Source to Sink Numerical Modeling of Whole Dispersal Systems

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COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

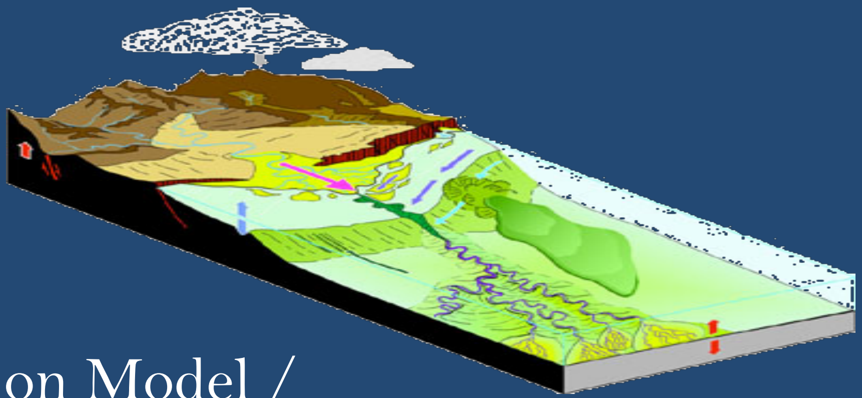
Source to Sink Numerical Modeling

S2S models come in all shapes and sizes, depending on:

i) intended goal,

ii) scale of interest (space and time), and

iii) processes & parameters being simulated



Three approaches are common:

1) LEM/SEM — Landscape Evolution Model / Seascape or Stratigraphic Evolution Model

2) MDM — Morphodynamic Model

3) STM — Sediment Transport Model

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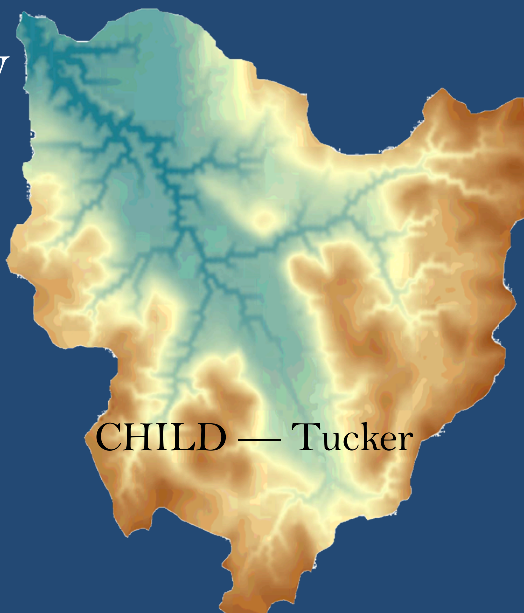
S2S Modeling: 1) Landscape / Seascape Evolution Models LEM/SEM

- ✧ simulate geological time and space scales.
- ✧ incorporate geophysical & geochemical feedbacks: e.g. isostasy, eustasy, faulting, other tectonics, climate change, sea level, post-depositional compaction & cementation.
- ✧ time-integrated fluxes, or event-based, scaled to geology
- ✧ siliciclastic &/or carbonate; abiotic or biotic
- ✧ science domain: geomorphology & stratigraphy
- ✧ time step: ~10^2 - 10^4 y; duration: ~10^4 - 10^7 y
- ✧ pixel size: ~10^2 m - 10^4 m;
- ✧ spatial domain: ~10^5 m - 10^7 m
- ✧ CSDMS LEMs: CHILD, Siberia, Caesar, Erode, GOLEM, MarsSim, WILSim
- ✧ CSDMS SEMs: SedFlux, cyclopath



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LEM generic example

$$\underbrace{\frac{\partial z}{\partial t}}_{1} = -\underbrace{\left(\frac{\sigma_r}{\sigma_s}-1\right)\frac{\partial e}{\partial t}}_{2} - \underbrace{\frac{\partial i_{sx}}{\partial x}}_{3} - \underbrace{\frac{\partial q_{sx}}{\partial x}}_{4} + \underbrace{\frac{\sigma_r}{\sigma_s}U}_{5} - \underbrace{E}_{6} + \underbrace{D}_{7}$$

Climate
5) Tectonics
Lithology
Eruptions
5) Isostasy
Initial Geometry

3) Glacial sediment flux

Melt Runoff PPT Runoff

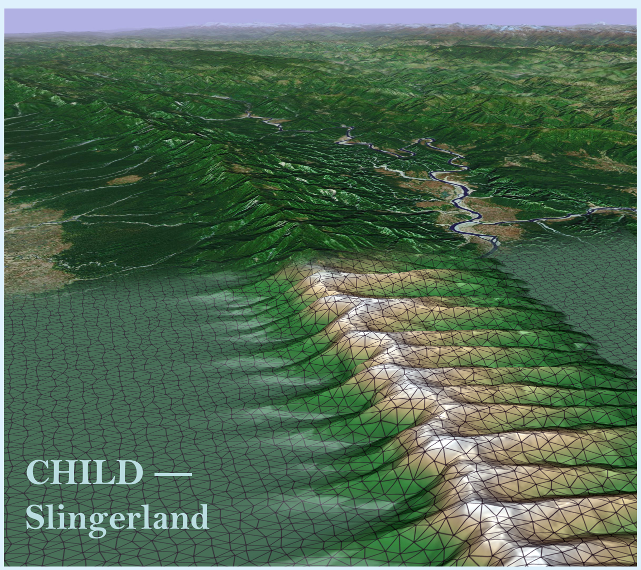
4) Mass Wasting
2) Bedrock Weathering
6) Water Erosion

Slides
Creep

6) Throughput
7) Storage

Washload
Bedload

Output to lowlands



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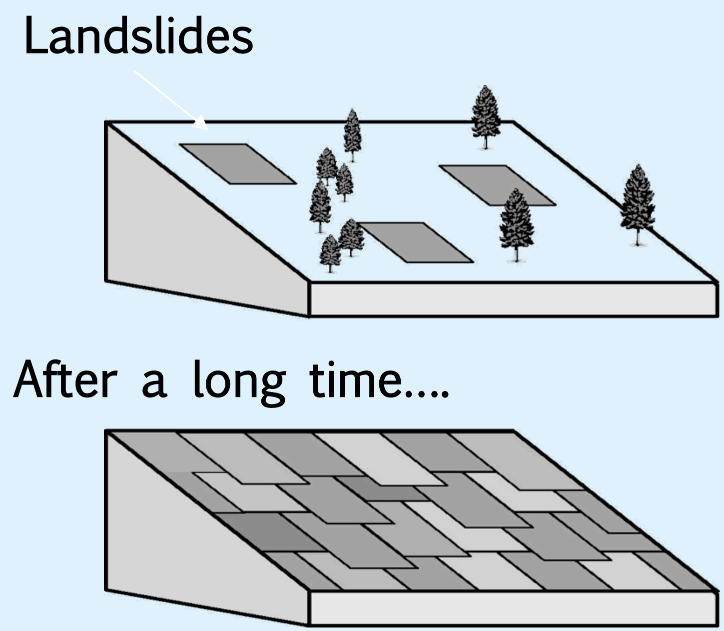
Each LEM term has many forms & options

e.g. (term 4) Mass transport by gravitational processes

$$\underbrace{\frac{\partial z}{\partial t}}_{1} = \underbrace{-(\frac{\sigma_r}{\sigma_s}-1)\frac{\partial e}{\partial t}}_{2} - \underbrace{\frac{\partial i_{sx}}{\partial x}}_{3} - \underbrace{\frac{\partial q_{sx}}{\partial x}}_{4} + \underbrace{\frac{\sigma_r}{\sigma_s}U}_{5} - \underbrace{E}_{6} + \underbrace{D}_{7}$$

$$F = \frac{c' + c + \left[(1-m)\rho_b g d + m\left(\rho_{sat} - \rho\right) g d\right]\cos^2\theta\tan\phi'}{\left[(1-m)\rho_b + m\rho_{sat}\right] g d \sin\theta\cos\theta}$$

$$-\nabla q_s = \left(\underbrace{\frac{K_f S}{1-\left(S/S_c\right)^{\alpha}}}_{slides}\right) - \left[\underbrace{\frac{\partial}{\partial x}\left(-K(z_x,t)\frac{\partial z}{\partial x}\right)}_{creep}\right] + \underbrace{\vartheta}_{other}$$



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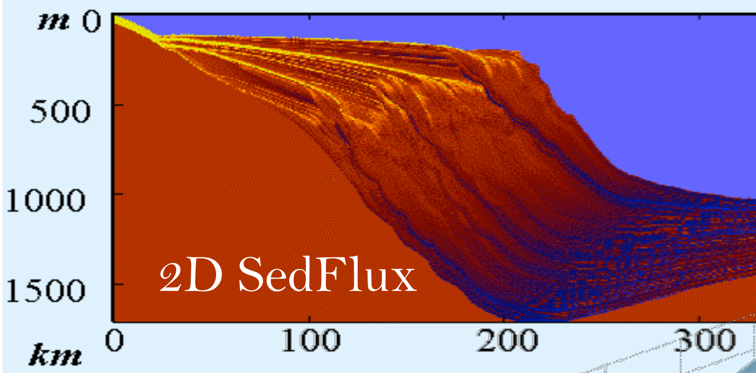
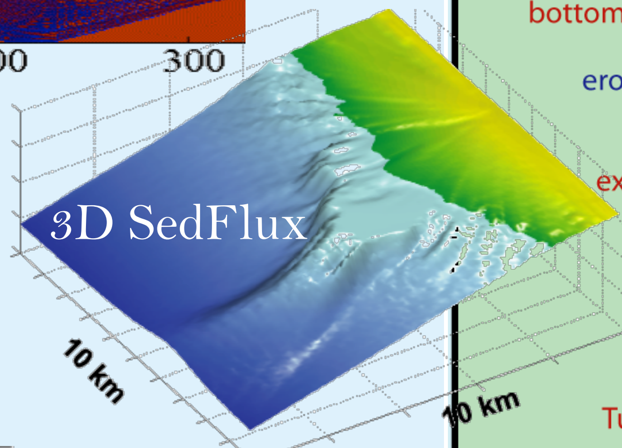


S2S SEM examples:



Delta Models:
distributary channel dynamics, channel hydraulics, bedload dynamics
longshore transport, tidal dynamics

River Plume Models:
hypopycnal plume dynamics, hyperpycnal plume dynamics

Shelf Transport Models:
bottom boundary layer dynamics (wave, current interactions)
fluid muds, upwelling, downwelling

erosion, deposition, seafloor properties, stratigraphy

Geotechnical Models:
compaction, porosity, permeability,
excess pore pressure, plasticity, sediment viscosity

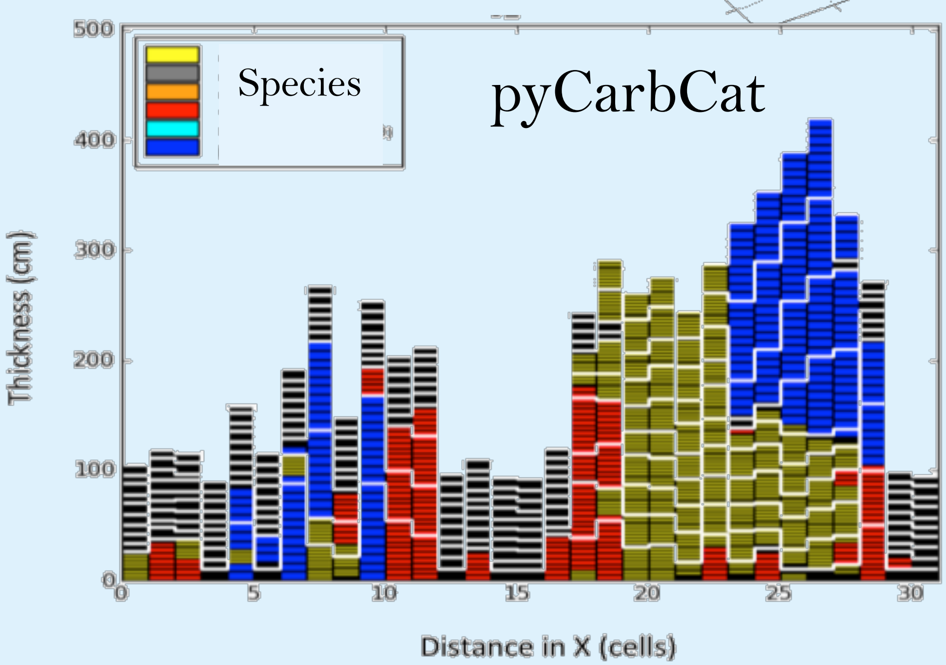
Slope Stability Models:
sediment strength, potential failure planes
earthquake loading, sediment loading

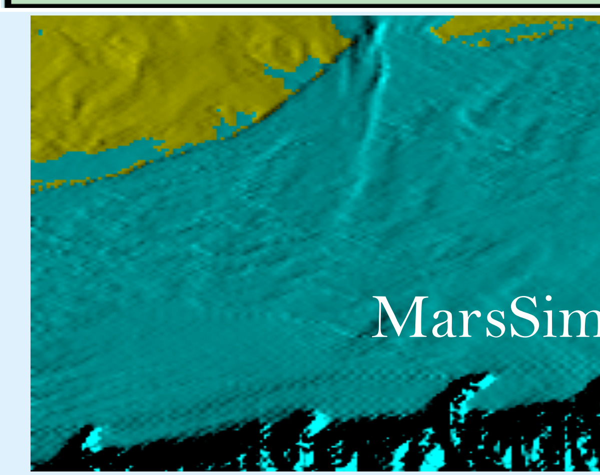
Failure volume and properties

Gravity Flow Models:
Turbidity Current dynamics, Debris flow dynamics

erosion, deposition, seafloor properties, stratigraphy

Geophysical Models:
tectonics (folding, faulting), isostasy, flexural response





Howard
Fagherazzi
Wiberg

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S2S Modeling: 2) Morphodynamic Models MDMs

- ✧ simulate the evolving transport pathway and mobile bed with dynamical feedback to fluid transport processes.
- ✧ may include ecodynamics.
- ✧ Advection-Diffusion Schemes, St. Venant Shallow Water Models, Reynolds-averaged Navier Stokes (RANS) models (few LES)
- ✧ both Newtonian to non-Newtonian fluids.
- ✧ science domains: engineering, hydraulics, sedimentology
- ✧ time step: ~10^1 - 10^4 s;
- ✧ duration: ~10^5 - 10^8 s
- ✧ pixel size: ~10^1 - 10^3 m;
- ✧ spatial domain: ~10^3 - 10^6 m
- ✧ CSDMS MDMs e.g.: MIDAS, CEM, Xbeach, SedFlux, Sakura, Hyper, Bing, & soon Delft3D, e-Parker

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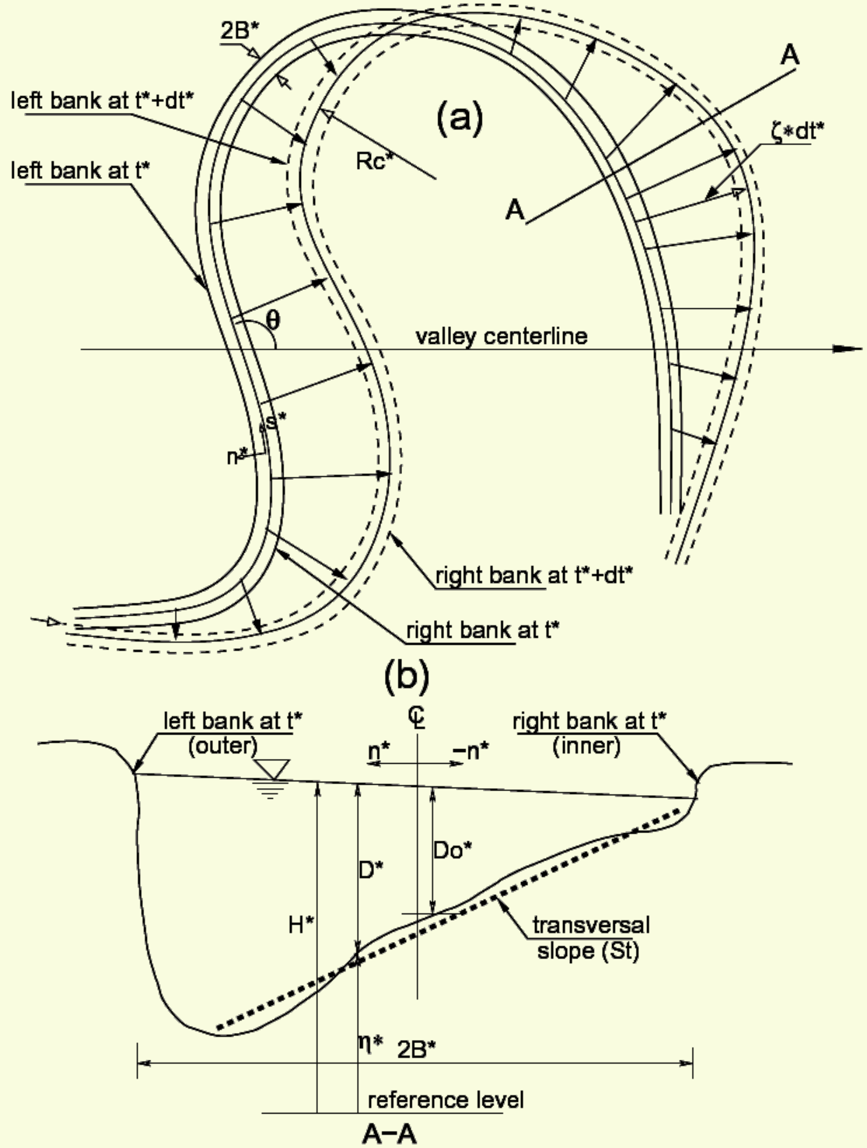
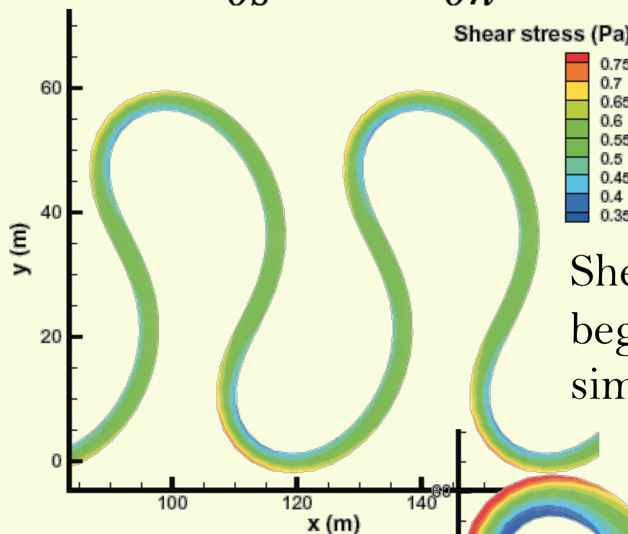
MDM Example: River meanders



$$U\frac{\partial U}{\partial s} + V\frac{\partial U}{\partial n} + \frac{\partial H}{\partial s} + \frac{\beta \tau_s}{D} = \nu_0 f_{11}$$

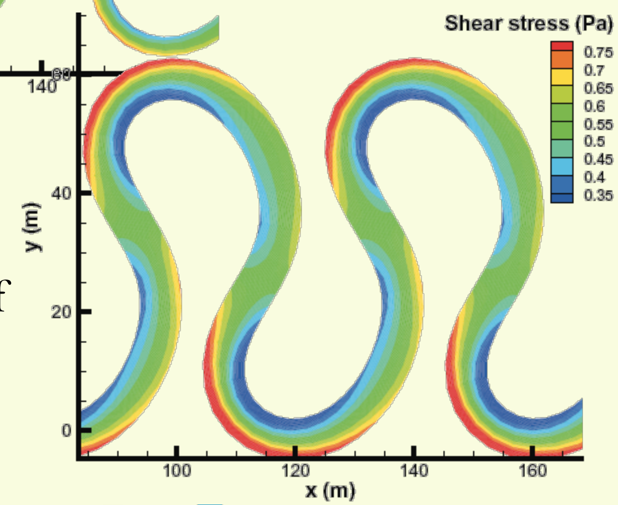
$$U\frac{\partial V}{\partial s} + V\frac{\partial V}{\partial n} + \frac{\partial H}{\partial n} + \beta\frac{\tau_n}{D} = \nu_0 g_{11}$$

$$\frac{\partial (DU)}{\partial s} + \frac{\partial (DV)}{\partial n} = \nu_0 m_{11}$$



after Motta et al., 2009

Shear stresses at beginning of simulation



Shear stresses after 4 years of simulation

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BING: Lagrangian depth-averaged debris flow MDM model

Continuity

$$\underbrace{\frac{\partial h}{\partial t}}_{(a)} + \underbrace{\frac{\partial}{\partial x}\left[U_p h_p + \frac{2}{3}U_p h_s\right]}_{(b)} = 0$$

Flow height (1a) inversely proportional to velocity (1b).

Momentum (shear (s) layer)

$$\underbrace{\frac{2}{3}\frac{\partial}{\partial t}\left(U_p h_s\right) - U_p\frac{\partial h_s}{\partial t} + \frac{8}{15}\frac{\partial}{\partial x}\left(U_p^2 h_s\right) - \frac{2}{3}U_p\frac{\partial}{\partial x}\left(U_p h_s\right)}_{(a)} =$$

$$\underbrace{h_s g\left(1-\frac{\rho_w}{\rho_m}\right)S}_{(b)} - \underbrace{h_s g\left(1-\frac{\rho_w}{\rho_m}\right)\frac{\partial h}{\partial x}}_{(c)} - \underbrace{2\left(\frac{\mu_m U_p}{\rho_m h_s}\right)}_{(d)}$$

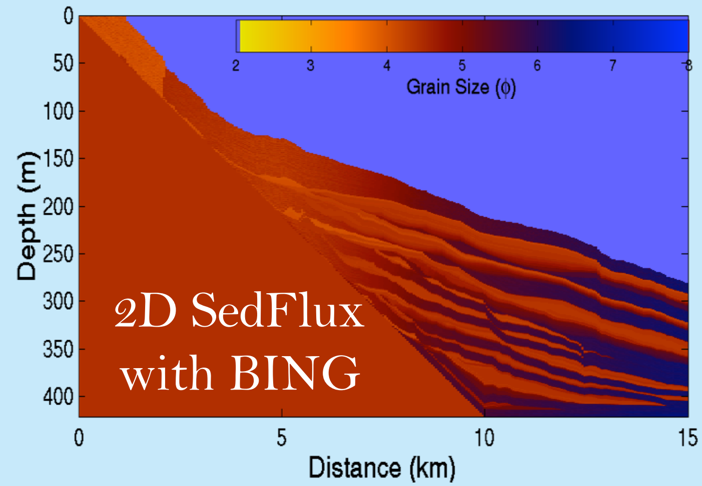
Momentum (a) balanced by flow mass scaled by seafloor slope (b); fluid pressure forces produced by flow height (c); and friction (d).

Momentum (plug flow (p) layer)

$$\underbrace{\frac{\partial}{\partial t}\left(U_p h_p\right) + \frac{\partial}{\partial x}\left(U_p^2 h_p\right) + U_p\frac{\partial h_s}{\partial t} + \frac{2}{3}U_p\frac{\partial}{\partial x}\left(U_p h_s\right)}_{(a)} =$$

$$\underbrace{h_p g\frac{\partial}{\partial x}\left(1-\frac{\rho_w}{\rho_m}\right)S}_{(b)} - \underbrace{h_p g\left(1-\frac{\rho_w}{\rho_m}\right)\frac{\partial h}{\partial x}}_{(c)} - \underbrace{\frac{\tau_m}{\rho_w}}_{(d)}$$

h=height; U=layer-averaged velocity; g=gravity; S=slope; ρ_w=ocean density; ρ_m=flow density; τ_m= yield strength, and μ_m=kinematic viscosity.



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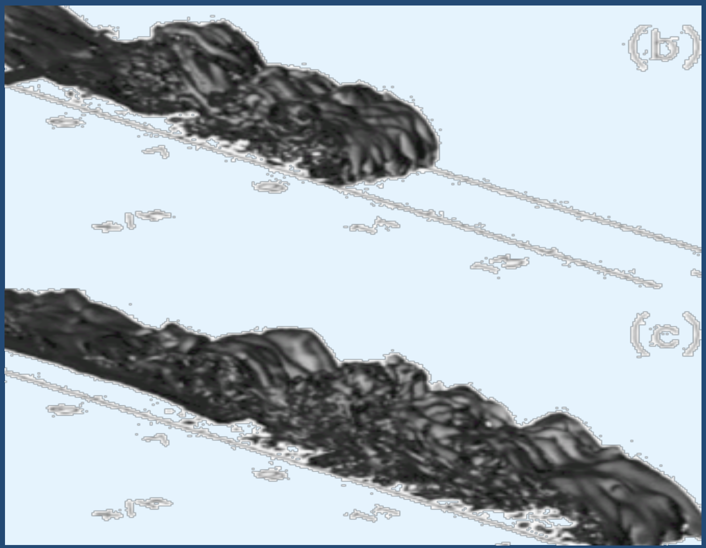
S2S Modeling: 3) Sediment Transport Models STMs



- ✧ material fluxes along a pathway.
- ✧ may cover multiple domains,
  e.g. river floods and ocean storms.
- ✧ computational fluid dynamics include
  Reynolds-averaged NS simulators,
  Large-Eddy Simulators,
  Direct Numerical Simulators,
  Boussinesq & non-hydrostatic approximations.
- ✧ science domains: oceanography, hydrology, sedimentology
- ✧time step: ~1 - 10^4 s; duration: ~10^5 - 10^8 s
- ✧ pixel size: ~10^1 - 10^5 m; spatial domain: ~10^6 m - 10^{10} m
- ✧ CSDMS STMs e.g.: WBM-BQART, TopoFlow-Psi,
  HydroTrend, QUAL2K, OTEQ, OTIS, SPARROW, GNE,
  HSPF, LOADEST, RHESSys, SWAT, ROMS, ADCIRC

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STM e.g. ROMS

$$\frac{\partial(H_z u)}{\partial t} + \frac{\partial(uH_z u)}{\partial x} + \frac{\partial(vH_z u)}{\partial y} + \frac{\partial(\Omega H_z u)}{\partial s} - f$$
$$H_z v = -\frac{H_z}{\rho_0}\frac{\partial p}{\partial x} - H_z g \frac{\partial \eta}{\partial x} - \frac{\partial}{\partial s}\left(\overline{u'w'} - \frac{\nu}{H_z}\frac{\partial u}{\partial s}\right)$$
$$-\frac{\partial(H_z S_{xx})}{\partial x} - \frac{\partial(H_z S_{xy})}{\partial y} + \frac{\partial S_{px}}{\partial s} \quad (1)$$

$$\frac{\partial(H_z v)}{\partial t} + \frac{\partial(uH_z v)}{\partial x} + \frac{\partial(vH_z v)}{\partial y} + \frac{\partial(\Omega H_z v)}{\partial s} + f$$
$$H_z u = -\frac{H_z}{\rho_0}\frac{\partial p}{\partial y} - H_z g \frac{\partial \eta}{\partial y} - \frac{\partial}{\partial s}\left(\overline{v'w'} - \frac{\nu}{H_z}\frac{\partial v}{\partial s}\right)$$
$$-\frac{\partial(H_z S_{yx})}{\partial x} - \frac{\partial(H_z S_{yy})}{\partial y} + \frac{\partial S_{py}}{\partial s} \quad (2)$$

$$\overline{u'w'} = -K_M \frac{\partial u}{\partial z}, \quad \overline{v'w'} = -K_M \frac{\partial v}{\partial z},$$
$$\overline{\rho' w'} = -K_H \frac{\partial \rho}{\partial z}$$

$$S_{xx} = kE\left[\frac{k_x k_x}{k^2} F_{CS}F_{CC} + F_{CS}F_{CC} - F_{SS}F_{CS}\right] + \frac{k_x k_x}{k}\frac{c^2}{L} A_R R_z$$
$$S_{xy} = S_{yx} = kE\left[\frac{k_x k_y}{k^2} F_{CS}F_{CC}\right] + \frac{k_x k_y}{k}\frac{c^2}{L} A_R R_z$$
$$S_{yy} = kE\left[\frac{k_y k_y}{k^2} F_{CS}F_{CC} + F_{CS}F_{CC} - F_{SS}F_{CS}\right] + \frac{k_y k_y}{k}\frac{c^2}{L} A_R R_z \quad (7)$$

$$0 = -\frac{1}{\rho_0}\frac{\partial p}{\partial s} - \frac{g}{\rho_0} H_z \rho \quad (3)$$

with continuity as

$$\frac{\partial \eta}{\partial t} + \frac{\partial(H_z u)}{\partial x} + \frac{\partial(H_z v)}{\partial y} + \frac{\partial(H_z \Omega)}{\partial s} = 0 \quad (4)$$

and scalar transport:

$$\frac{\partial(H_z C)}{\partial t} + \frac{\partial(uH_z C)}{\partial x} + \frac{\partial(vH_z C)}{\partial y} + \frac{\partial(\Omega H_z C)}{\partial s}$$
$$= -\frac{\partial}{\partial s}\left(\overline{c'w'} - \frac{\nu_\theta}{H_z}\frac{\partial C}{\partial s}\right) + C_{source} \quad (5)$$
$$C_{source,m} = -\frac{\partial w_{s,m} C_m}{\partial s} + E_{s,m}$$
$$E_{s,m} = E_{0,m}(1-\phi)\frac{\tau_{sf} - \tau_{ce,m}}{\tau_{ce,m}}, \quad \text{when } \tau_{sf} > \tau_{ce,m}$$

SWAN (wave action density)

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_w}{\sigma}$$

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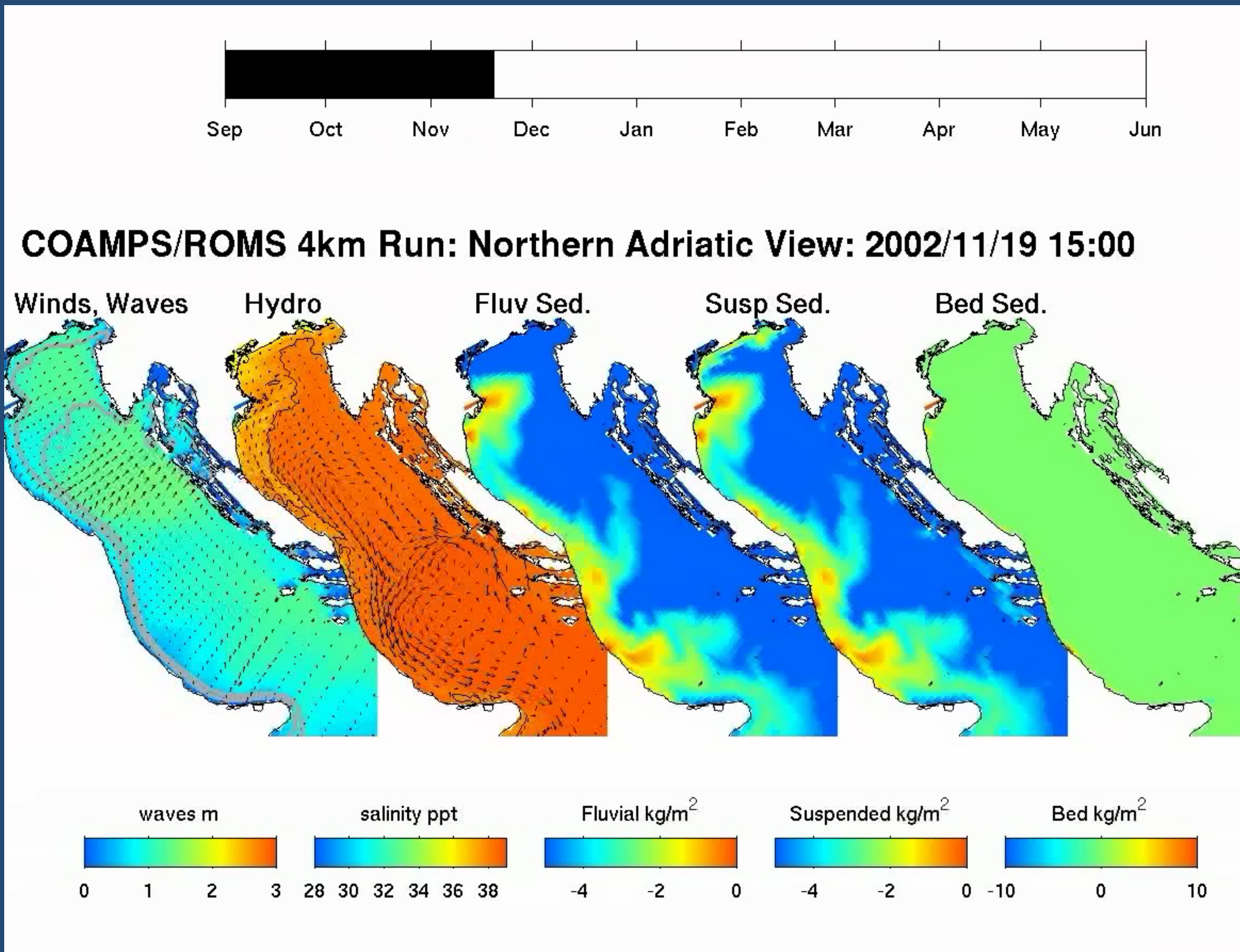
STM model nesting



Application of multiple model nesting, including HydroTrend, ROMS, SWAN, COAMPS, NOGAPS, CSTMS.

Duration 1 year

C. Sherwood & R Signell

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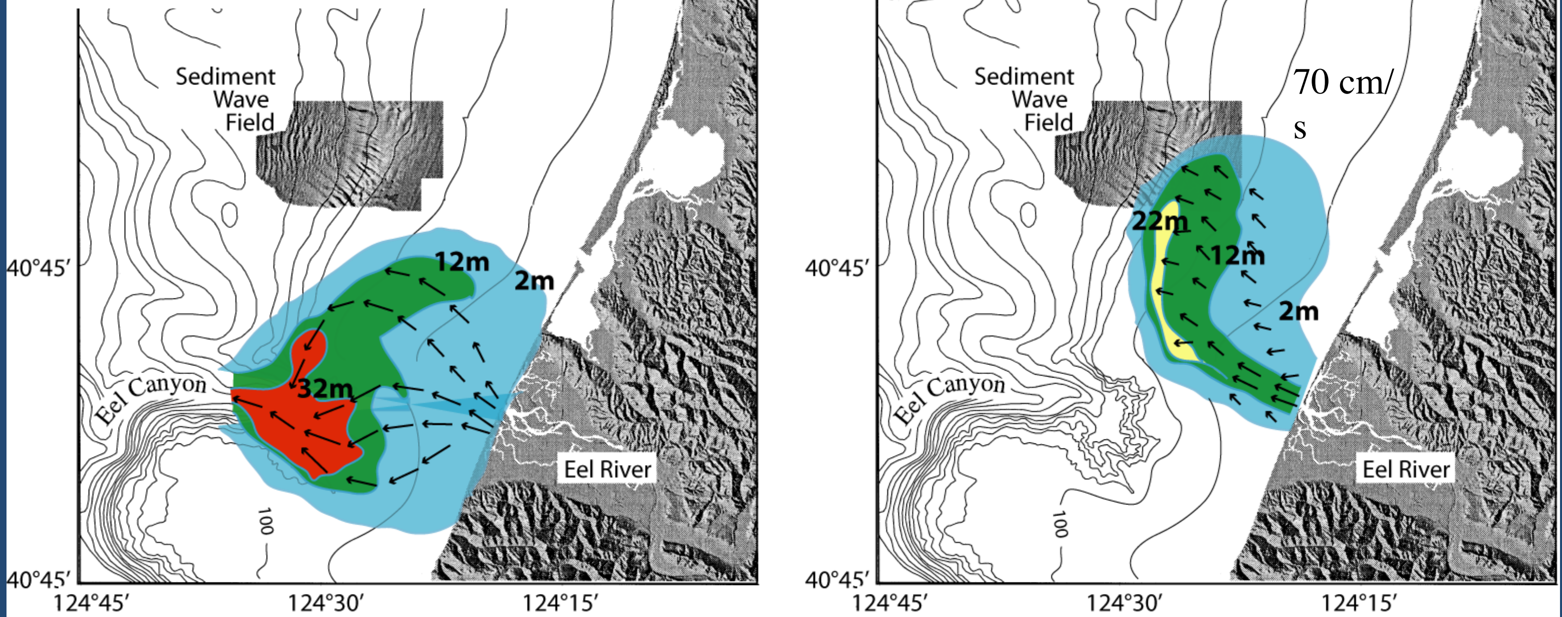
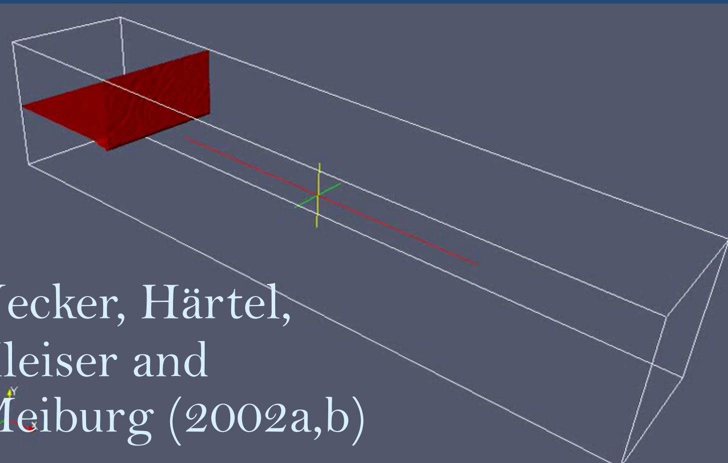
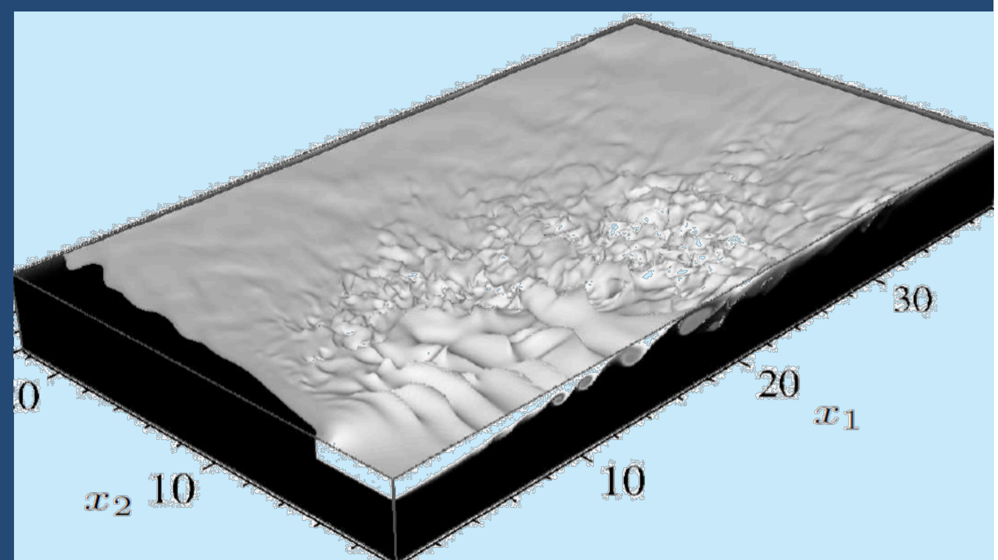
Imran & Syvitski, 2000, Oceanography





Necker, Härtel, Kleiser and Meiburg (2002a,b)



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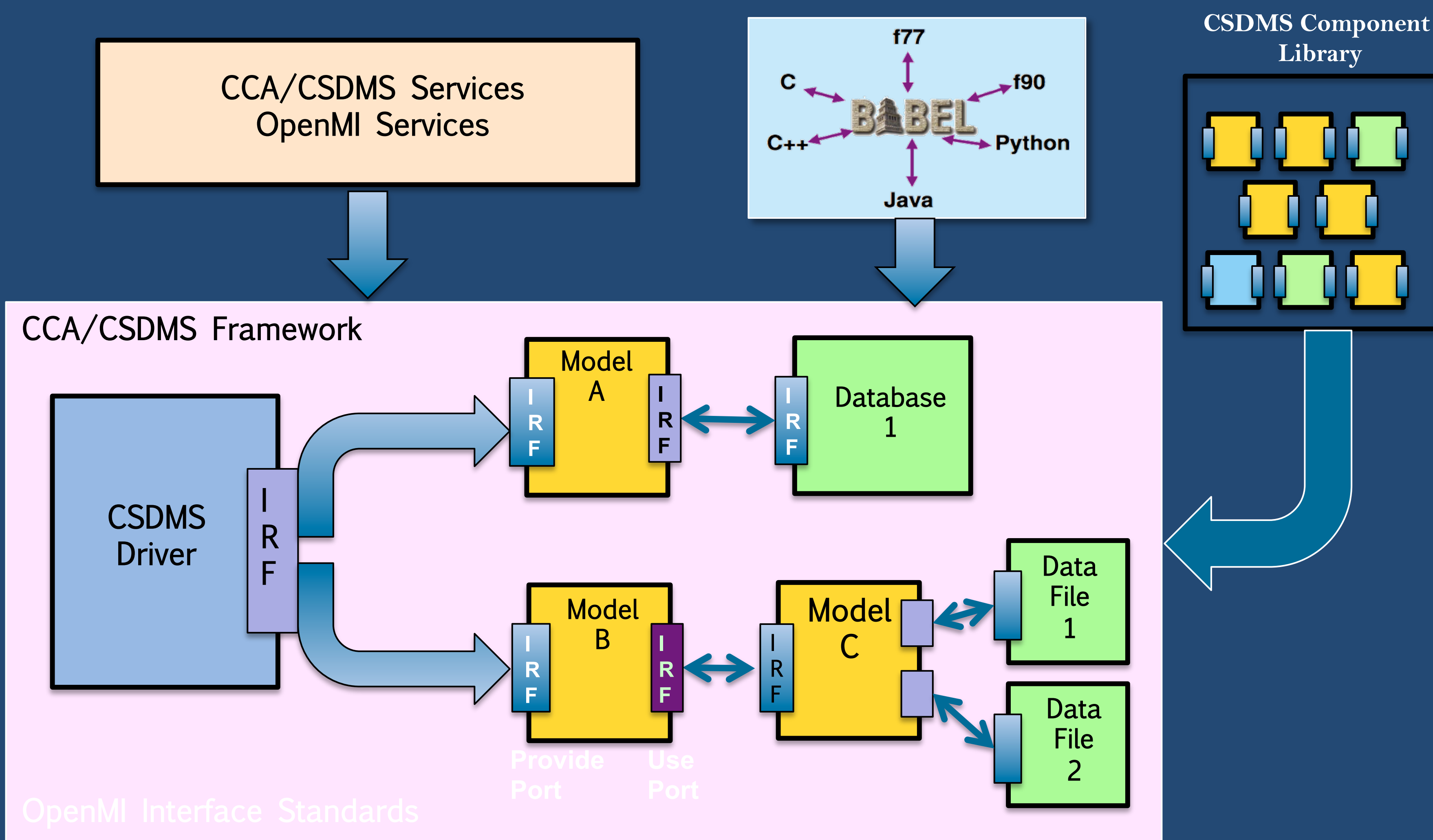
The CSDMS Modeling Tool, CMT, allows S2S components to be linked to similar open-source components, with due consideration of appropriate time & space resolution and process requirements.



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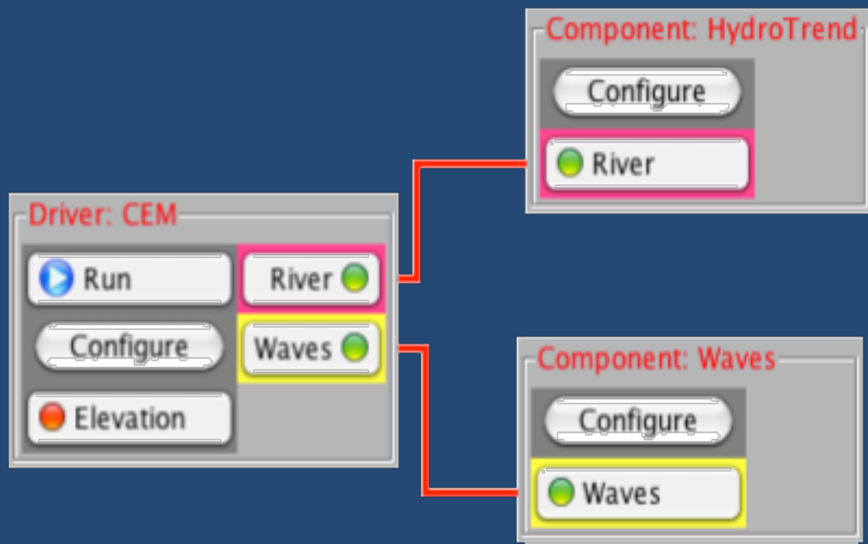

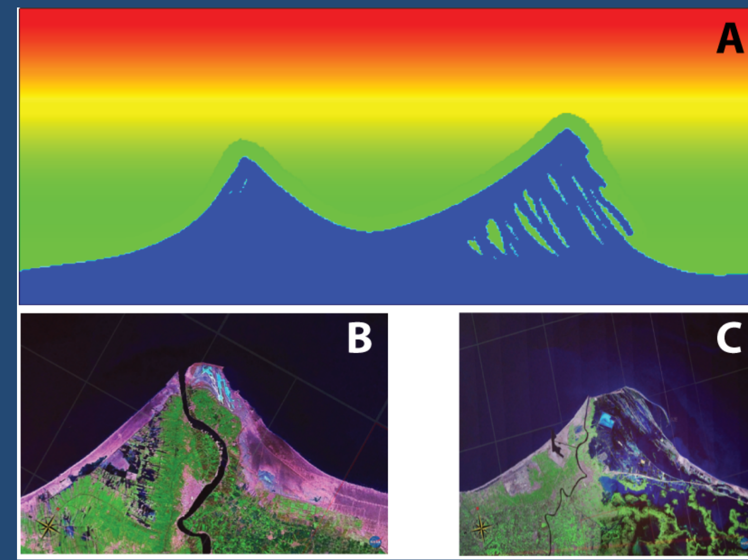

CSDMS CMT S2S Coupling

1) LEM/SEM: CHILD + SedFlux
2) STM + MDM: HydroTrend + CEM + Waves
3) STM: GC2D + TopoFlow; HydroTrend + ROMS;
   WBM + BQART/PSI
4) STM + SEM: HydroTrend + SedFlux

CSDMS models mostly used in stand alone mode, ie >8000 downloads
49 of 164 CSDMS models are now CMT components
S2S coupled examples are being developed annually

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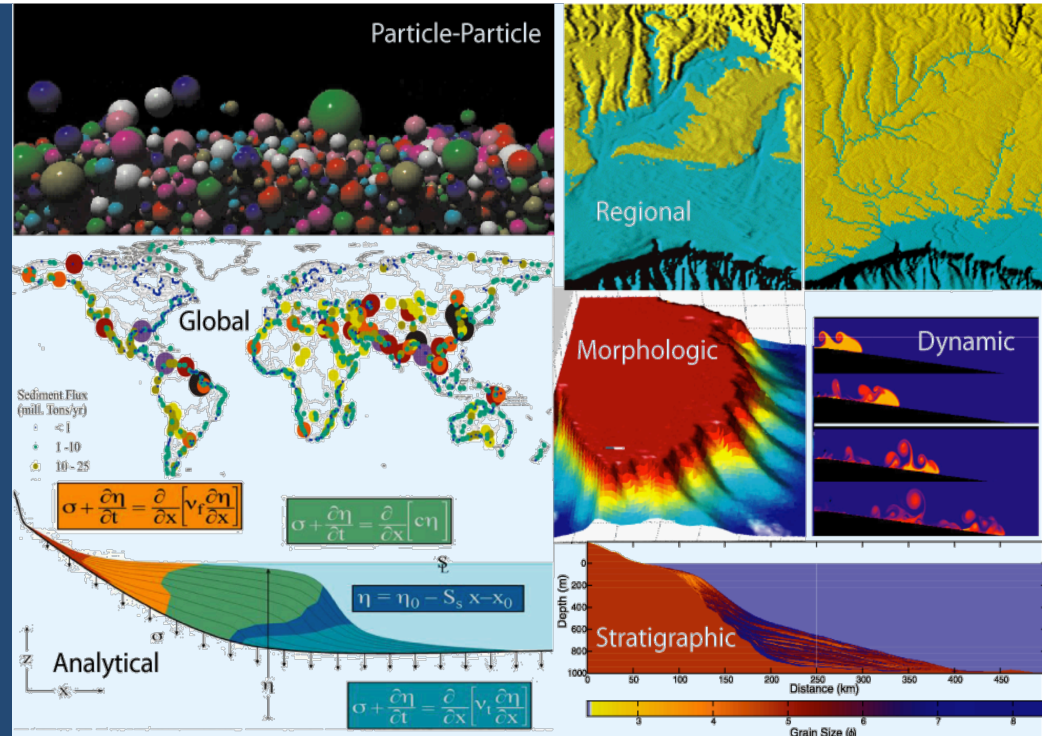
Summary of S2S Modeling

- Complete S2S modeling has a distance to go
- LEM/SEM coupling has great potential with CHILD to SedFlux being the first 'type' example, but many components are missing



- MDM model coupling is in its infancy and the next decade will see examples limited to couplings of 2 or 3 environments
- STM model coupling also has great potential as global earth-system modeling develops. These models however will never offer stratigraphy or geomorphology. Geodynamics will be missing, but the models offer important linkages to geochemistry, and ecosystem dynamics

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