Sediment dynamics in an energetic estuary

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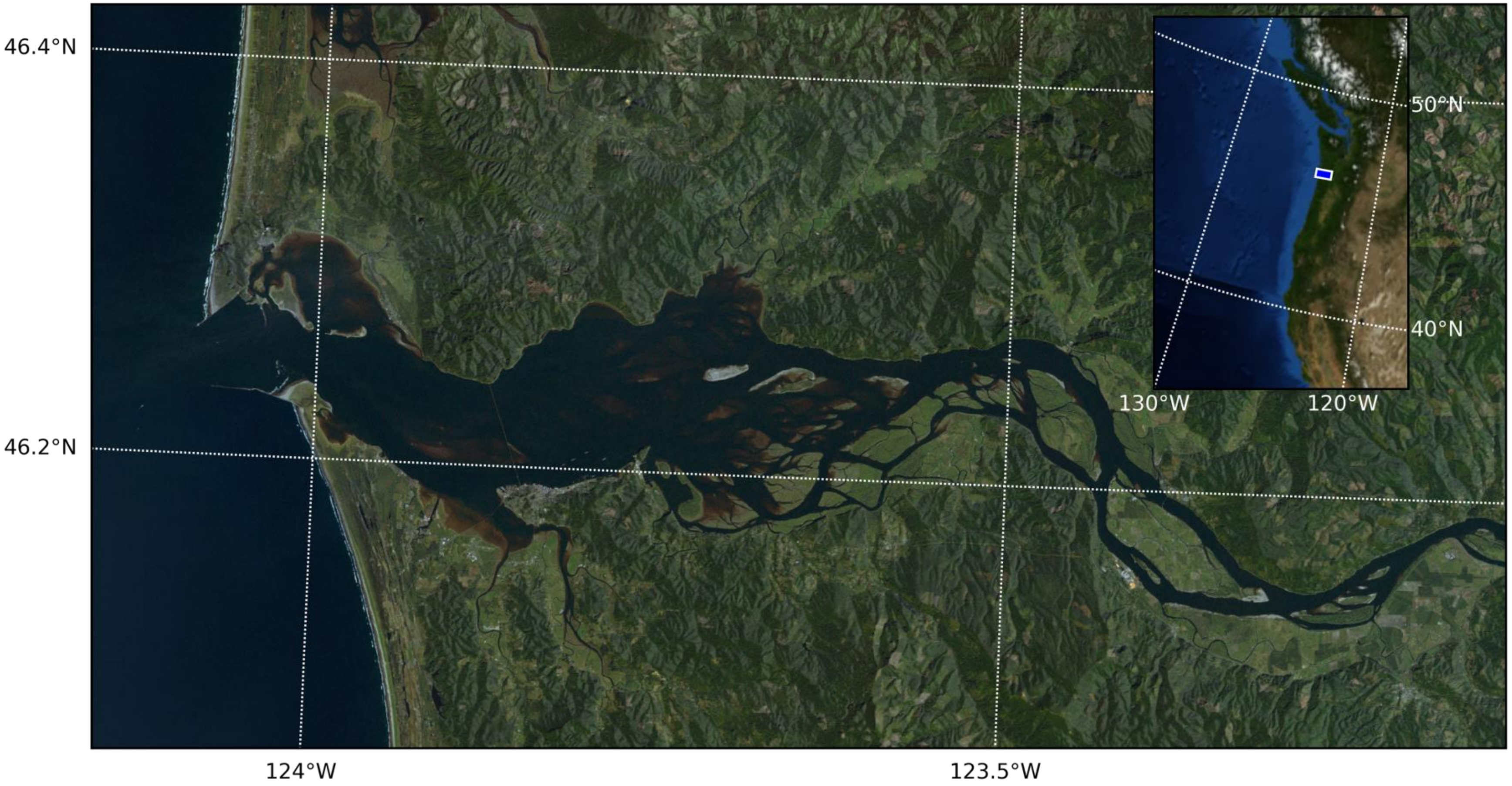
The Columbia River Estuary



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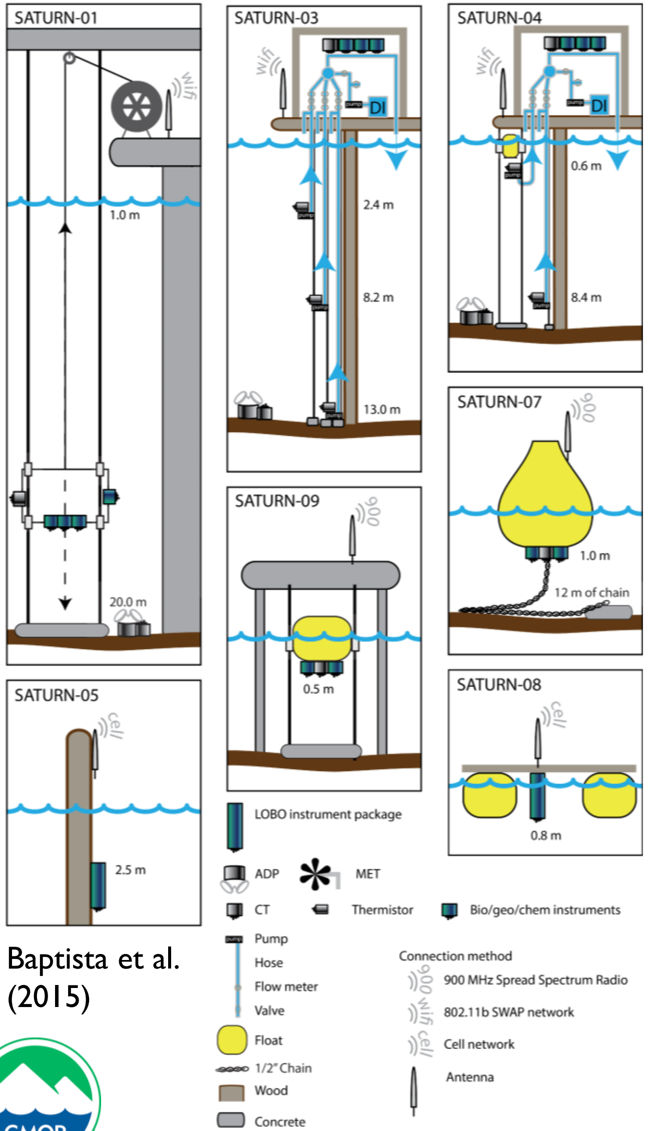
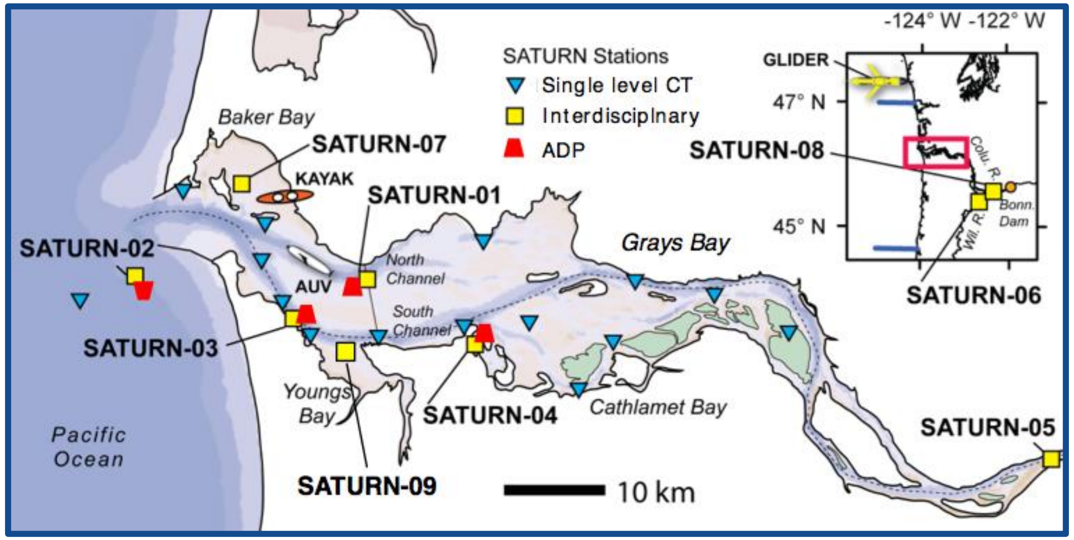
SATURN Observatory – Characterizing variability

Sensor network



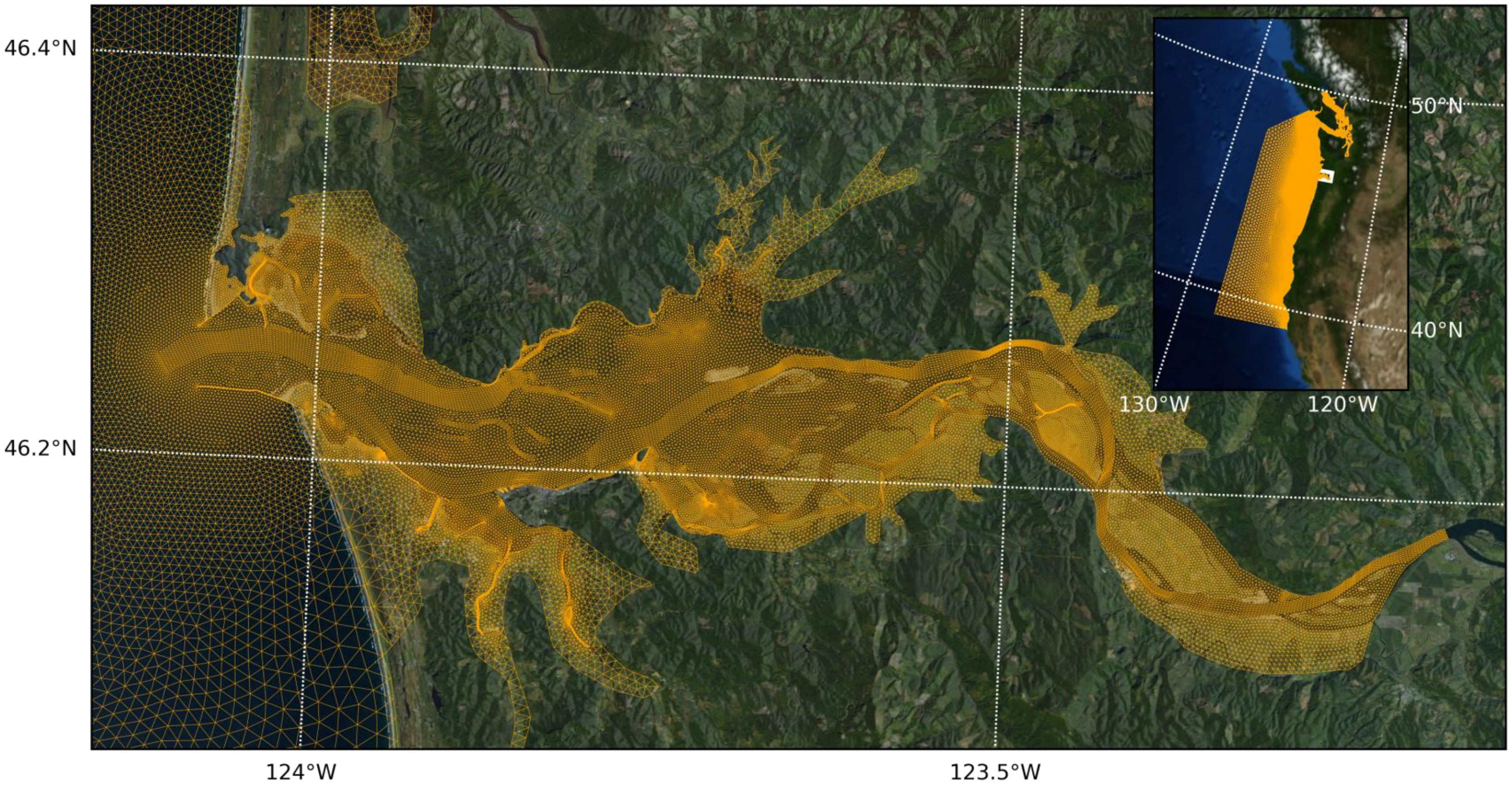
Baptista et al. (2015)



Physical	Surface elevation, velocity, temperature, salinity, river discharge, winds
Biogeochemical	CDOM, chlorophyll, nitrate, pCO2, phycoerytherin, oxygen

Mobile platforms

SELFE Columbia River model

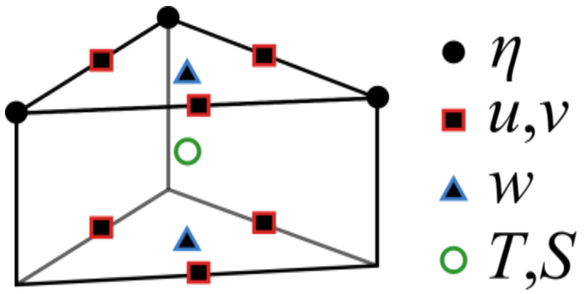


- Solve for hydrodynamics + sediment dynamics
  - Biological and biogeochemical modules available
- Large domain to capture important processes in river-to-ocean continuum
- Realistic forcings for atmospheric and boundary conditions

SELFE modeling system

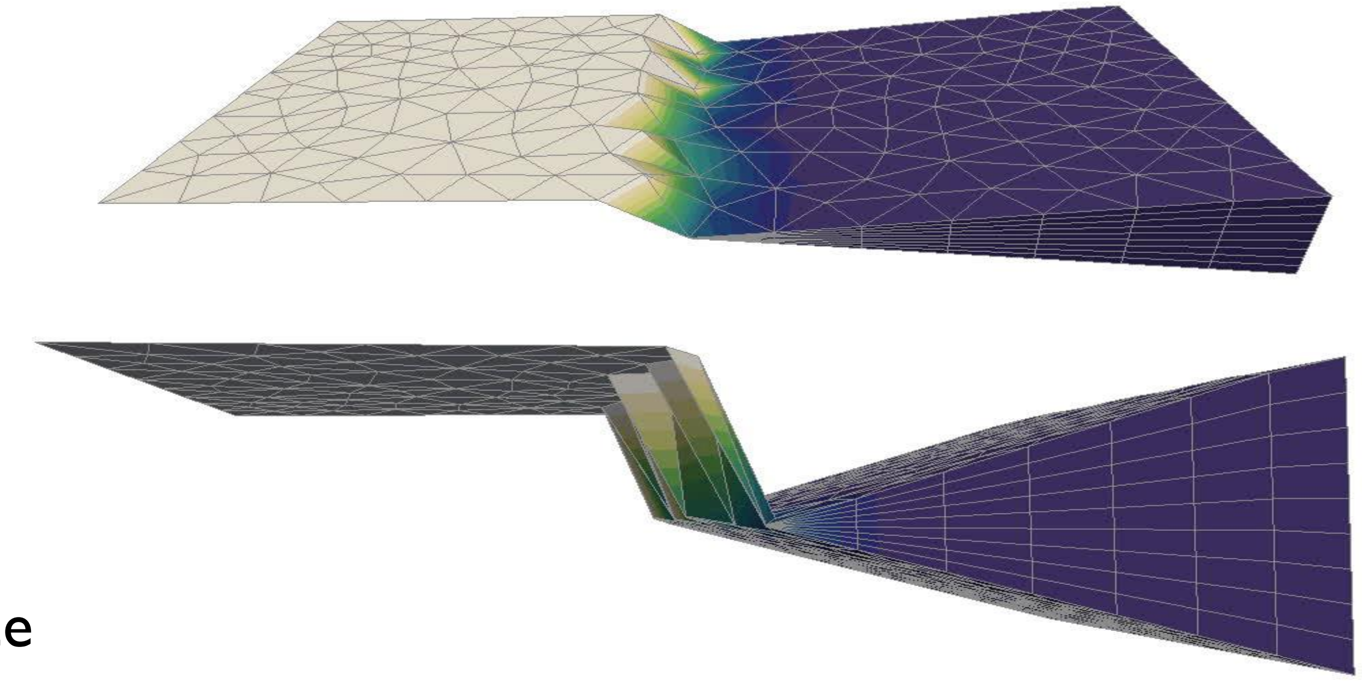
Semi-implicit Eulerian-Lagrangian Finite Element

- Solves Reynolds-averaged Navier-Stokes
  - Hydrostatic & Boussinesq assumptions
- Solves transport of temperature and salinity



Spatial discretization

- Elevation @nodes (p1)
- Velocity @sides (p1)
- Vertical velocity @prisms (FV)
- Tracers @prisms (FV)



Temporal discretization

- Implicit 2D mode for free-surface
- Semi-Lagrangian (ELM) advection of momentum

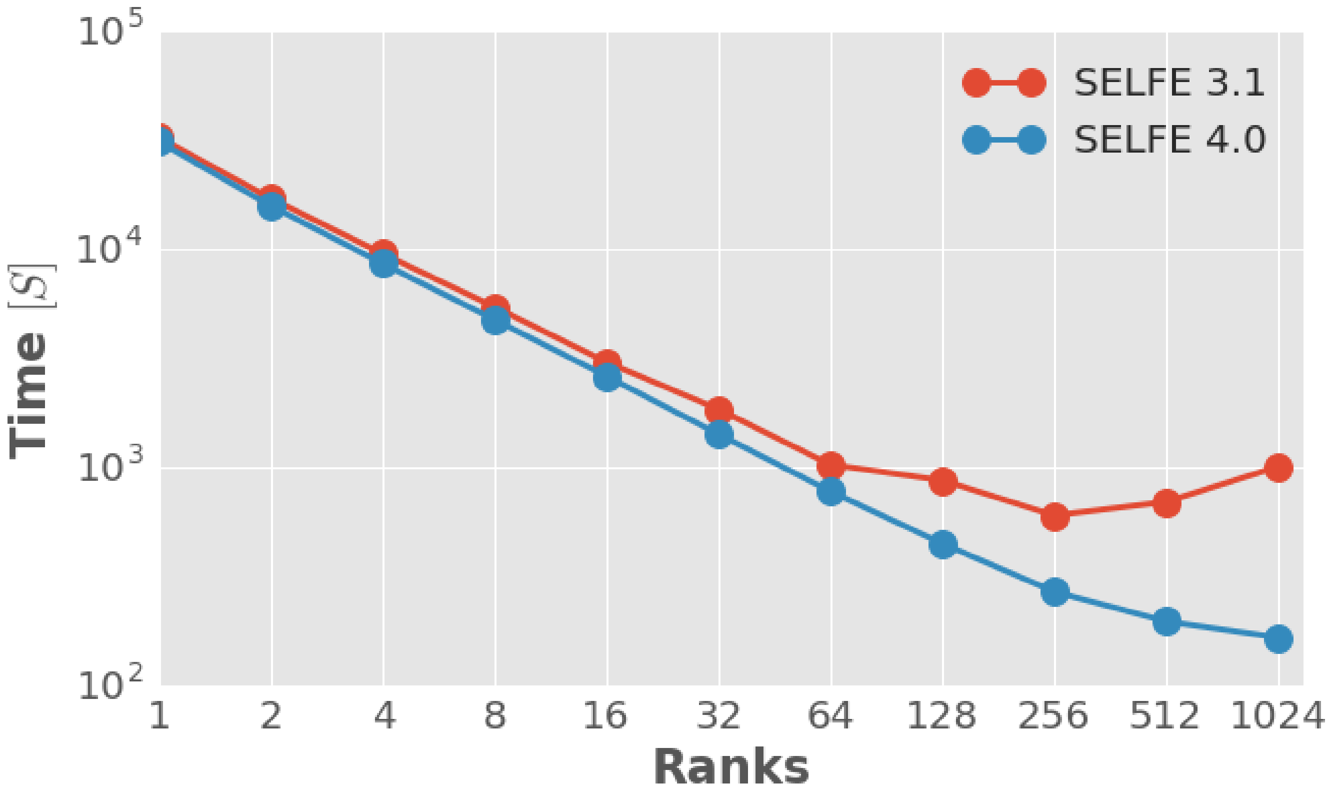
SELFE – Governing equations

	Dimensionality	Equations
Continuity	**2D**	$\frac{\partial \eta}{\partial t} + \nabla \cdot \int_{-h}^{\eta} \mathbf{u} dz = 0, \nabla \cdot \mathbf{u} = 0$
Momentum	**3D**	$\frac{D\mathbf{u}}{Dt} = \mathbf{f} - g\nabla\eta + \frac{\partial}{\partial z}\left(\nu \frac{\partial \mathbf{u}}{\partial z}\right)$
Explicit terms		$\mathbf{f} = -f\mathbf{k} \times \mathbf{u} + \alpha g \nabla \hat{\psi} - \frac{1}{\rho_0}\nabla p_A - \frac{g}{\rho_0}\int_z^{\eta} \nabla \rho d\zeta + \nabla \cdot (\mu \nabla \mathbf{u})$
GLS *TKE*	**1D**	$\frac{Dk}{Dt} = \frac{\partial}{\partial z}\left(\nu_k^{\psi} \frac{\partial k}{\partial z}\right) + K_{mv}M^2 + K_{hv}N^2 - \epsilon$
Length scale		$\frac{D\psi}{Dt} = \frac{\partial}{\partial z}\left(\nu_{\psi} \frac{\partial k}{\partial z}\right) + \frac{\psi}{k}\left(c_{\psi 1}K_{mv}M^2 + c_{\psi 3}K_{hv}N^2 - c_{\psi 2}F_{wall}\epsilon\right)$
Stability function		$\psi = \left(c_{\mu}^{0}\right)^{p} k^{m} l^{n}$
Transport	**3D**	$\frac{Dc}{Dt} = \frac{\partial}{\partial z}\left(\kappa \frac{\partial C}{\partial z}\right) + Q + \nabla \cdot (\kappa_h \nabla c), c = (S, T)$

SELFE – Optimization

Optimizations

- PETSc to solve 2D continuity
- Optimized IO
  - Caching of NetCDF boundary conditions
- Optimized transport
- Generally, improved:
  - memory locality
  - vectorization



Strong-scaling test

- NERSC Edison system
- 98K 2D nodes, 3.5M 3D elements

SELFE - Performance results

Version	Test	Cores	Total time	Time per day	Speed Up
3.1	Hydrodynamics	128	8:54	0:38	-
4.0	Hydrodynamics	128	4:31	0:19	x2
4.0	Hydrodynamics	1024	1:32	0:06	x6
3.1	Hydrodynamics + 4 tracers	128	4:22	2:11	-
4.0	Hydrodynamics + 4 tracers	128	1:07	0:32	x4

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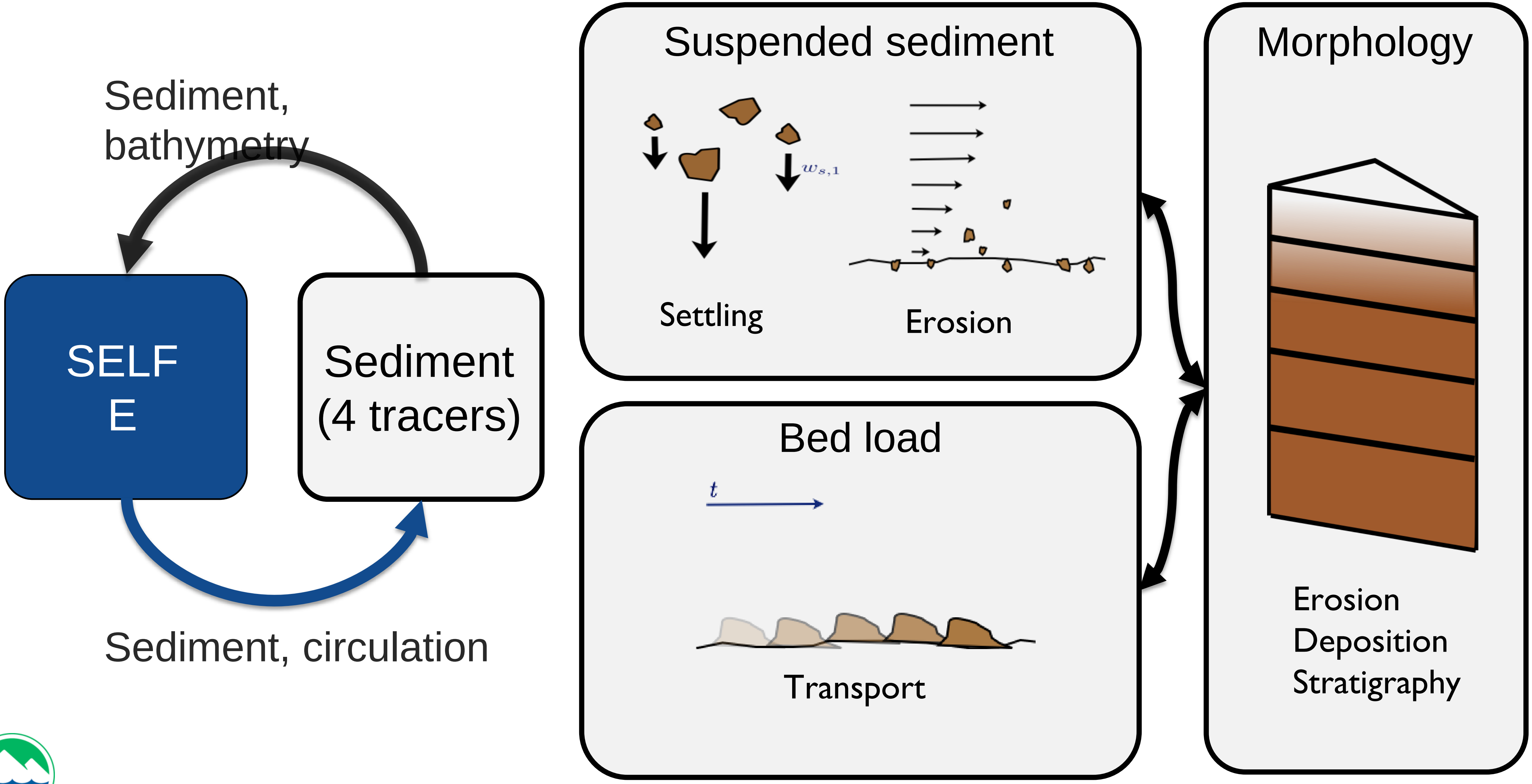
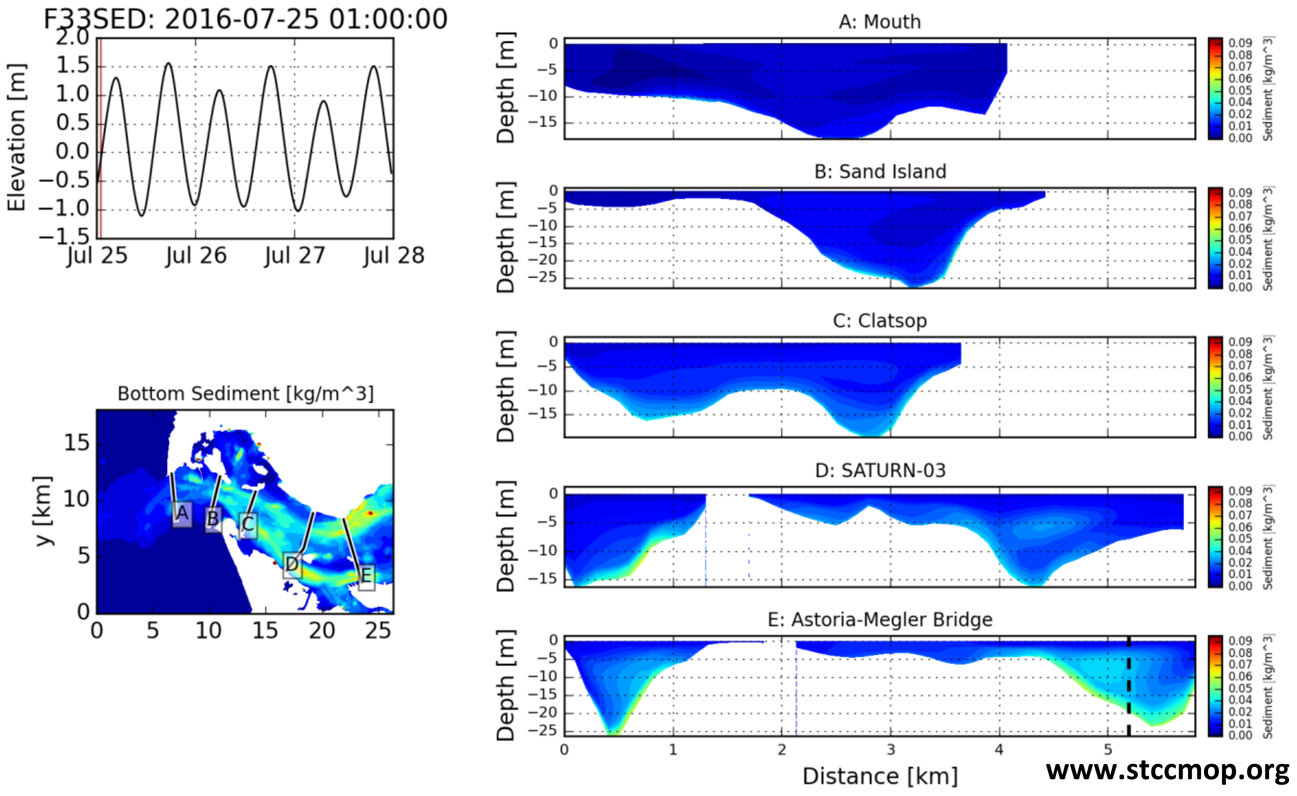
SELFE - Sediment model



Sediment forecast model

Forecasts

- Enabled by optimized model
- 3 day forecast



Applications

- Production sediment forecast
- Guide research cruises and AUVs
- Trigger collection of transient features

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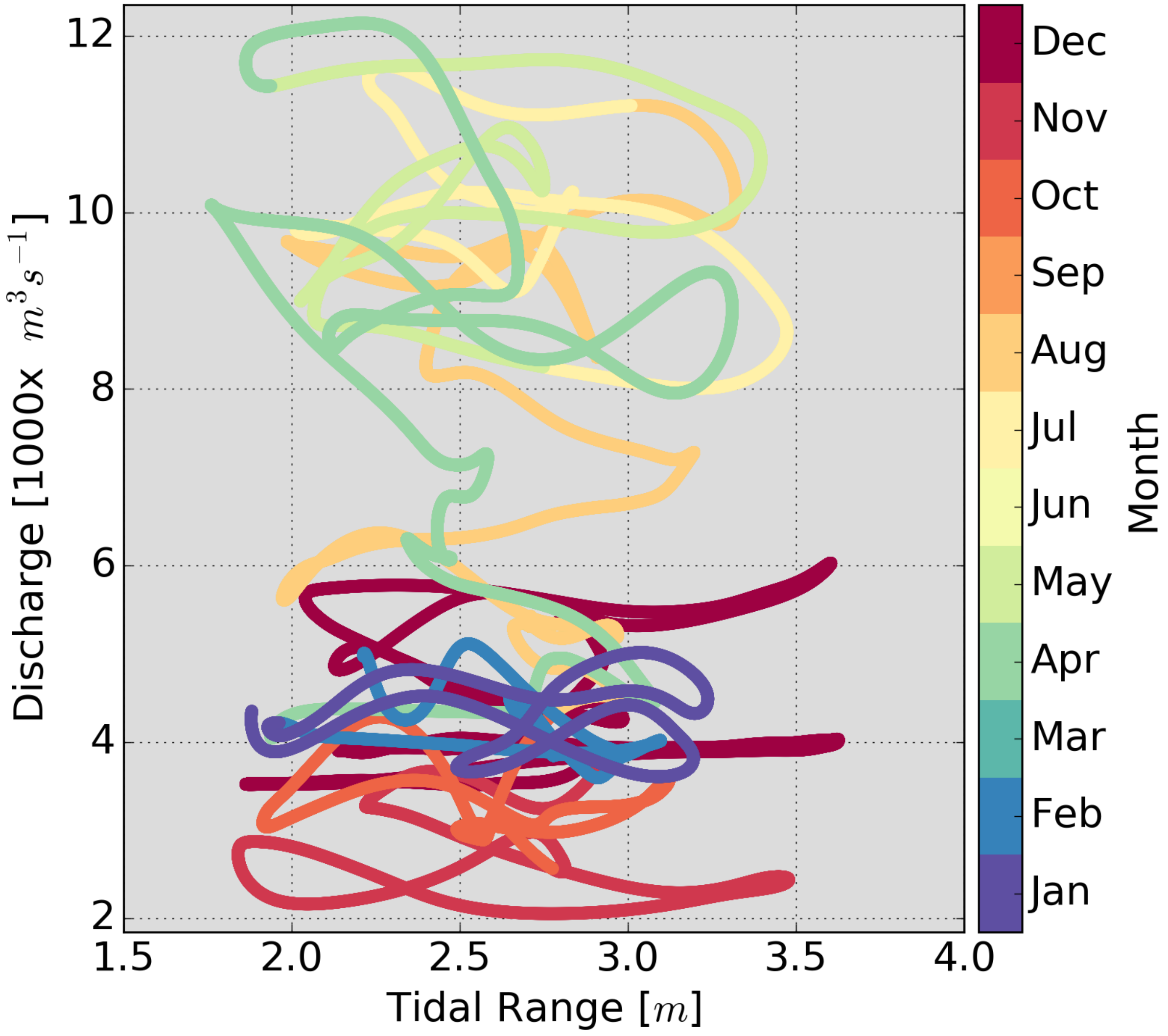
Capturing variability - Annual simulations

Columbia River Dynamics

- River discharge + tides control circulation and sediment dynamics
- River discharge – strong seasonal variability
- Tides - vary over ~14 day period

Sediment simulations

- Simulate entire year
  - 36 s time step
- Cover the range of seasonal forcings



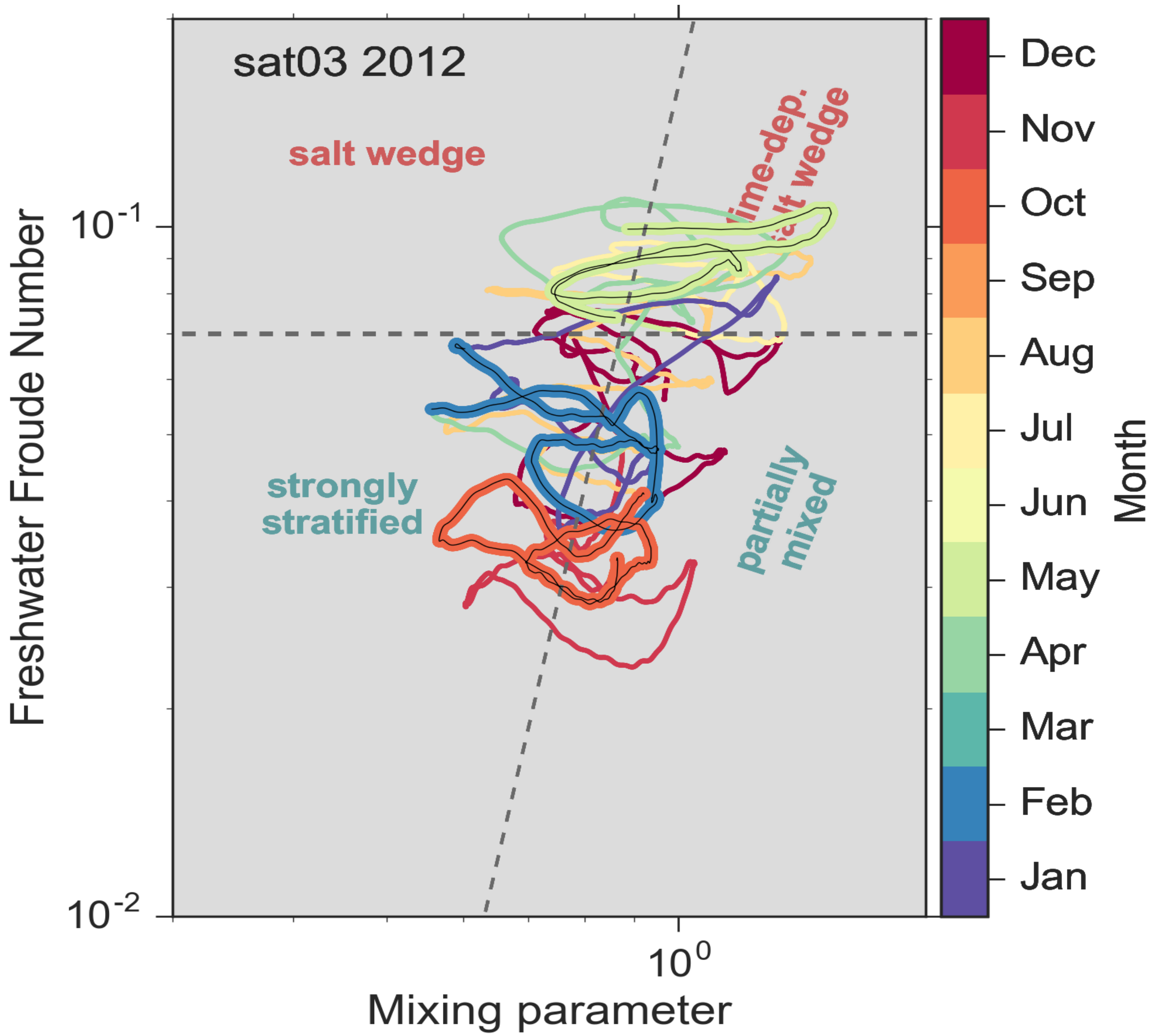
Annual simulations

Columbia River Dynamics

- River discharge + tides control circulation and sediment dynamics
- River discharge – strong seasonal variability
- Tides - vary over ~14 day period

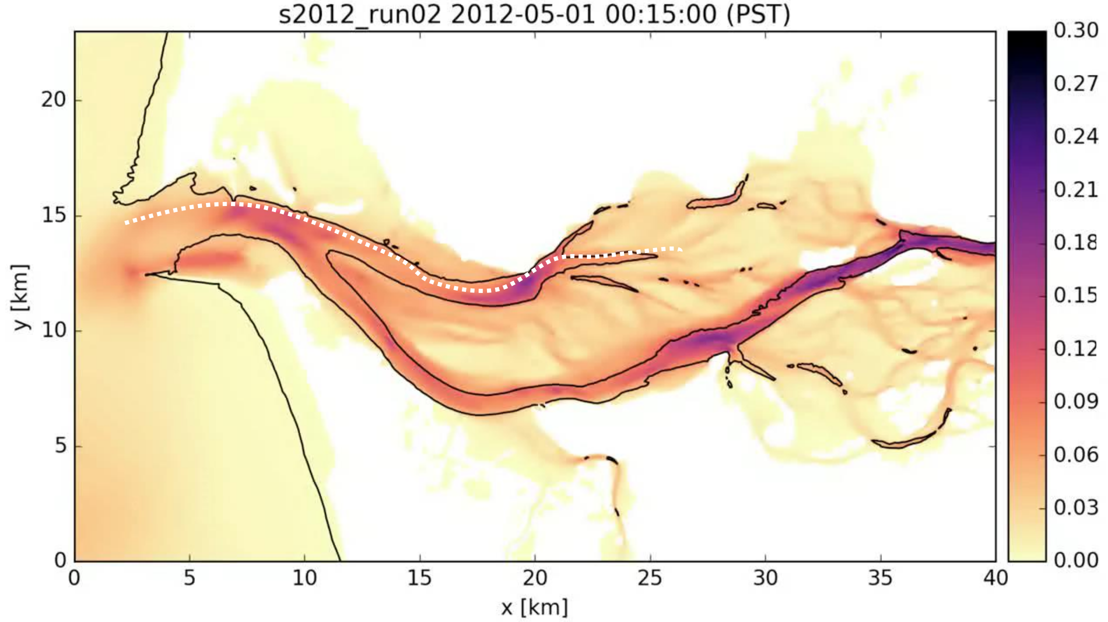
Sediment simulations

- Simulate entire year
  - 36 s time step
- Characterize dynamics in ***estuarine regimes***

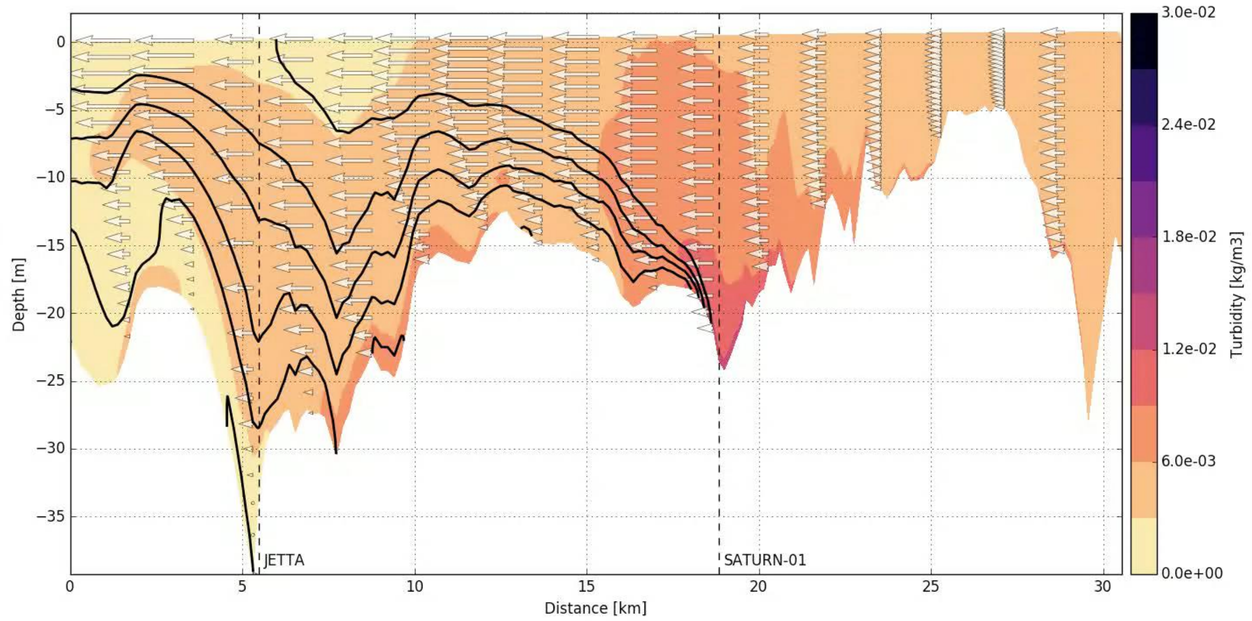


Suspended sediment dynamics

Ocean River



Ocean River



Depth integrated suspended sediment

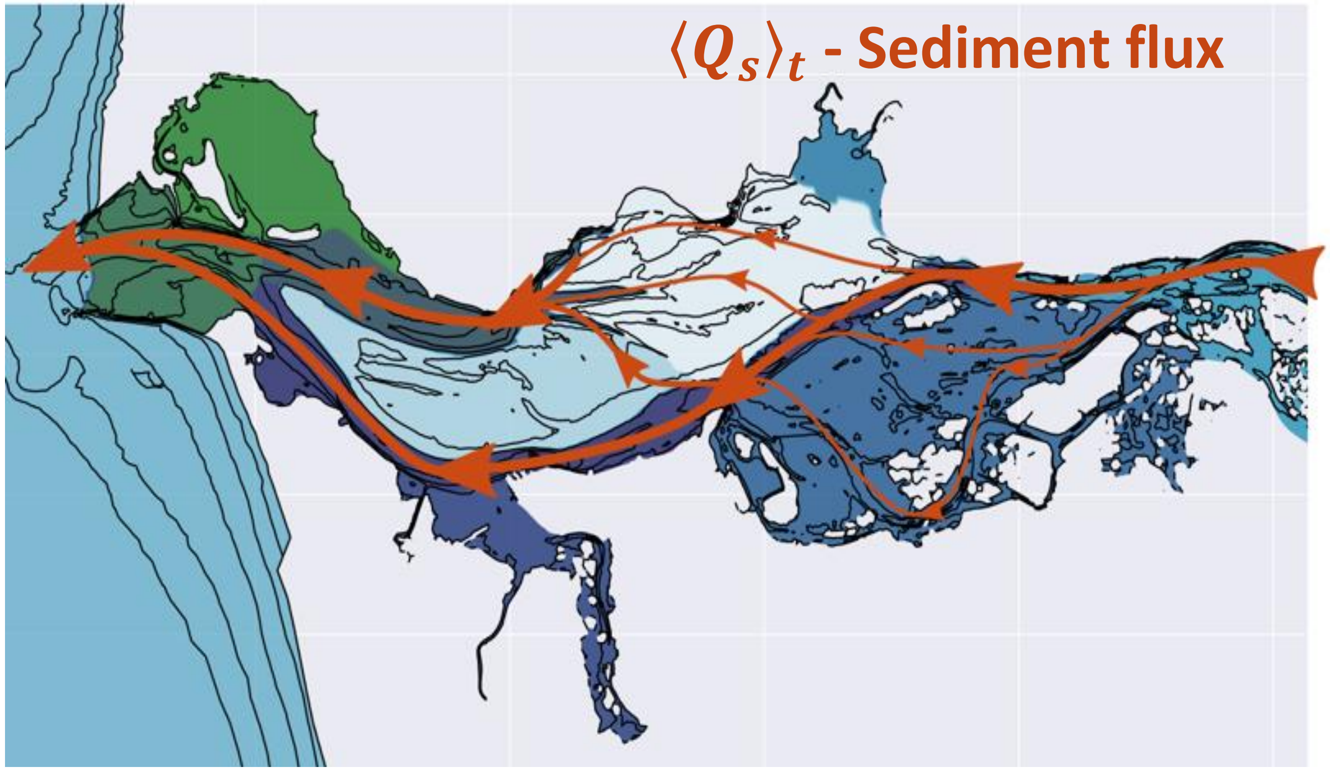
$$\boldsymbol{S}(x,y) = \int_{-h}^{\eta} S(x,y,z)\,dz$$

Along-channel transect:

- Salinity
- Along-channel velocity
- Suspended sediment

Low High

Sediment pathways



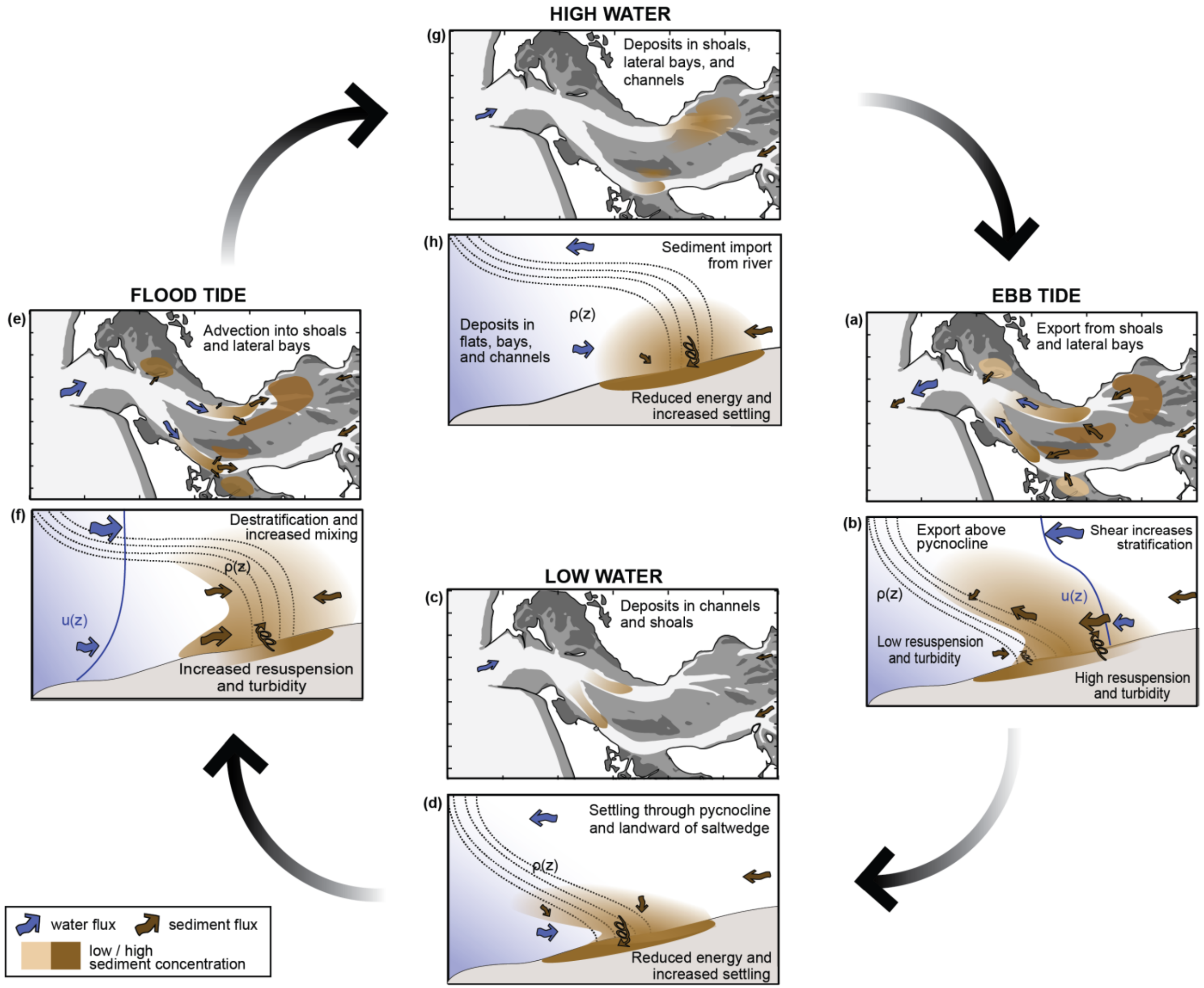
Sediment pathways

- Depth and temporally integrated

$$\langle Q_s \rangle_t = \int_{t+T}^{t+T} \int_{-h}^{\eta} Q_s(z,t)dzdt$$

- Exposes complexity of channel system and interactions between channels, tidal shoals, and bays
- Dominant pathways invariant across tidal, tidal month, and seasonal time scales

Conceptual model of sediment dynamics



Conceptual Model

1. High water – Low energy
   - SSC deposits
2. Ebb tide – High energy
   - SSC moves downstream
   - Patch of SSC over salt wedge
3. Low water – Low energy
   - Low energy – SSC deposits
4. Flood tide – High energy
   - SSC moves upstream
   - SSC concentrated in salt wedge (Classical ETM)

Summary

- SELFE optimized with improved efficiency and strong-scaling
- Optimized model enabled:
  - Development of production forecast sediment simulations
  - Guidance of observations to capture transient features
  - Long-term studies of Columbia River estuary circulation and sediment dynamics
- Science facilitated by HPC systems + optimized model include:
  - Detailed characterization of sediment dynamics in Columbia River estuary
  - Unifying conceptual model of sediment dynamics in Columbia River estuary

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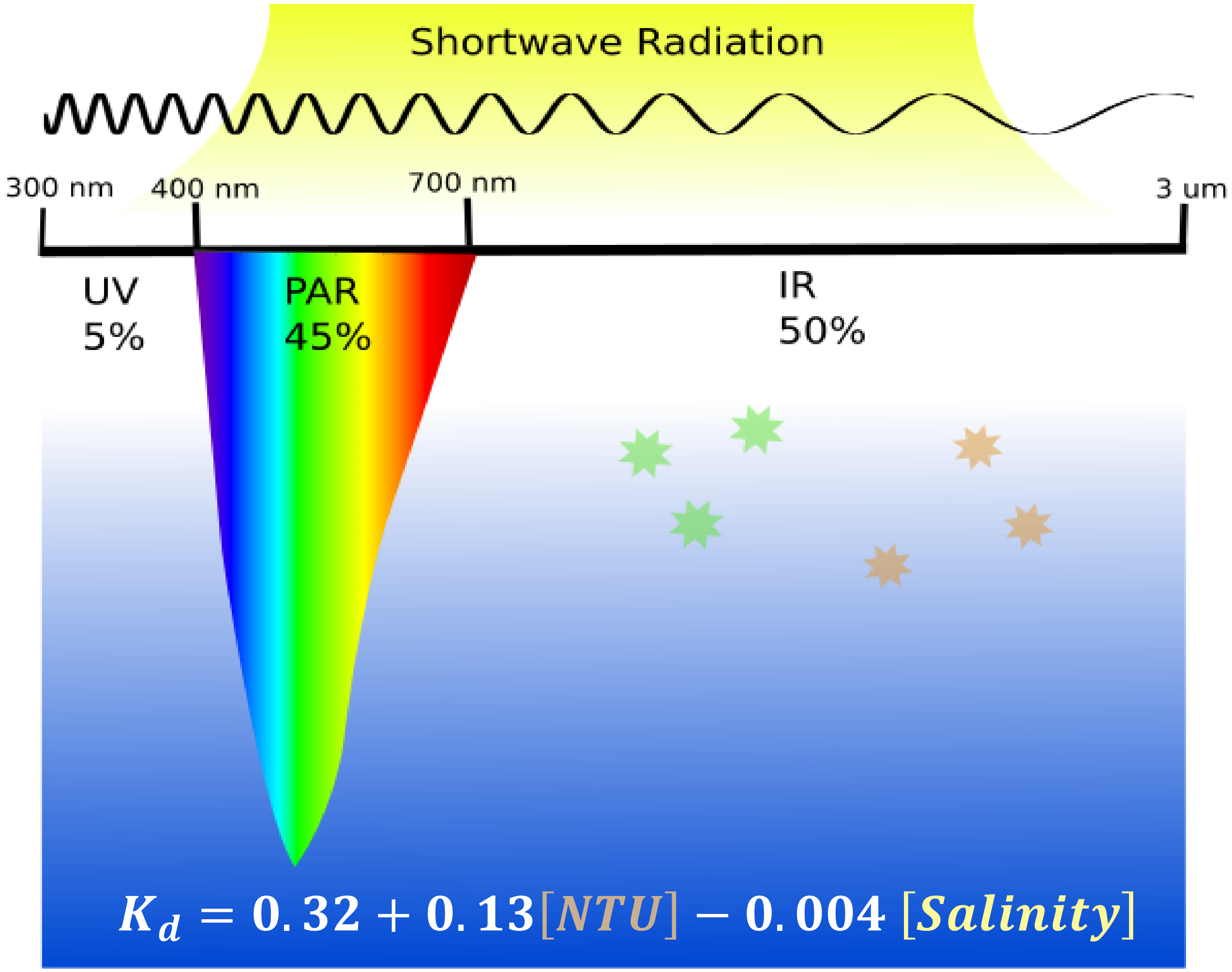
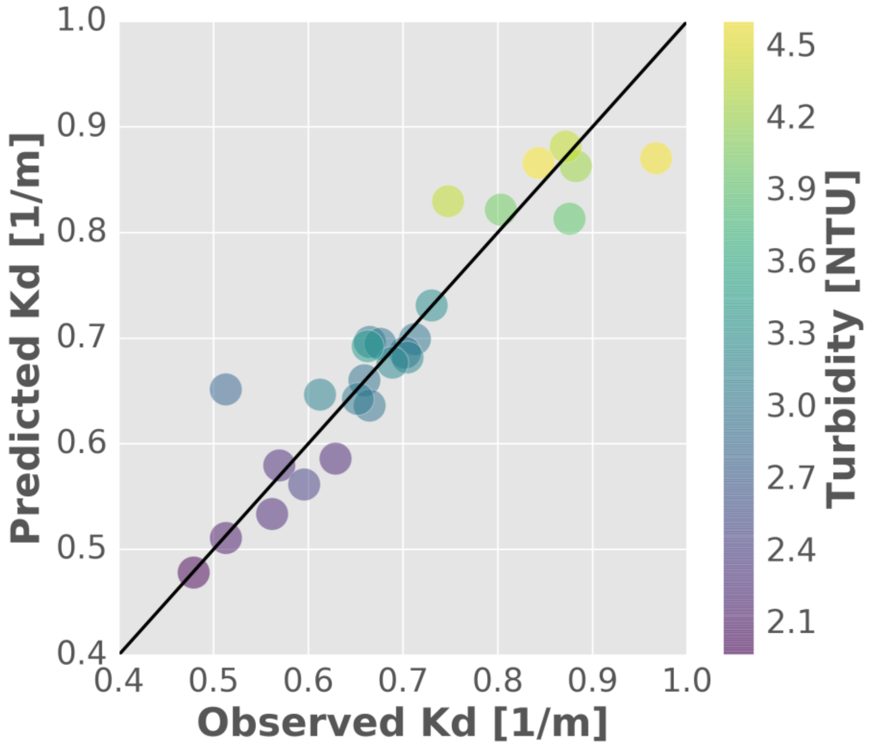
Application: Light attenuation $K_d(PAR)$

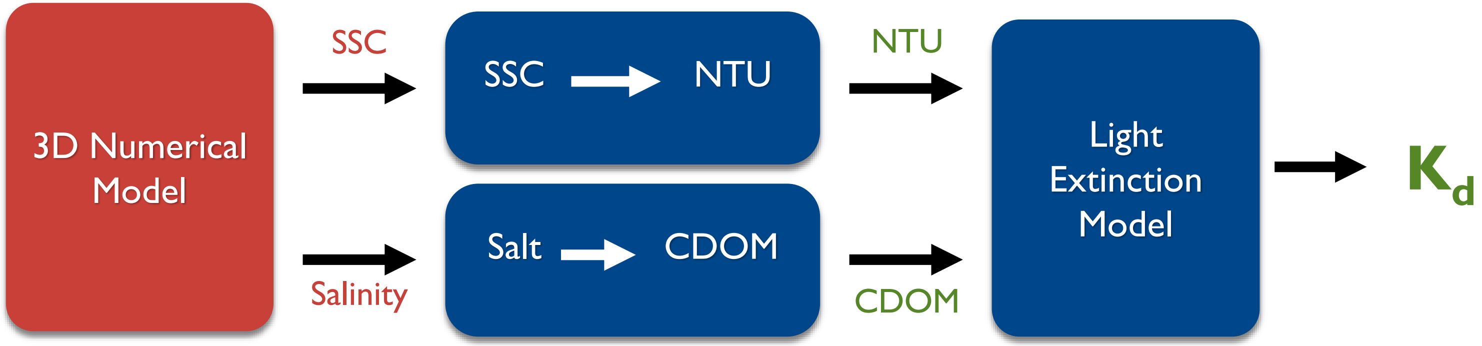


$K_d(PAR)$

- Describes attenuation of light through water column
- Dependent on suspended and dissolved material

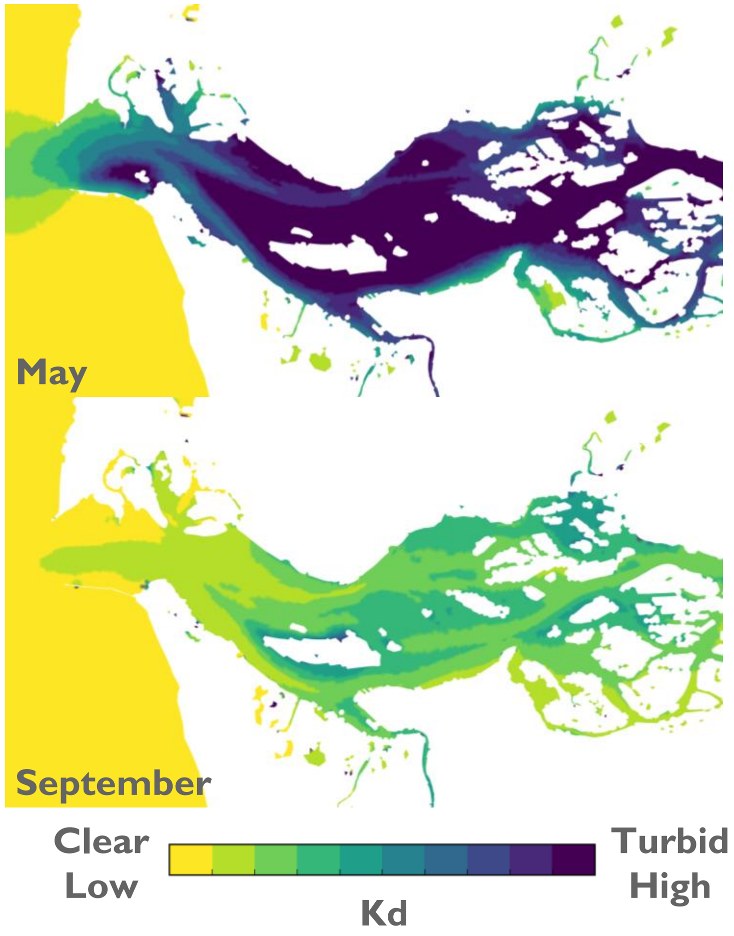


Application: Light attenuation model



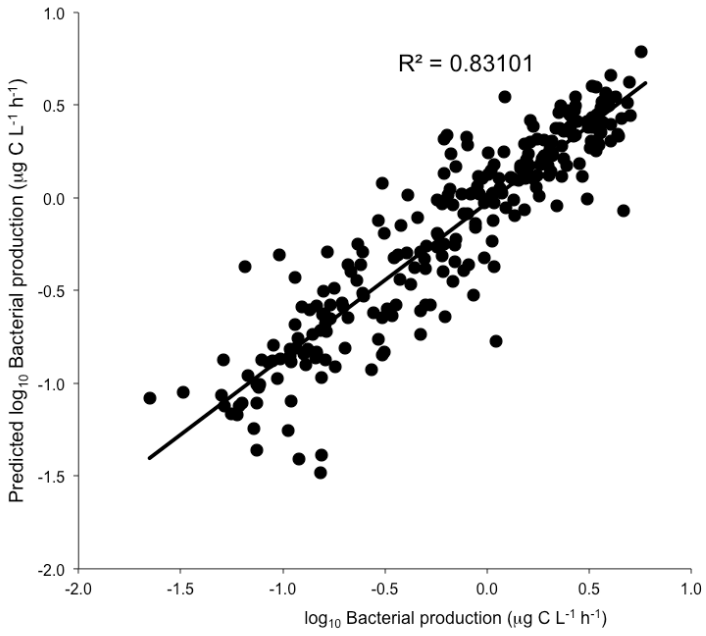
- Characterized light variability over tidal to seasonal time scales

- Kd model implemented in circulation model to provide time-dependent attenuation of solar radiative heat transfer

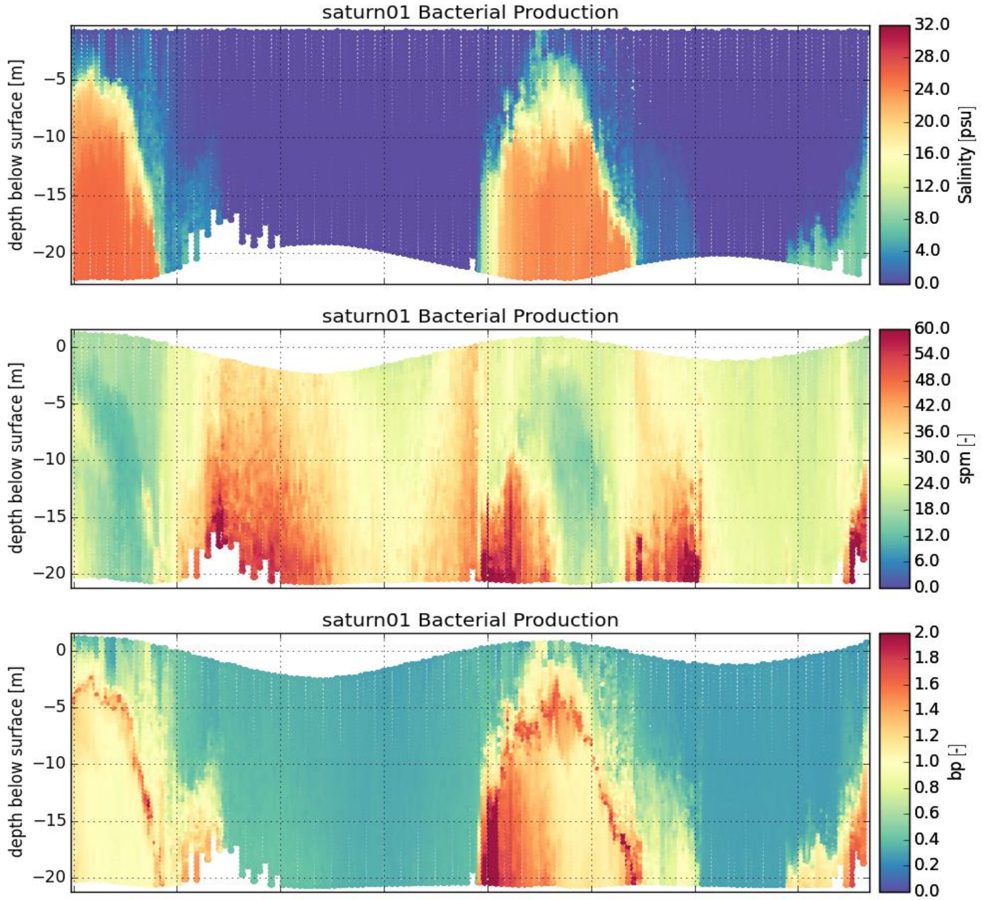


Application: Estimates of bacterial productivity

- How productive are bacteria in the estuary?



Predictions based on Generalized Linear Model



Empirical model applied to observations at SATURN-01