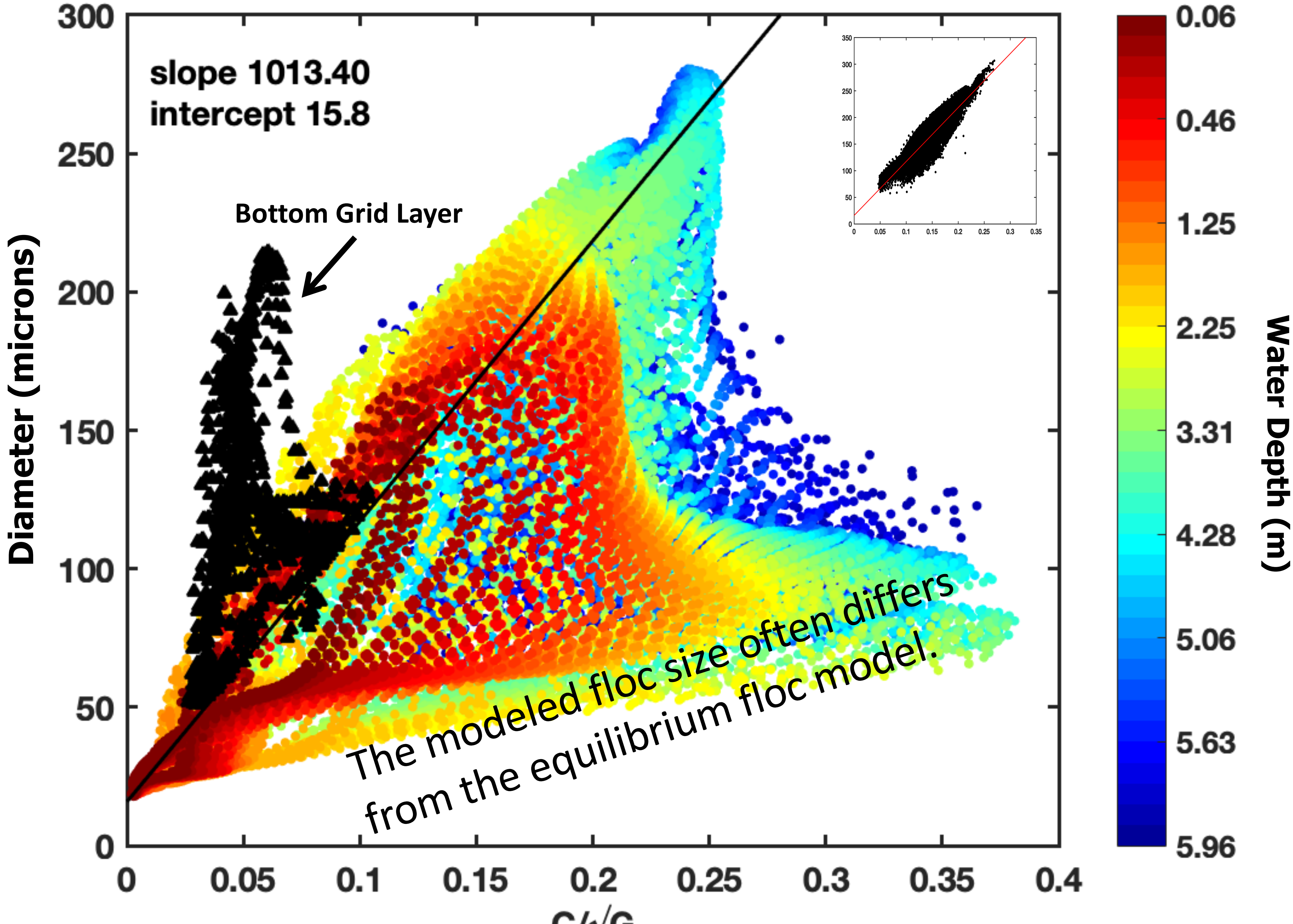
*Winterwerp, 1998*




*Sherwood et al., 2018*

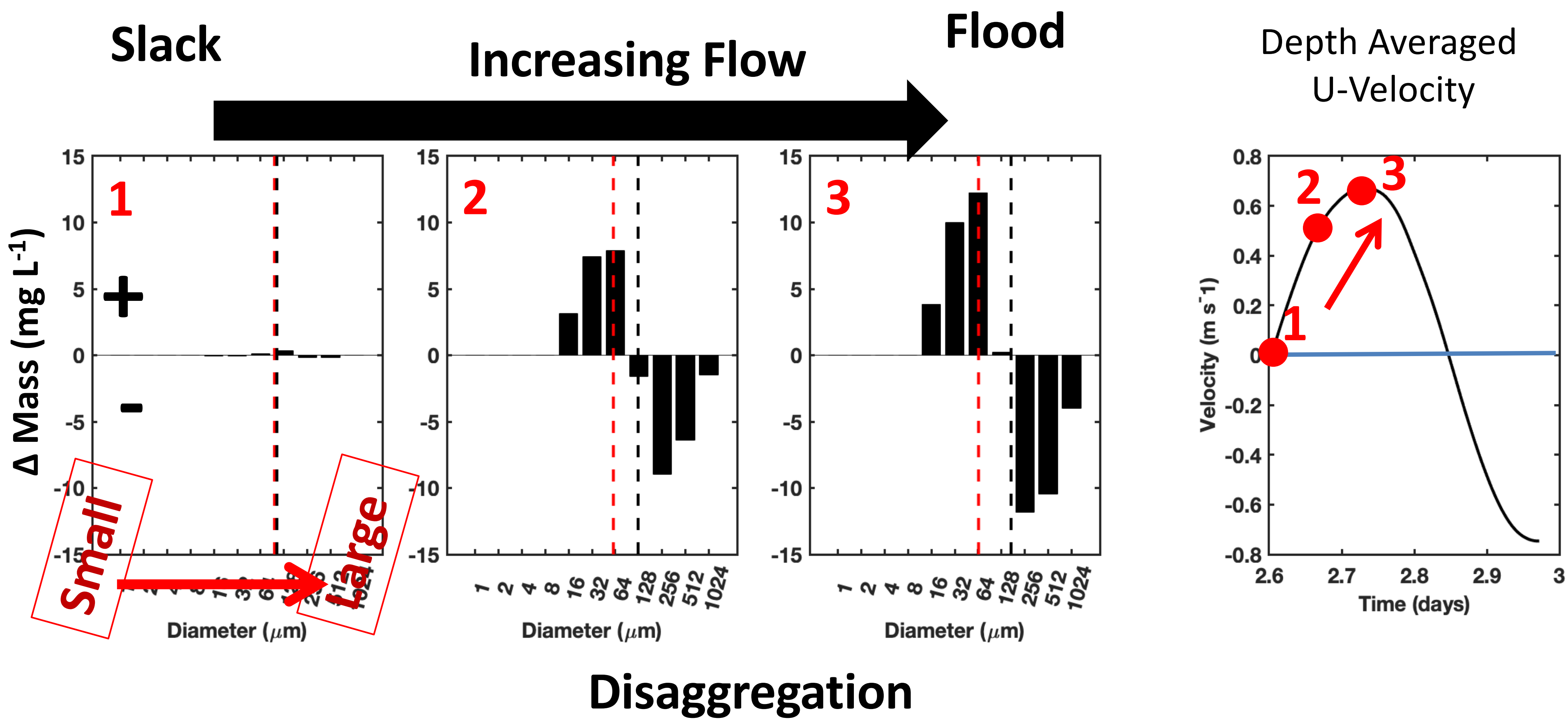


ETM
FLOOD
EBB
Diameter ($\mu$m)
C/√G
Depth (m)
0.06
0.46
1.25
2.25
3.31
4.28
5.06
5.63
5.96
0
50
100
150
200
250
300
0.05
0.1
0.15
0.2
0.25
0.3

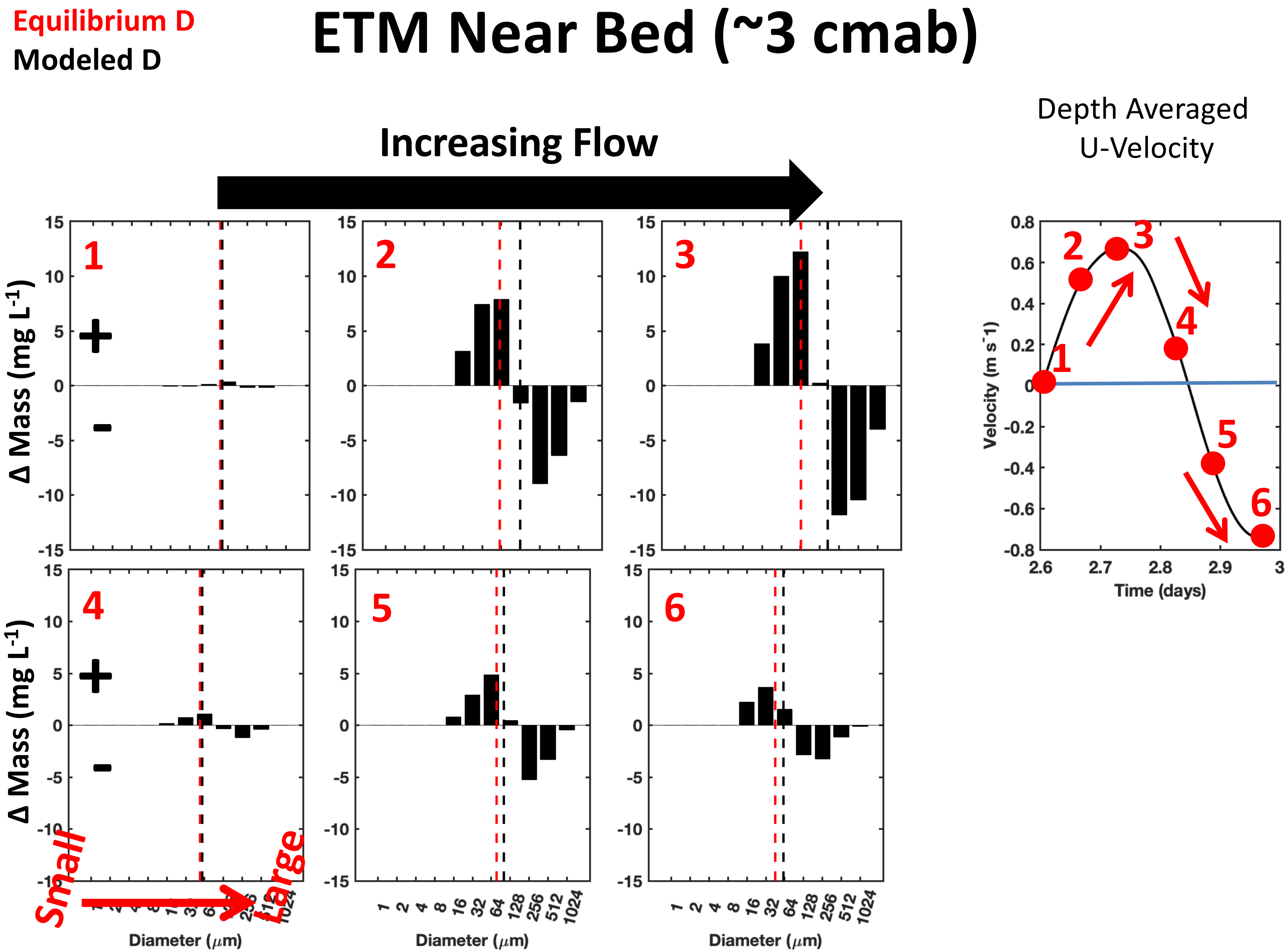

slope 1013.40
intercept 15.8
Bottom Grid Layer
The modeled floc size often differs
from the equilibrium floc model.
Diameter (microns)
0
50
100
150
200
250
300
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
C/√G
Water Depth (m)
0.06
0.46
1.25
2.25
3.31
4.28
5.06
5.63
5.96

Equilibrium D
Modeled D

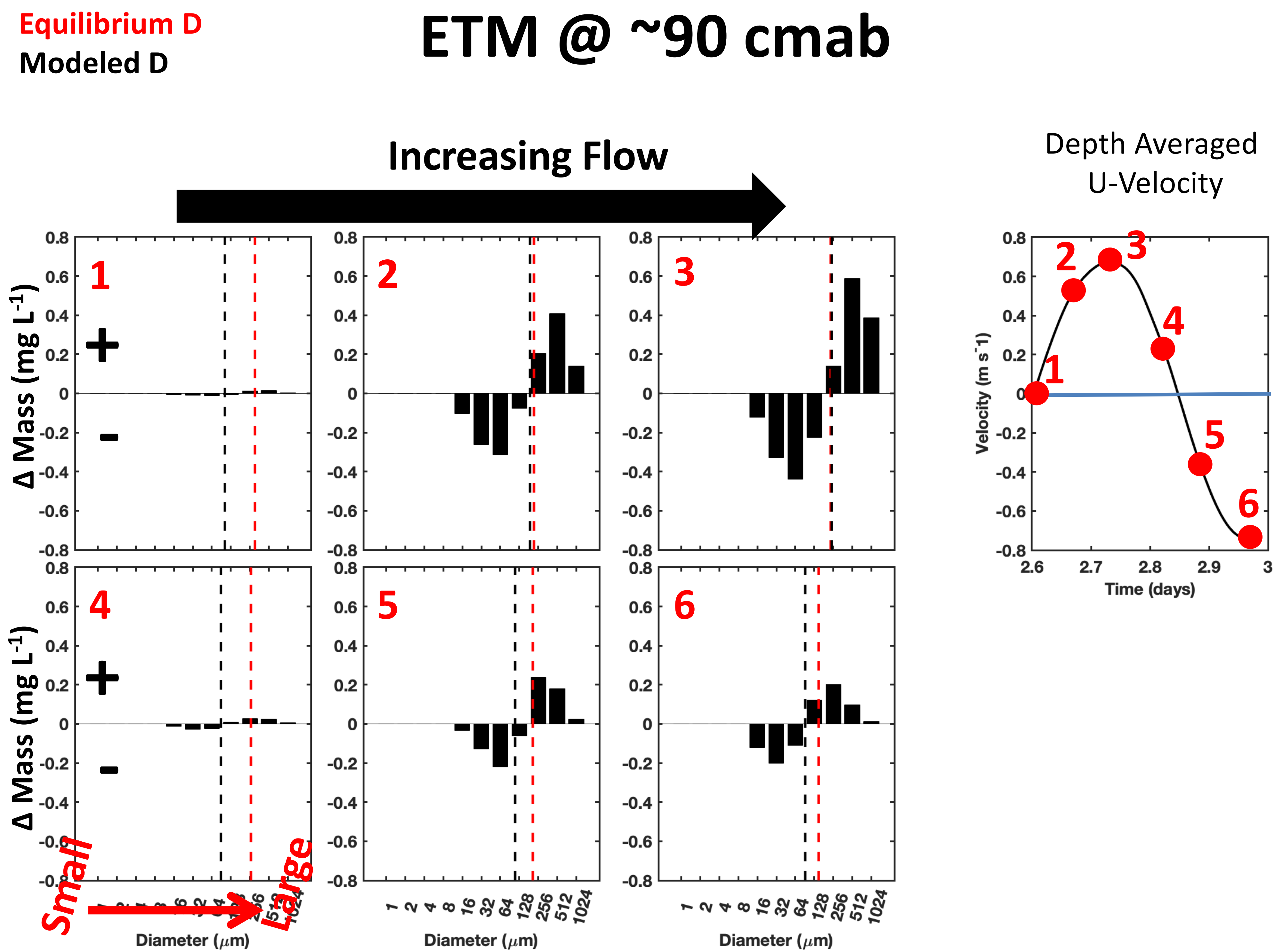
# ETM Near Bed (~3 cmab)



# ETM Near Bed (~3 cmab)



# ETM @ ~90 cmab



Equilibrium D
Modeled D
Increasing Flow
Depth Averaged U-Velocity
1
2
3
4
5
6
Δ Mass (mg L-1)
+
-
Small
Large
Diameter (μm)
1 2 4 8 16 32 64 128 256 512 1024
0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8
Velocity (m s-1)
Time (days)
2.6 2.7 2.8 2.9 3

# Conclusions from Idealized Estuary:

- The idealized estuary model reproduced key features such as estuarine circulation the ETM, and and relied on inclusion of cohesive processes (bed consolidation and flocculation). *(Tarpley et al. 2019)*

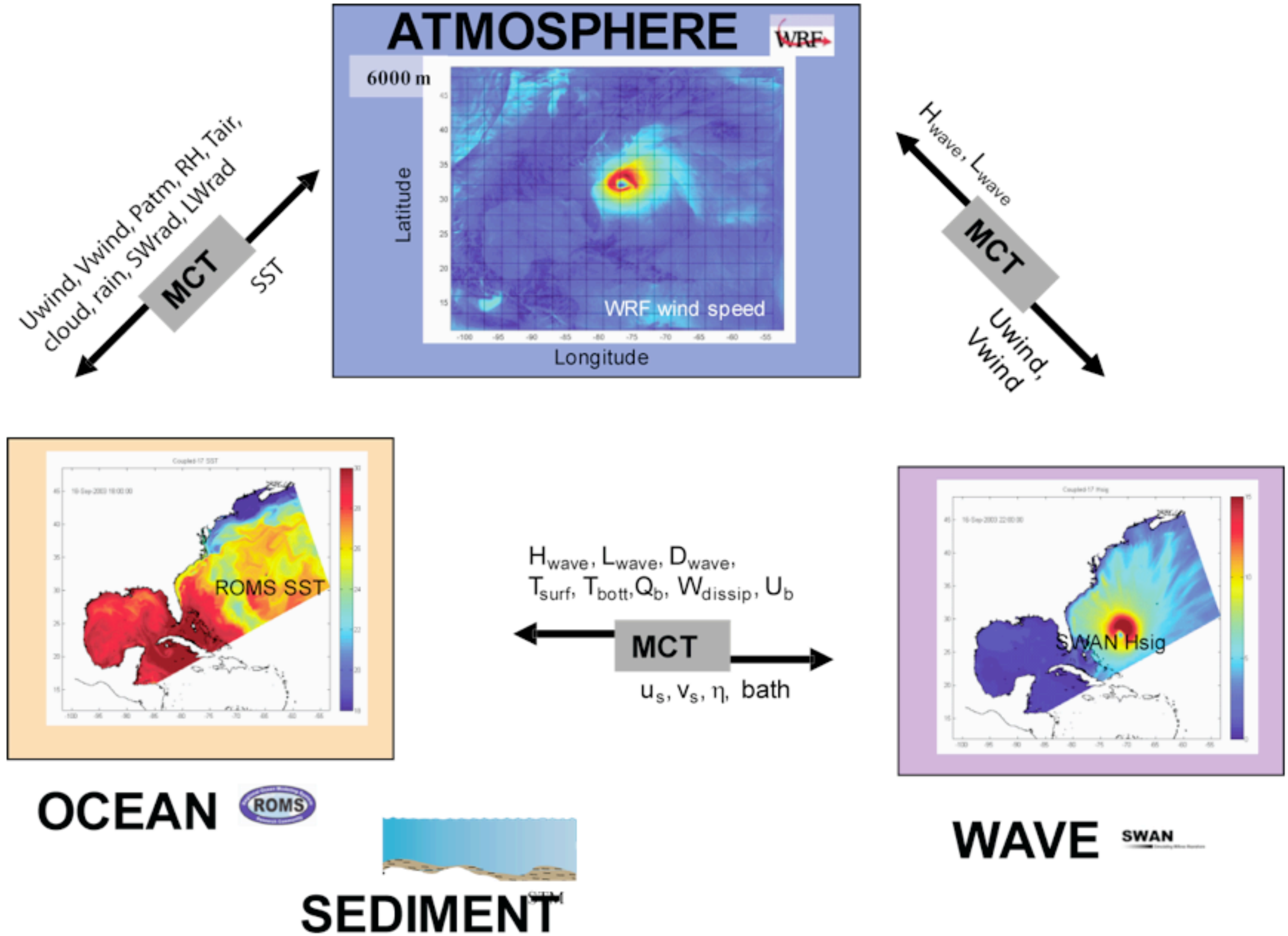
- Flocculation had the largest impact on SSC within the ETM. It reduced the average depth-integrated suspended mass by ~50% there. *(Tarpley et al. 2019)*

- Outside of the ETM, bed consolidation had the largest impact. It decreased the average depth-integrated suspended mass by ~50%. *(Tarpley et al. 2019)*

- Flocculation transferred as much or more sediment mass than horizontal and vertical advection and settling in the ETM.

- The floc model produced floc sizes that were often not equilibrated with the scaling expected by $C/\sqrt{G}$

# COAWST: Model Coupling




from: https://woodshole.er.usgs.gov/operations/modeling/COAWST/