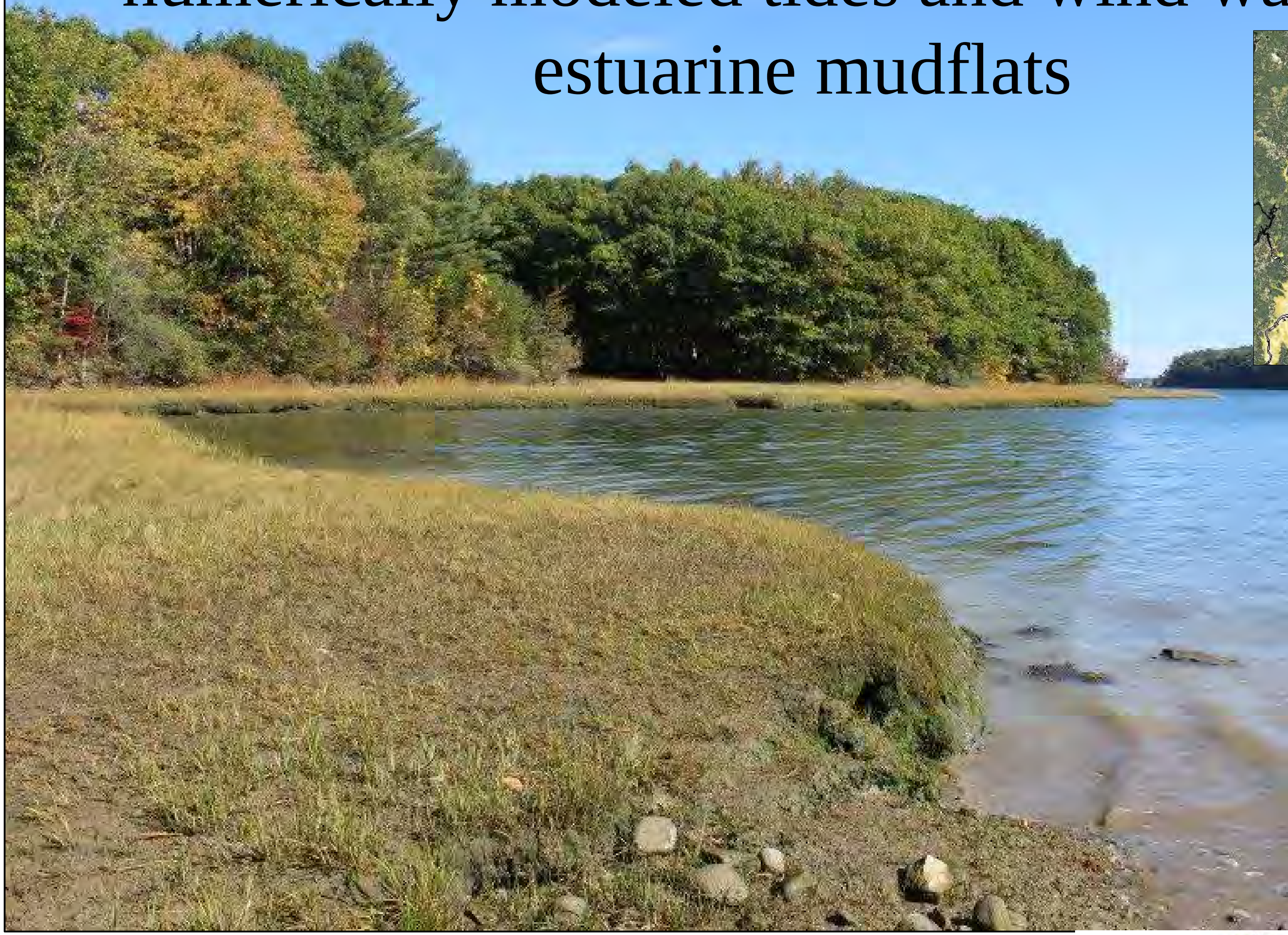
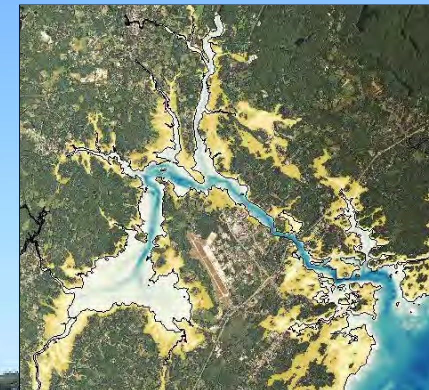
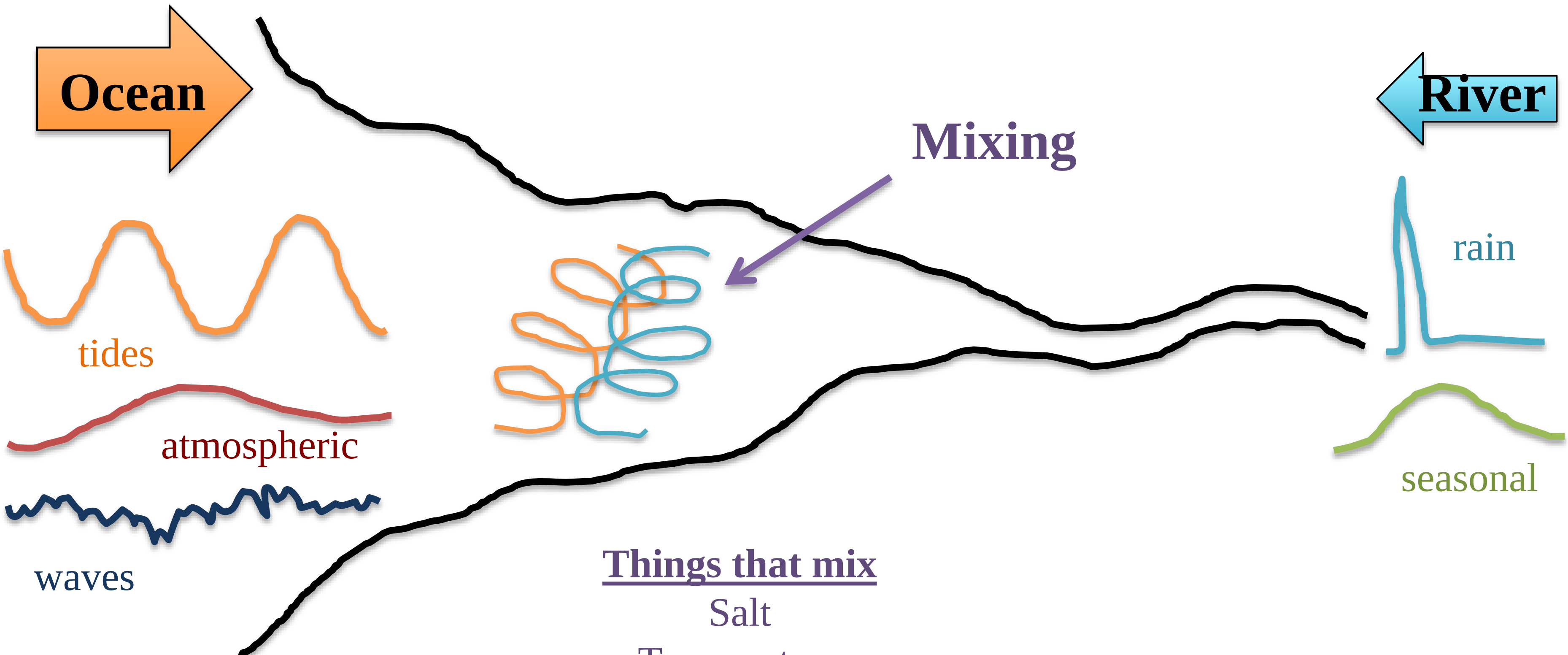
# Estimating bed shear stress distribution from numerically modeled tides and wind waves on estuarine mudflats





By Salme Cook and Tom Lippmann
University of New Hampshire

# *Estuaries*



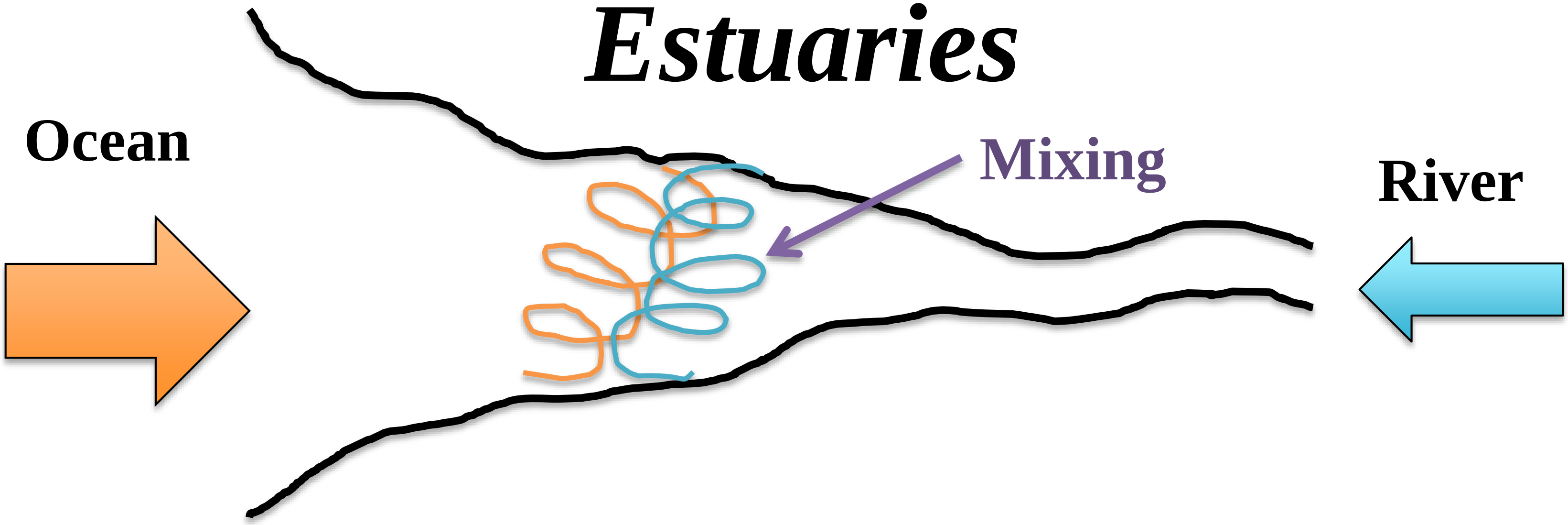

**<u>Things that mix</u>**

Salt
Temperature
Sediment
Nutrients
Pollutants

**<u>Mixing Processes</u>**

Advection and Diffusion
Turbulence

# Estuaries



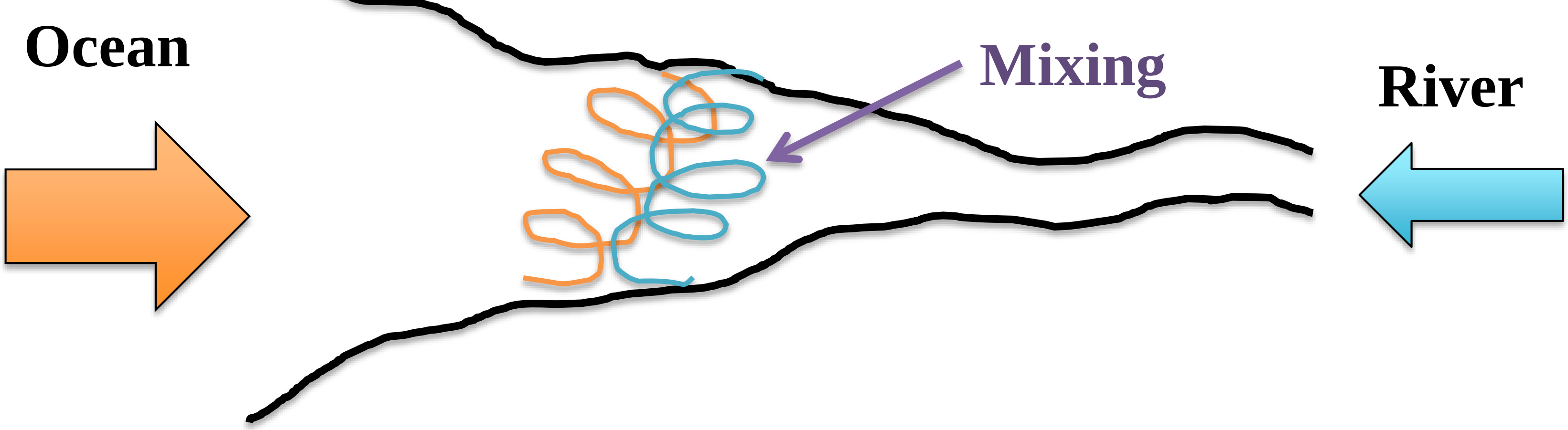

## Ecosystem Services

- ✧ "buffer zone" that removes nutrients, sediment, and pollutants
- ✧ Nitrogen/Phosphorus Cycling
- ✧ Habitats ~ "Nursery of the sea"
- ✧ Shore stabilization/Flood regulation
- ✧ High primary productivity
  Carbon Sequestration

## Economic Value

- ✧ **22** of the 32 largest cities in the world are located on estuaries
- ✧ **14%** of coastal communities in the United States produce **45%** of the nations GDP
- ✧ **76%** of trade involves some form of marine transportation
- ✧ Coastal recreation brings in $8-12 Billion dollars to the United States every year

# Estuaries

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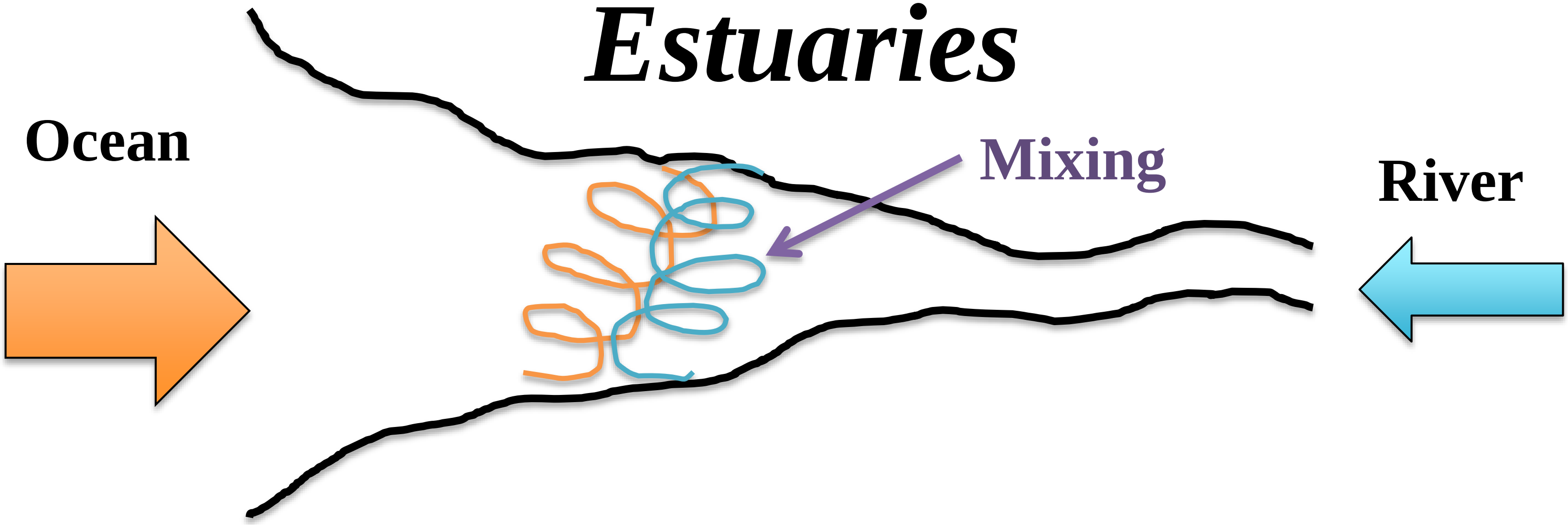


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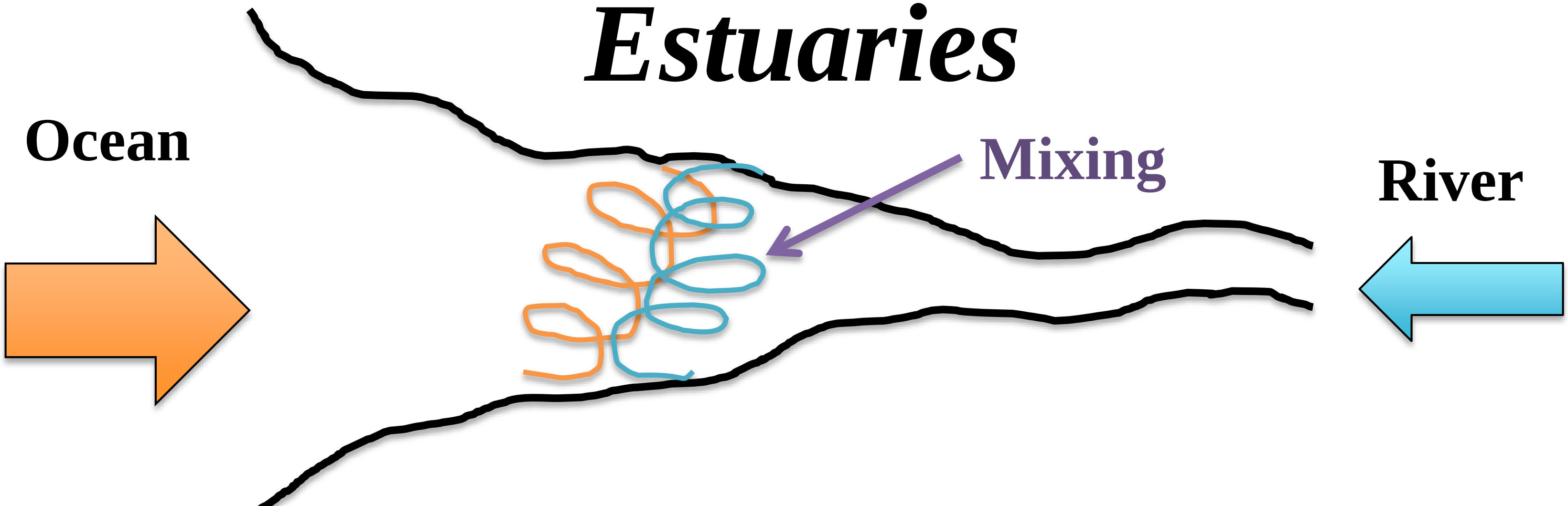



## Major Threat: Eutrophication

Eutrophication is induced by excess nutrients (mainly nitrogen and phosphorus) from increased human activity

It is one of the most widespread, costly, and challenging environmental problems.

# The Nutrient Problem

## Non-Point Source

Transportation

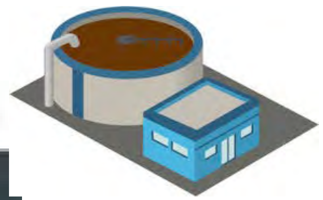
Industrial operations

Runoff : Fertilizer and Animal Waste

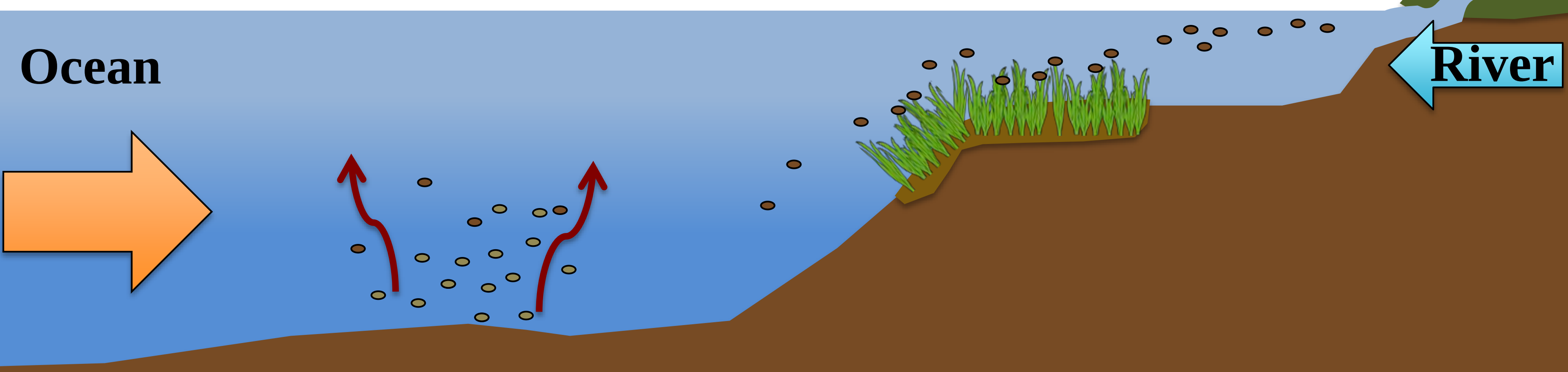

## Point Source

Storm water Outfall

Wastewater Treatment



**Does sediment resuspension contribute to nutrient loading?**



**Does sediment resuspension contribute to nutrient loading?**

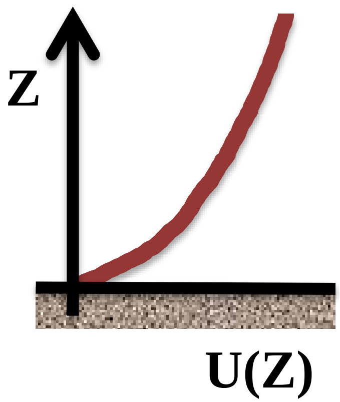
# Shear stress and nutrient loading

Applied Shear stress → Sediment Resuspension → Nutrient/Pollutant Release

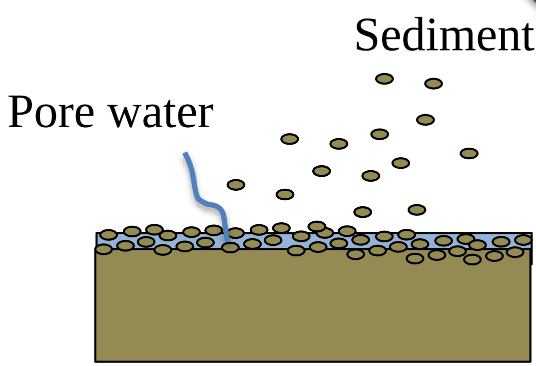
**>50% mud fraction**
**0.35 N/m2 for nutrient release**
**Percuoco (2013)**

$\tau_b > \tau_{critical}$

Hydrodynamics




Based on sediment characteristics

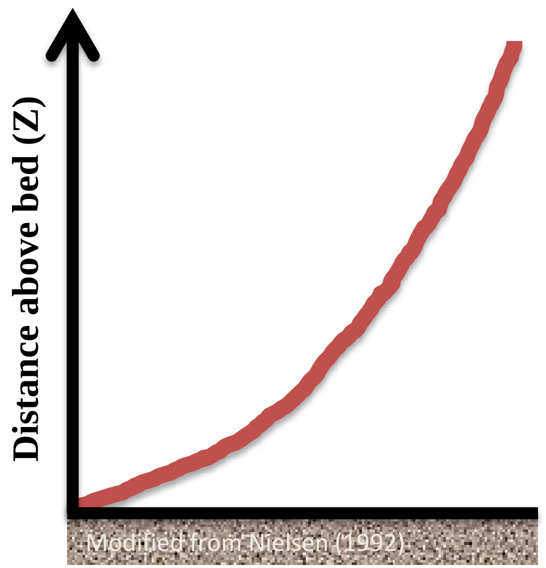



**Challenge: Cannot measure shear stress directly !**

**Research Goal: estimate the distribution of shear stress from tides and waves using a verified numerical model.**

# Shear Stress and velocity

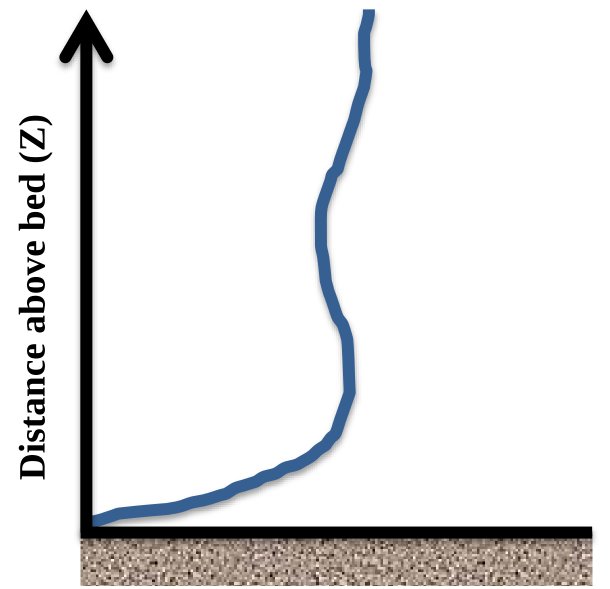
$$\tau_b \propto \mu \frac{\partial u}{\partial z} \propto \rho \upsilon \frac{\partial u}{\partial z}$$




## Tidal Boundary

| Quadratic Drag | Logarithmic "law of the wall" |
|---|---|
| $\tau_b = \rho C_d u\lvert u\rvert$ | $\tau_b = \rho {u_*}^2$<br>$\lvert u\rvert = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$ |

Function of the tidal current and a drag coefficient



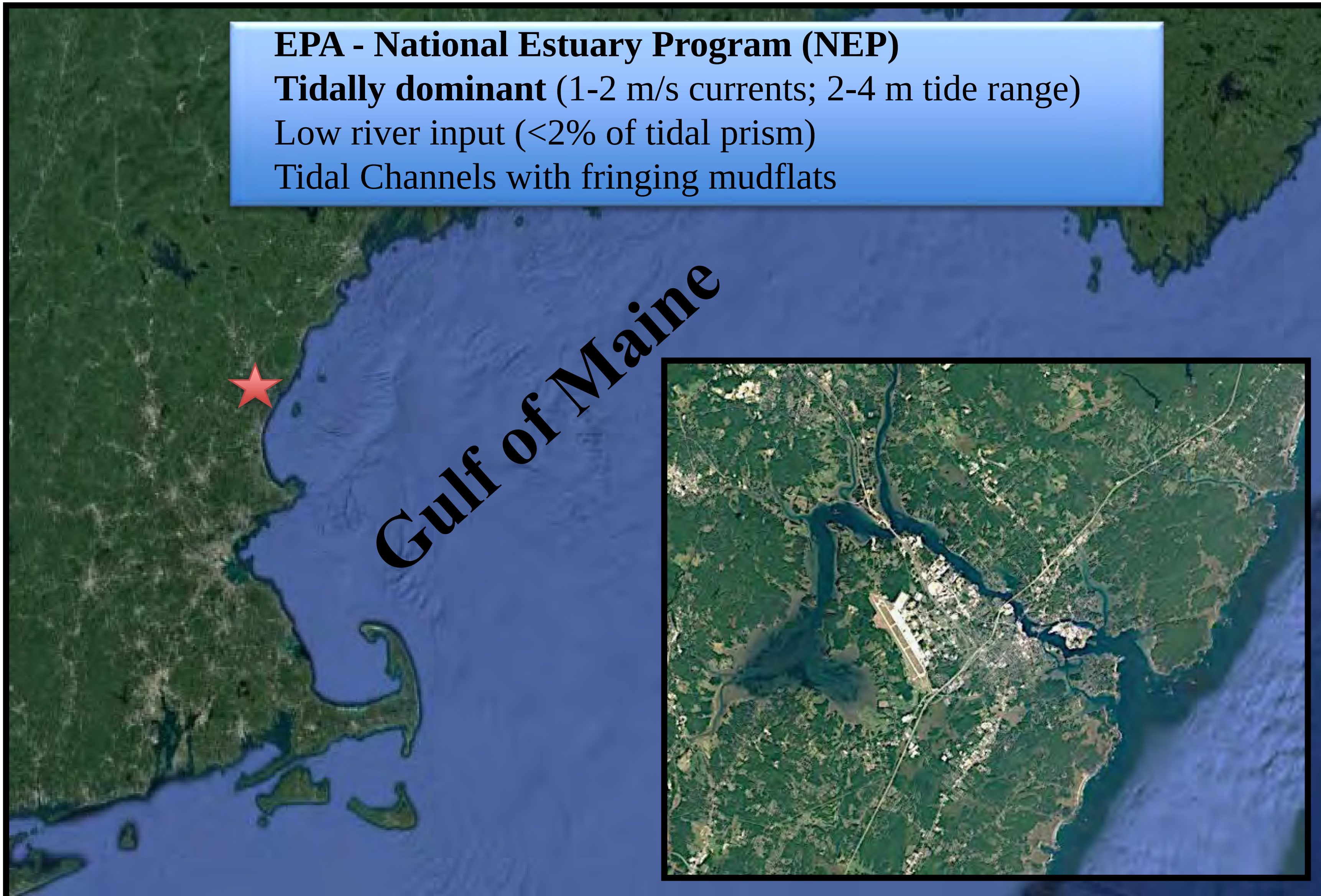

## Wave Boundary

$$\tau_{bw} = 0.5 f_w {u_b}^2$$

Function of the wave friction factor and wave orbital velocity

# Study Site: Great Bay estuary, New Hampshire, US

**EPA - National Estuary Program (NEP)**
**Tidally dominant** (1-2 m/s currents; 2-4 m tide range)
Low river input (<2% of tidal prism)
Tidal Channels with fringing mudflats



# Modeling System

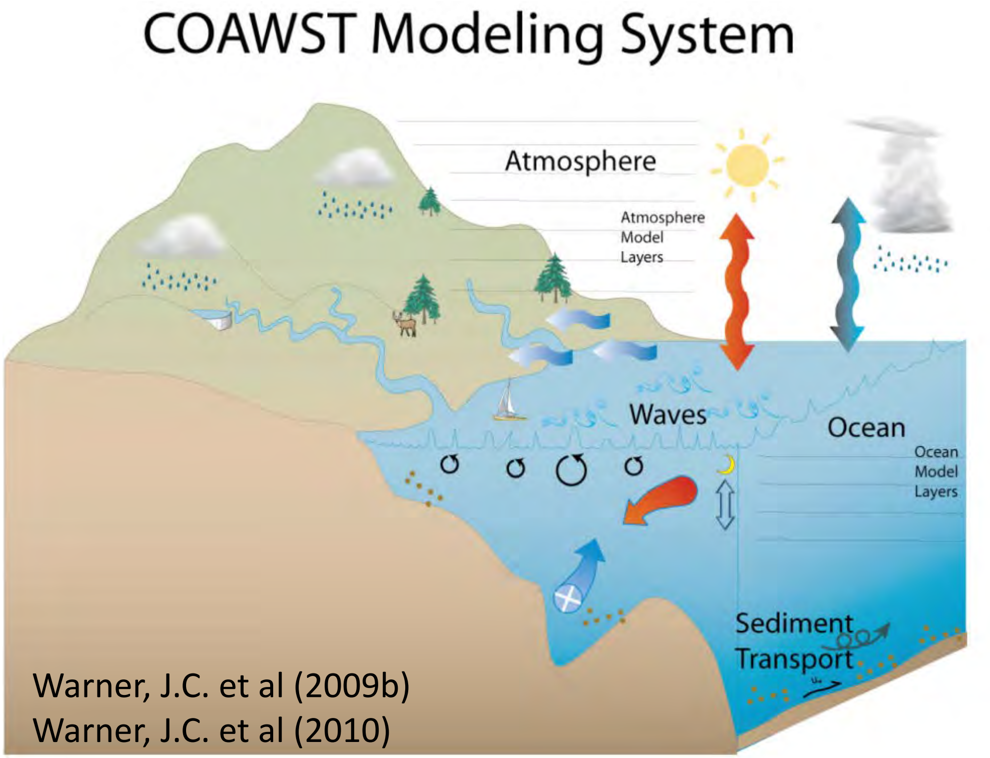
**C** – Coupled

**O** – Ocean (**ROMS**)

**A** – Atmosphere (WRF)

**W** – Wave (SWAN)

**ST** – Sediment Transport

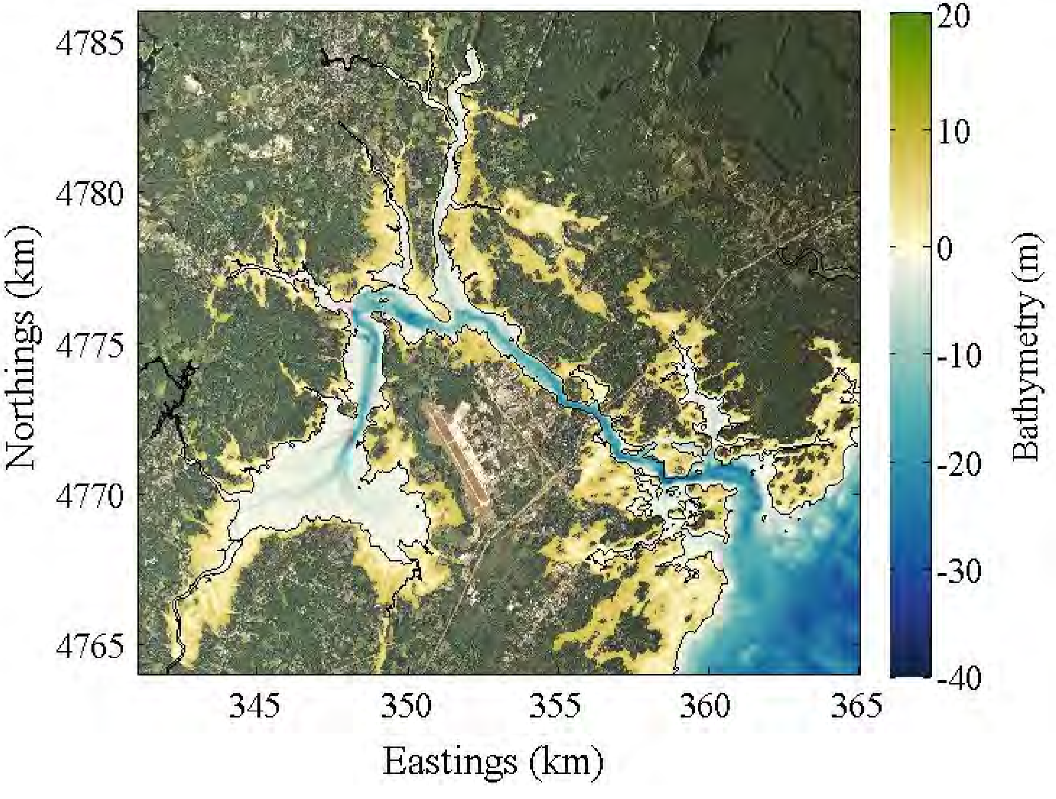



## **R**egional **O**cean **M**odeling **S**ystem (**ROMS**)

- 3-D, free surface, topography following numerical model
- Solves finite difference approximations of RANS equations
- Written in F90/95, uses C-preprocessing to activate different options. Output data is written into NetCDF files for post-processing.

Shchepetkin and McWilliams (2005), Shchepetkin et al., (2009a), Shchepetkin et al (2009b), and Haidvogel et al.,(2008)

# Model Grid




**Horizontal:** 30 meter (and 10 meter)
**Vertical:** 8 vertical sigma layers

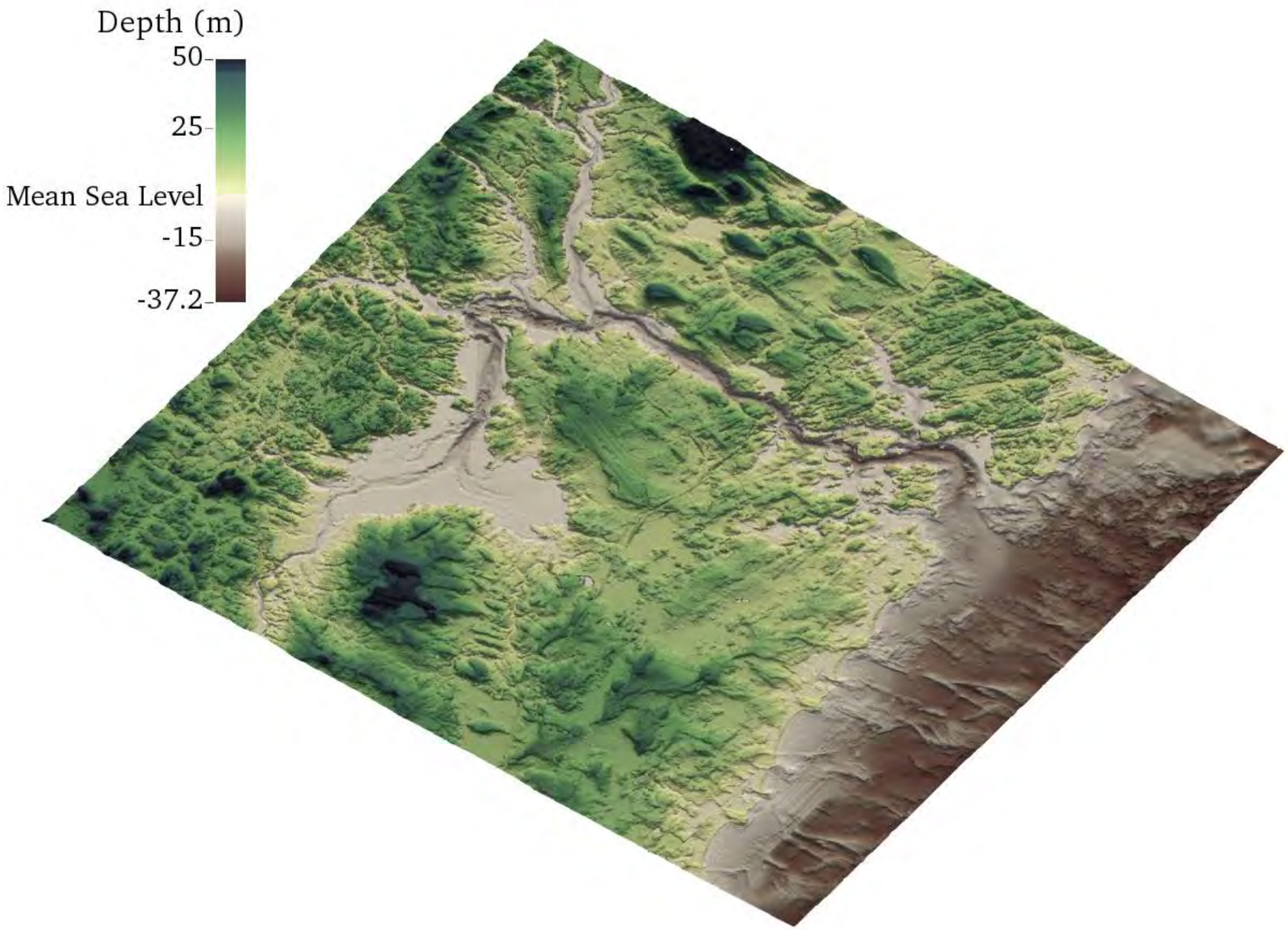
**Grid Development**

- Islands (LIDAR or Coastline file)
- Great Bay/Little Bay 2016 Survey
- Rivers (USACE surveys)
- Western Gulf of Maine (WGOM) 8m survey (CCOM - Paul Johnson)
- Low lying land (LIDAR - NOAA, FEMA, USGS)

Gridding routines in Matlab to create a netcdf formatted file

# Model Grid

Visualization using ParaView



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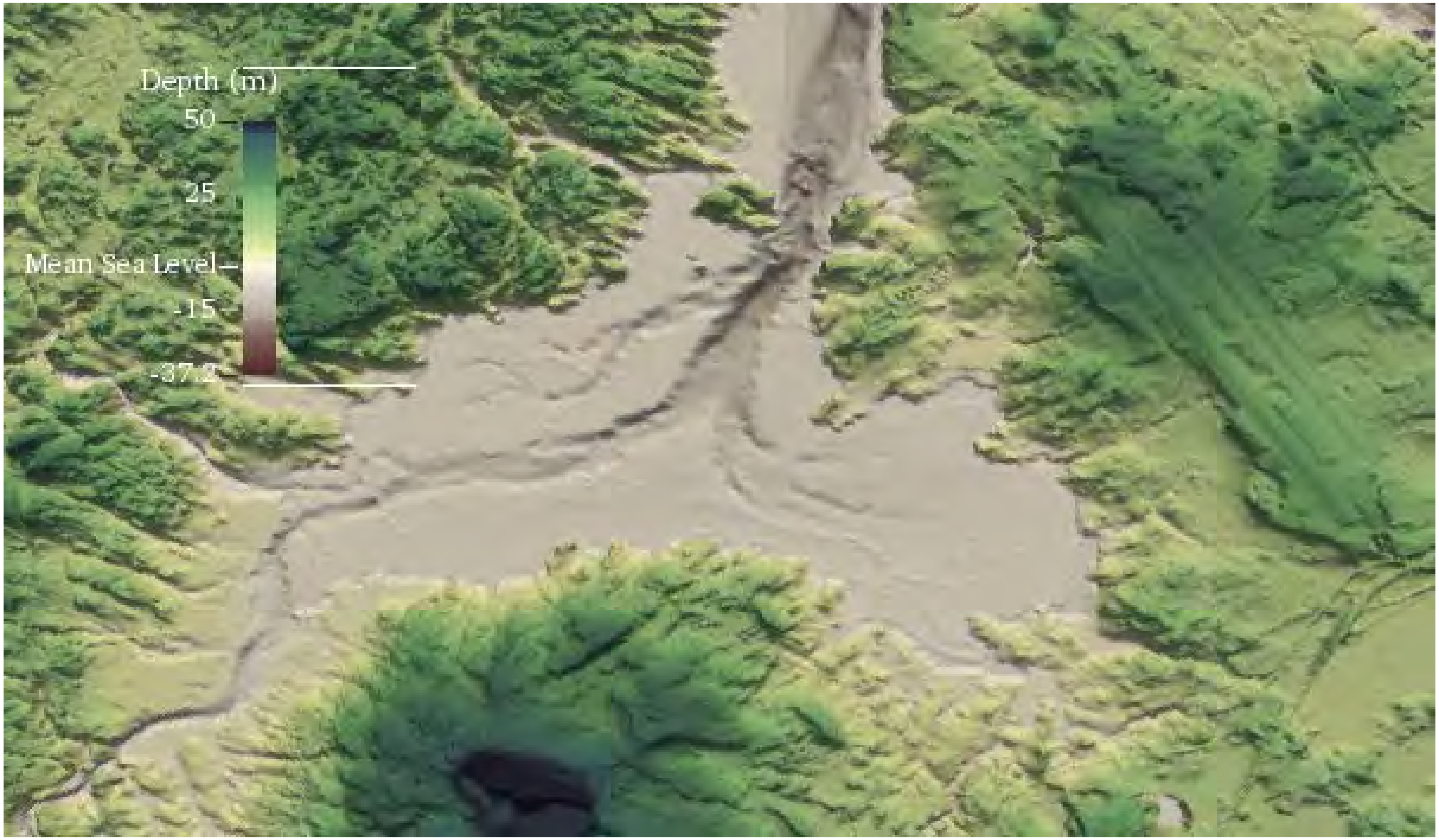



5 km x 5 km

| 30 meter grid Model Configuration | |
|---|---|
| DT | 1-1.5 s |
| Horizontal Resolution | 734 x 834<br>(22 km x 25 km) |
| Vertical resolution | 8 sigma layers |
| Run Length | 30 days |
| $z_o$ | 0.015 m, 0.020 m, 0.025 m, 0.030m |
| Other: Wetting and Drying algorithm, Forcing ramped up over 1 day | |

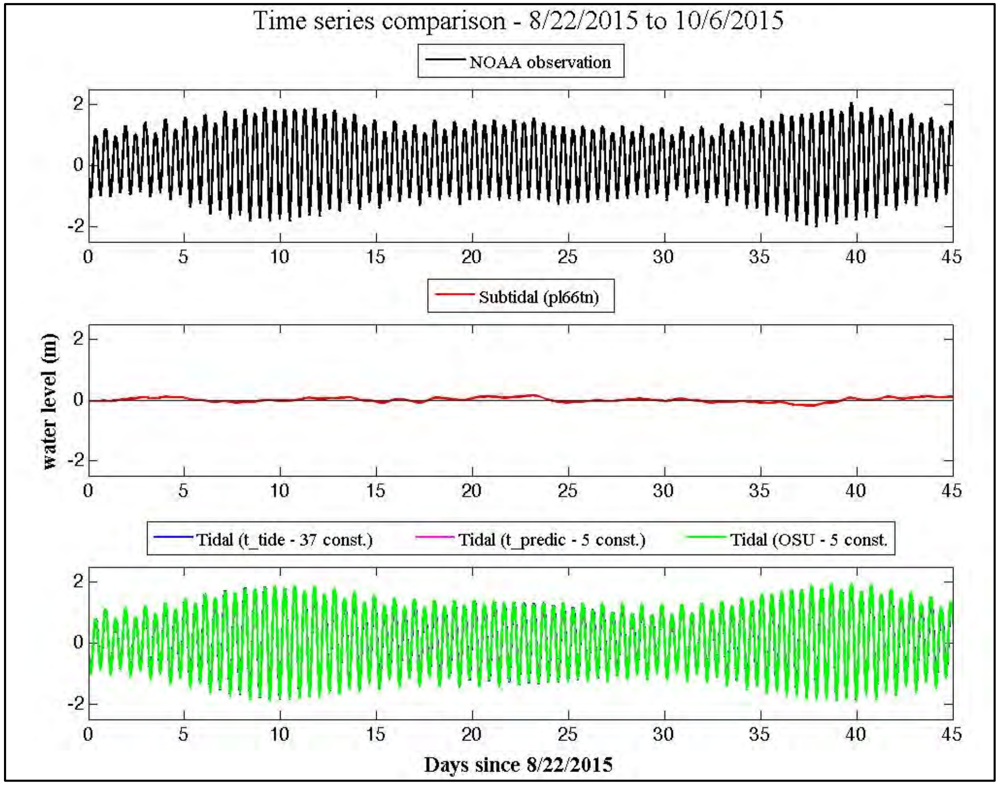
$$C_f = \frac{\kappa^2}{\left(\ln \frac{z}{2z_0}\right)^2}$$

$$|\tau_b| = C_d |\bar{U}|^2$$

Observations

Subtidal Observations

Tidal Predictions



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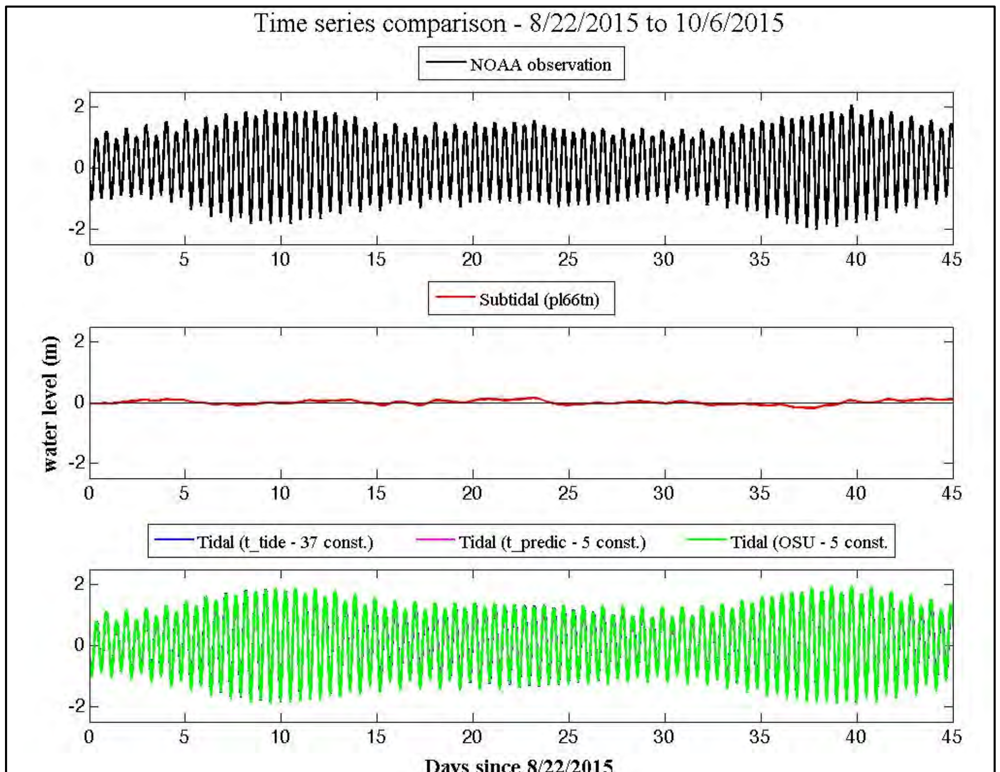
Observations

Subtidal Observations

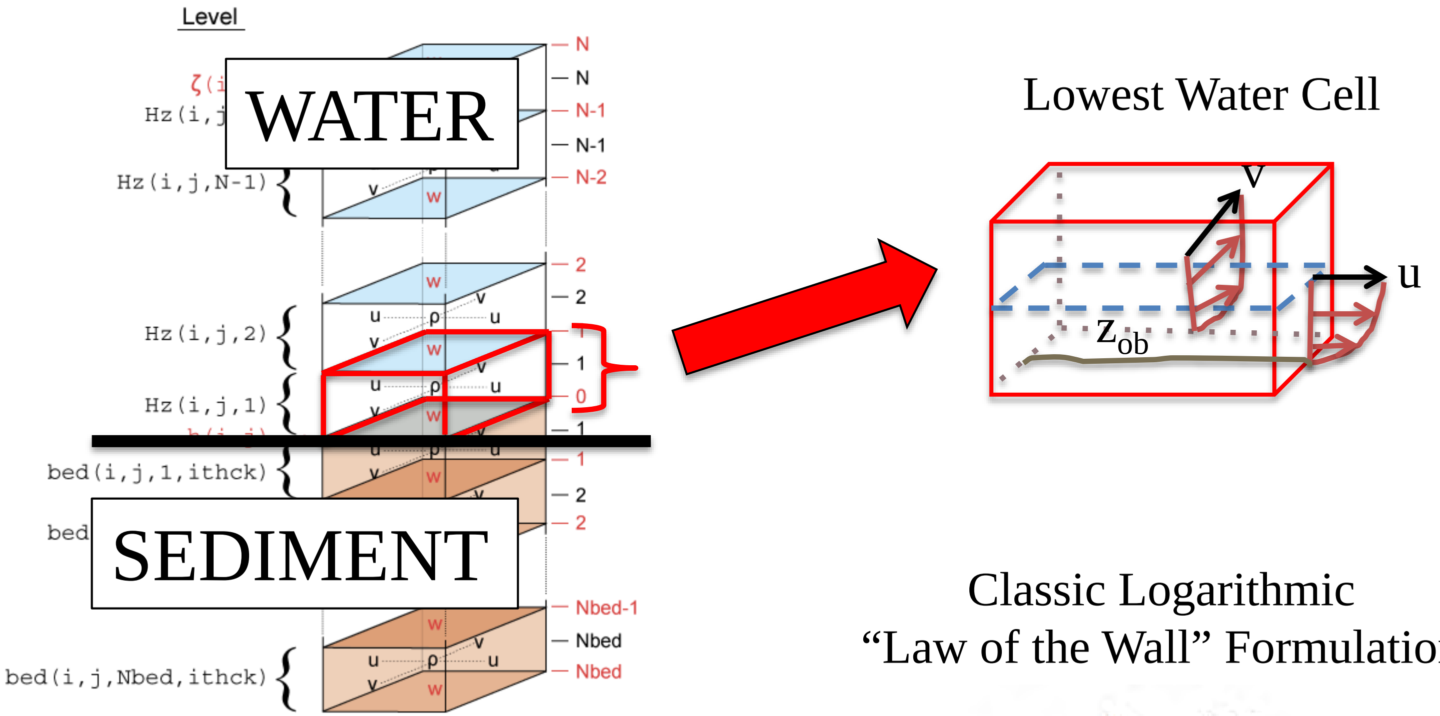
**Not that important**

Tidal Predictions




**Validated model Submitted to *Ocean Modeling*, May 2018**

# Estimates of Shear Stress based on a Numerical Model

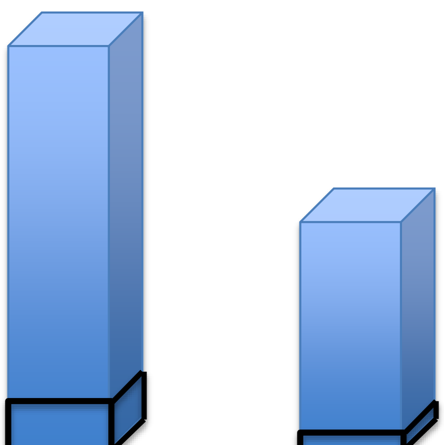



Classic Logarithmic
"Law of the Wall" Formulation

$$|u| = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

$$(\tau_b^x) = \rho_0 \left(\frac{\kappa}{\ln(z/Z_{ob})}\right)^2 u|u|$$

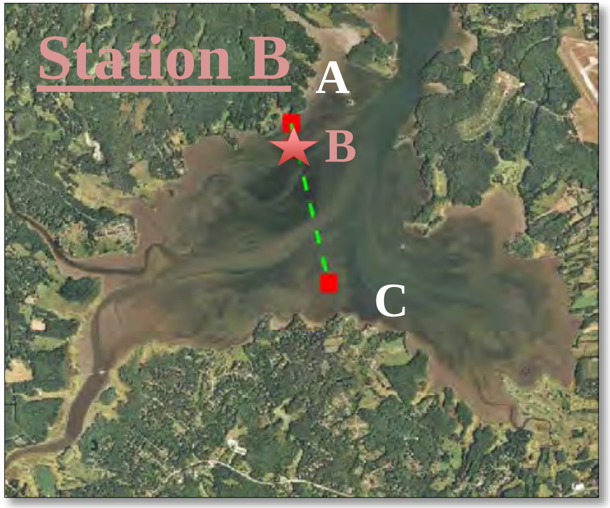
$$(\tau_b^y) = \rho_0 \left(\frac{\kappa}{\ln(z/Z_{ob})}\right)^2 v|v|$$

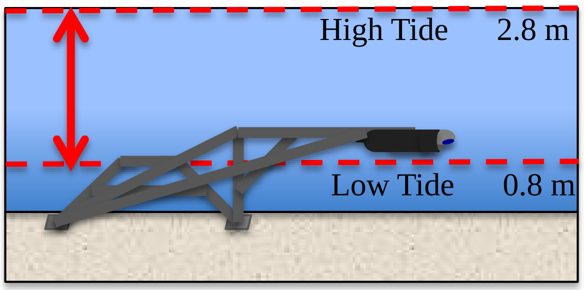


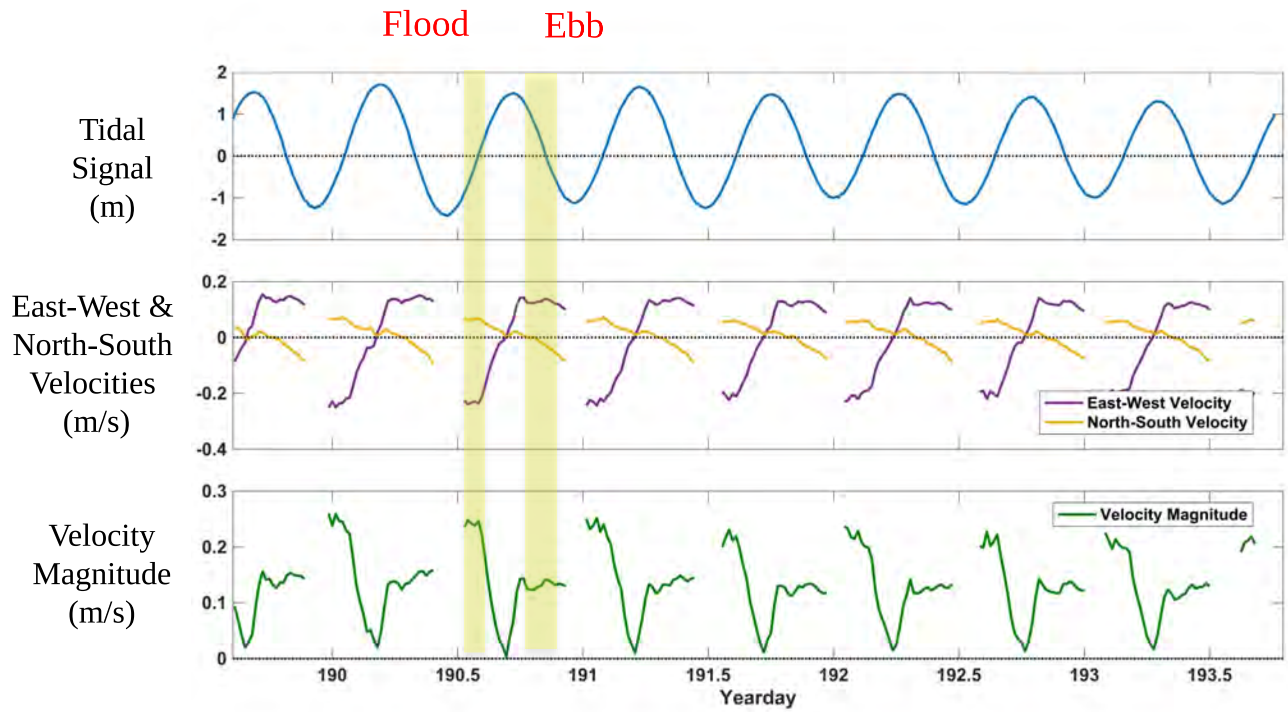
High Tide Low Tide

# Estimates of Shear Stress based on Observations

Kara Koetje, Diane Foster, Tom Lippmann




"Law of the Wall" Formulation

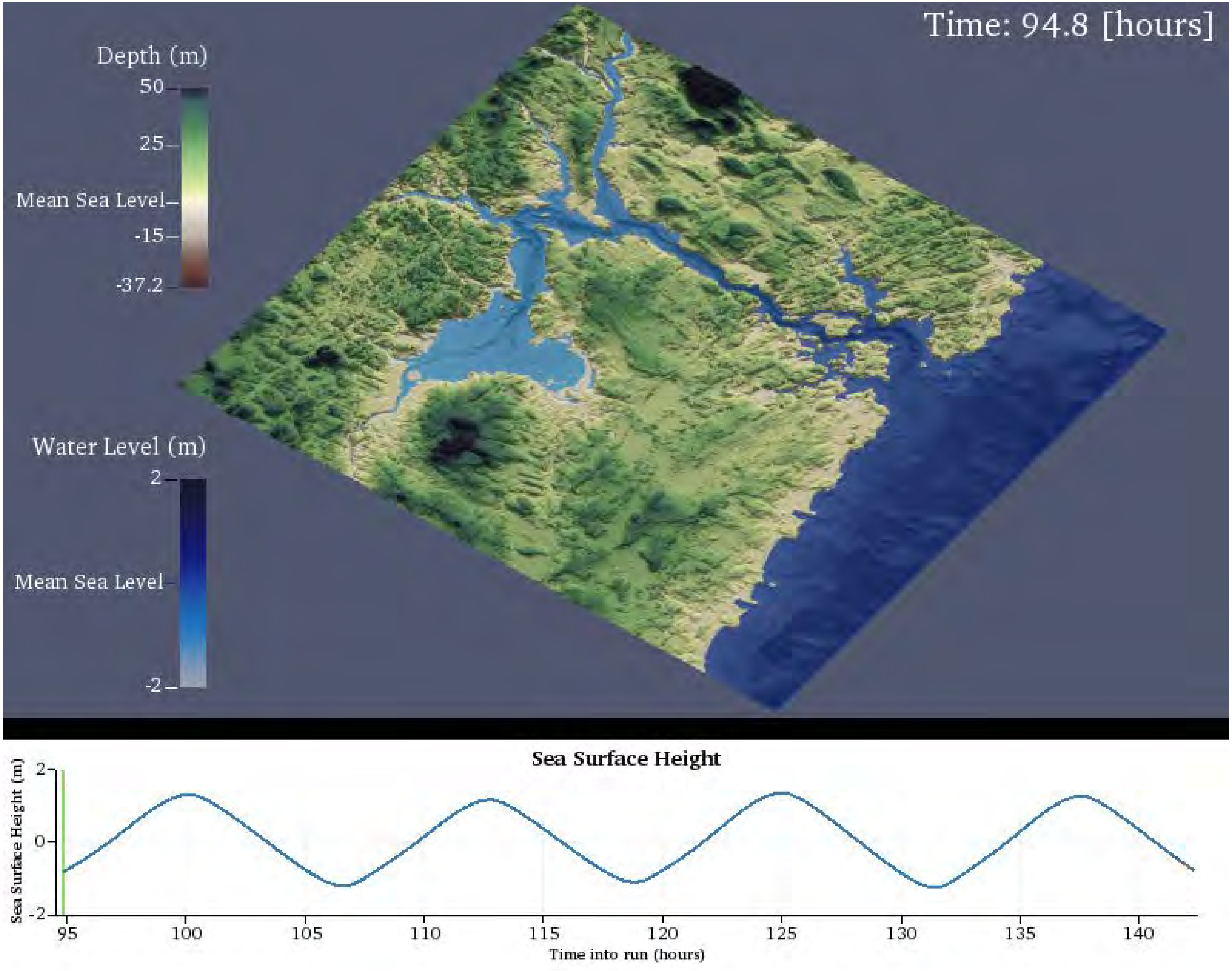
$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \Rightarrow u_* = \frac{du}{dz}\kappa z \Rightarrow \boxed{\tau = \rho u_*^2}$$

**Flood Shear Stress Estimate: 0.41 N/m$^2$**

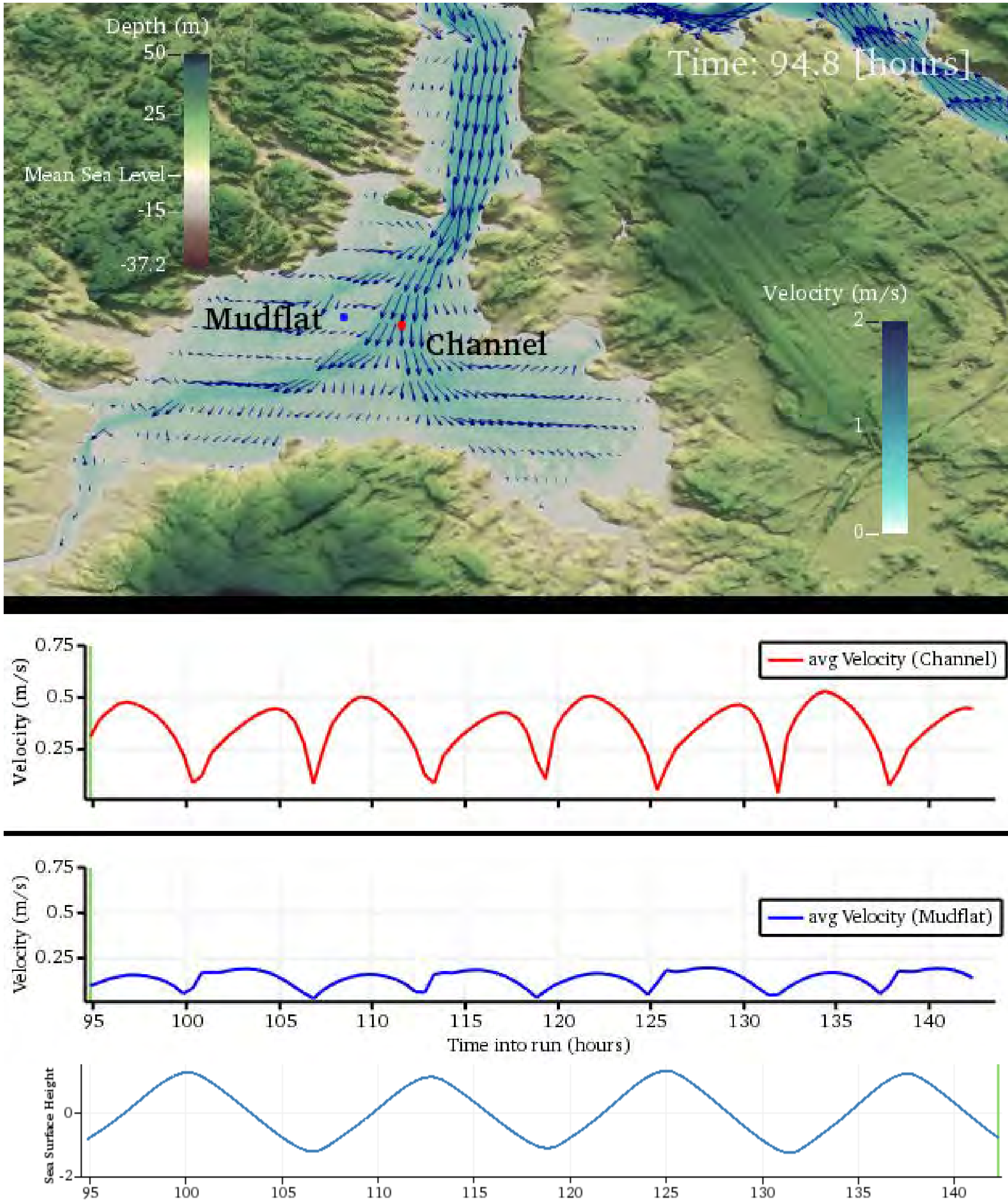
**Ebb Shear Stress Estimate: 0.23 N/m$^2$**

*Note: these observational estimates are preliminary*

# TIDAL SIGNAL



# VELOCITY MAGNITUDE/DIRECTION



# SHEAR STRESS

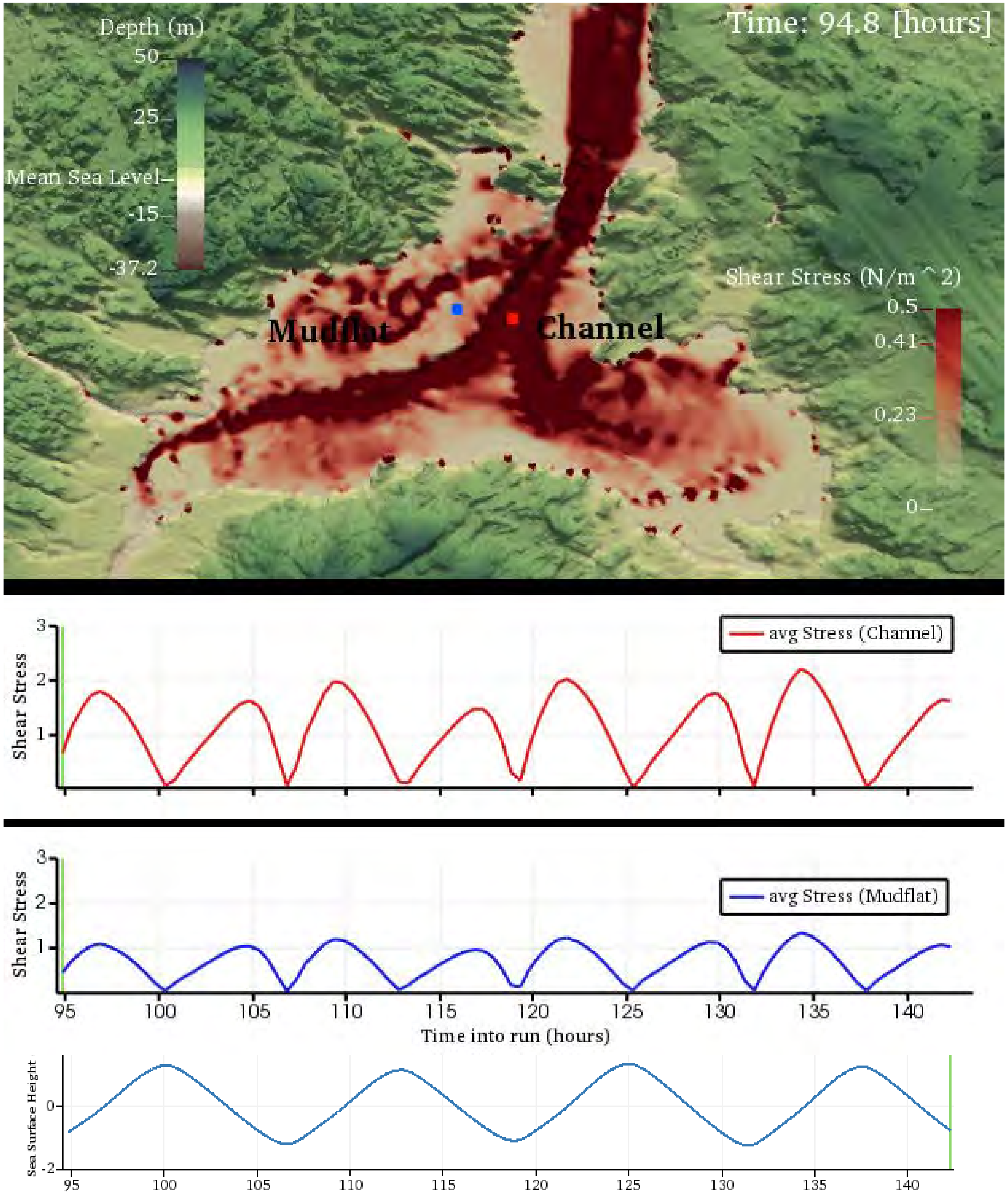
**Field Estimates**

Flood Tide ~ 0.41

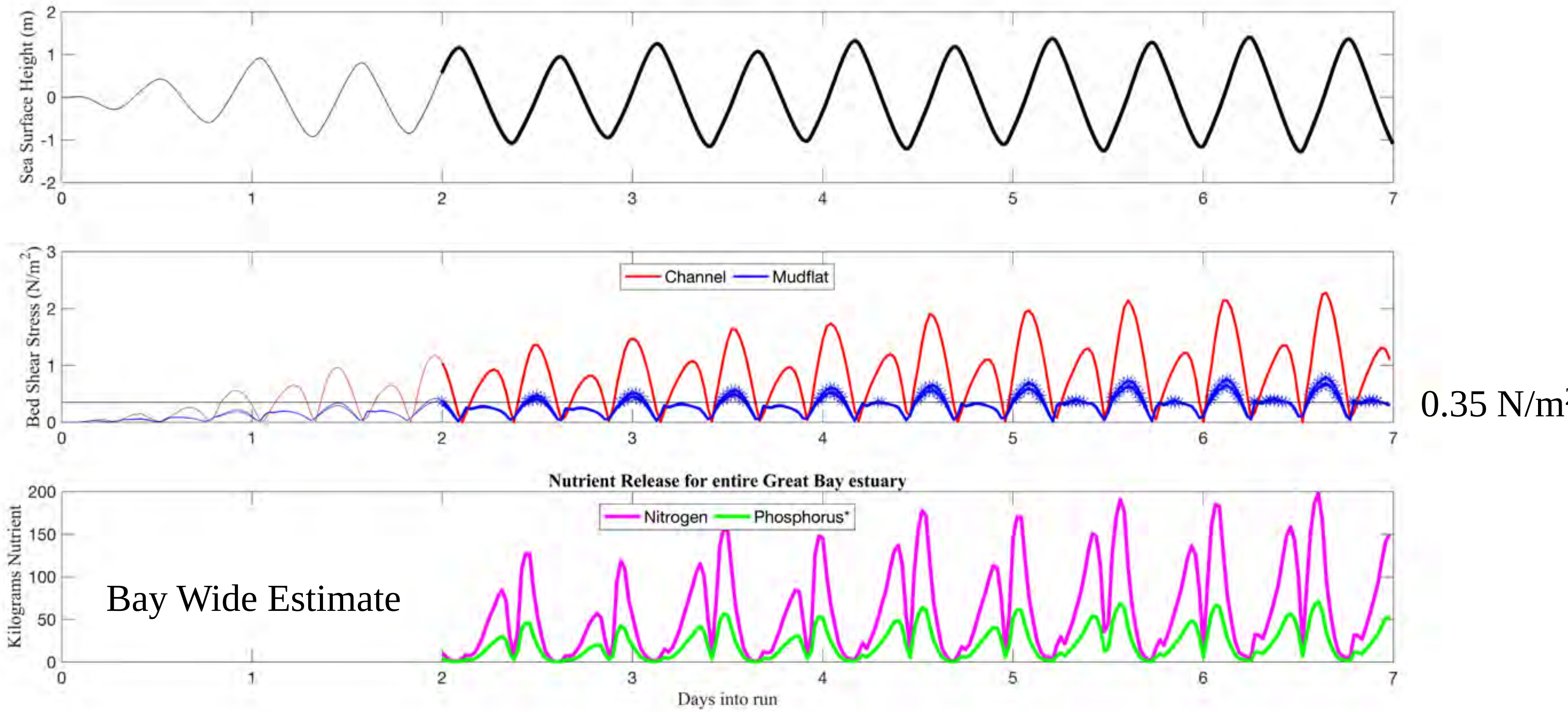
Ebb Tide ~ 0.23

**Lab Estimates**

Nutrient Release ~ 0.35



# Nutrient release over 5-day simulation




Nutrient Estimate:

Step 1: Area with > 50% mud fraction

Step 2: Area with shear stress > 0.35 N/m2

Step 3: Calculate Nutrient Load

# Nutrient Load :

Step 1: Area with > 50% mud fraction

Step 2: Area with shear stress > 0.35 N/m2

Step 3: Calculate Nutrient Load

| | Dissolved Inorganic Nitrogen (DIN) | Phosphorus (P) |
|---|---|---|
| | (kg/month) | (kg/month) |
| **River** [A]<br>(Fall, Sept-Nov) | 1,200 | 70 |
| (Winter, Dec-Feb) | 3,700 | 92 |
| (Spring, Mar-May) | 17,000 | 720 |
| (Summer, June-Aug) | 1,300 | 120 |
| **Sediments (modeled)** | **2880** | **1020*** |
| | (kg/event) | (kg/event) |
| **Event (Storm-Irene)** [B] | 220 | 80* |
| **One Tidal Cycle (Average)** | **96** | **34*** |
| **Neap Tide (Minimum)** | **13** | **5*** |
| **Spring Tide (Maximum)** | **123** | **44*** |

[A] Oczkowski (2002)

[B] Wengrove (2014)

* Based on results from Percuoco (2013). Uptake not considered for Phosphorus.

# Summary of Work

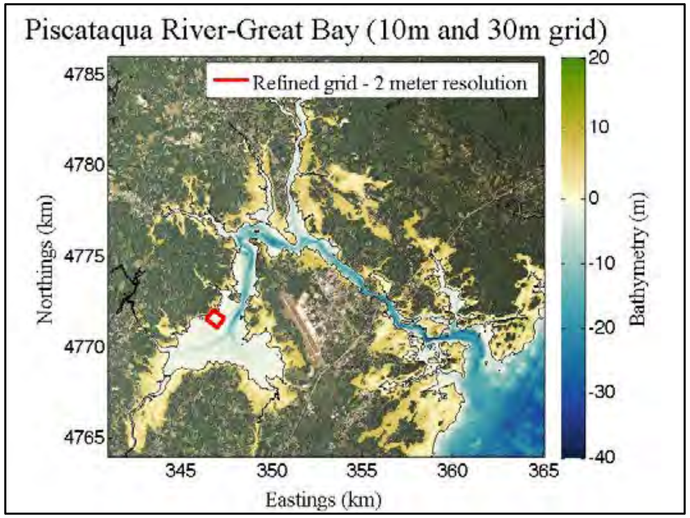
**Research Goal:** estimate the distribution of shear stress from tides and waves using a verified numerical model.

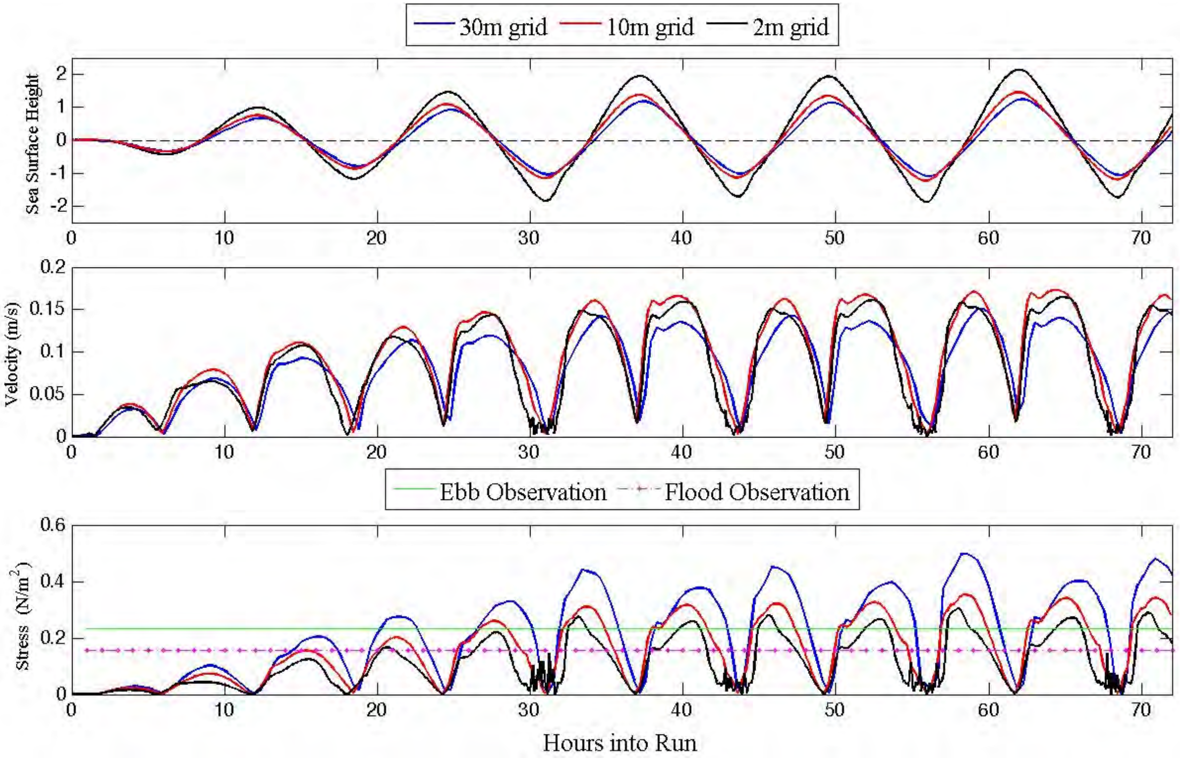
**Conclusion**: Sediment resuspension due to tides has been shown to be a **potentially significant source of nutrient release** during a typical tidal cycle

- Using a verified a numerical model for tidal/subtidal forcing
  - (Cook et.al., *Submitted May 2018/In Review - Ocean Modeling )*
- Estimate was based on observational estimates of shear stress during tidal cycle and lab studies
- Observations were of one location in the bay.
  - Need more observation-based estimates of shear stress on mudflats across the bay (~1-2 masters students)

# Future Work… sneak peak

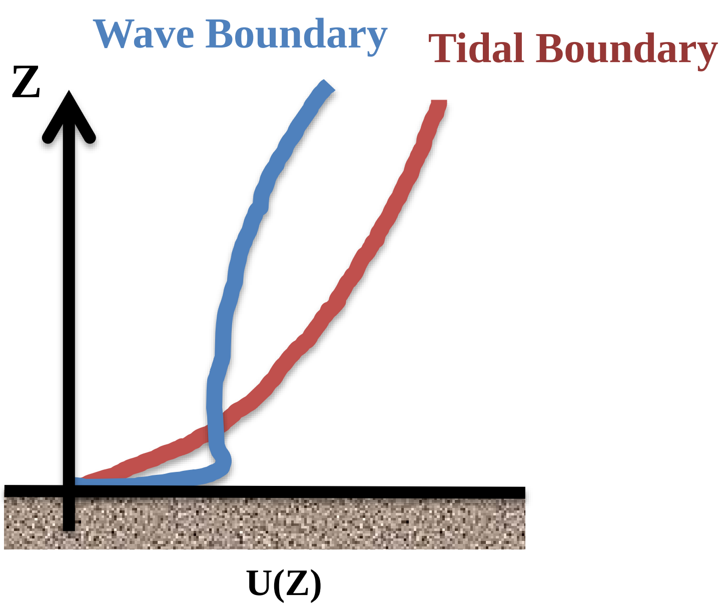
**Is there a model resolution that can accurately represent bed shear stress? If so, what is it?**



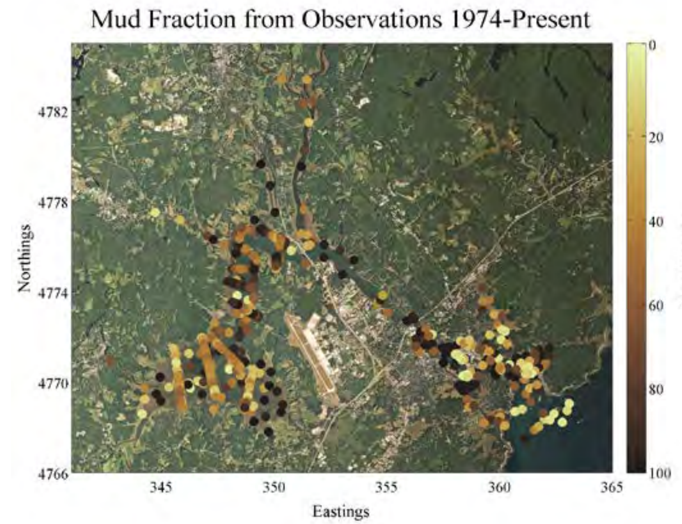



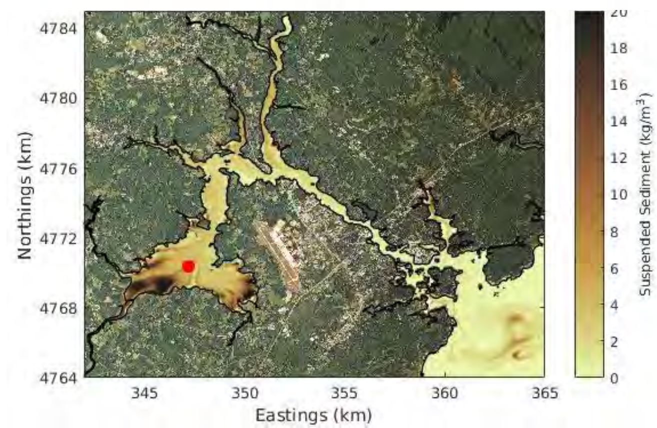

10 meter grid can only run on Blue Waters….

# … future work


## Sediment Transport




- More vertical levels (10? 15?)
- Relationship between horizontal resolution and $z_o$
- Waves!

# Future Work - Waves (Summer 2018)

**UNH Wave Tank**

**Capacitance Wave Gauge**

**Spotter Buoy**

**Great Bay, NH**

Jim Irish
Jamie Pringle (UNH)
Chris Sherwood (USGS)
Karl Kammerer (NOAA)
Kara Koetje
Diane Foster
Mark Van Moer
Jaehyuk Quak
and many others…

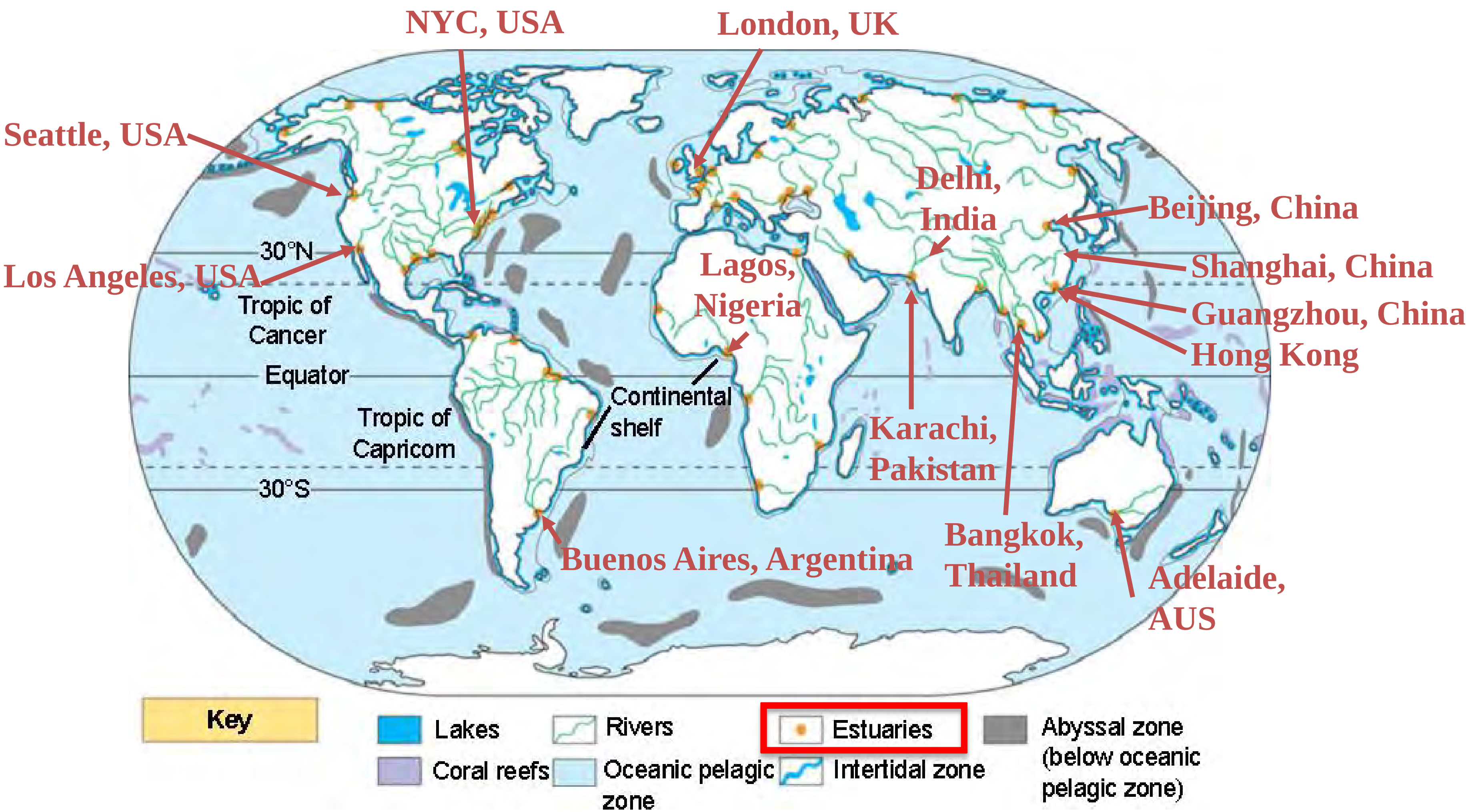
# Thank you!

*This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications.*

*Computations were performed on Trillian, a Cray XE6m-200 supercomputer at UNH supported by the NSF MRI program under grant PHY-1229408. (Jim Raeder)*

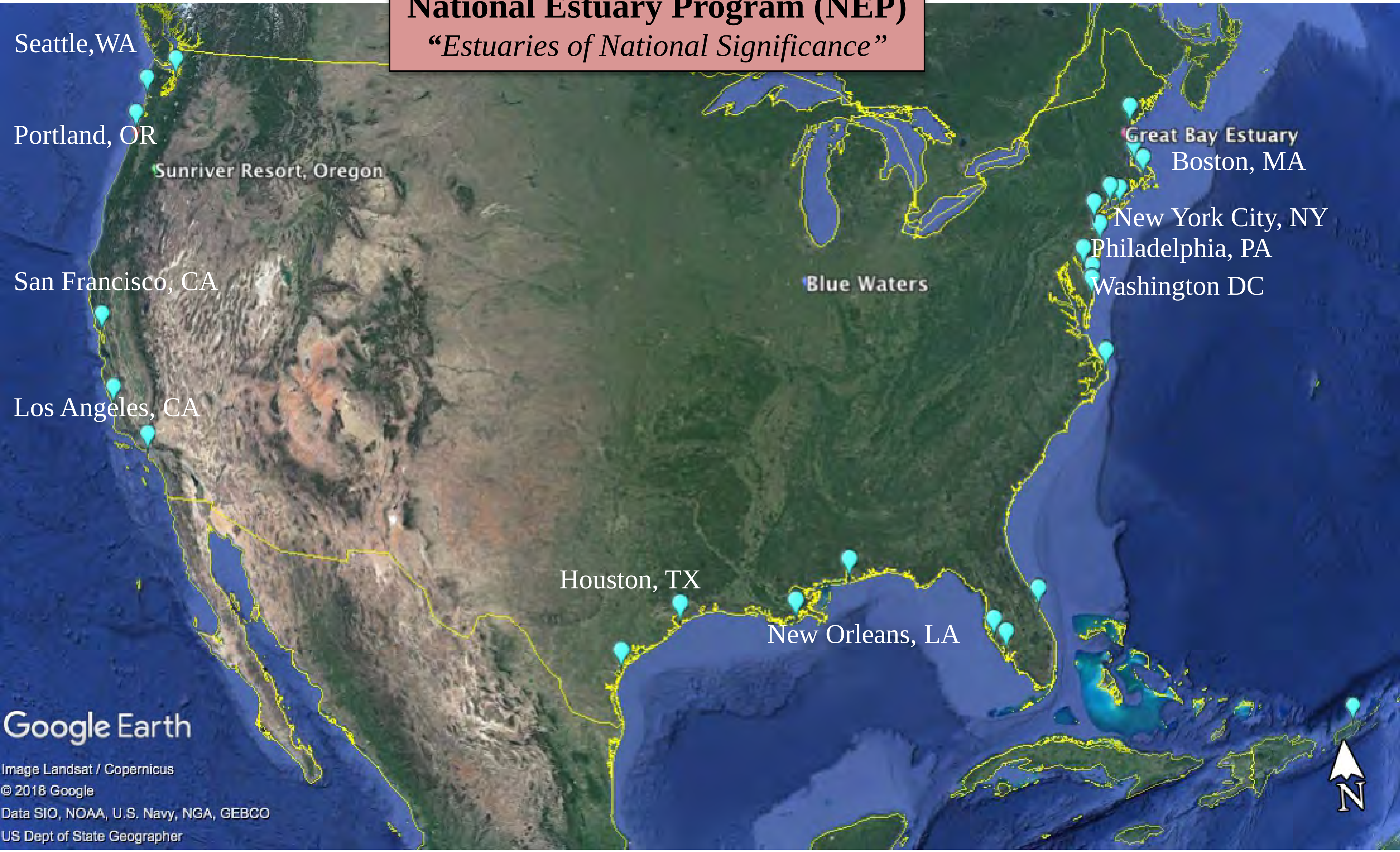
University of New Hampshire

# Estuaries distributed across the World



# National Estuary Program (NEP)

*"Estuaries of National Significance"*



# Future Application

- Oyster larval transport
- Nutrient budgets
- Sediment transport studies
- Eelgrass studies

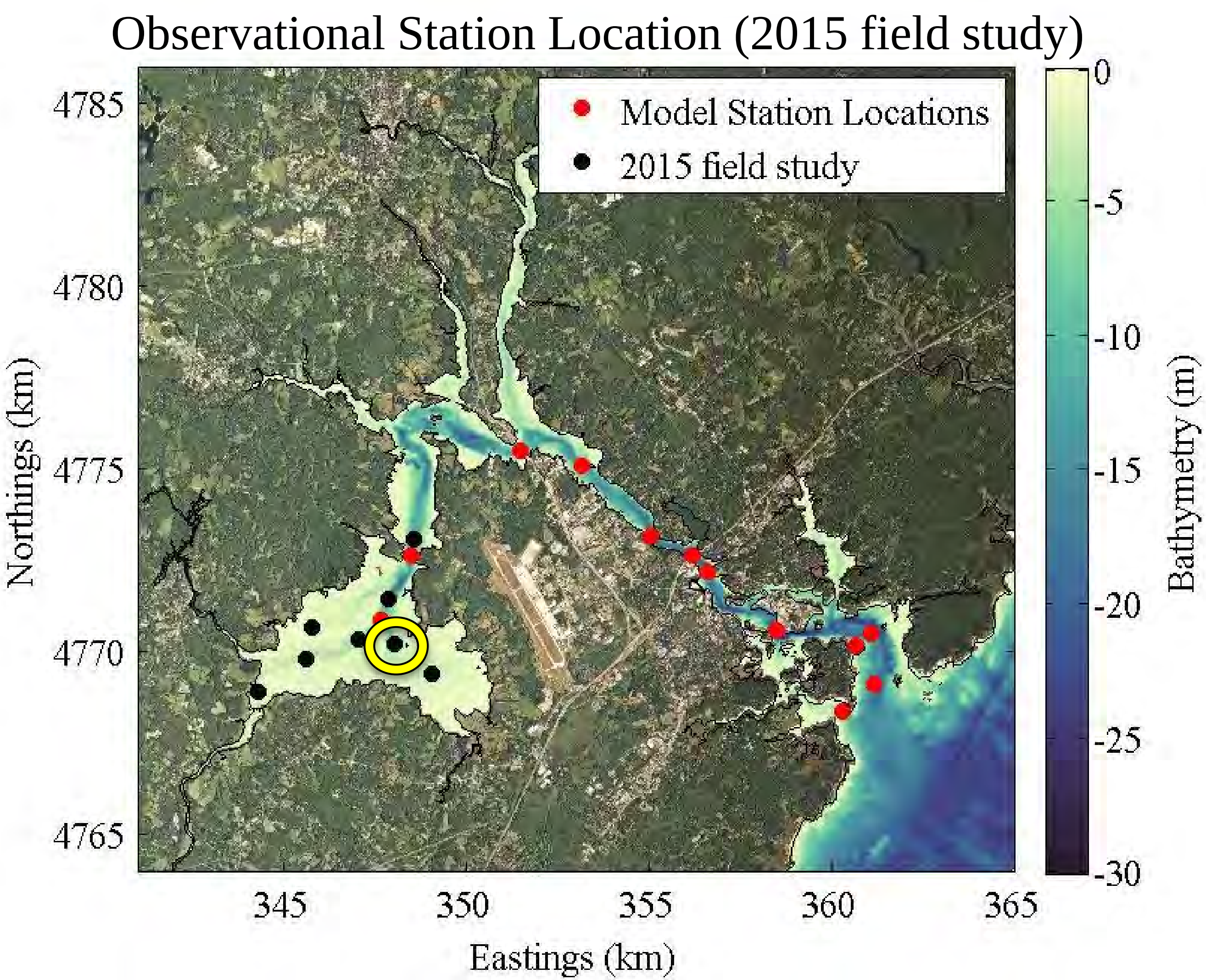
# How does the model perform?

- Tidal dissipation and nonlinear growth of the tides
- Vertical current structure follows observations
- Good for tides!
- Submitted a paper two weeks ago describing results

# TIDAL DISSIPATION

# Task #1: Implement and verify model

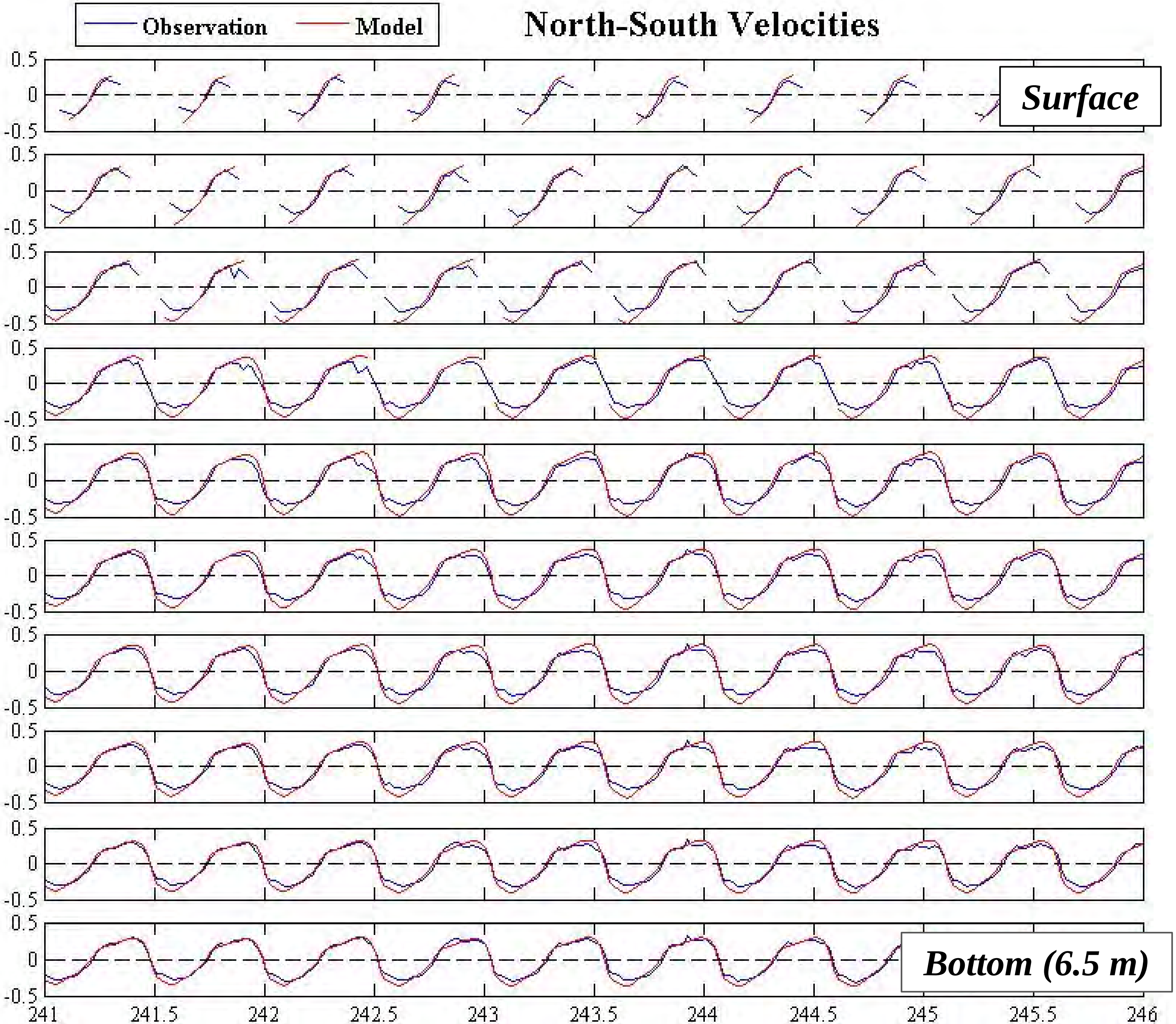
## Vertical Structure of the Currents

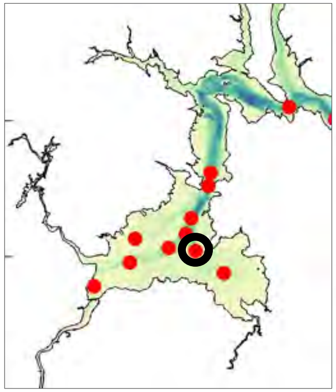


V

North-South Direction

± 0.5 m/s



# Some Blue Waters Stats…

- 30 meter run for 30 days
- 10 meter run for 30 days
- Run duration
- File size
-