Cheryl Ann Blain

Oceanography Division
Naval Research Laboratory
Stennis Space Center, MS

Spent 18 years at the Naval Research Laboratory building and leading a team ranging from 5-8 researchers and students.

Focused on development and application of unstructured grid models for coastal ocean dynamics and prediction.

Background in numerical methods and modeling of groundwater and surface water problems, with expertise in storm surge modeling.

Over the last 5-8 years, I’ve migrated into coastal, estuarine and river dynamics, data assimilation, and development of predictive systems.

The Naval Research Laboratory

The Navy’s Corporate Research Laboratory

Fundamental Research in Science and Engr.
Applied Research and Engineering
Transition of Tactical Products to Operations

Monterey, CA
- Marine Meteorology

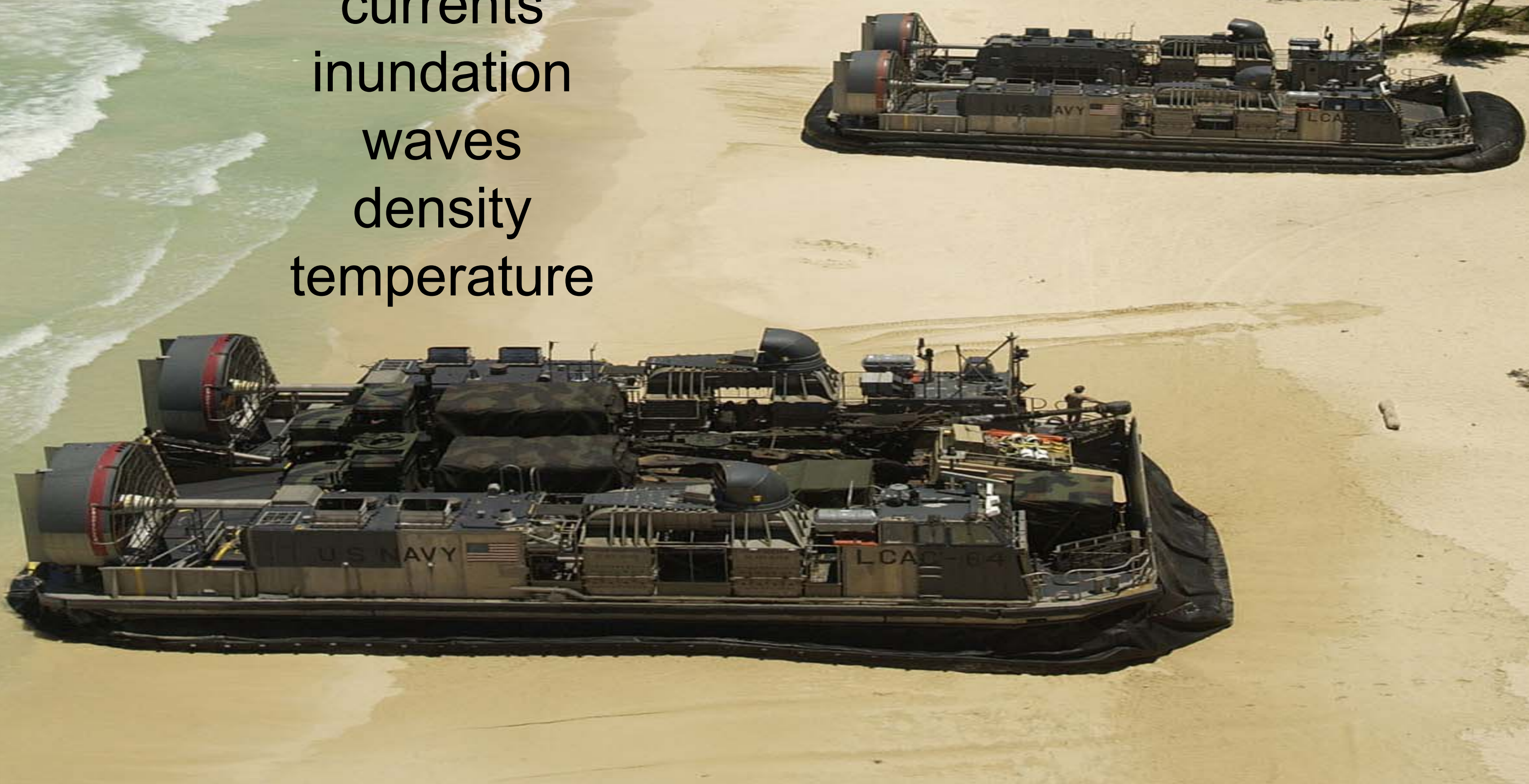
Washington, DC
- Chemistry
- Material Science
- Plasma Physics
- Remote Sensing
- Radar
- Optical Science
- Electronics
- Information Technology
- Space Science
- Bimolecular Science

Stennis Space Center, MS
- Oceanography
- Marine Geosciences
- Acoustics

Impact of the Coastal Environment on Navy Operations

Physical Parameters

water levels
currents
inundation
waves
density
temperature



Impact of the Coastal Environment on Navy Operations

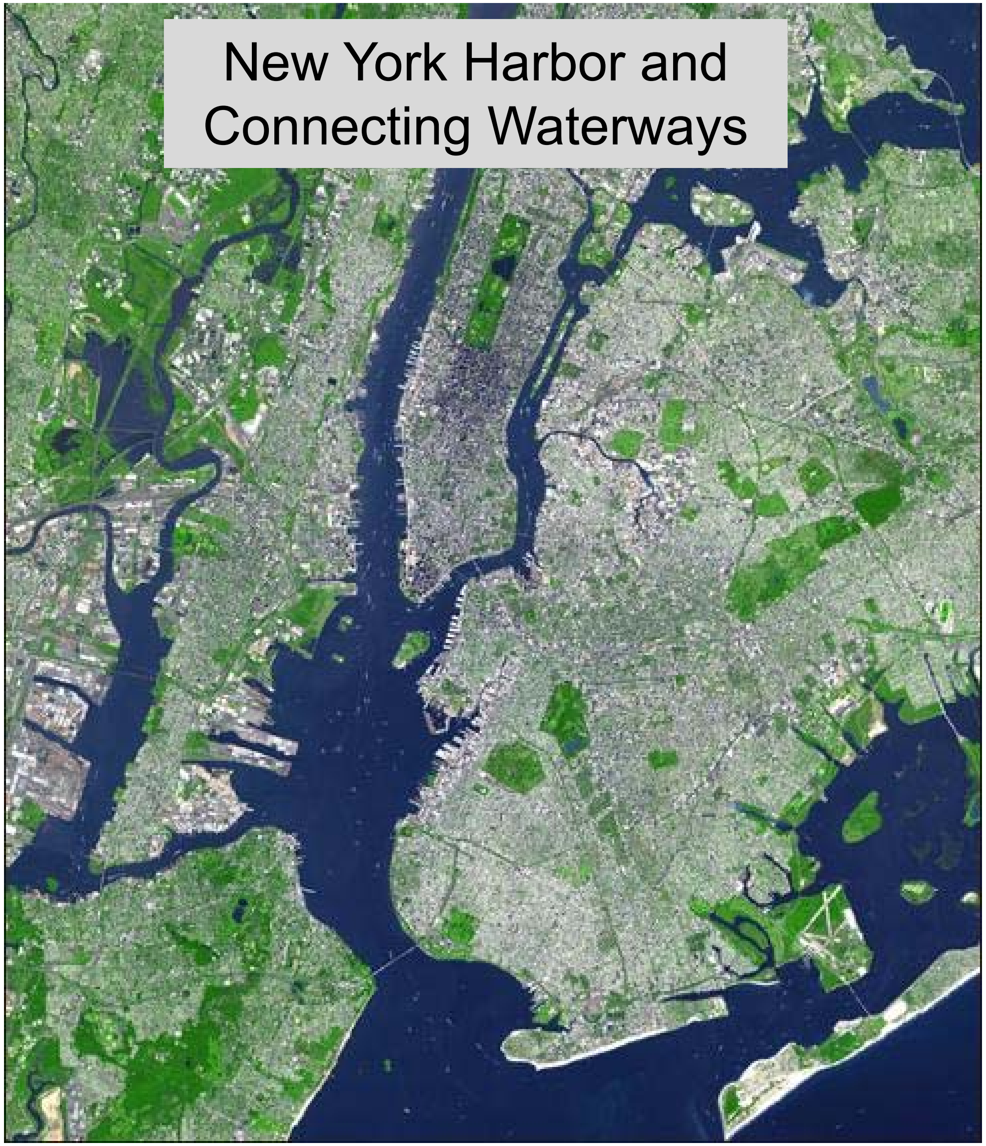
Military Operations

swimmers
diver visibility
beach trafficability
stability of landing craft
acoustic propagation
propulsion systems
AUVs






Challenges of the Coastal Environment

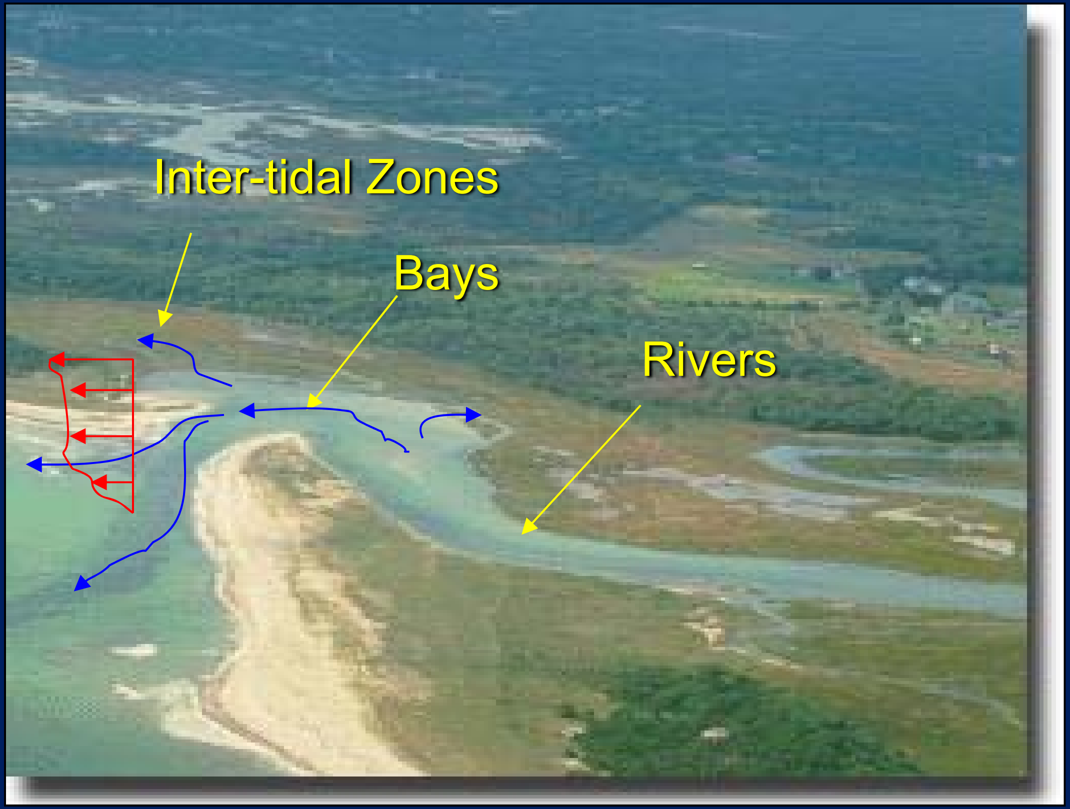


- Diversity and nonlinearity of the processes
- High spatial and temporal variability
- Wide range of scales – hours to days, meters to km
- Complex shorelines and waterway geometry
- Lack of high resolution data (in space and time)
  - bathymetry
  - topography
  - real-time river fluxes
  - atmospheric fluxes
  - wind stress

What can we do?

Predictive Capability for Coastal Circulation

- High resolution (meters) currents and water levels in littoral environments that include bays, inter-tidal marshes and rivers



ADCIRC Model

- 3D dynamics
- Forcing from tides, wind, waves, buoyancy, and rivers
- Shoreline inundation/recession
- Utilizes unstructured grids (based on finite elements)
- MPI parallelization

A Numerical Tide and Storm Surge Model

ADCIRC

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Pan-American Studies Institute, PASI
Universidad Técnica Federico Santa María,
2–13 January, 2013 — Valparaíso, Chile

A Numerical Tide and Storm Surge Model

ADCIRC

Outline

1) Description, features and solution strategy
2) Motivation for the GWCE equation
3) Finite element discretization
4) Governing equations
5) Representation of tidal forcing
6) Computational efficiency
7) Coupled dynamics
8) Coastal tide and wave-tide applications
9) Background for the lab exercises

ADCIRC Overview

- ADCIRC is an evolving framework to compute flow and transport in coastal oceans, shelves, estuaries, inlets, floodplains, rivers and beaches
- Specifically solve for “long wave” circulation which assumes that horizontal scales of motion are greater than the vertical scales of motion
- Applications
  - Coastal inundation due to tides and hurricanes
  - Navigation
  - Sediment movement
  - Pollutant transport
  - Fisheries

ADCIRC Overview

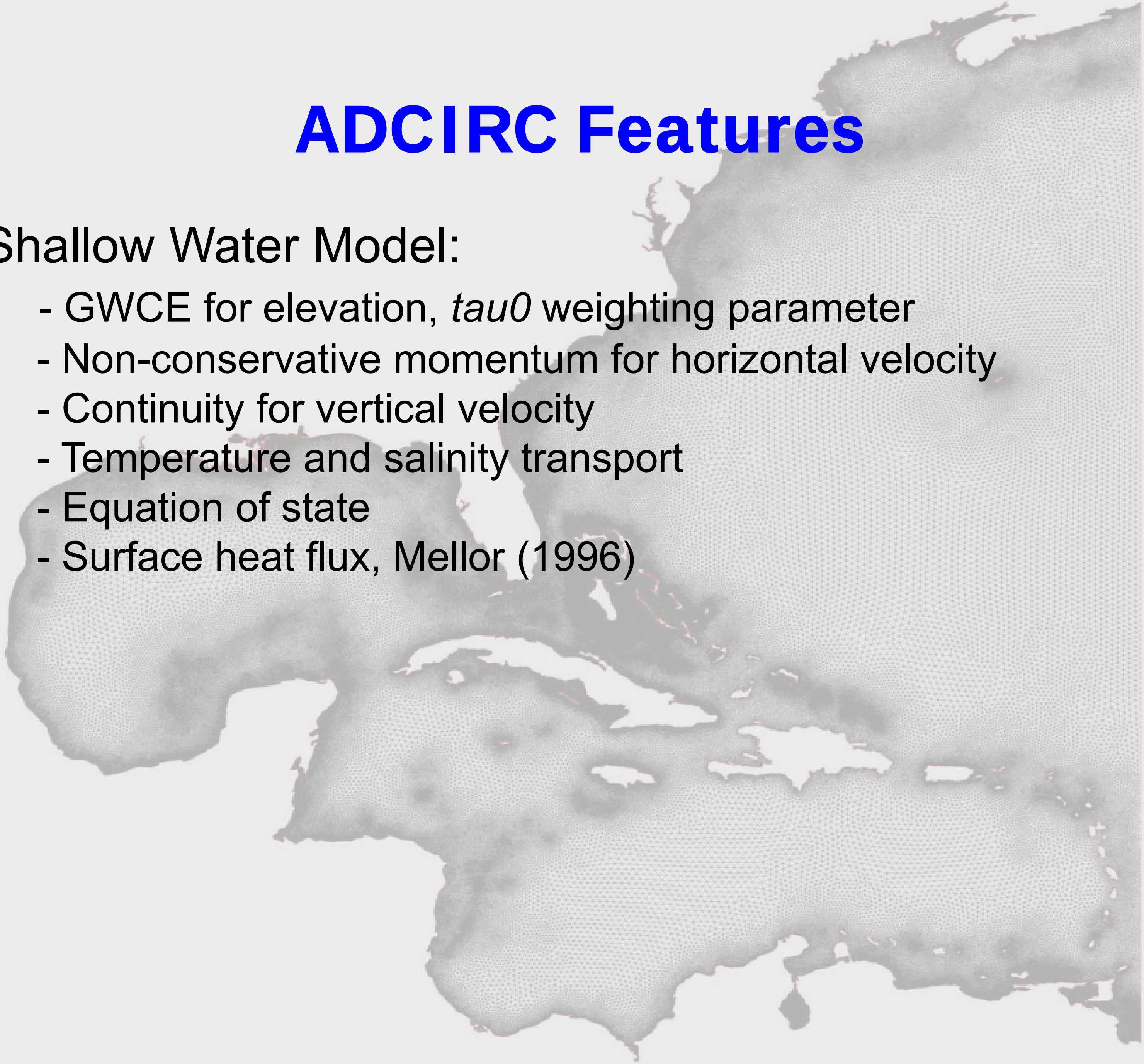
- ADCIRC has been extensively verified and validated
  - Verification: Prove that the code is solving the stated partial differential equations
  - Validation: Prove that the code is able to simulate flows correctly by comparing to measured data

- ADCIRC applications
  - ADCIRC is used for tidal and wind driven coastal ocean calculations worldwide by the U.S. Army and Navy
  - Study domains range from basin scale to inlets and rivers
  - Processes vary from tides, wind driven flow, density driven flow, sediment transport, to constituent transport

http://www.adcirc.org/Related_publications.html

ADCIRC Features

- Shallow Water Model:
  - GWCE for elevation, *tau0* weighting parameter
  - Non-conservative momentum for horizontal velocity
  - Continuity for vertical velocity
  - Temperature and salinity transport
  - Equation of state
  - Surface heat flux, Mellor (1996)



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- Discretization:
  - linear Galerkin finite elements in horizontal
  - generalized sigma coordinate in vertical
  - z-level computations of baroclinic pressure gradient
  - finite difference in time (2nd order)
  - mode splitting

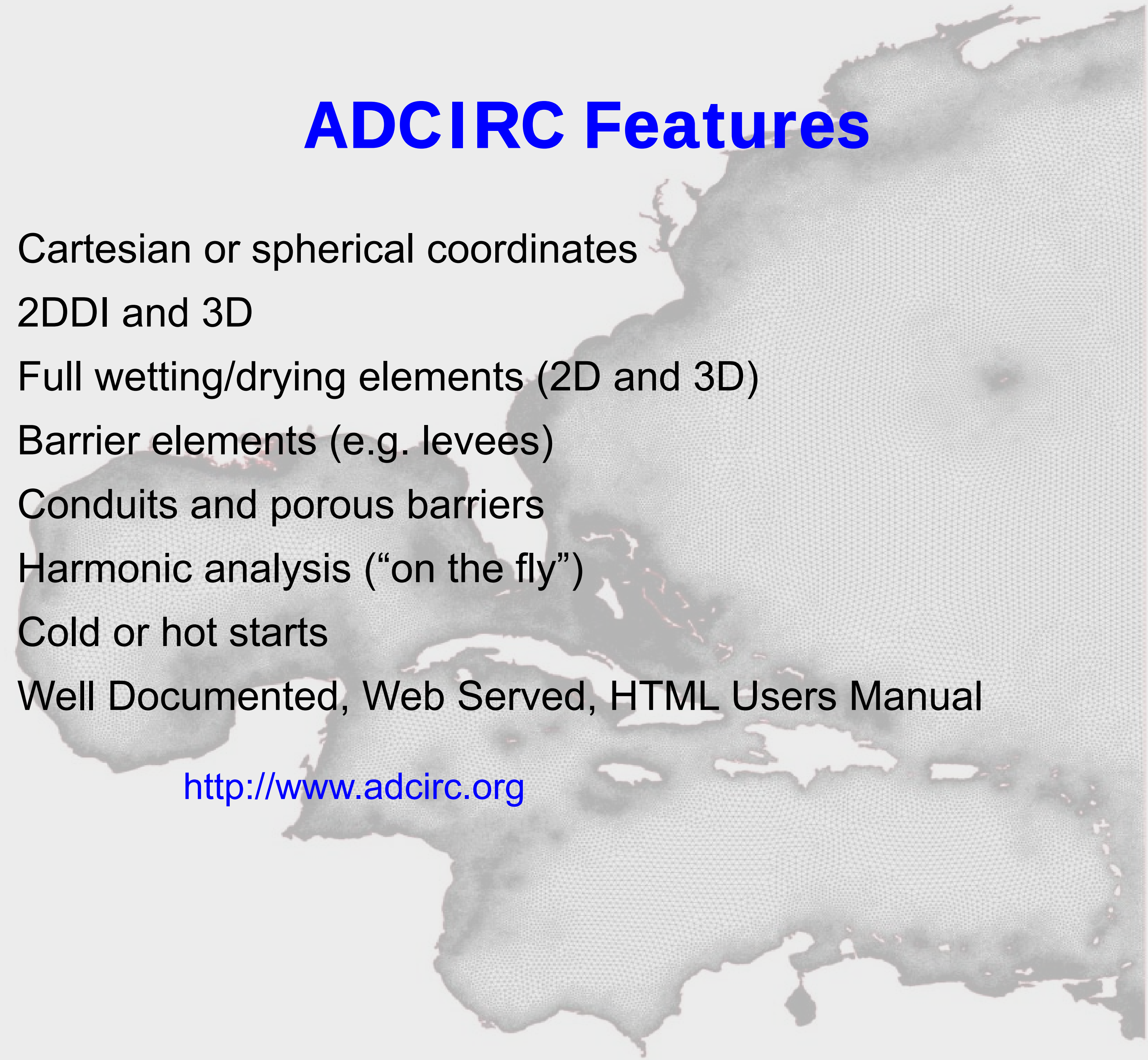
ADCIRC Features

- ADCIRC accommodates the following forcing functions
  - Gravity
  - Tidal potential
  - Earth load/ self-attraction tide
  - Wind and atmospheric pressure
  - Elevation, flow and radiation boundary conditions
  - Dynamic coupling with hydrologic, wave and sediment models

ADCIRC Features

- Cartesian or spherical coordinates
- 2DDI and 3D
- Full wetting/drying elements (2D and 3D)
- Barrier elements (e.g. levees)
- Conduits and porous barriers
- Harmonic analysis (“on the fly”)
- Cold or hot starts
- Well Documented, Web Served, HTML Users Manual

http://www.adcirc.org



Solution Strategy

- Apply GWCE based reformulation of the shallow water equations prior to any numerical discretization

- GWCE = Generalized Wave Continuity Equation
  - Manipulation of governing Shallow Water Equations (SWE)

$$\frac{\partial(PCE)}{\partial t} + \tau_0(PCE) - \nabla \cdot M_c = 0$$

where *PCE* is the primitive continuity equation and M_c is the conservative momentum equation

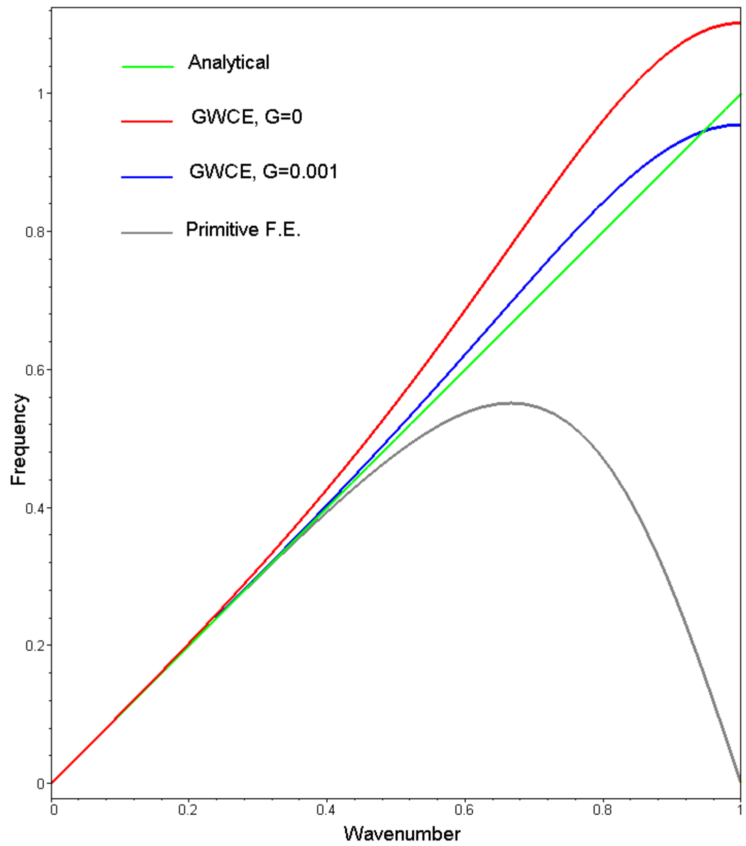
A parameter controls the relative weight of the primitive continuity equation,

$\tau_0 \rightarrow 0$ Pure wave equation

$\tau_0 \rightarrow \infty$ Pure continuity equation

Solution Strategy

- The full primitive solution leads to a folded dispersion curve
  - Low wavenumber (long wave) physical wave
  - High wavenumber (short wave) spurious wave (noise)



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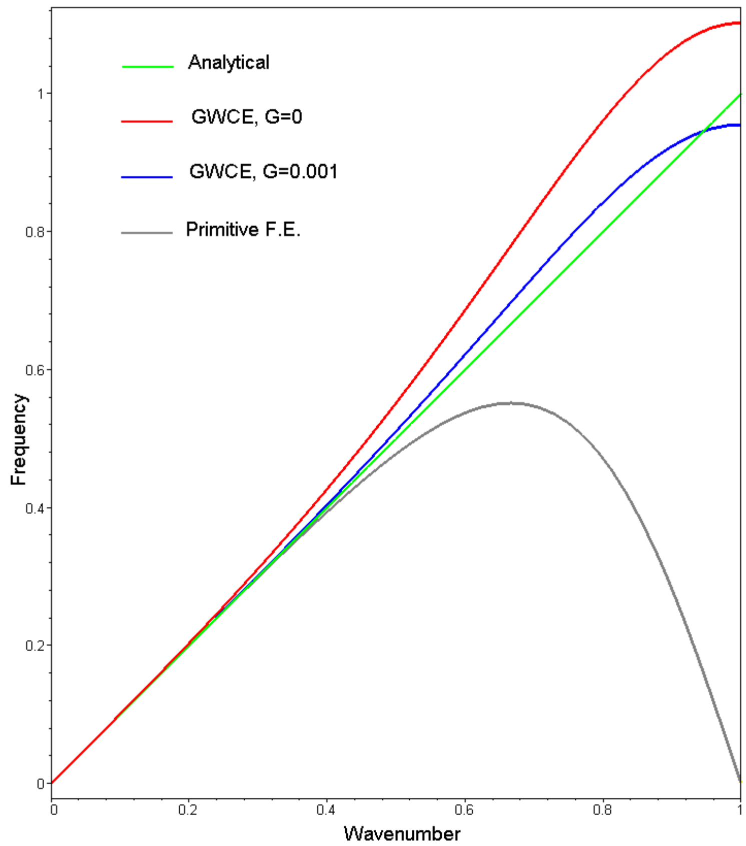


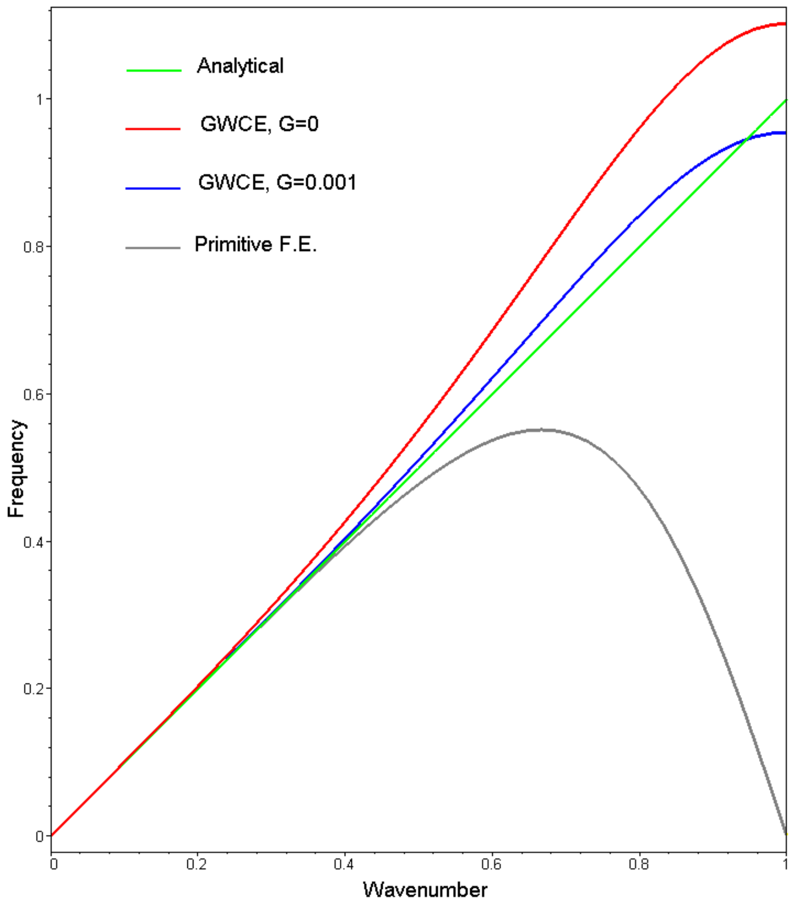
Use of the GWCE, instead of the primitive continuity equation, solved in conjunction with the momentum equations, yields a monotonic dispersion curve

– Only a low wavenumber (long wave) physical wave

– Monotonic dispersion relationship prevents generation of spurious oscillations

Solution Strategy

- Effect of parameter selection
  - too low, poor local mass conservation
  - too high, folded dispersion curve, spurious modes



Correct selection of range is related to the local frictional balance

$$1 \leq \frac{\tau_0}{\tau_{\max}} \leq 10$$

where $\tau_{\max} = \max \left| C_d \frac{\sqrt{u^2 + v^2}}{H} \right|$

Solution Strategy

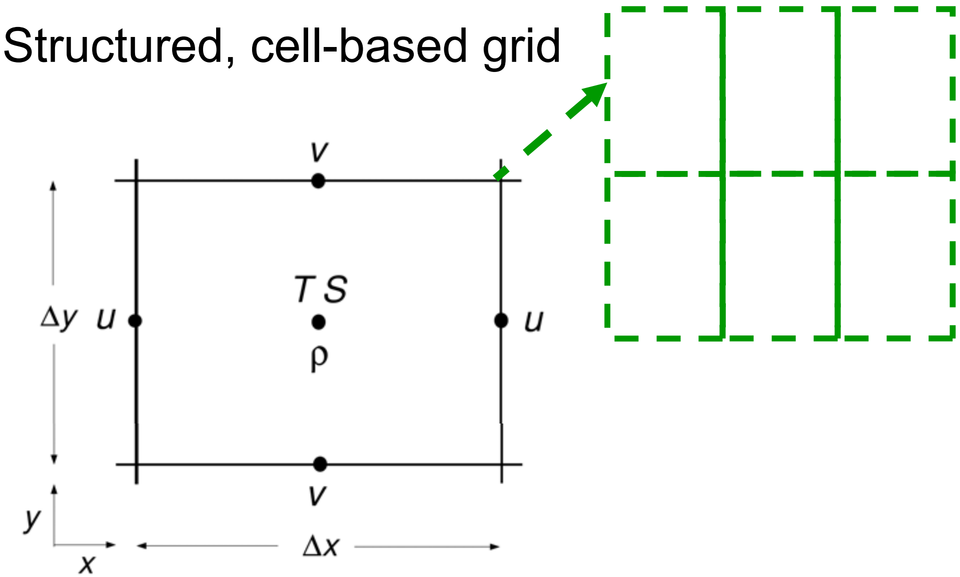
- ADCIRC GWCE solution is functionally equivalent to EDF's TELEMAC model
  - TELEMAC is based on the quassi-bubble (QB) algorithm which enriches the velocity field with one extra node per element

- If we select, $\tau_0 = \dfrac{i\omega + 3\tau}{2}$ then the GWCE and QB scheme
  - Have identical truncation terms up to fourth order
  - The dispersion curves are almost identical
  - Results are almost identical

Two Discrete Approaches

Finite Difference

Structured, cell-based grid



Arakawa-C grid

- Staggered variables
    - *T,S,p,h* at cell center
    - *u,v* at opposing cell edges

Methodology

- approximate the derivatives in the governing equations

Advantages

- simple to implement
- generally efficient
- easy to derive accuracy

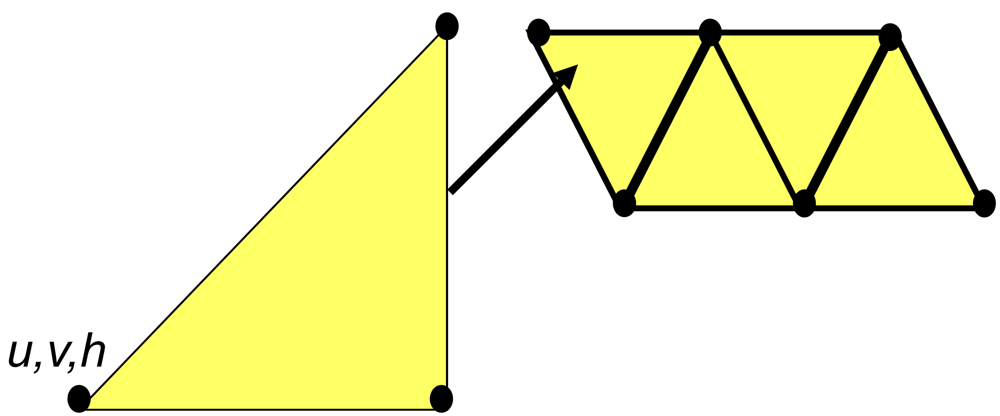
Disadvantages

- difficult to fit arbitrary geometry
- difficult to implement derivative boundary conditions
- difficult to refine critical regions

Two Discrete Approaches

Finite Element

Unstructured, variable resolution mesh



Triangular Element

• Vertex-defined variables

Methodology

• approximate the unknowns over discrete elements and minimize the global error of the solution

Advantages

• highly flexible mesh
• simple boundary condition implementation
• good accuracy characteristics

Disadvantages

• conceptually more complex
• computationally more expensive

Solution Strategy

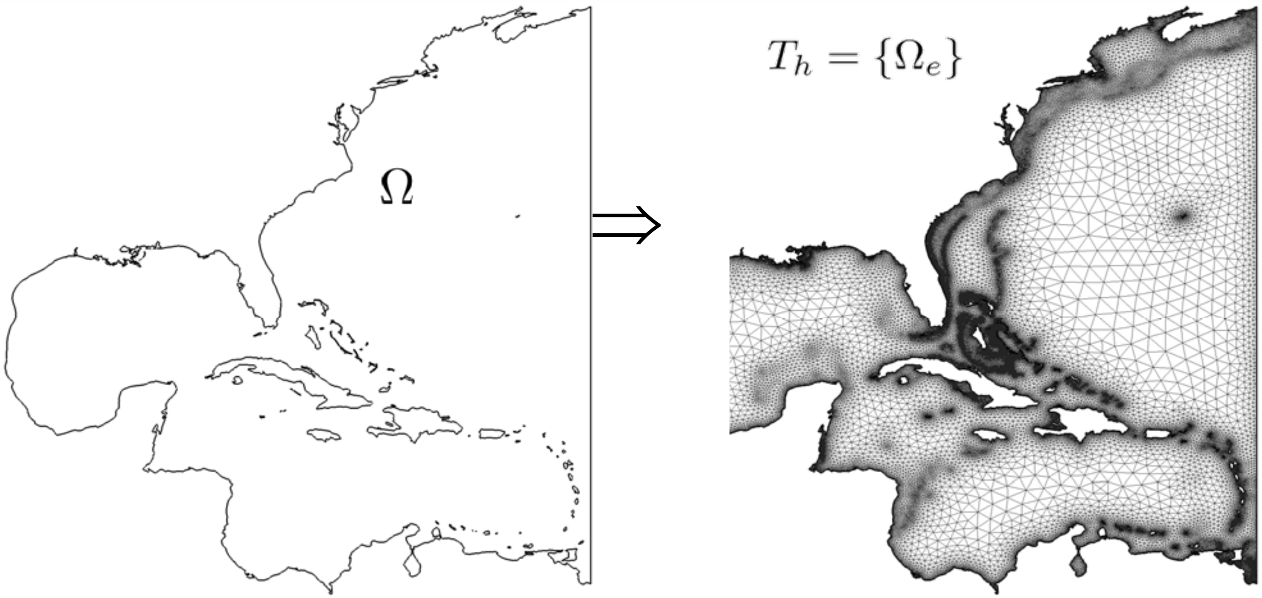
- Accurate solutions require discrete points to be closely spaced where the solution varies rapidly

- ADCIRC's Finite Element based solution strategy allows for a very large numbers of discrete points to be placed in a highly flexible unstructured manner

  – Provide localized refinement to the degree required improving accuracy while minimizing computational cost

  – Allows the definition of large domains to simplify the specification of boundary conditions and to improve the accuracy of the results due to improved exchange

Finite Element Discretization



- Use a weak (or variational) form of the problem.
- Given a finite element partition T_h of Ω, multiply by a test function *v* and integrate over the elements:

$$\int_{\Omega_e} \frac{\partial u}{\partial t} v d\Omega + \int_{\Omega_e} \nabla \cdot \mathbf{F} v d\Omega = \int_{\Omega_e} s v d\Omega \qquad (1)$$

- Apply Galerkin method on linear triangular elements, C^0 functional continuity

Temporal Solution Strategy

- Three level implicit time discretization of the GWCE
- Two level implicit Crank-Nicolson time discretization of the momentum equations
  - Except advection terms which are treated explicitly

Governing Equations for ADCIRC 2DDI

Generalized Wave Continuity Equation

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} - \mathbf{q}\nabla\cdot\tau_0 - \nabla\cdot\left\{\nabla\cdot(\mathbf{q}v) + \mathbf{f}\times\mathbf{q} + \tau_0\mathbf{q} + H\nabla\left[\frac{p_a}{\rho_0} + g(\zeta - \alpha\eta)\right] - \frac{\boldsymbol{\tau}_s + \boldsymbol{\tau}_b}{\rho_0} - \varepsilon\nabla^2(\mathbf{q})\right\} = 0$$

for $\mathbf{q} = H\mathbf{v}$

Non-conservative Momentum Equation

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\nabla\cdot(\mathbf{v}) + \mathbf{f}\times\mathbf{v} + \nabla\left[\frac{p_a}{\rho_0} + g(\zeta - \alpha\eta)\right] - \frac{\boldsymbol{\tau}_s + \boldsymbol{\tau}_b}{\rho_0 H} - \frac{\varepsilon}{H}\nabla^2(H\mathbf{v}) = 0$$

Acceleration

Advection

Coriolis

Atmos. Pressure

Gravity

Tides

Surface stress wind/waves

Bottom Stress

Momentum dispersion

Governing Equations for ADCIRC 2DDI

Newtonian Equilibrium Tidal Potential

$$\eta(\lambda,\phi,t)=\sum_{n,j} C_{jn} f_{jn}(t_0) L_j(\phi) \cos[2\pi(t-t_0)/T_{jn} + j\lambda + V_{jn}(t_0)]$$

λ, ϕ - degrees longitude and latitude

j= 0,1,2 - tidal species [j=0 declinational, j=1 diurnal, j=2 semi-diurnal

C_{jn} - Amplitude of constituent *j*, species *n*

$f_{jn}(t)$ – time dependent nodal factor

$L_0 = 3\sin^2(\phi)-1$

$L_1 = \sin(2\phi)$

$L_2 = \cos^2(\phi)$

T_{jn} - Period of constituent *j*, species *n*

V_{jn}(t) - Period of constituent *j*, species *n*

α = effective Earth elasticity factor (0.69)

Computational Efficiency

- Algorithmic and code design criteria
  - Very low numerical damping model allows model parameters to be based on physically relevant values
  - At least second order accurate
  - Robust and stable
  - Modular

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- Highly Efficient Code
  - Loop-level Optimization
  - Temporal –Fully Implicit Time Marching available
  - Single thread and parallel versions yield same solution to machine precision
  - Spatial – Parallel Computing
  - Domain Decomposition
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- Linear speed up or better on 256+ processors
- Operates at more than 1 gigaFLOPS per processor on a Cray XT3

ADCIRC-SWAN Coupling

‘Tight’ Coupling of SWAN+ADCIRC:

- Models use same unstructured mesh
- Information passed dynamically through local cache
- Coupled model is efficient to 1000s of computational cores
- SWAN is as accurate as other, structured-mesh wave models

Current Features:

- Swell Propagation on Fine Meshes
- Integral Coupling of Bottom Friction
- Wind Drag Based on Storm Sectors
- Controlling Errors with Limiters on Spectral Propagation Velocities

ADCIRC-SWAN Coupling

Simulating WAves Nearshore (SWAN):

- Solves the action balance equation:

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} \cdot \left[\left(\vec{c}_g + \vec{U} \right) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = \frac{S_{tot}}{\sigma}$$

Passing of Radiation Stress Gradients:

- Integrate action density to get radiation stresses:

$$S_{xx} = \rho_0 g \iint \left(n \cos^2 \theta + n - \frac{1}{2} \right) \sigma N d\sigma d\theta$$

$$S_{xy} = \rho_0 g \iint \left(n \sin \theta \cos \theta \right) \sigma N d\sigma d\theta$$

$$S_{yy} = \rho_0 g \iint \left(n \sin^2 \theta + n - \frac{1}{2} \right) \sigma N d\sigma d\theta$$

"Tight Coupling"

- Pass the gradients as surface stresses to ADCIRC:

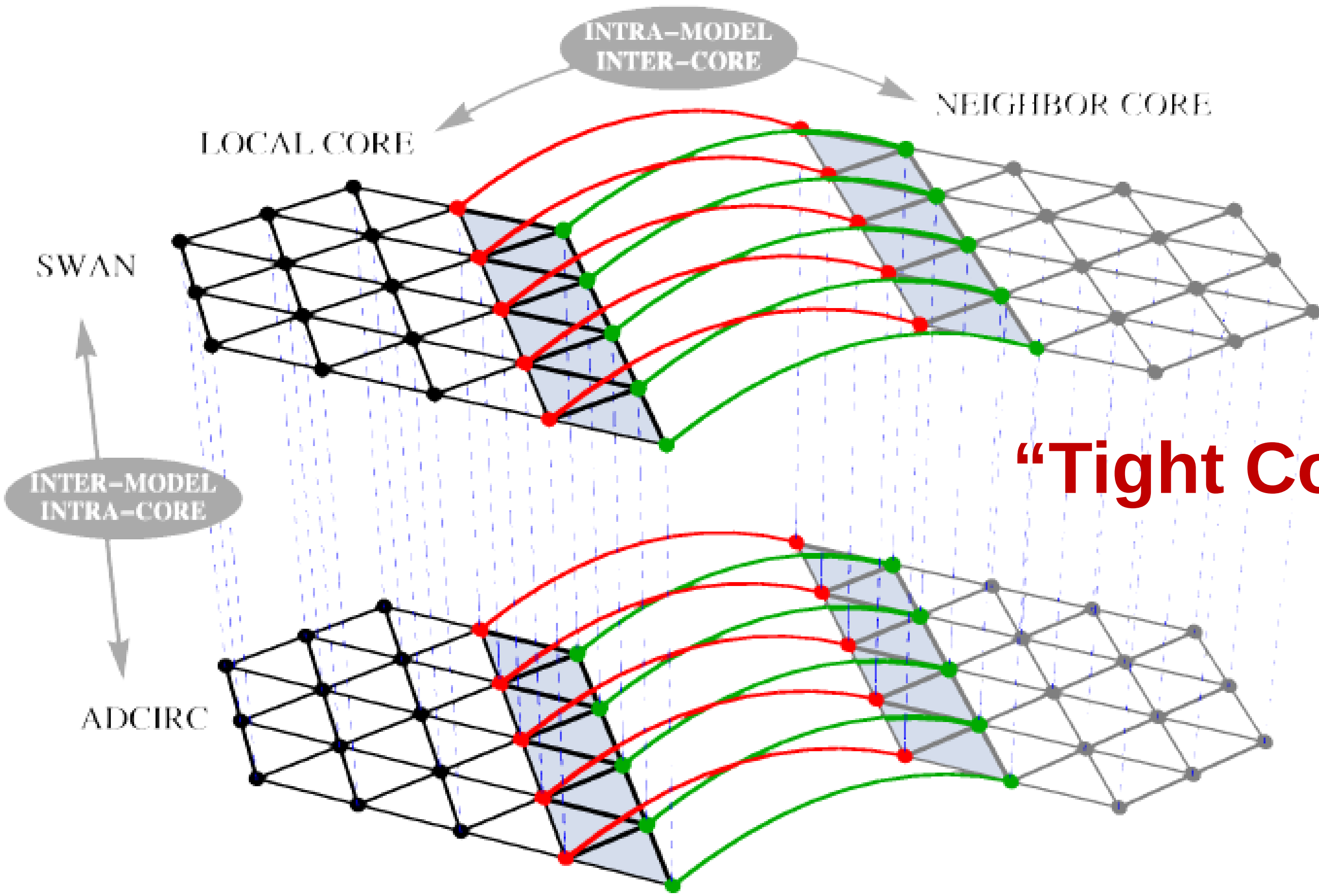
$$\tau_{sx,waves} = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}$$

$$\tau_{sy,waves} = -\frac{\partial S_{xy}}{\partial x} - \frac{\partial S_{yy}}{\partial y}$$

ADCIRC-SWAN Coupling

Simulating WAves Nearshore (SWAN):

- Communication is optimized for high-performance computing:

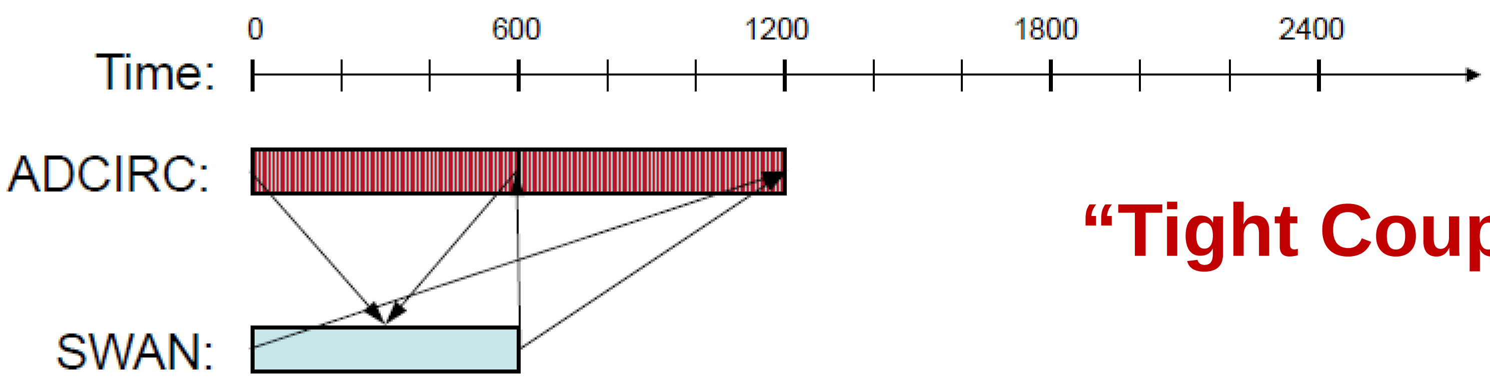


"Tight Coupling"

ADCIRC-SWAN Coupling

Schematic of Coupling:

- ADCIRC is run for 600 seconds (Δt = 1 sec)
- Water levels (ζ) and currents (U,V) are passed to SWAN
- SWAN is run for 600 seconds (Δt = 600 sec)
- Radiation stresses (S) and their gradients ($\tau_{s,waves}$) are computed; gradients are passed to ADCIRC
- Repeat

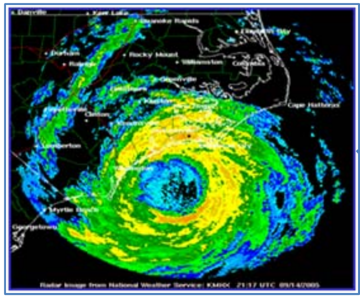


"Tight Coupling"

- SWAN and ADCIRC are always extrapolating in time

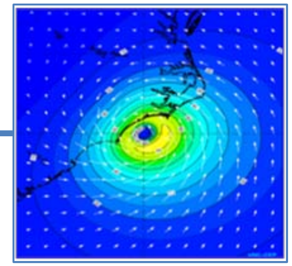
Coupled Hydrologic-Wave-Surge Models

Precipitation

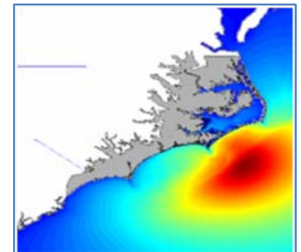


Hydrology Model

Wind Model



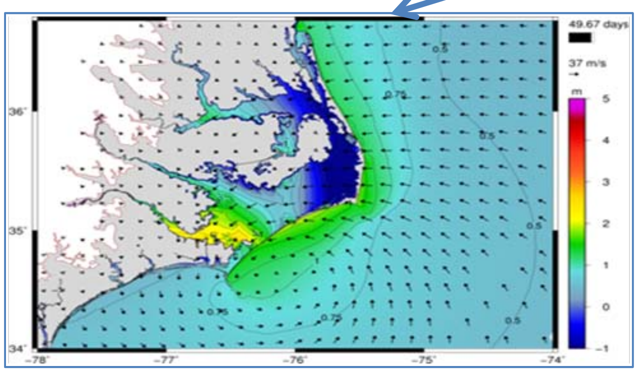
Wave Model



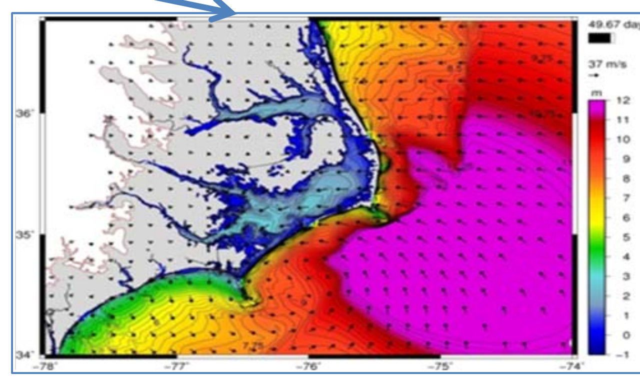
SWAN

Hydrodynamic Model

ADCIRC



Total Water Levels

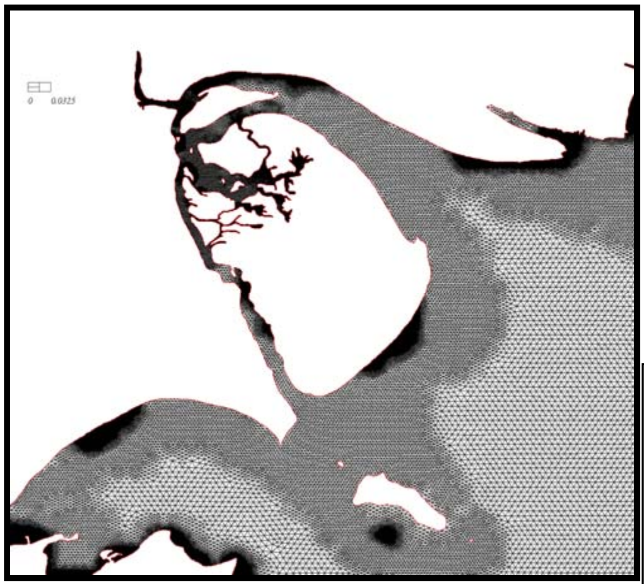


Significant Wave Heights

CI-FLOW system: VanCooten et. al 2011, Bul Am. Met. Soc

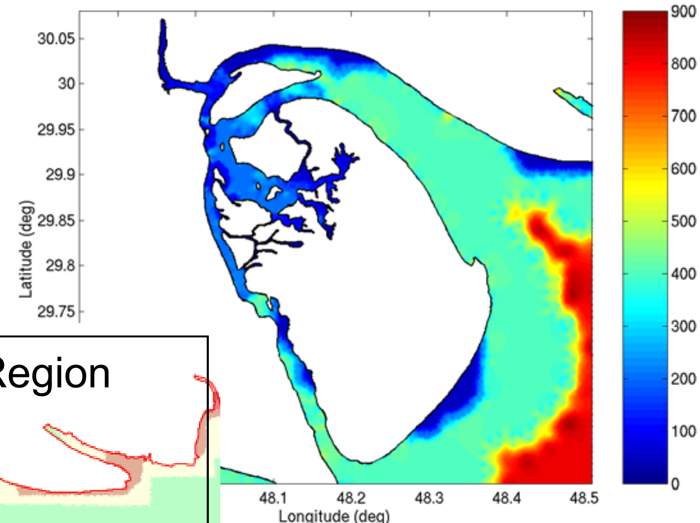
A Tidal Model in the N. Persian Gulf

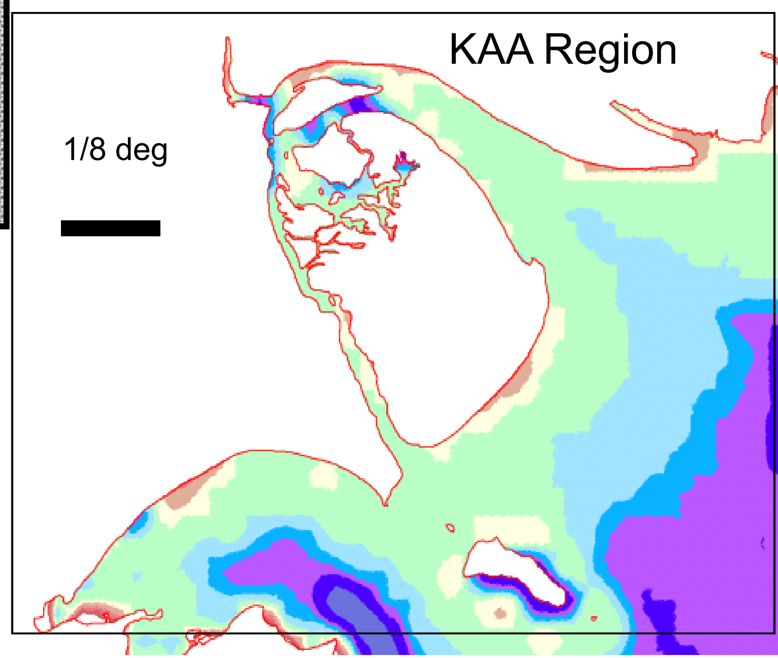
A Tidal Model in the N. Persian Gulf

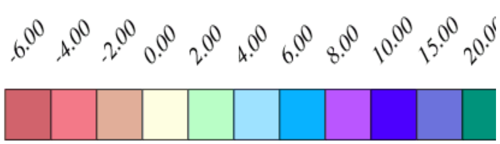


No. nodes	247,767
No. elements	480,001
Resolution	2 m – 1 km

Resolution (m)



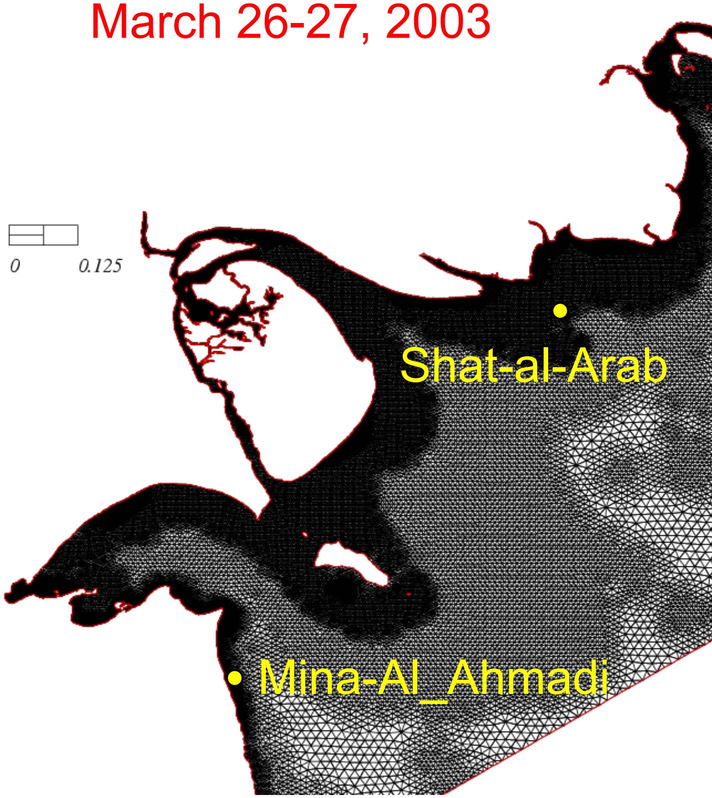


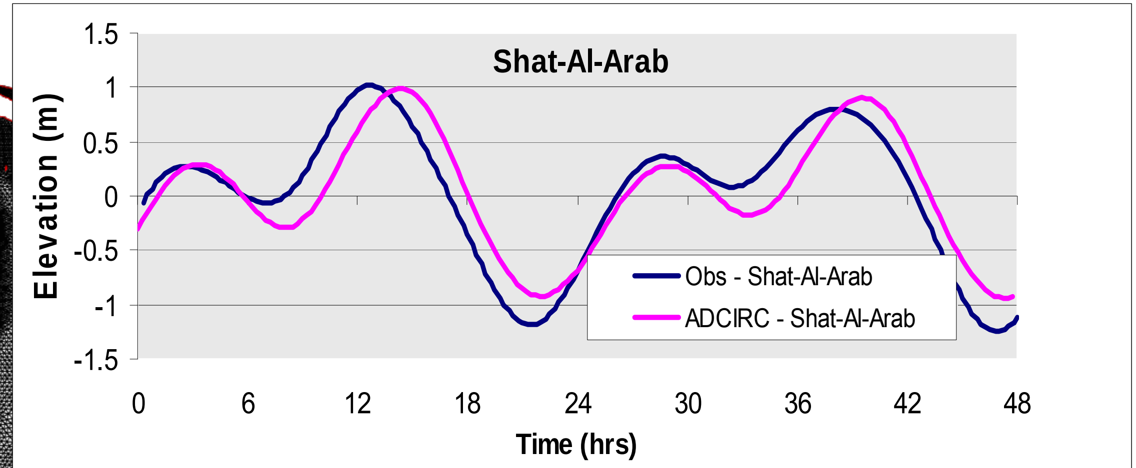


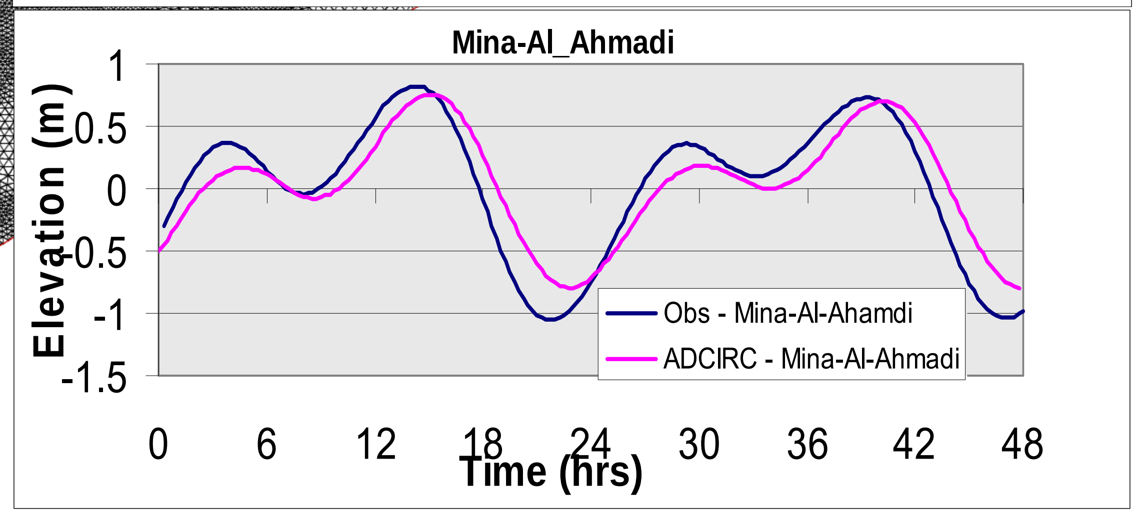
Bathymetry (m)

Validation of the Tidal Elevations

March 26-27, 2003







● IHO Stations

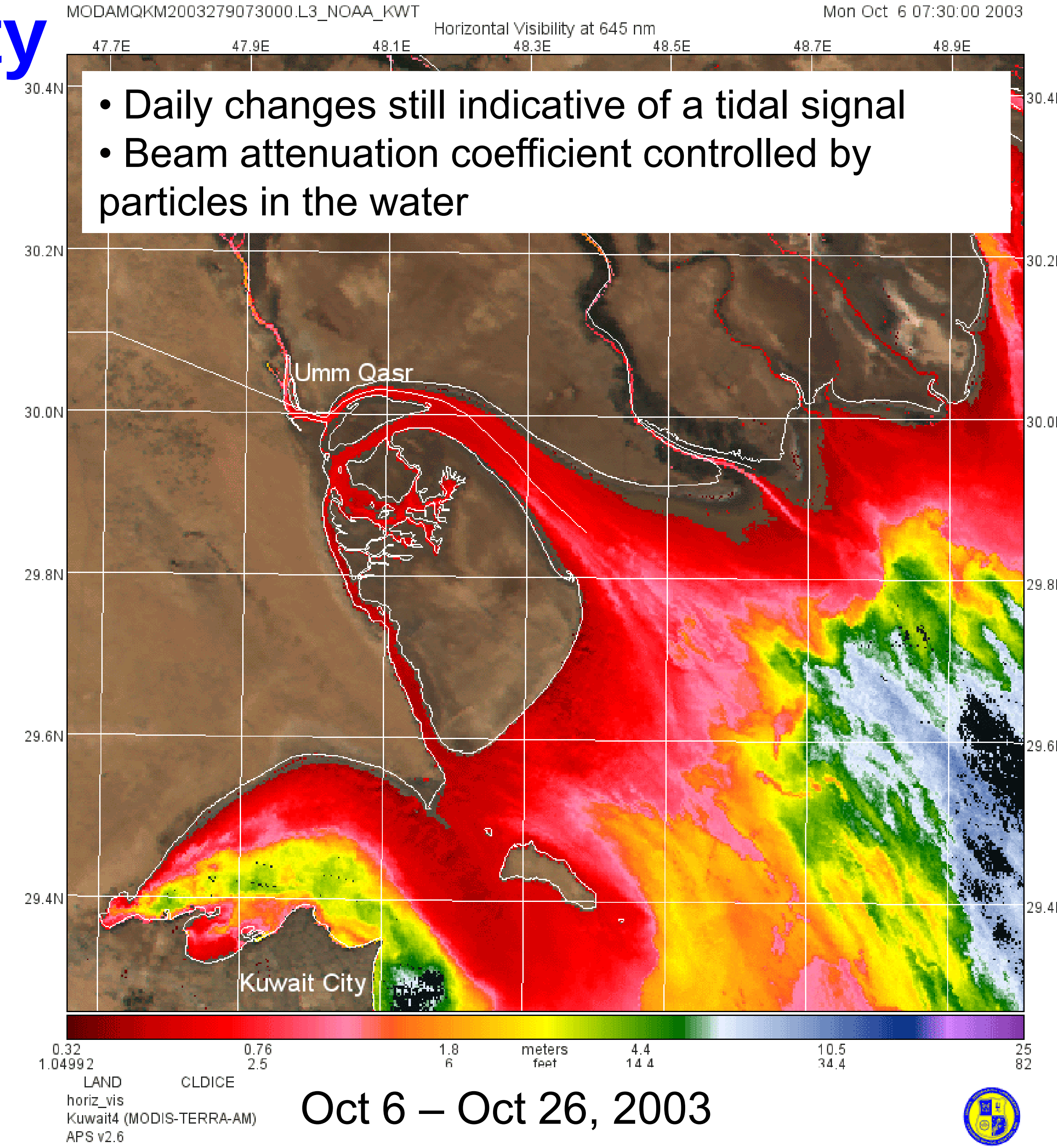
RMS Error	25 cm
Mean Absolute Error	20 cm
Phase Lag	15-30 min
Time series correlation	0.98

Diver Visibility

Derived using beam attenuation coefficient from the MODIS satellite

- AQUA and Terra 250 m channels

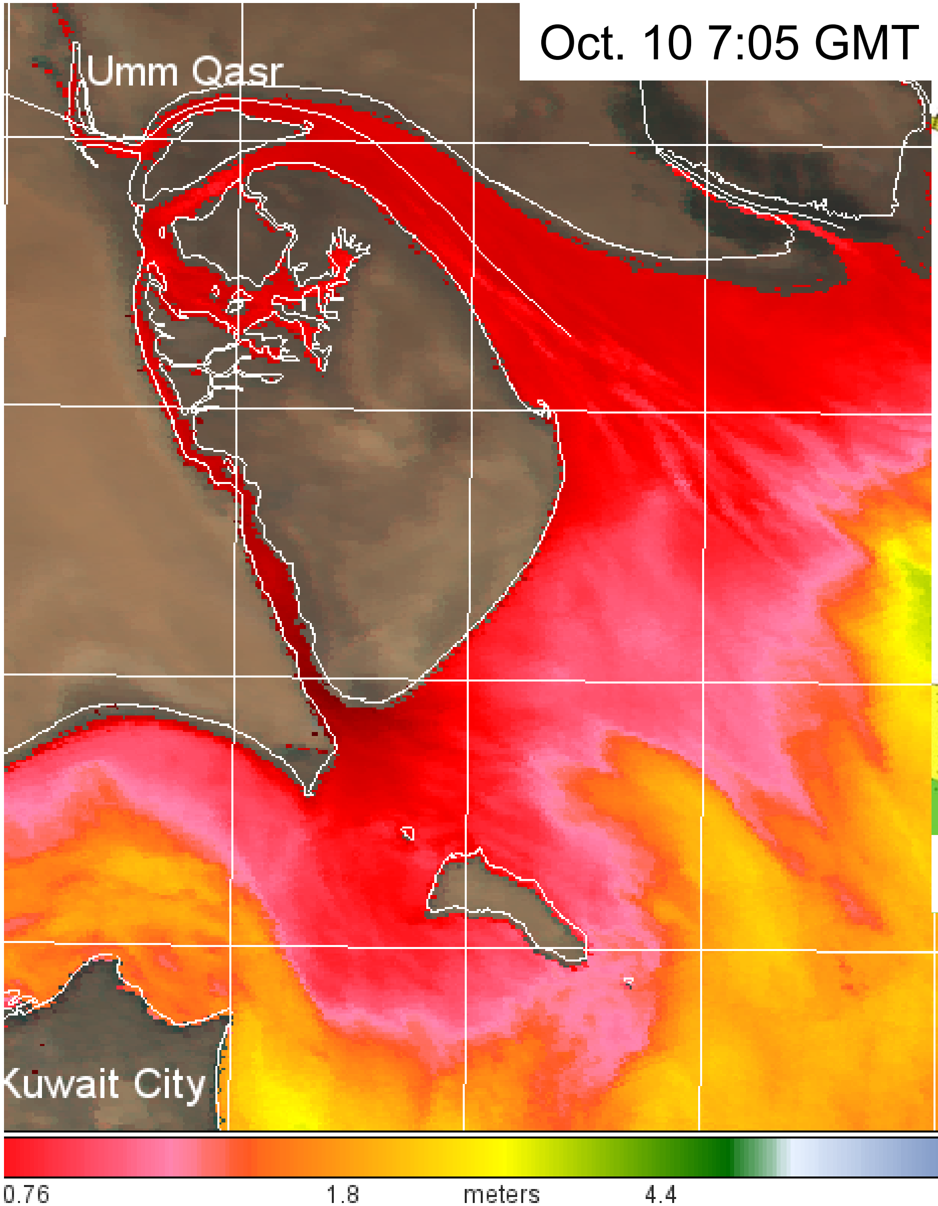
- AM: 7- 9 GMT
- PM: 22-24 GMT

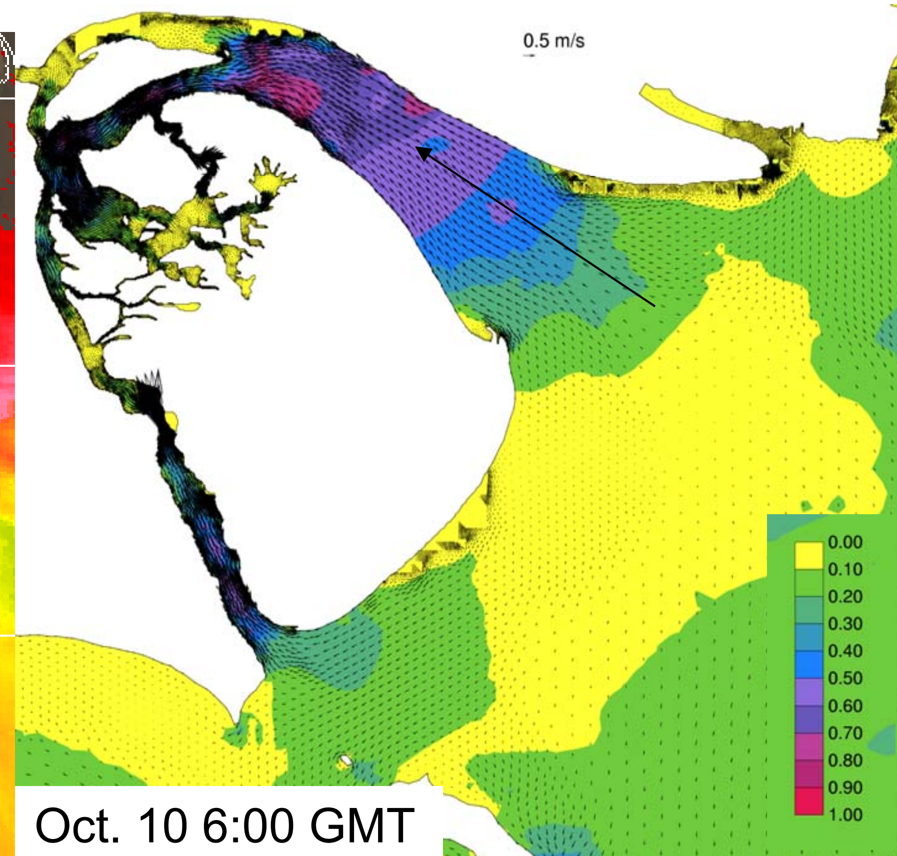


- Daily changes still indicative of a tidal signal
- Beam attenuation coefficient controlled by particles in the water

Oct 6 – Oct 26, 2003

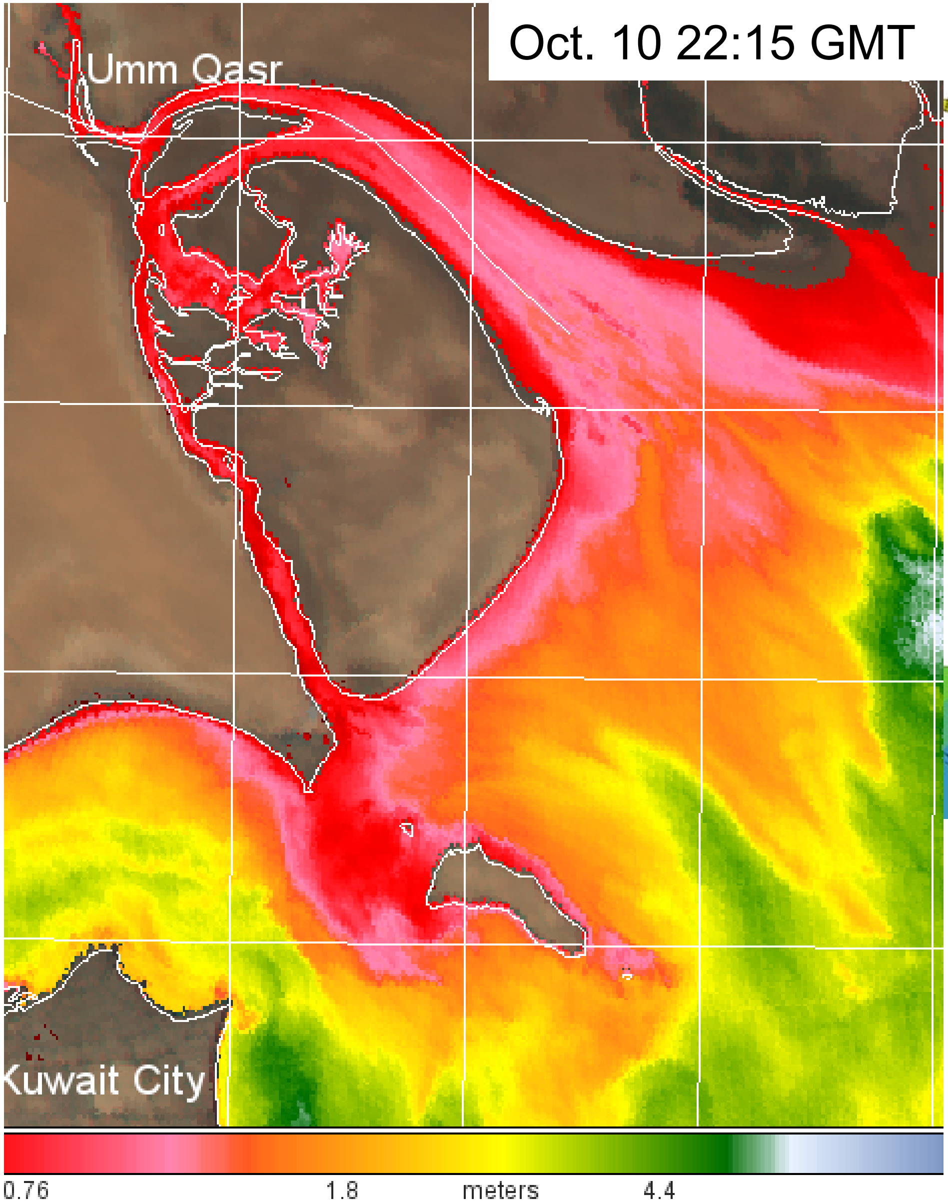
Low Visibility

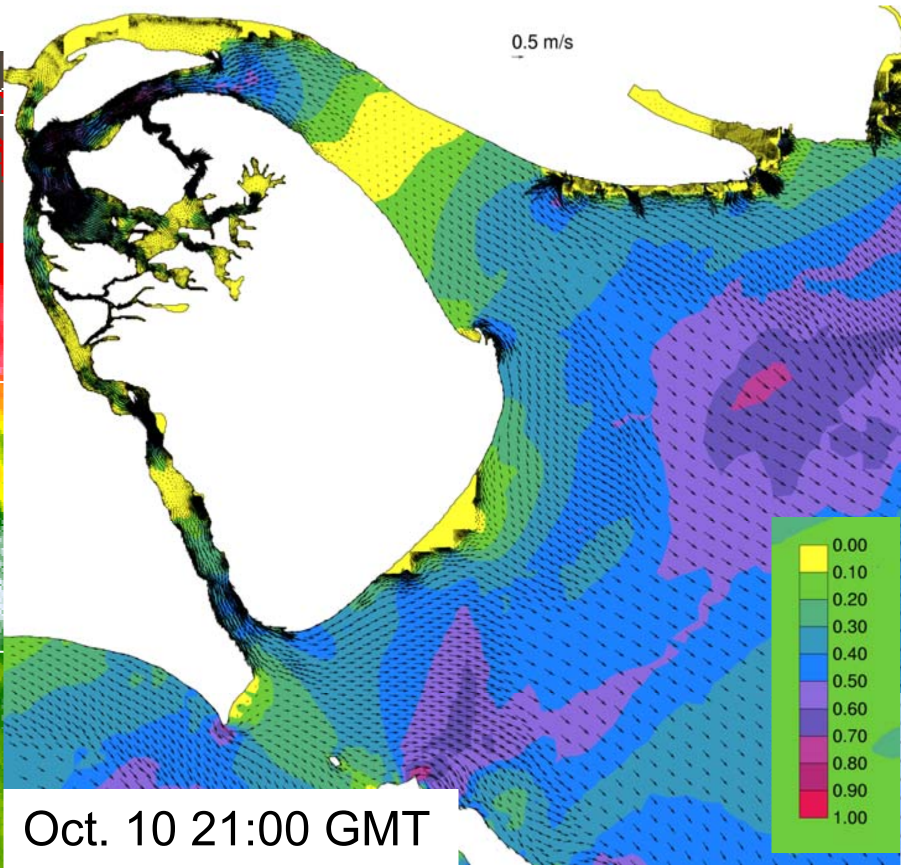




Higher velocities result in more mixing and thus increased turbidity

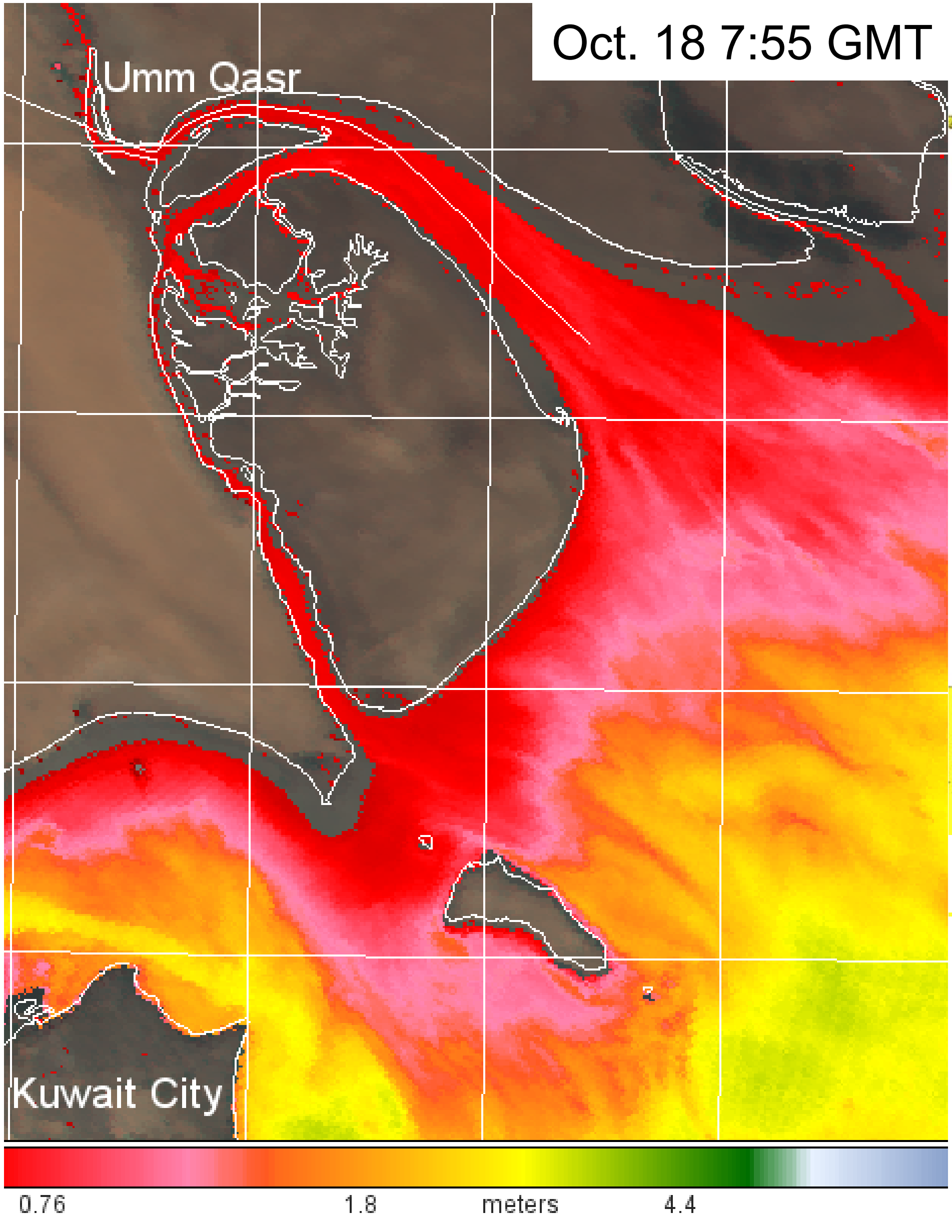
Increased Visibility

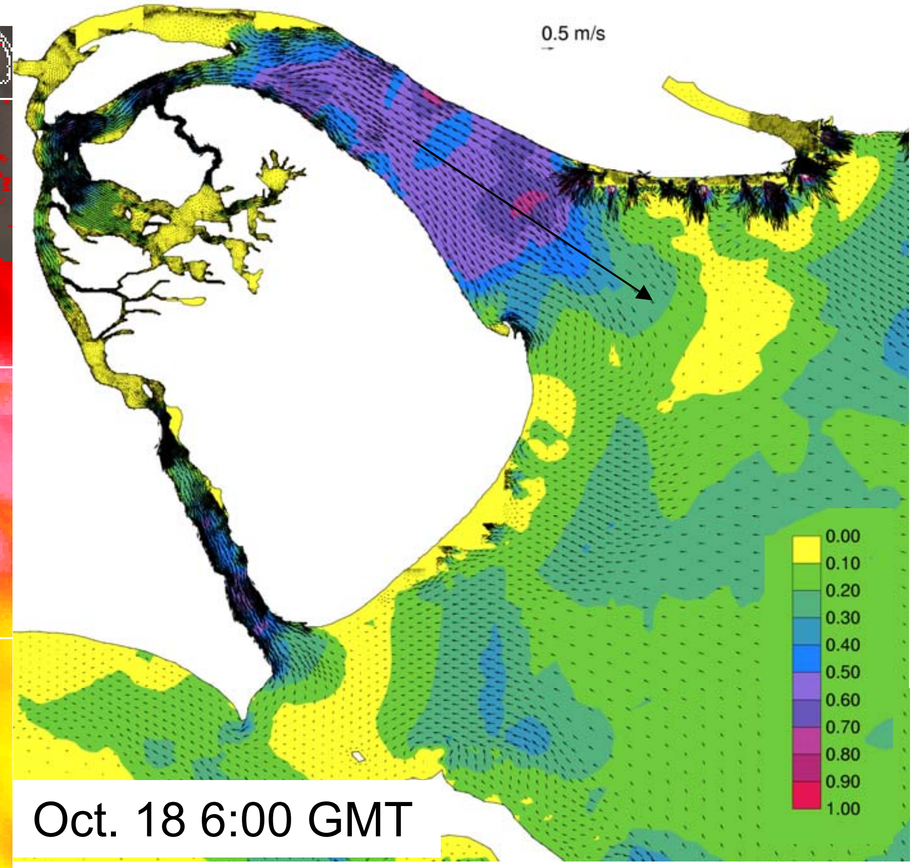




Low velocities allow particle settling and reduce turbidity

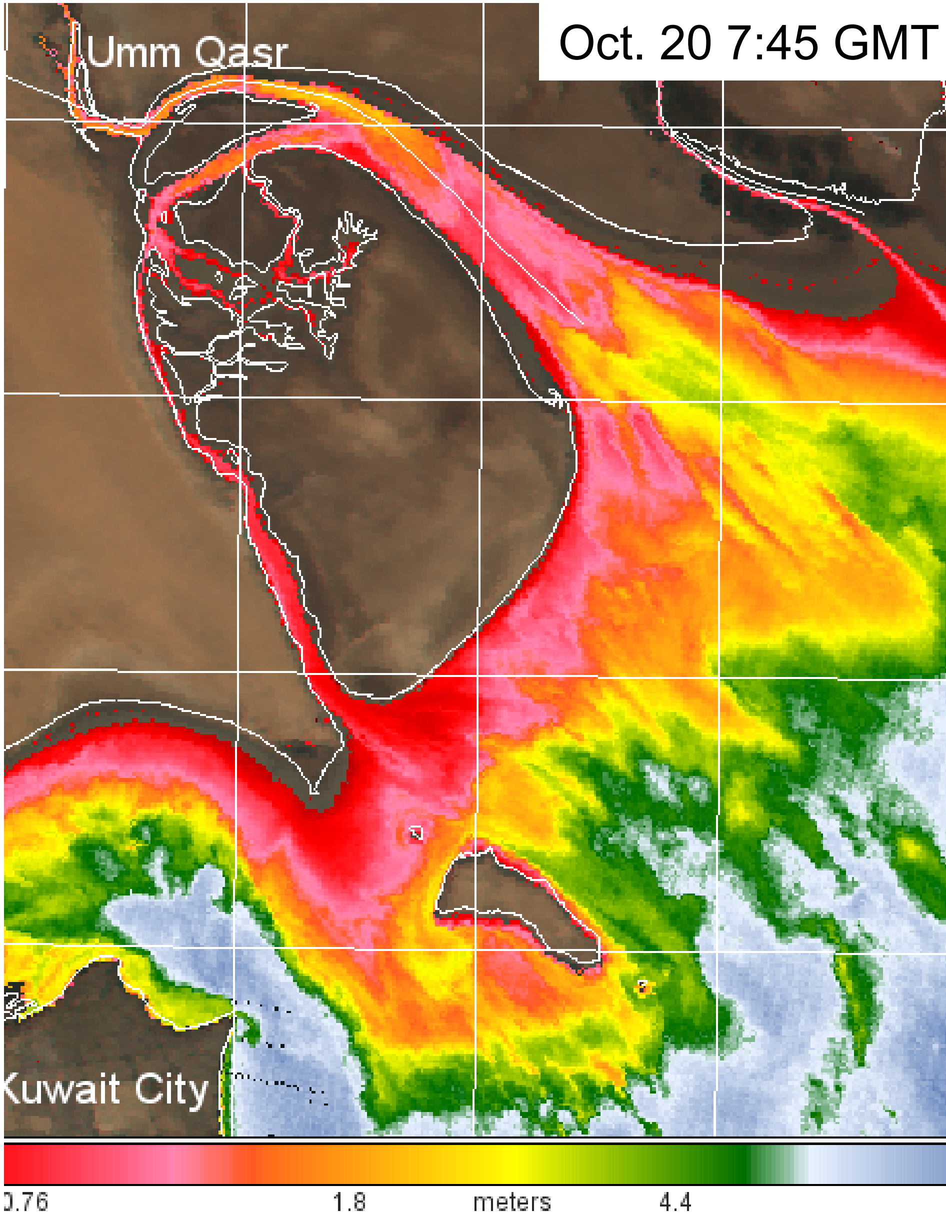
Low Visibility

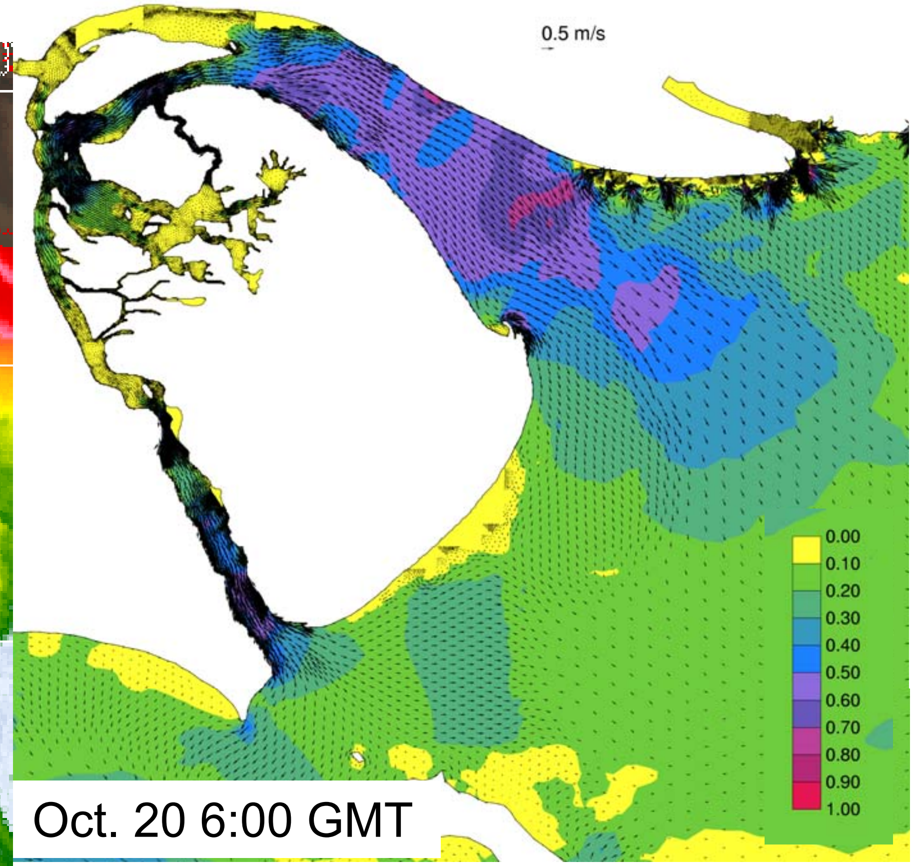




The magnitudes of the ebb tide are not as strong as for flood tide

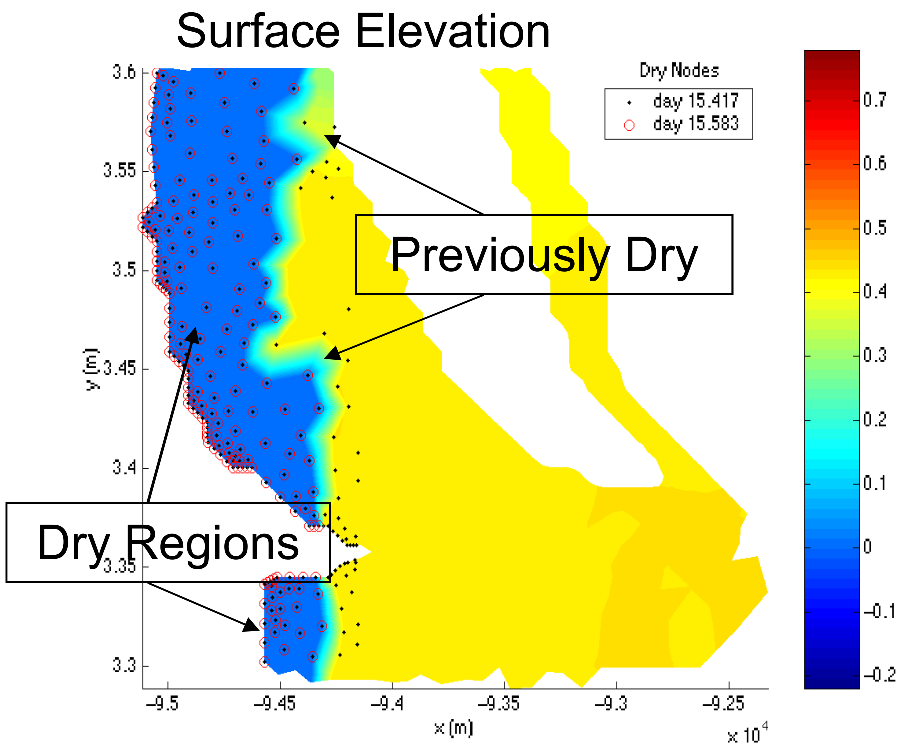
Increased Visibility

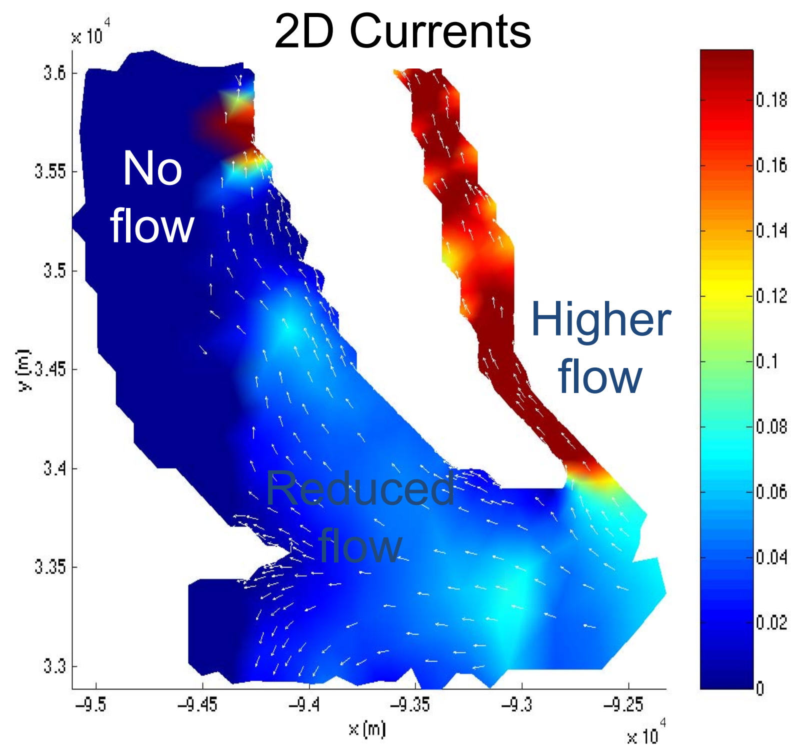




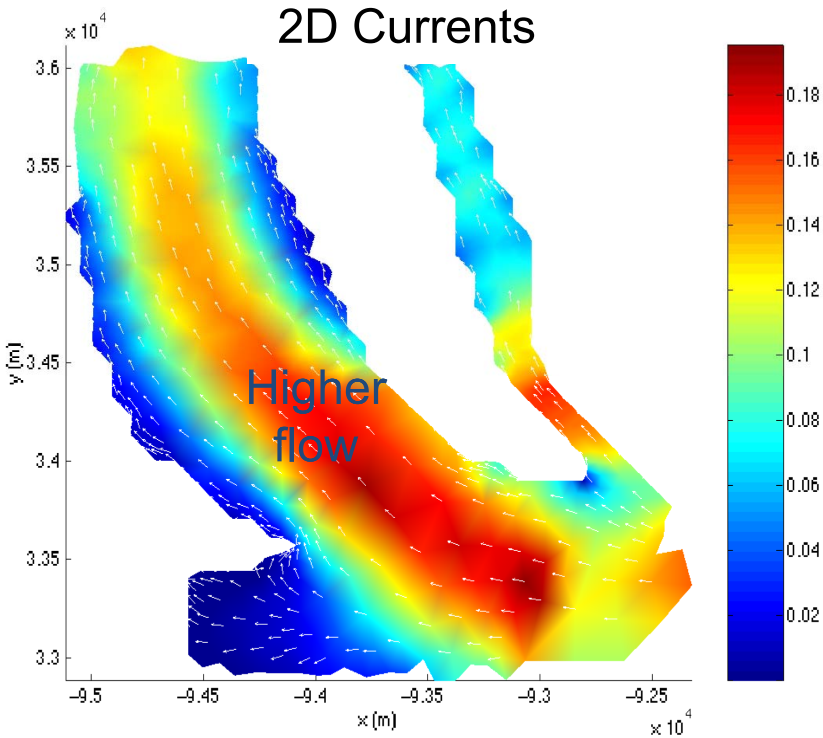
Non-tidal processes likely to be contributing to the increased visibility

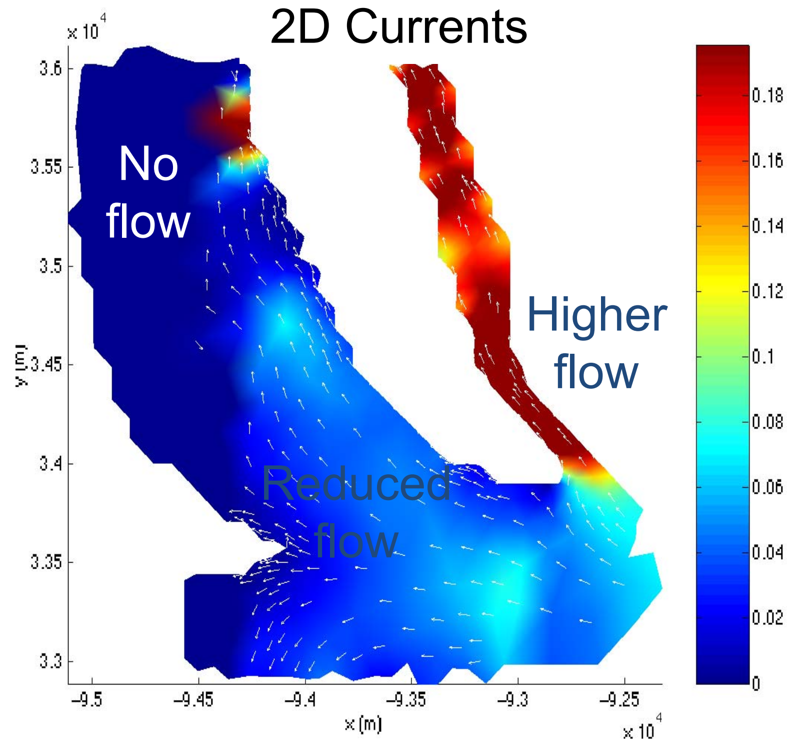
Importance of Including Inundation





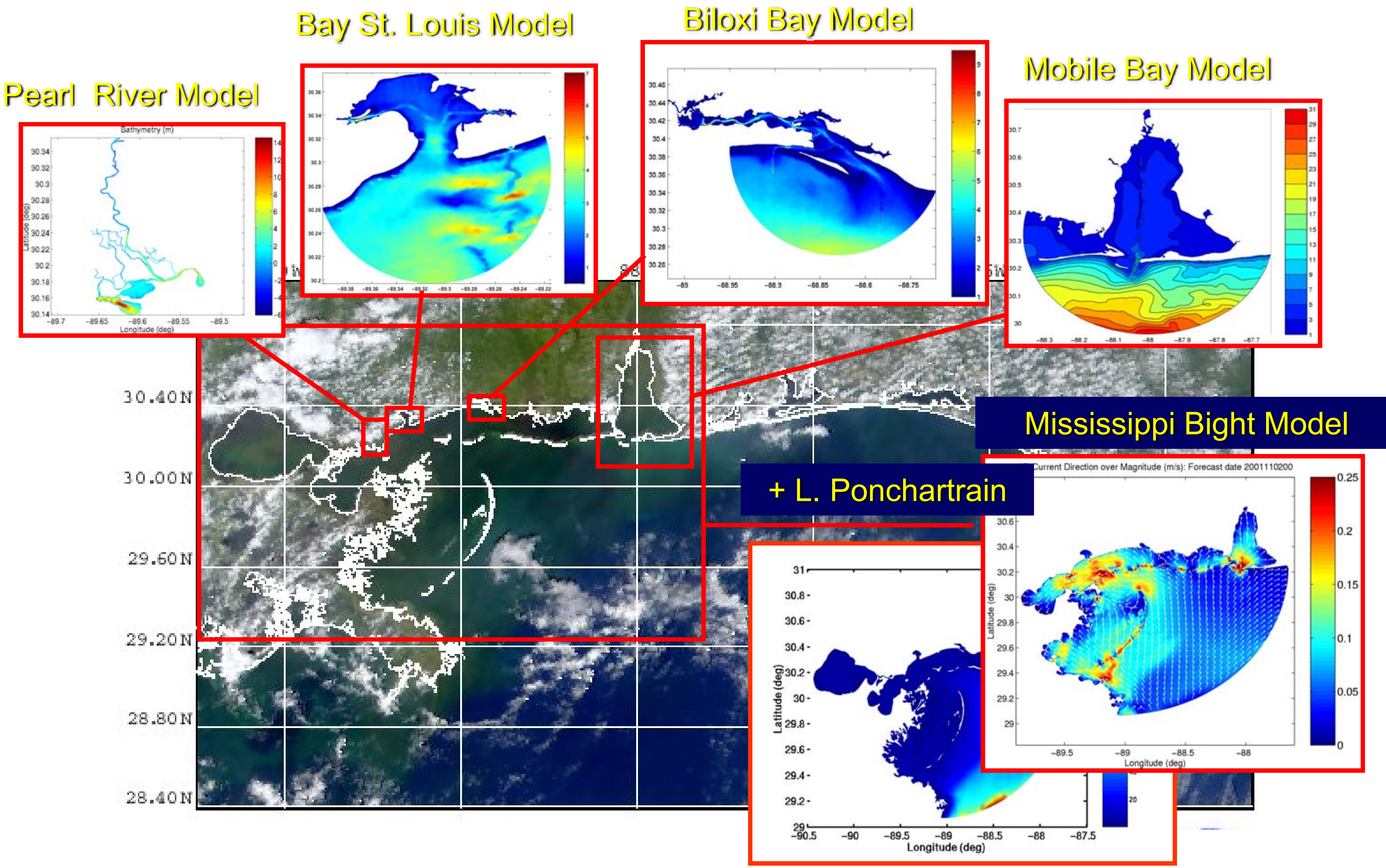
Importance of Including Inundation





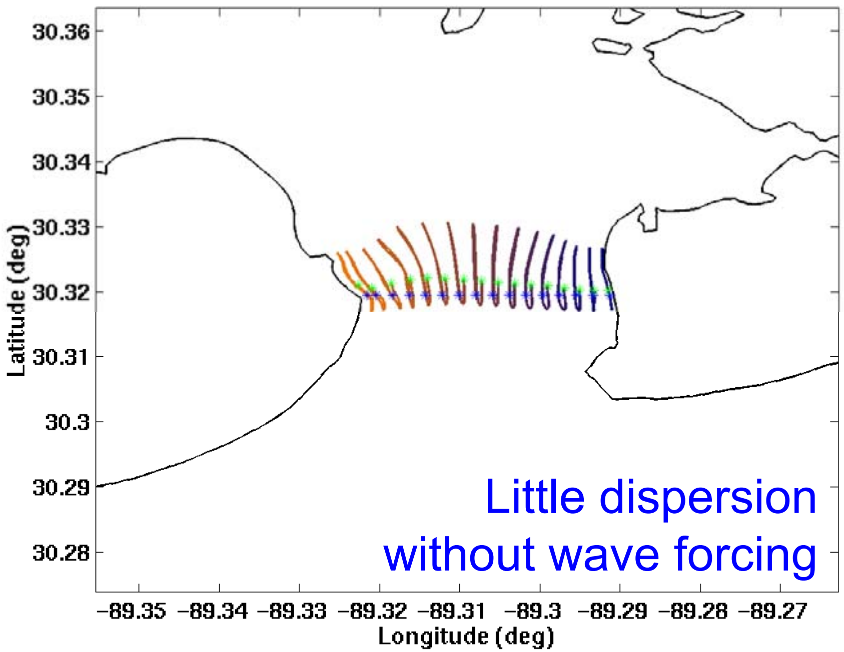
No Shoreline
Inundation/Drying

Tidal Currents



Coupled Wave-Tide Circulation in Bay St. Louis

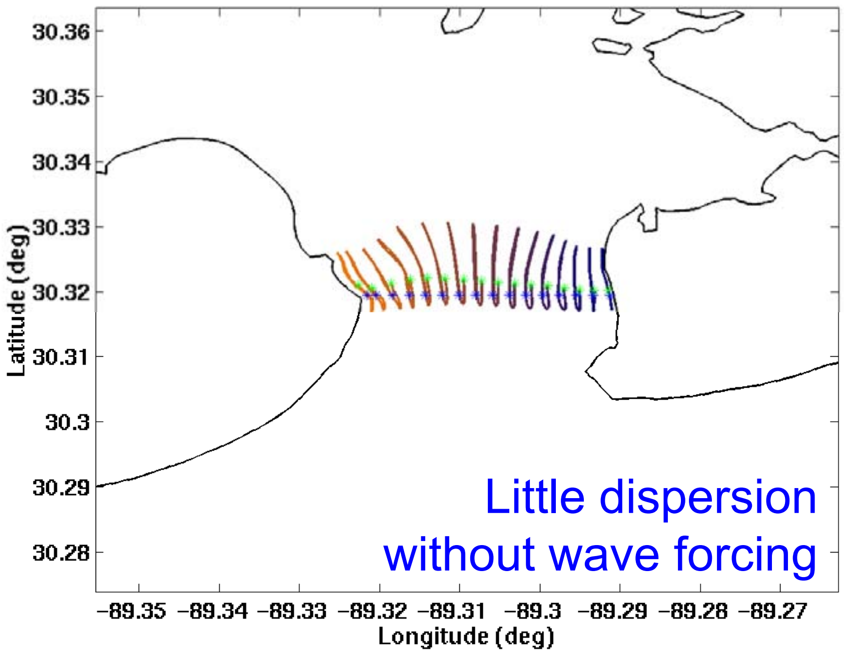
Tides Only



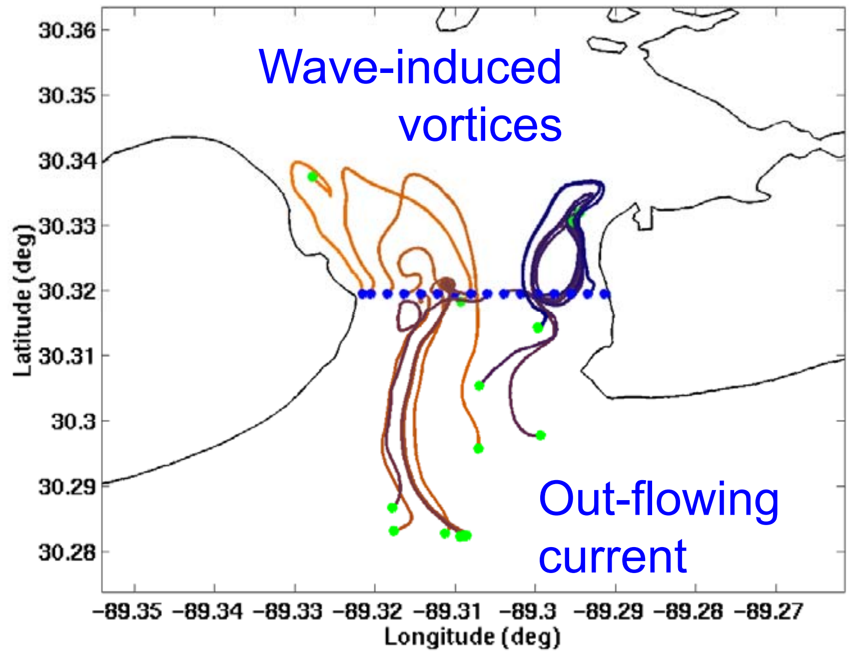
Cobb and Blain, MTS, 2002

Coupled Wave-Tide Circulation in Bay St. Louis

Tides Only



Tides + Waves

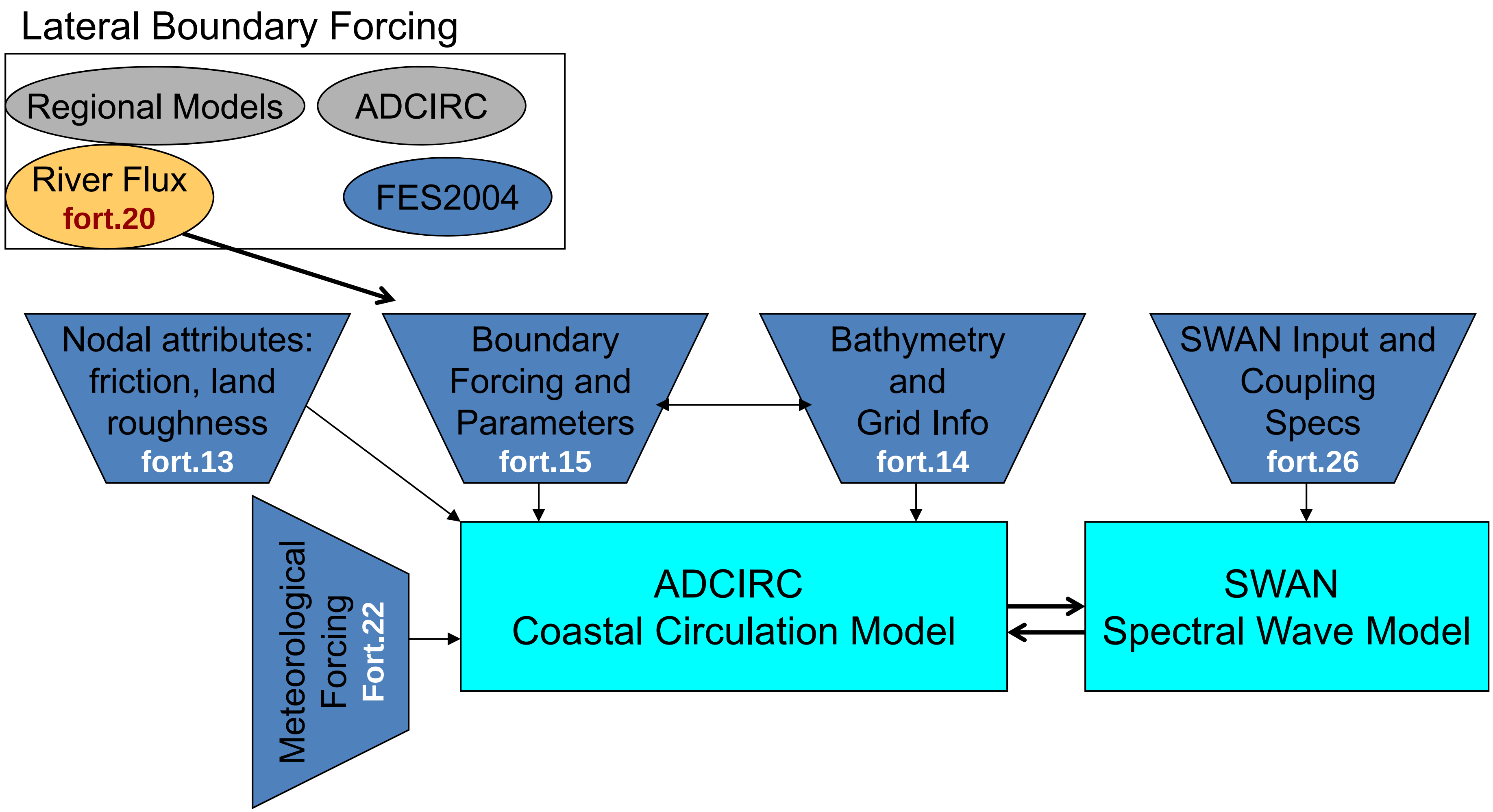


Cobb and Blain, MTS, 2002

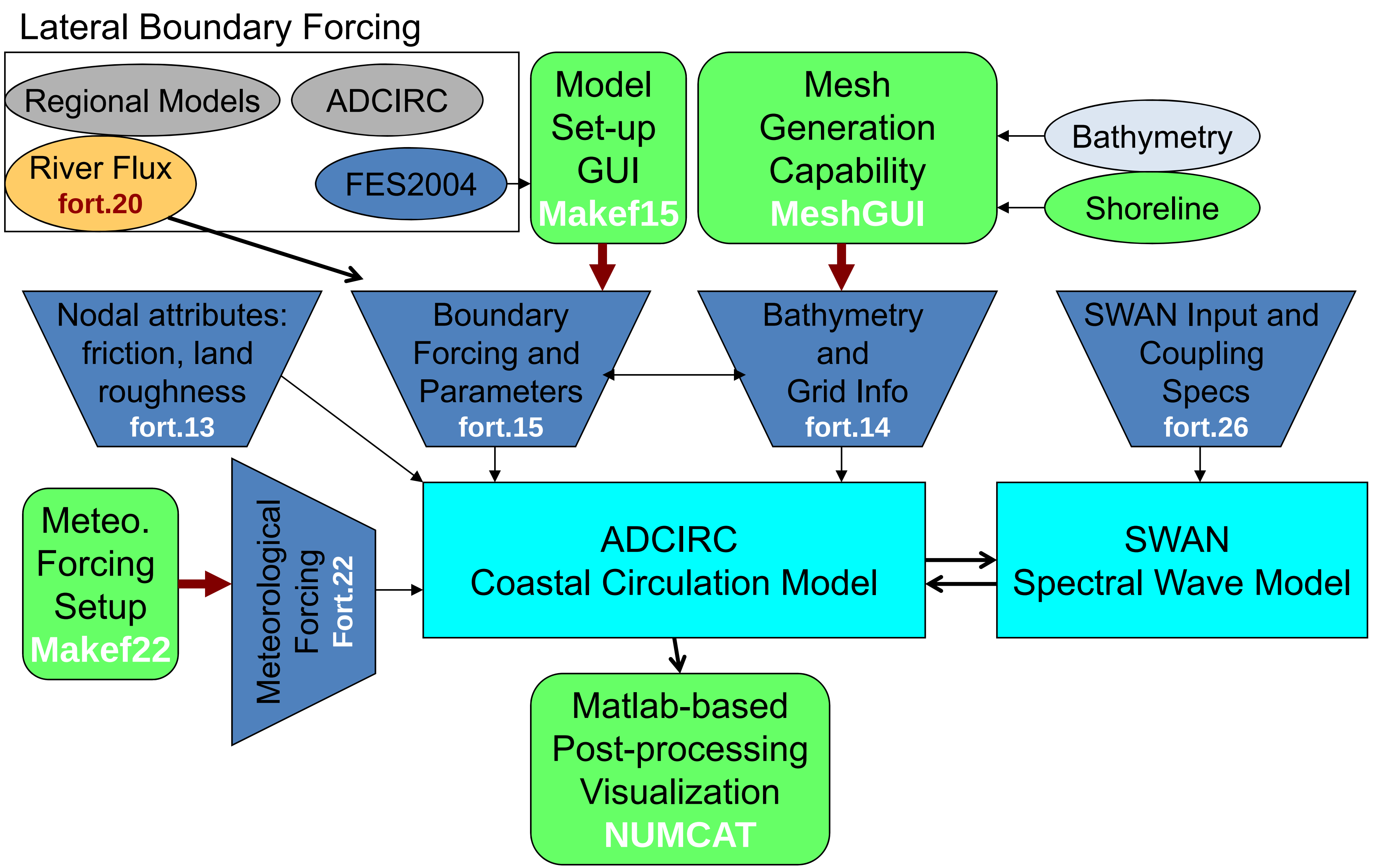
ADCIRC Model Project

- Automated mesh generation
- Shoreline extraction from imagery
- Model parameter and boundary forcing set-up
- Model compilation
- Model execution on multiple processors
- Post-processing using NUMCAT Matlab tools
- Example problems:
  - Tides in the South Atlantic Bight
  - Nonlinear tides in the Bight of Abaco
  - Storm surge in the Gulf of Mexico – Hurricane Katrina
  - Operational storm surge prediction – Hurricane Irene
  - A challenge – Hurricane Isabel
  - A challenge – coupled ADCIRC-SWAN – Hurricane Gustav

ADCIRC Code Structure



ADCIRC Code Structure



Navy Unstructured Mesh Configuration and Analysis Tools (NUMCAT)

MeshGUI

Blain, C.A., R.S. Linzell, and T.C. Massey, “MeshGUI: A Mesh Generation and Editing Toolset for the ADCIRC Model,” Naval Research Laboratory, Stennis Space Center, MS, NRL/MR/7322--08-9083, February, 2008.

MakeF15

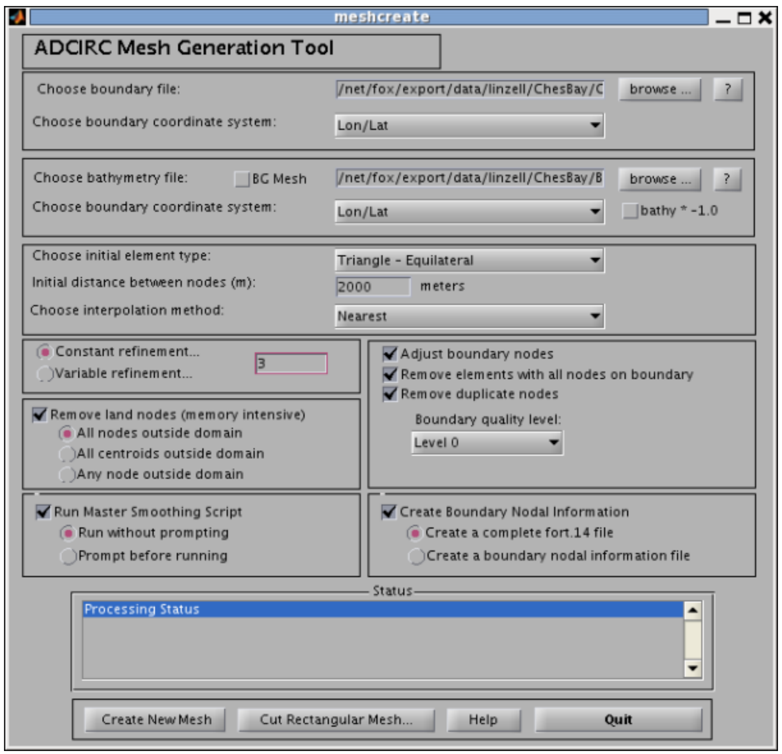
Blain, C.A. and R.S. Linzell, “Makef15: An ADCIRC Model Fort.15 Input File Creation GUI for Parameter Specification and Periodic Boundary Forcing,” Naval Research Laboratory, Stennis Space Center, MS, NRL/MR/7320--07-9081, December, 2007.

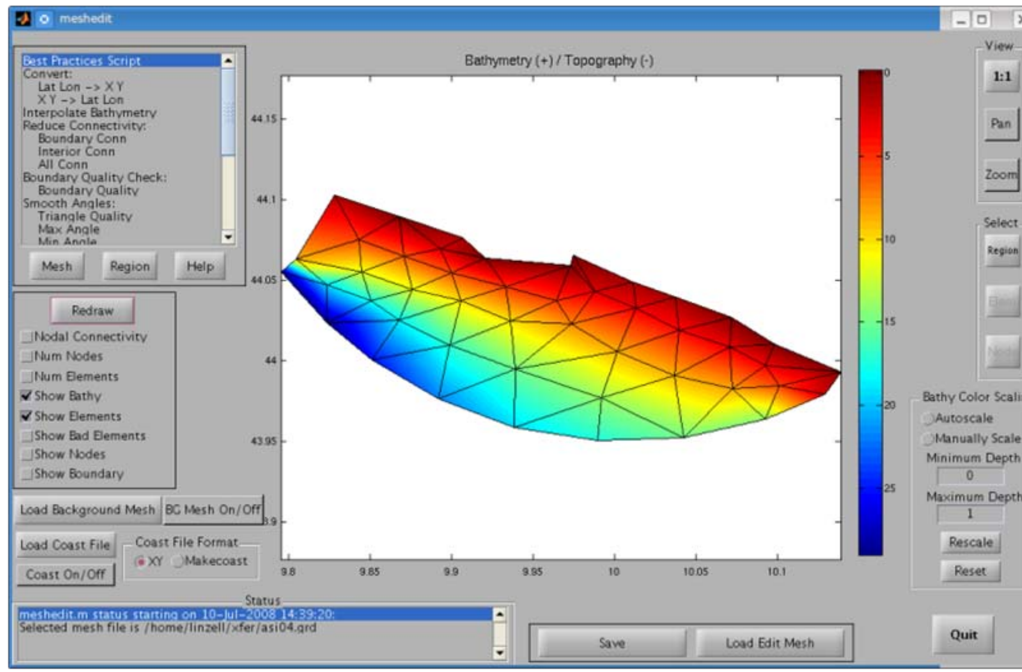
MakeF22

Blain, C.A., R.S. Linzell, and B. Estrade, “Makef22: An ADCIRC Model Fort.22 Input File Creation Tool for Surface Wind and Pressure Forcing,” Naval Research Laboratory, Stennis Space Center, MS, NRL/MR/7320--07-9082, December, 2007., 2008.

Navy Unstructured Mesh Configuration and Analysis Tools (NUMCAT)

MeshGUI





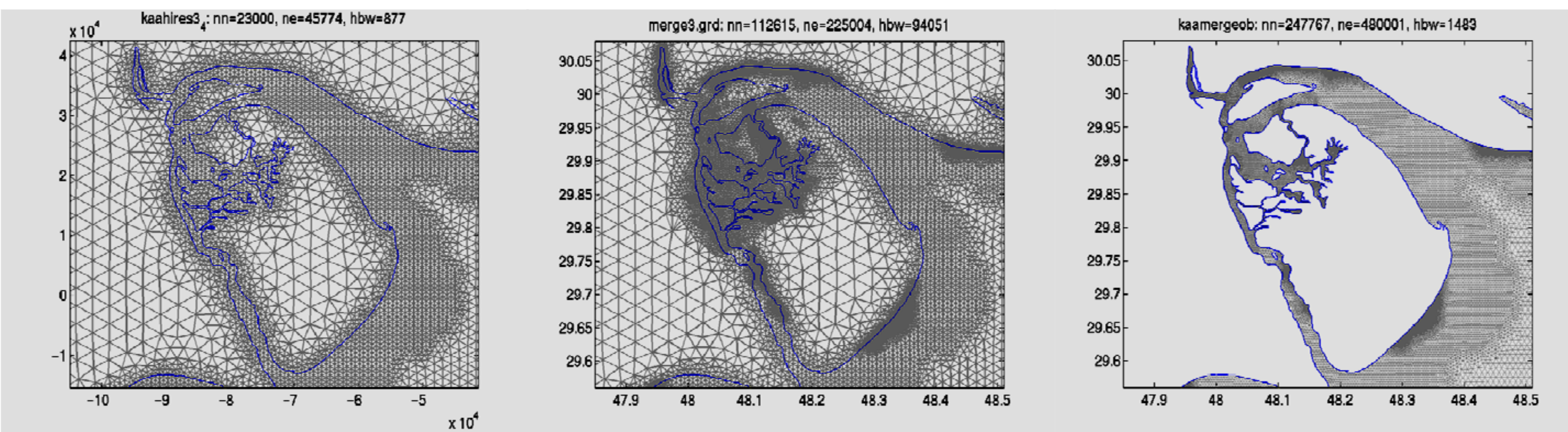
- ***meshedit***, a GUI-based finite element mesh editing tool

meshcreate, an automated unstructured mesh creation tool

Navy Unstructured Mesh Configuration and Analysis Tools (NUMCAT)

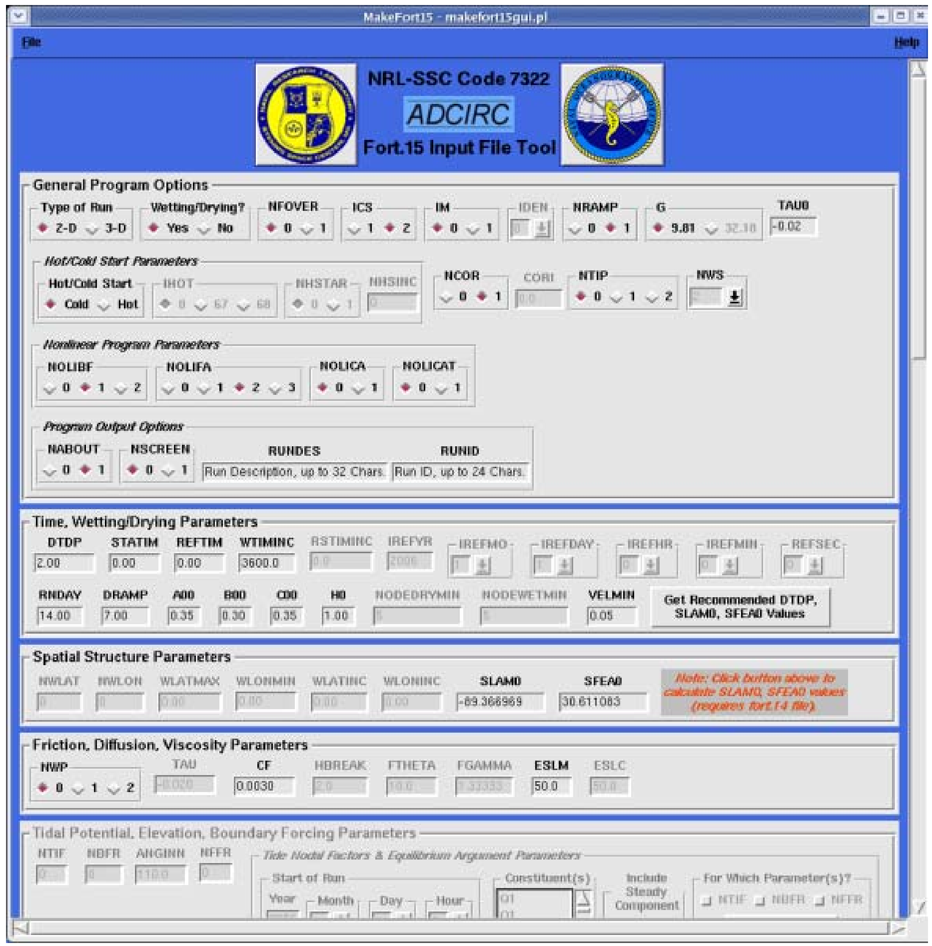
MeshGUI

- developed a GUI interface for Matlab software
- executes on Windows, LINUX, UNIX machines
- mesh refinement by depth criteria
- accommodates user specified levels for refinement
- provisions for user intervention and return for boundary processing
- integrated mesh quality checks (shape, connectivity)
- automated mesh adjustment based on quality checks
- interactive boundary creation tool
- diagnostics for computing resolution, CPU requirements



Navy Unstructured Mesh Configuration and Analysis Tools (NUMCAT)

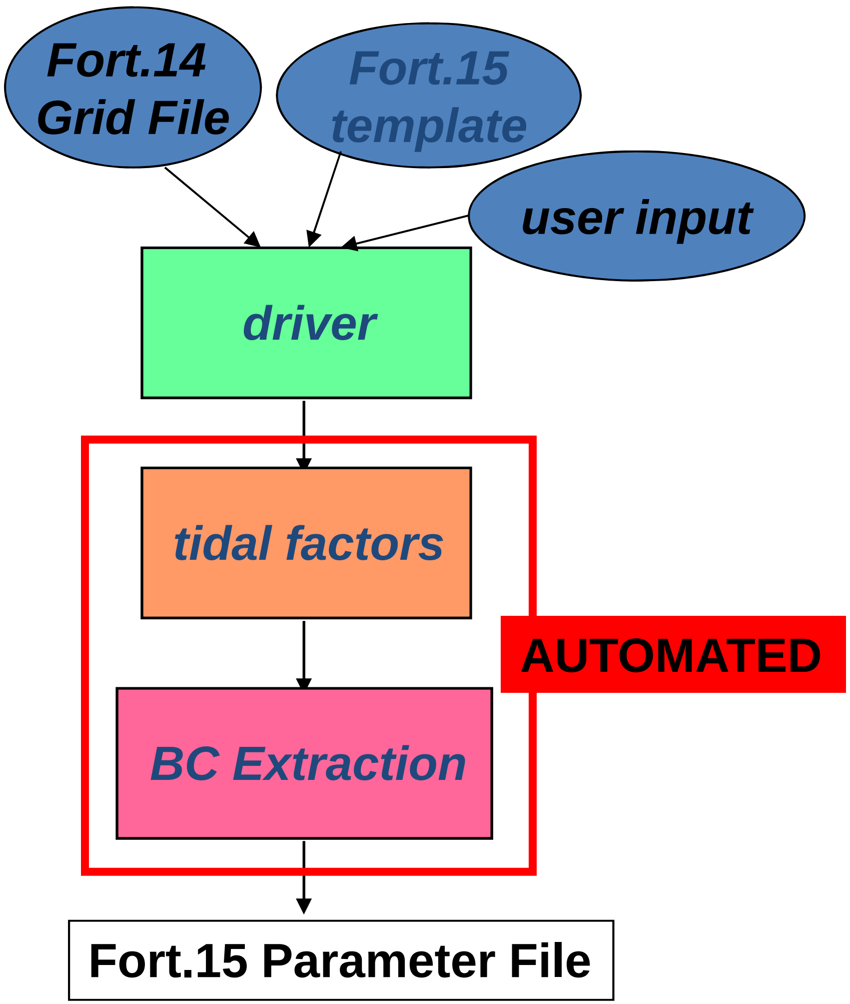
MakeF15



- ***makefort15gui.pl***, a GUI-based tool for parameter and periodic boundary forcing file configuration (*fort.15, ADCIRC)*

Navy Unstructured Mesh Configuration and Analysis Tools (NUMCAT)

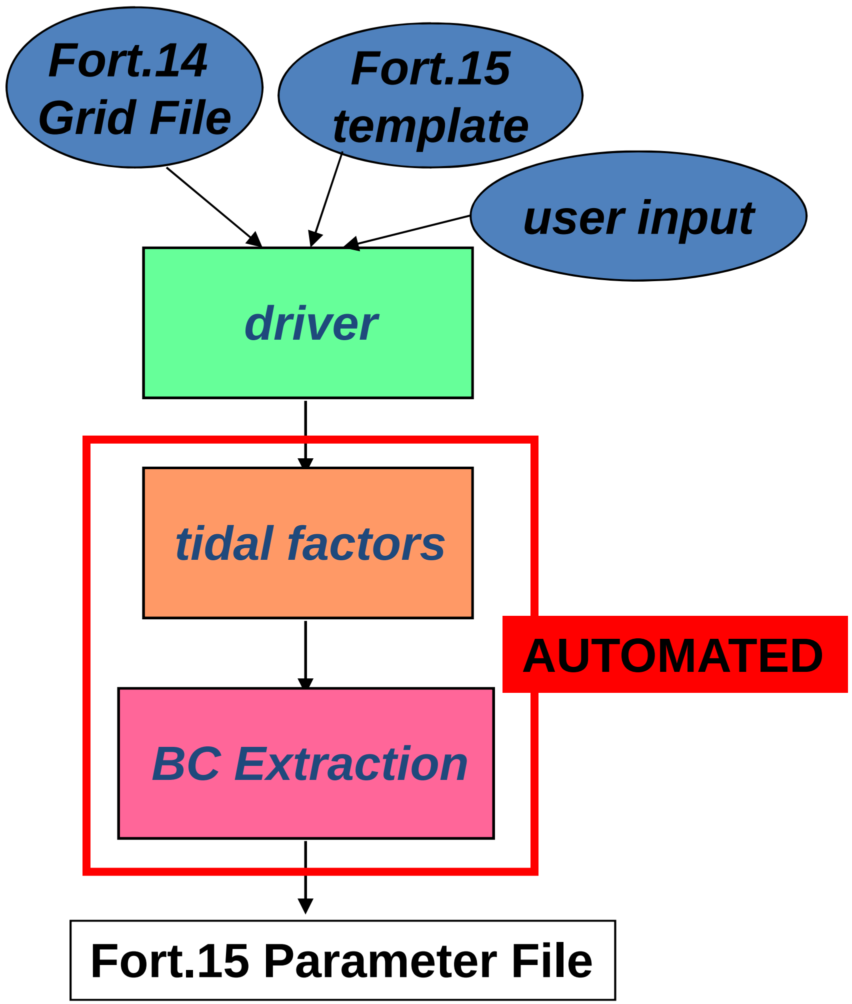
MakeF15



✓ Written in Perl
✓ Compatible with ADCIRC v45.11
✓ supports options for wetting/drying, 2D/3D, nonlinearities, forcing
✓computes tide node factors and equilibrium arguments based on date of simulation and latitude of mesh
✓ extracts boundary forcing from global tidal database, FES99, for elevation-specified nodes in the ADCIRC grid file
✓ automated time step computation from Courant no. analysis of computational mesh
✓ automated parameter consistency
✓mouse over tool tips
✓ embedded ADCIRC 45.11 manual

Navy Unstructured Mesh Configuration and Analysis Tools (NUMCAT)

MakeF15



1. The user specifies the appropriate options for forcing type and source, model dynamics, and model output.
2. The driver controls the generation of the fort.15 by applying user input to the required template.
3. The date and latitude dependent tide nodal factors and equilibrium arguments are computed using the *tidal factor* plug-in.
4. Boundary forcing is extracted from a database using the *BC extraction* plug-in. Currently supported are elevation specified nodes and the global tidal database, FES99 .