Towards Heterogeneous Process and Scale Coupling in Coastal Ocean and Floodplain Hydrodynamic Modeling

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January 16, 2019

The hydrodynamics of the coastal ocean and floodplain

Understanding coastal sustainability and risk means understanding water levels, currents, and wind waves from the shelf to the inland floodplain

Coastal flooding

Wave forces

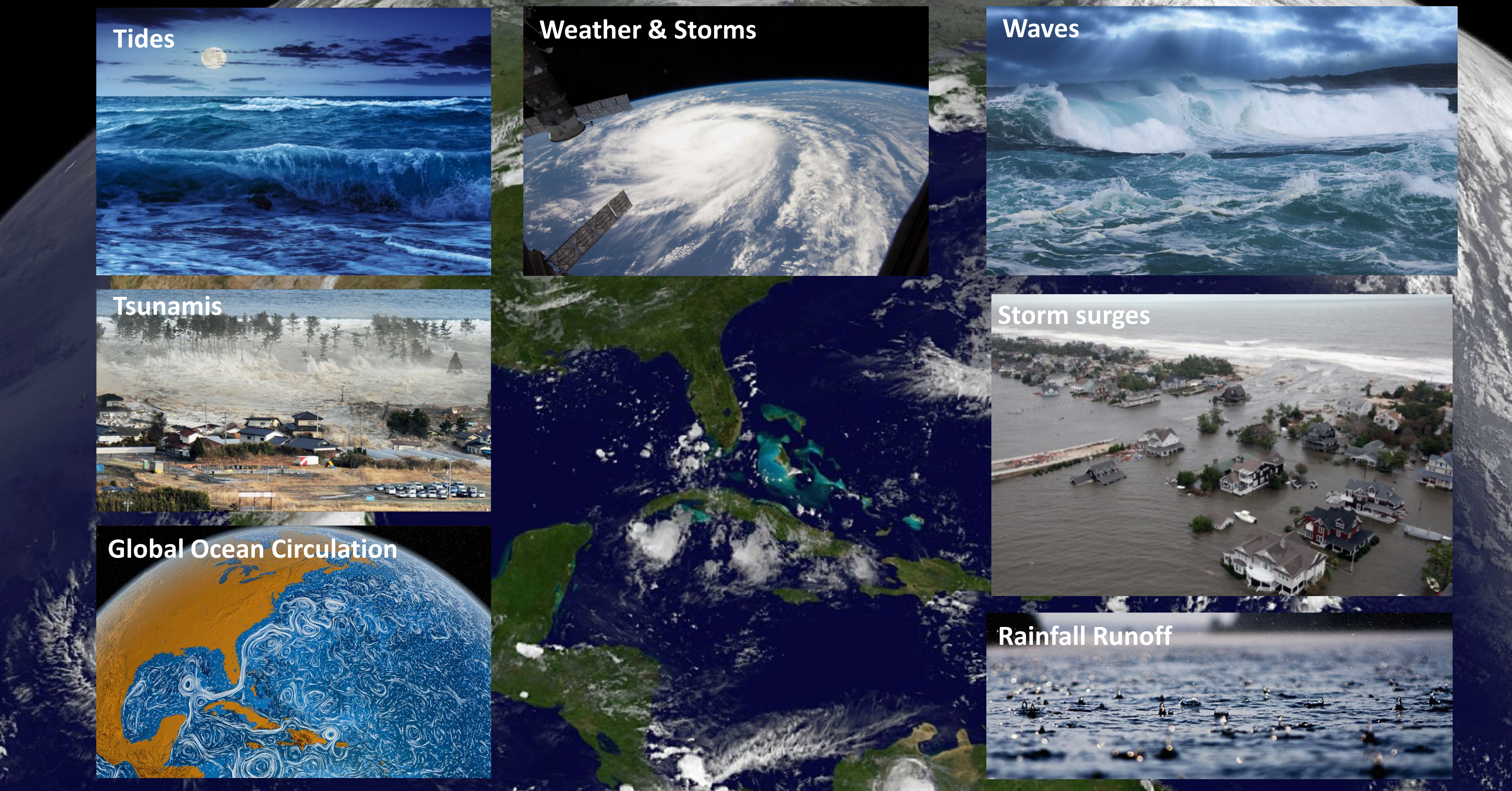
Sinking deltas

Wetland degradation

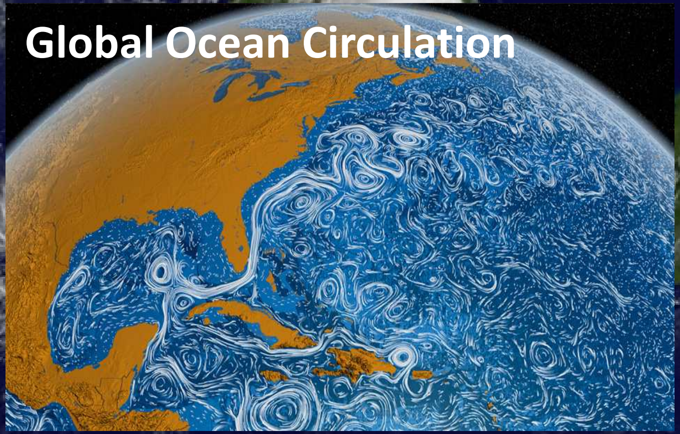
Coastal dead zones

Marine larval transport

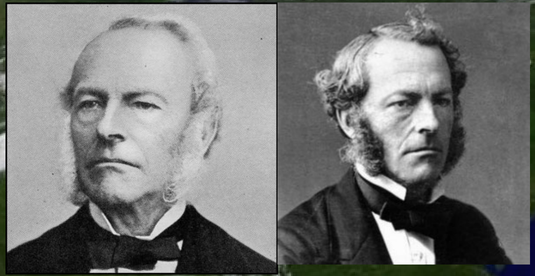
Processes in the ocean and coastal floodplain



Processes in the ocean and coastal floodplain



Navier Stokes Equations (1822)



Mass & momentum conservation

Describes all processes

Solve for 10^{34} unknowns per day of real time

Processes in the ocean and coastal floodplain

Process & Scale Separation

Shallow water equations

Laplace 1776

Processes in the ocean and coastal floodplain

Process & Scale Separation

Waves

Boussinesq equations

Boussinesq 1872

Peregrine 1967

Tsunamis

Processes in the ocean and coastal floodplain

Process & Scale Separation

Spectral action balance equation

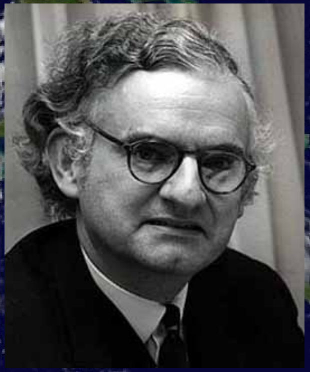
Hasselman 1988

Gelci et al. 1957

Processes in the ocean and coastal floodplain

Process & Scale Separation

Kinematic wave equation
Dynamic wave equation

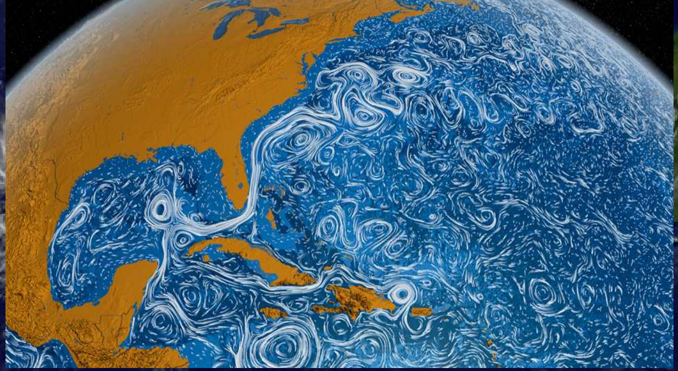


Lighthill 1955

Processes in the ocean and coastal floodplain

Process & Scale Separation

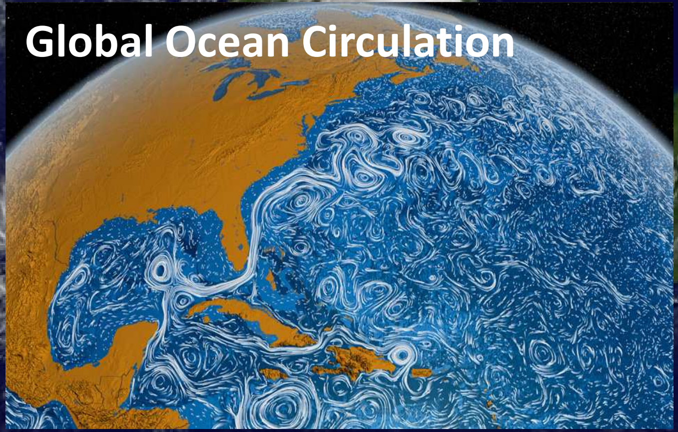
Global Ocean Circulation



Prognostic ocean circulation equations

Kirk Bryan 1969

Processes in the ocean and coastal floodplain



Process Separation

Domain & Resolution Separation

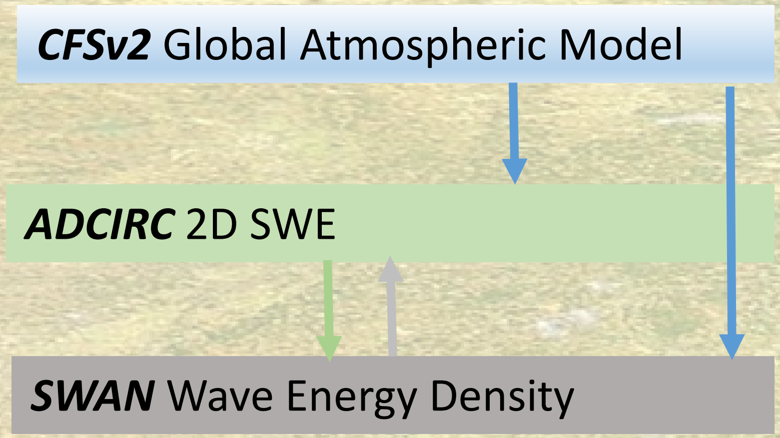
Provide affordable resolution for domain size and alias the rest

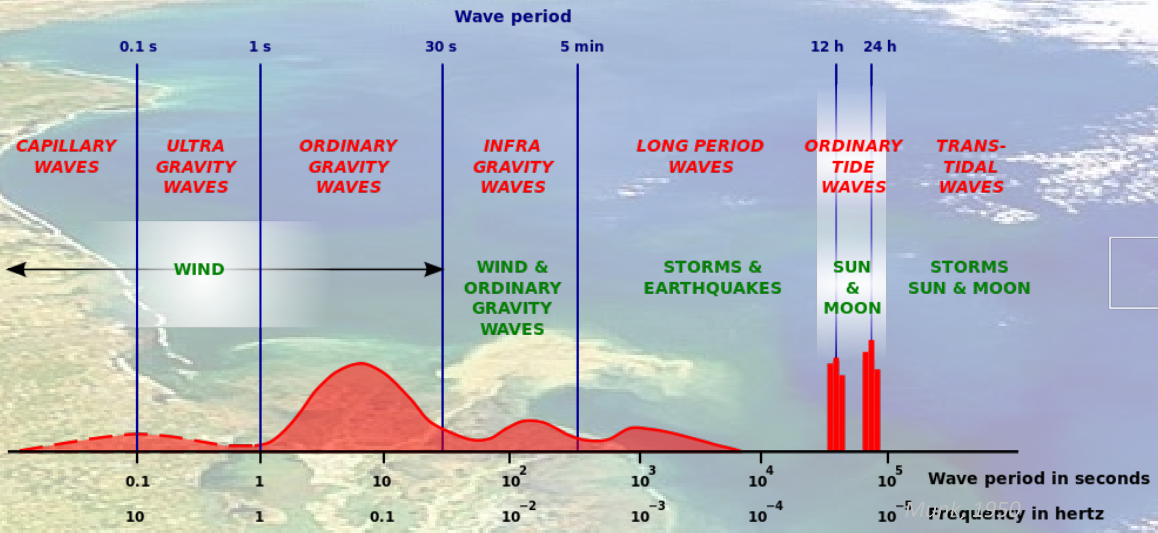
Nesting

Data assimilate for missing physics and scales

Evolution of coastal ocean hydrodynamics models – the recent past

Dynamic ADCIRC & SWAN Coupling





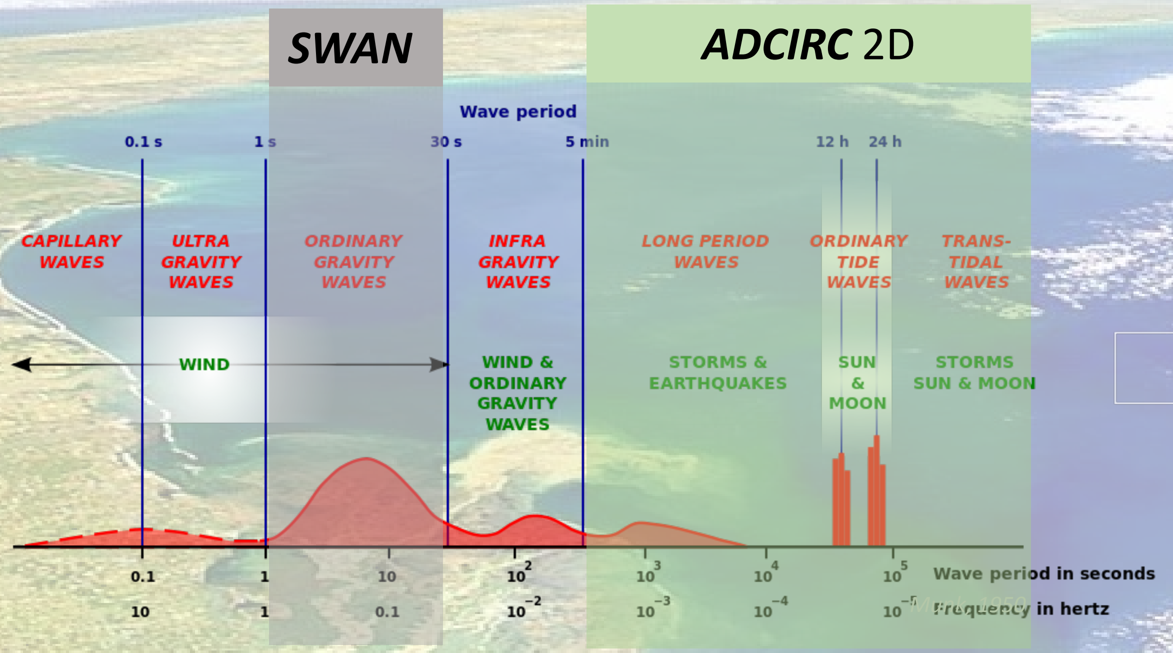
Evolution of coastal ocean hydrodynamics models – the recent past

Dynamic ADCIRC & SWAN Coupling

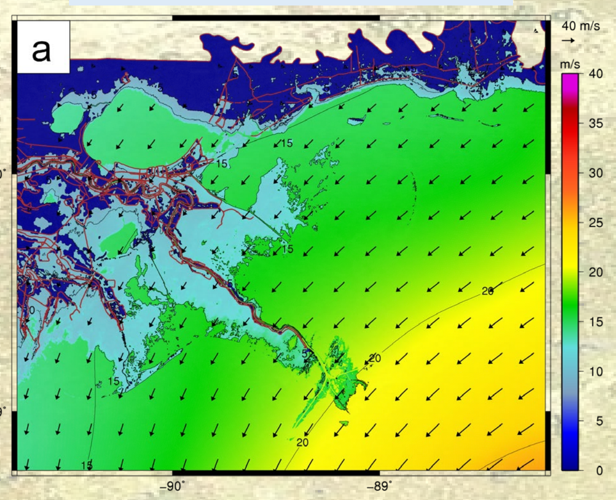
CFSv2 Global Atmospheric Model

ADCIRC 2D SWE

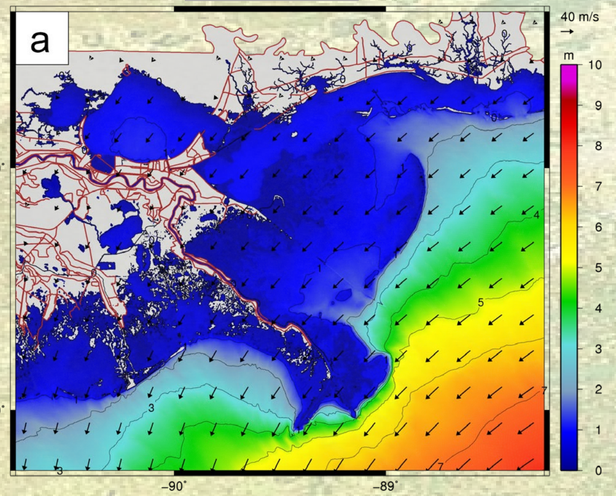
SWAN Wave Energy Density



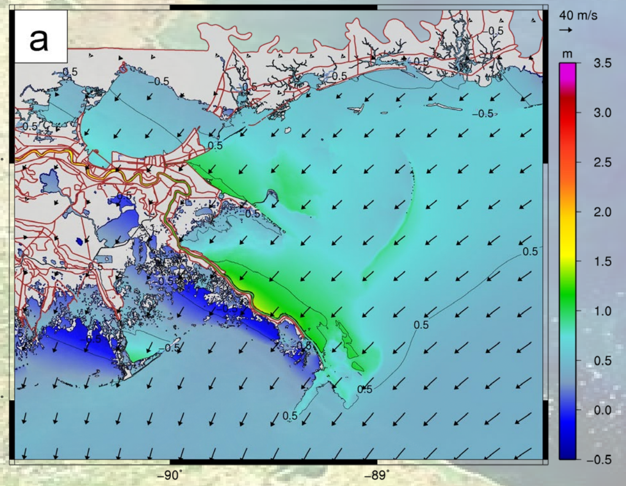
CFSv2



SWAN

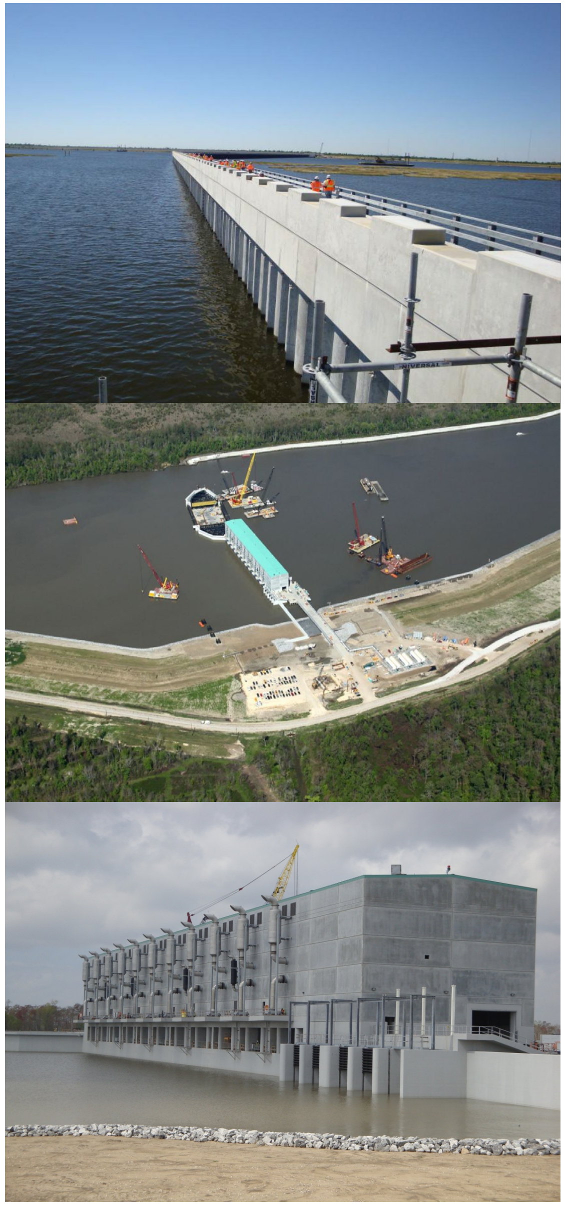


ADCIRC 2D



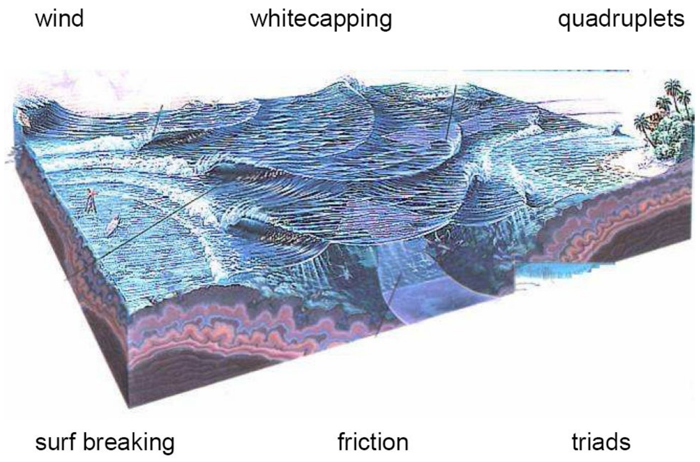
ADCIRC+SWAN: Coastal ocean circulation and wave models – the past

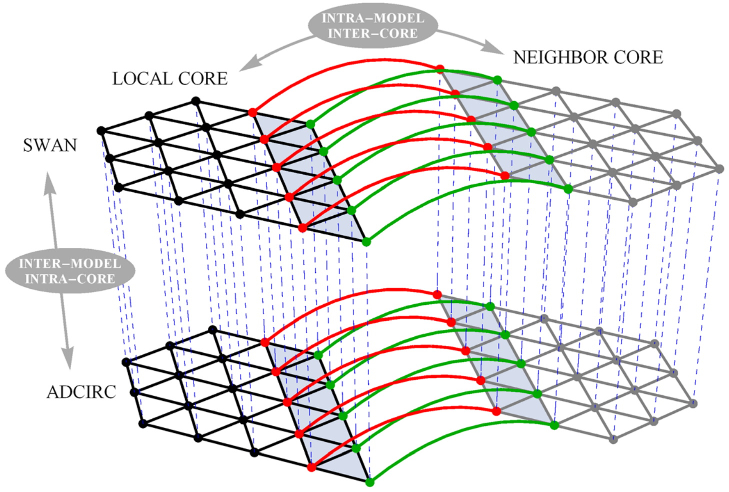
- ADCIRC solves the shallow water equations in 2D and 3D
- ADCIRC applies Galerkin FEM using highly unstructured linear finite element grids over large ocean domains
- ADCIRC usage highlights in U.S.
  - USACE: Design Metropolitan New Orleans levees post Katrina; Post Sandy flood risk study along East and Texas coasts
  - NOAA: Extra-tropical real time forecasting models (ESTOFS)
  - FEMA: Flood Insurance Studies for U.S. Gulf, East and Great Lakes coasts
  - NRC: Nuclear power station risk evaluation



ADCIRC+SWAN: Coastal ocean circulation and wave models – the past

- SWAN solves the wave action density and is a non-phase resolving wave model with wave energy represented by a spectrum
- SWAN has been implemented as an unstructured grid model with the degrees of freedom at triangle vertices
- ADCIRC and SWAN interact
  - Water levels and currents affect waves
  - Wave breaking forces water level setup and currents

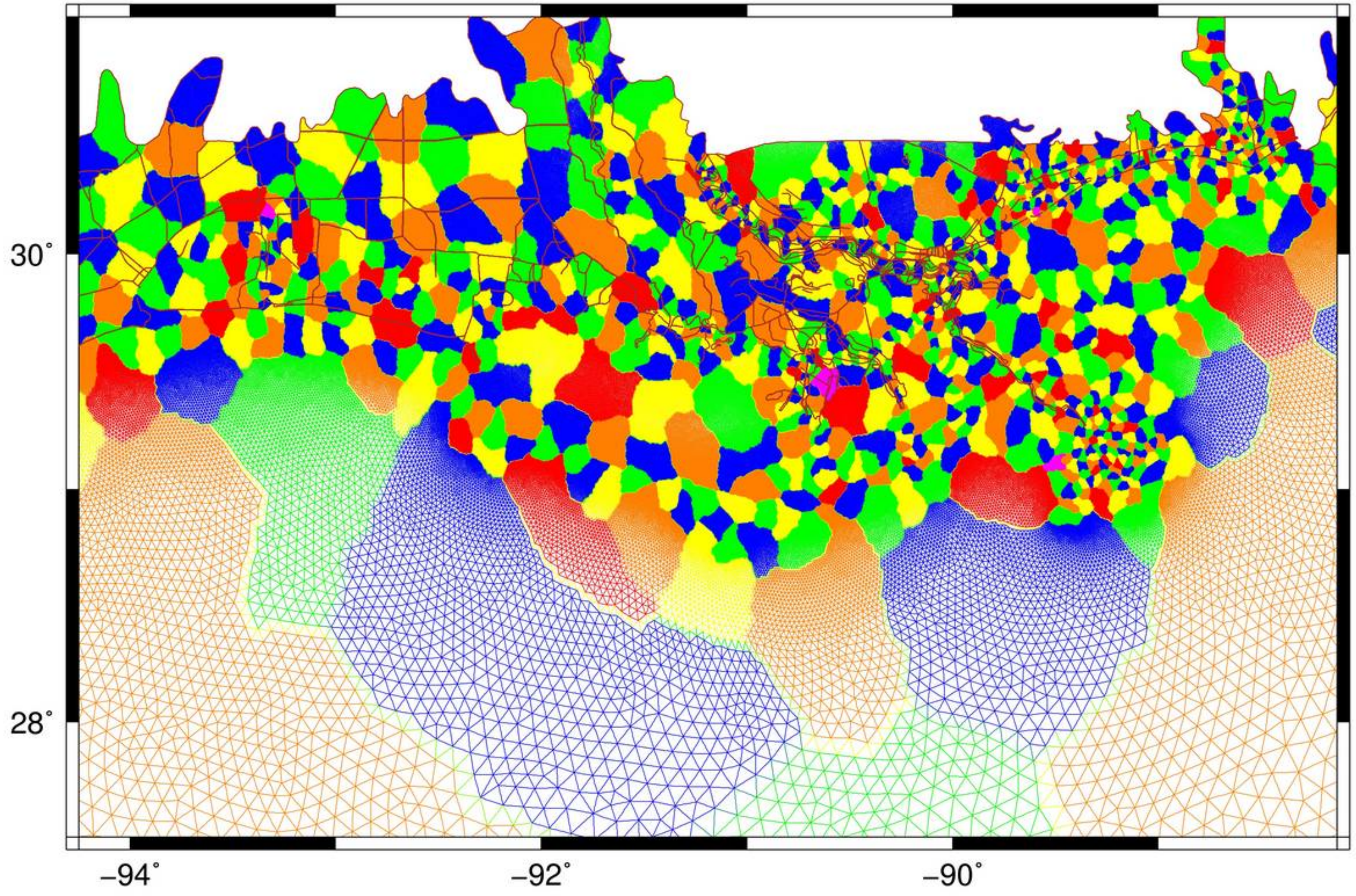




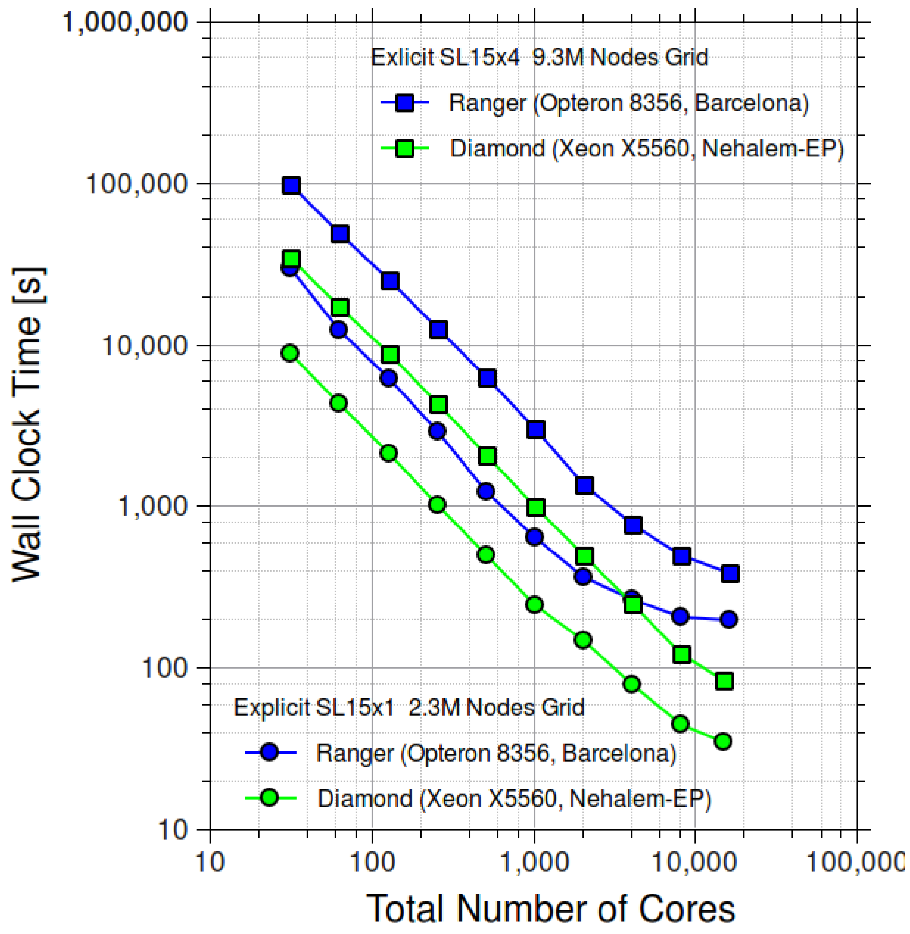
Dietrich et al., *Coastal Engineering*, **58**, 45-65, 2011.
Dietrich et al., *Journal of Scientific Computing*, **52**, 468-497 2012.

ADCIRC+SWAN: Coastal ocean circulation and wave models – the past

HPC: MPI Based Domain Decomposition – Overlapping Element Layer Node to Node Communication

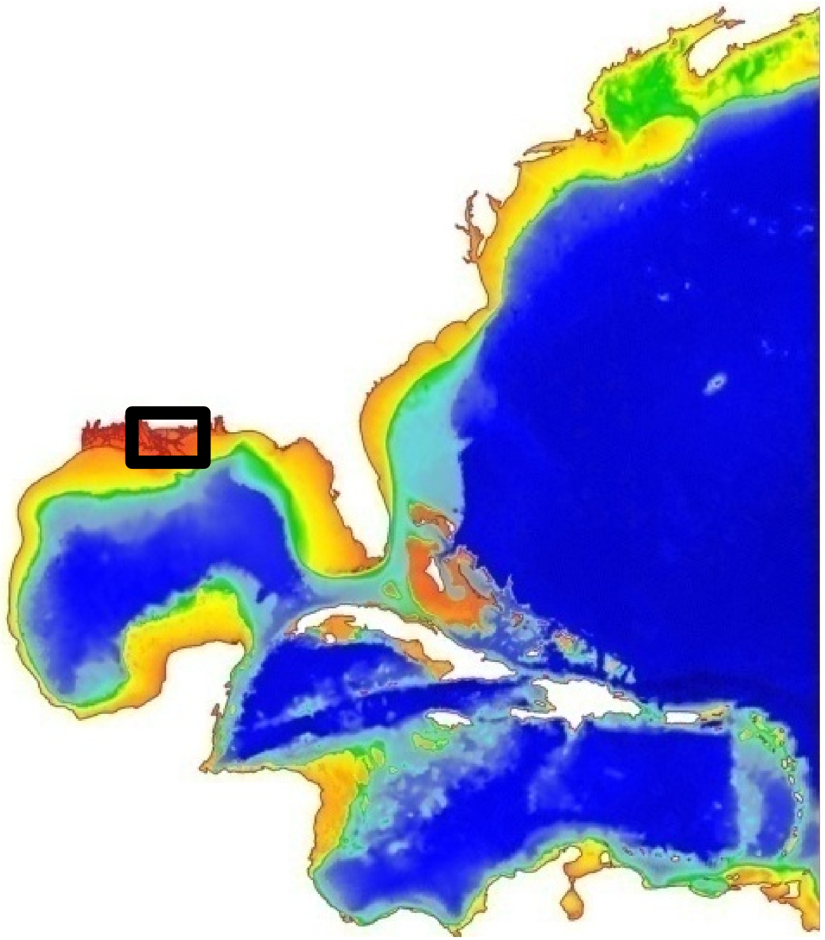


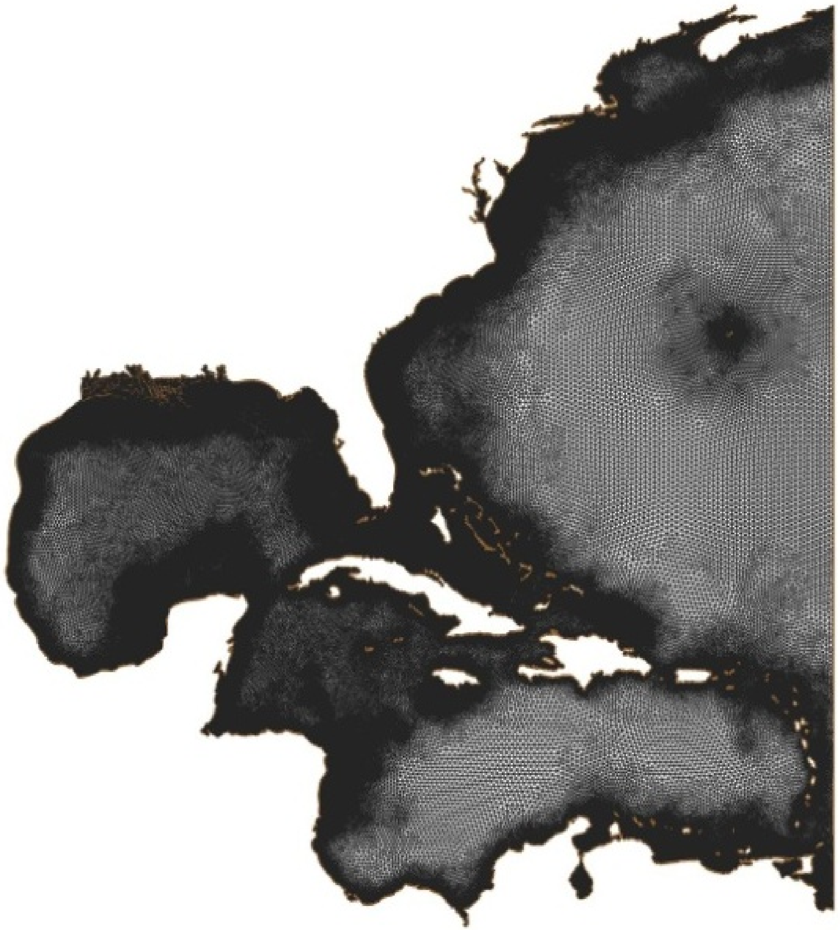
HPC: Parallel Performance



ADCIRC+SWAN: Coastal ocean circulation and wave models – the past

SL16v18 model bathymetry and topography and unstructured mesh

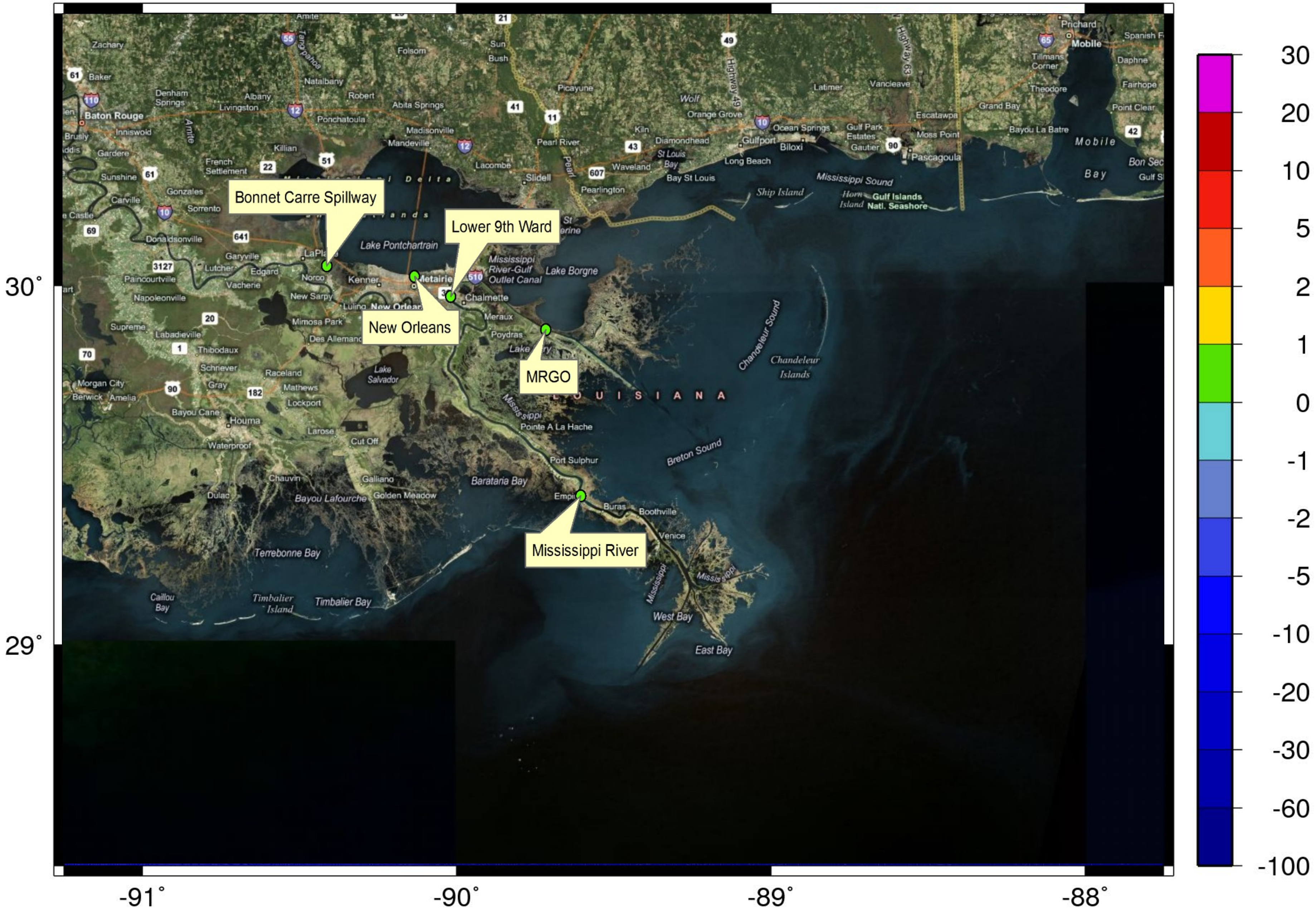




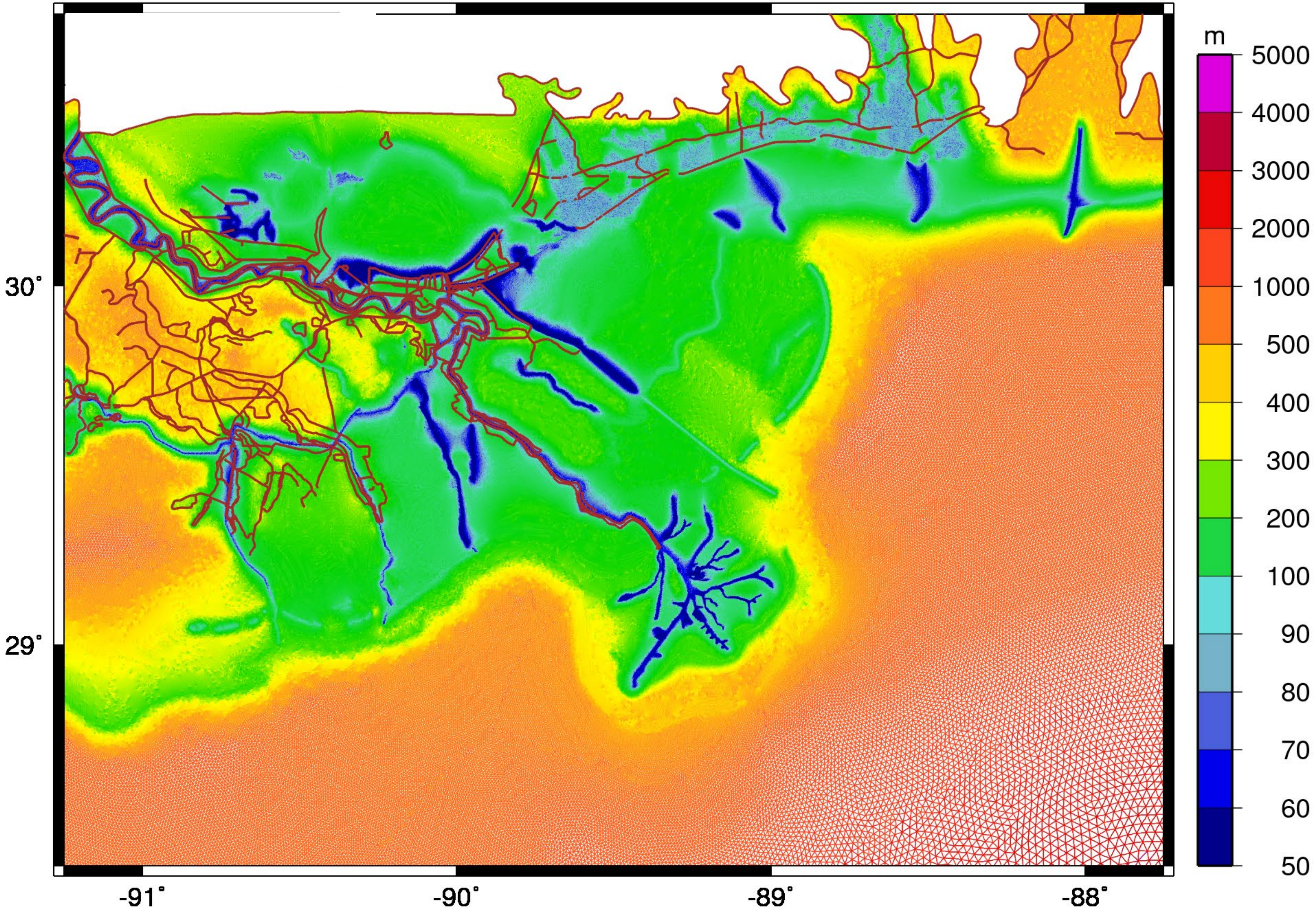
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.
Kennedy et al., ***Geophysical Research Letters***, **38**, L08608, 2011.
Kerr et al., ***Journal of Waterway, Port, Coastal, and Ocean Engineering***, **139,** 326-335, 2013.

Martyr et al., ***Journal of Hydraulic Engineering***, **139**, 5, 492-501, 2013.
Hope et al., ***Journal of Geophysical Research: Oceans***, **118**, 4424-4460, 2013.
Kerr et al., ***Journal of Geophysical Research: Oceans*****, 118,** 5129–5172, 2013.

SL16v18 model bathymetry & topography in SE Louisiana

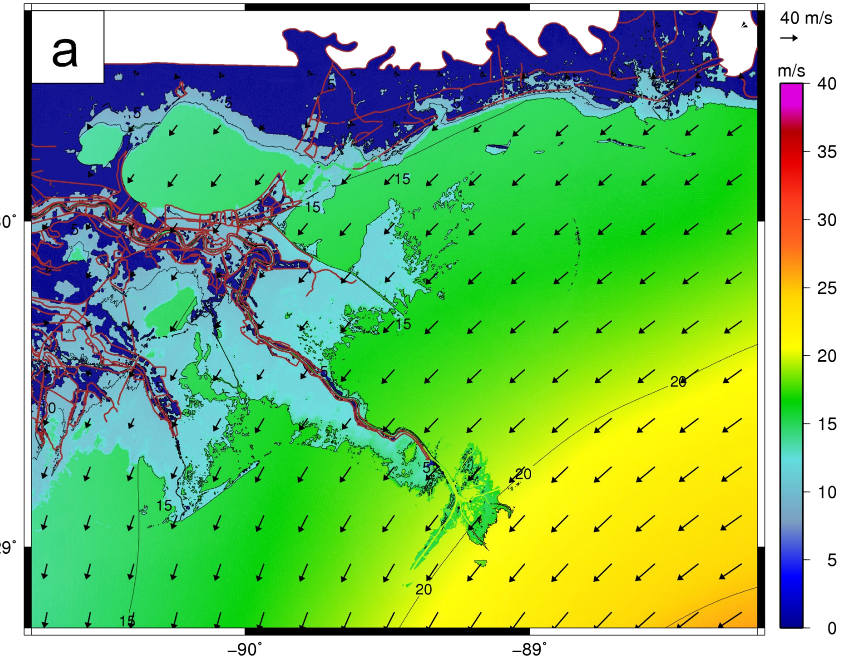


Models: SL16v18 mesh size in SE Louisiana

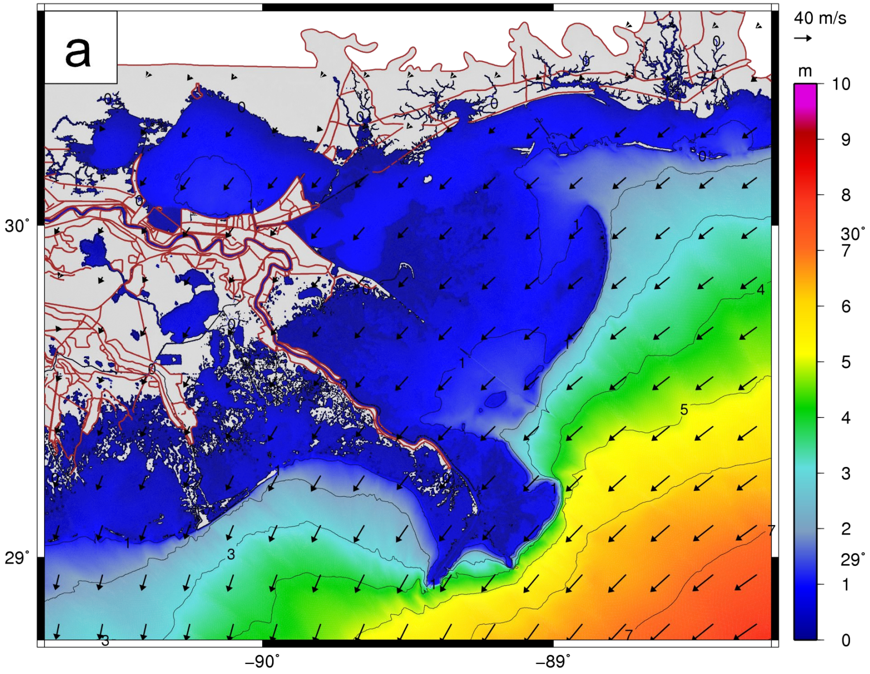


Hurricane Gustav: 2008 / 09 / 01 / 0200 UTC

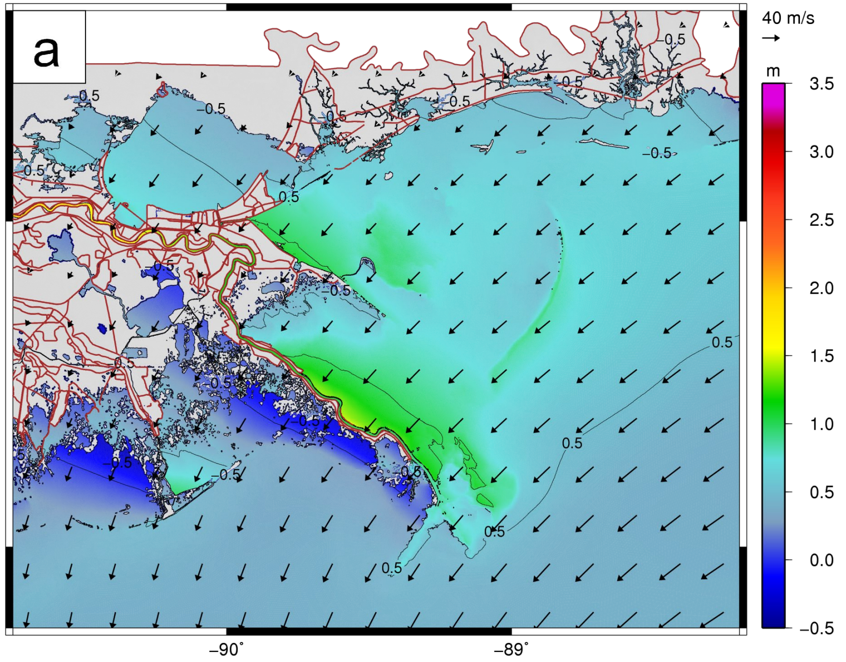
Winds (m/s)



Waves (m)



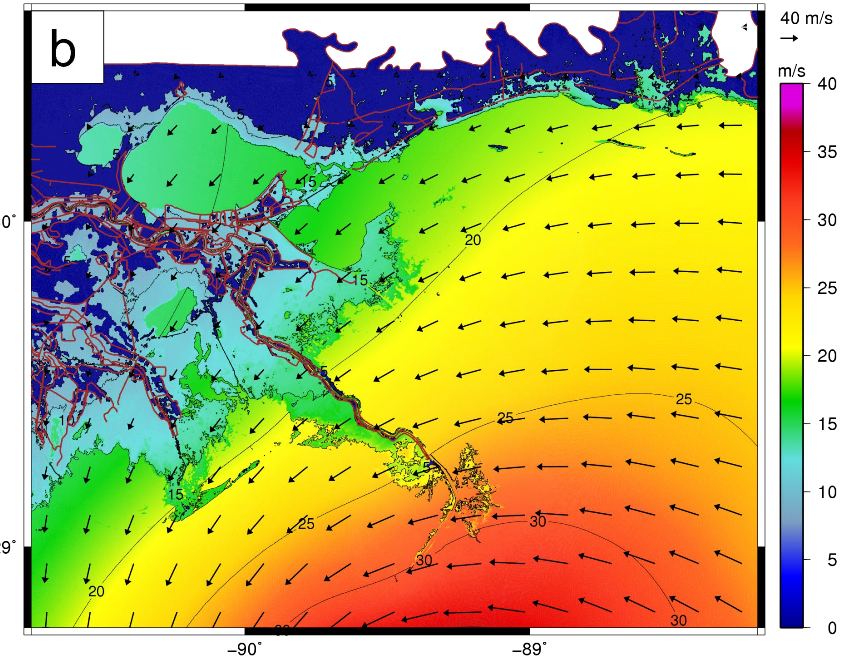
Water Elevations (m)



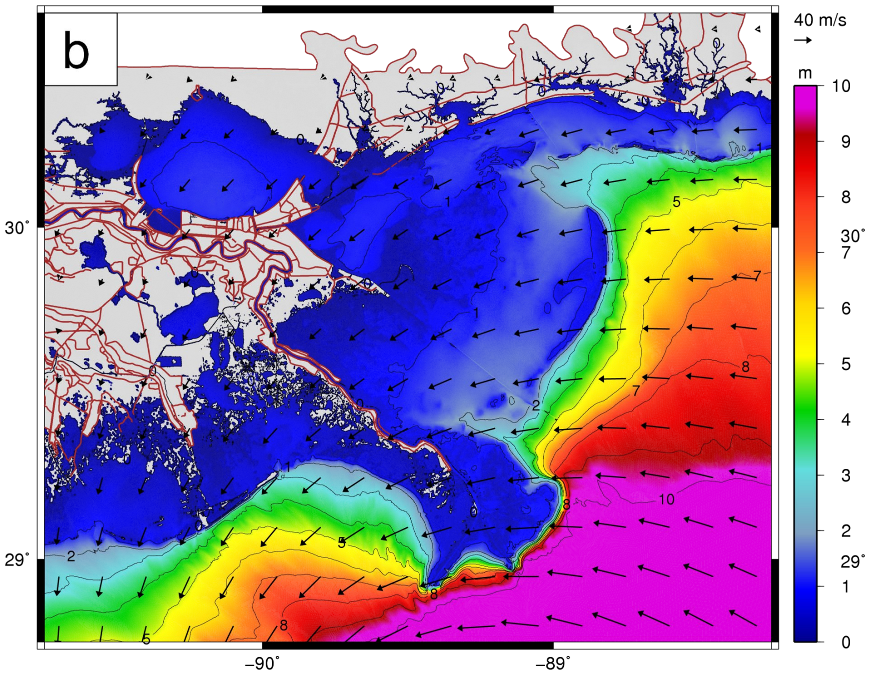
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 0800 UTC

Winds (m/s)



Waves (m)



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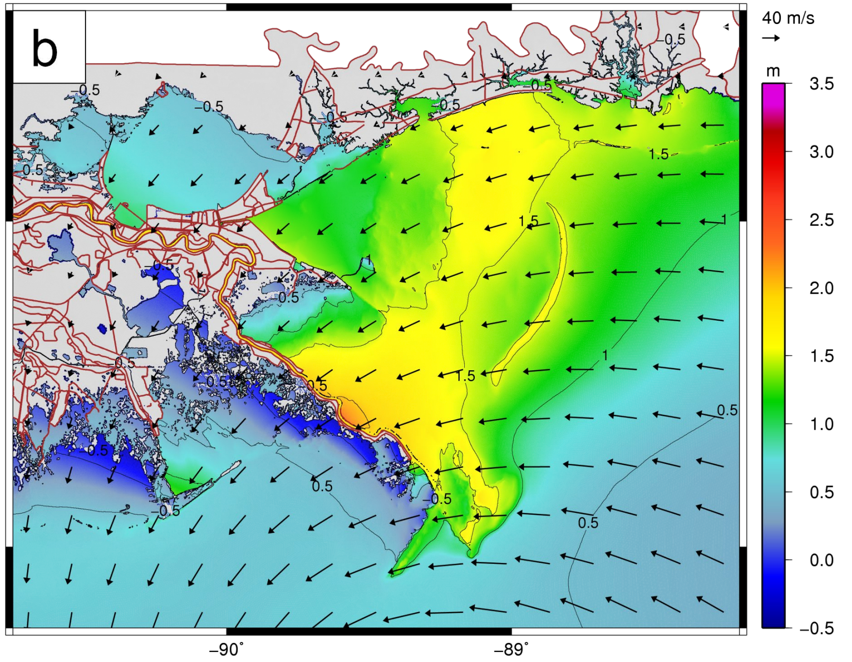
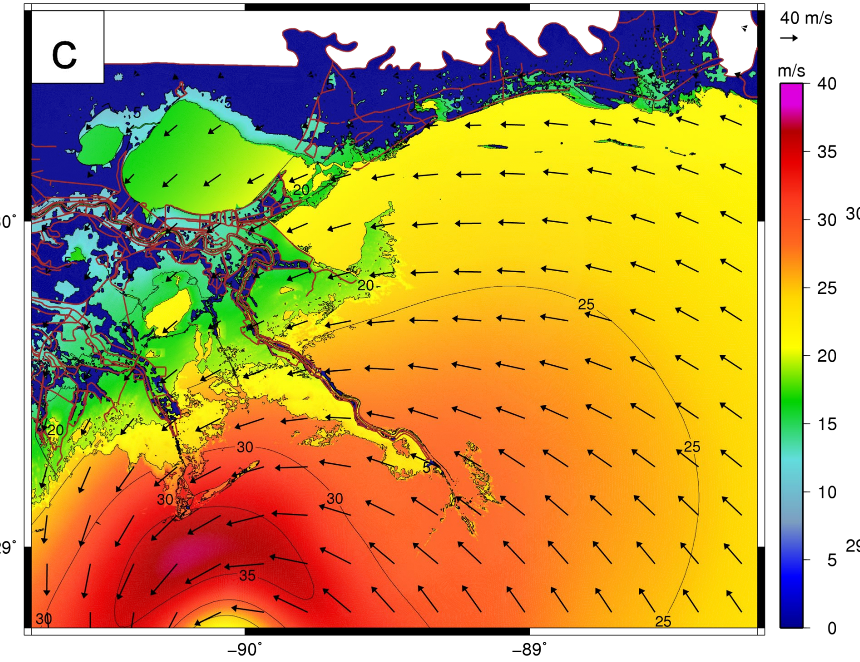


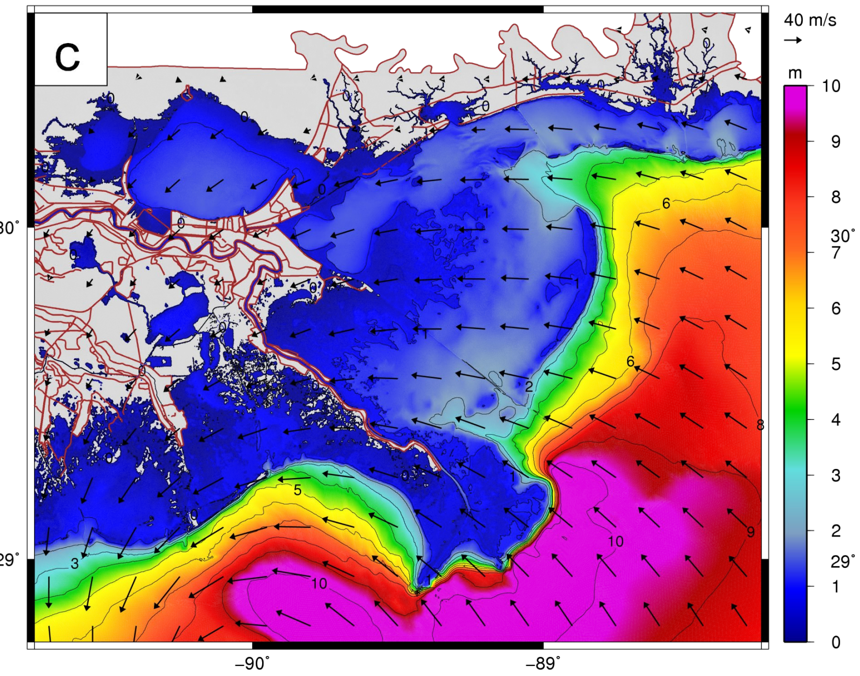
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 1100 UTC

Winds (m/s)



Waves (m)



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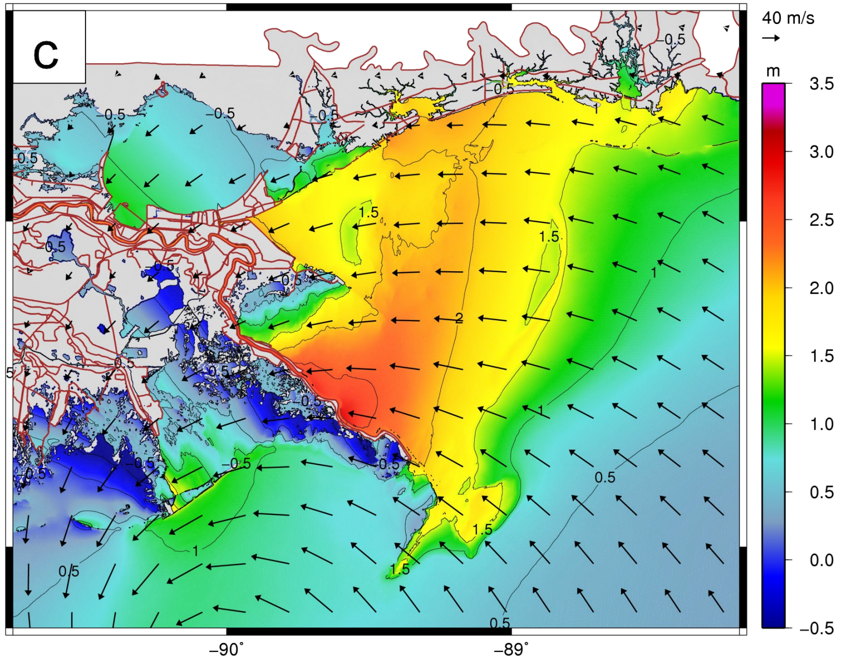
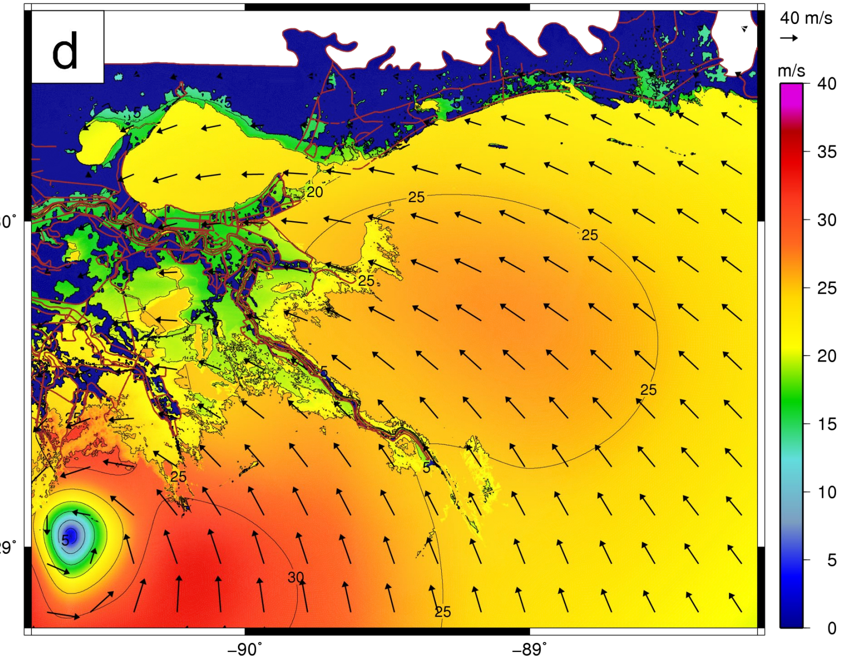


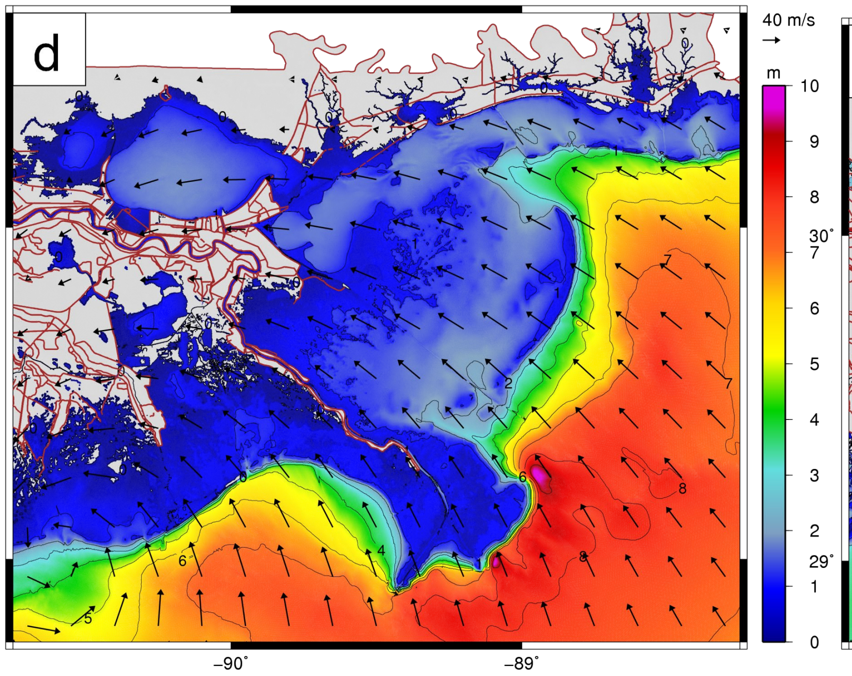
Dietrich et al., ***Monthly Weather Review*, 139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 1400 UTC

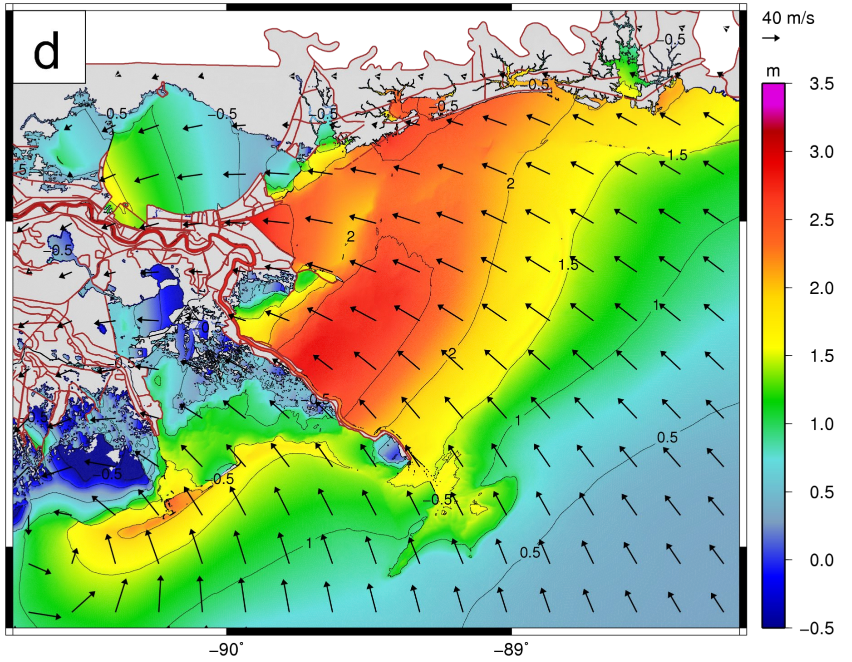
Winds (m/s)



Waves (m)



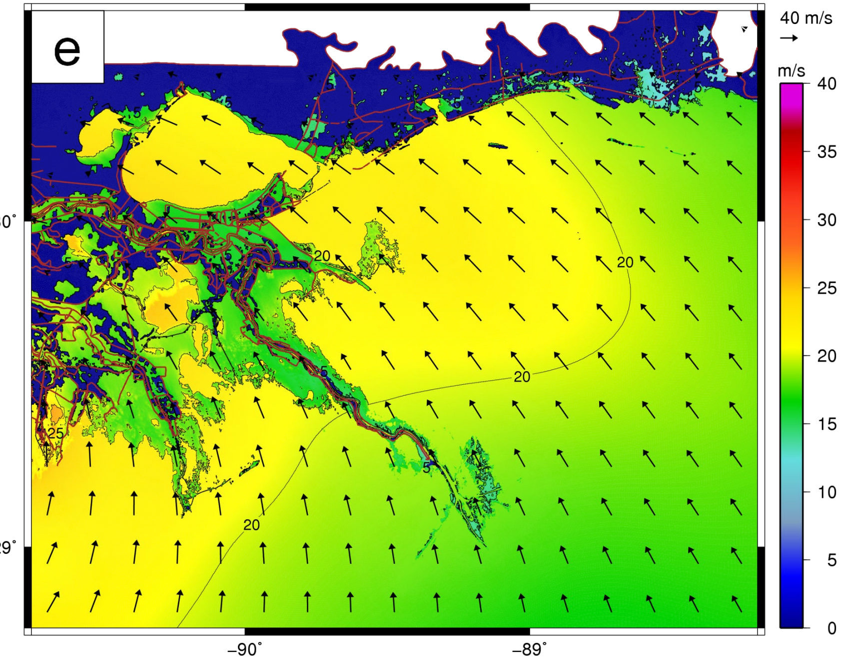
Water Elevations (m)



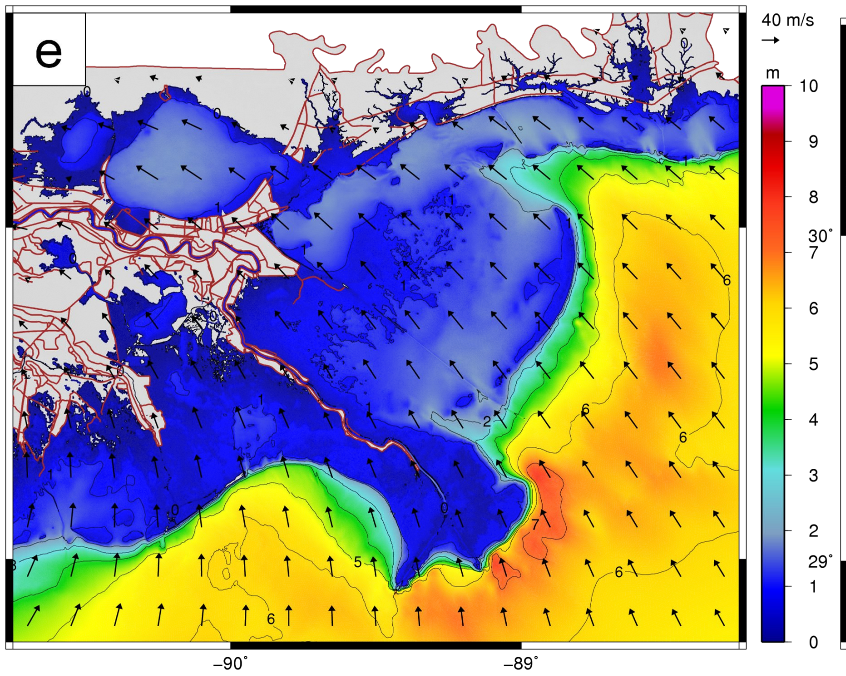
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 1700 UTC

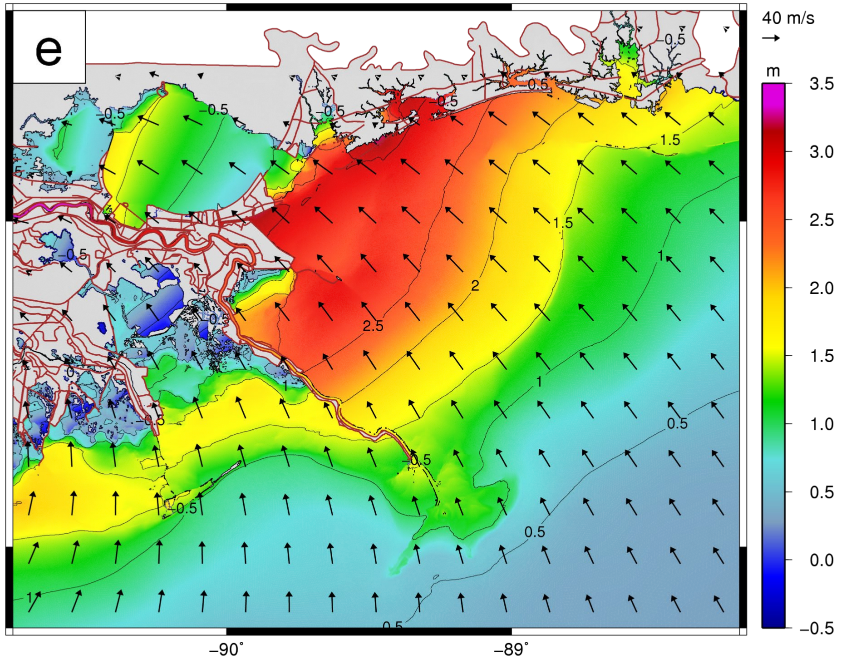
Winds (m/s)



Waves (m)



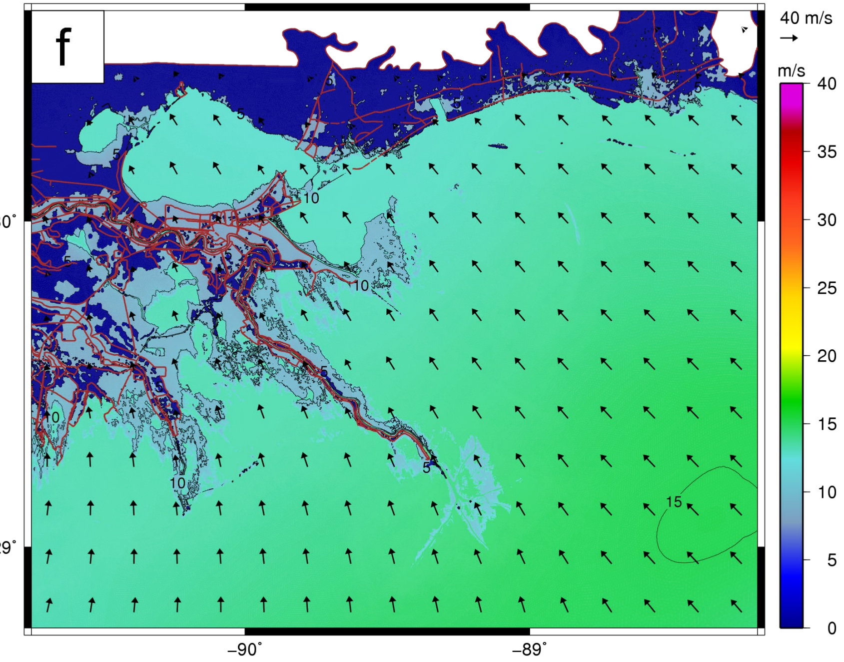
Water Elevations (m)



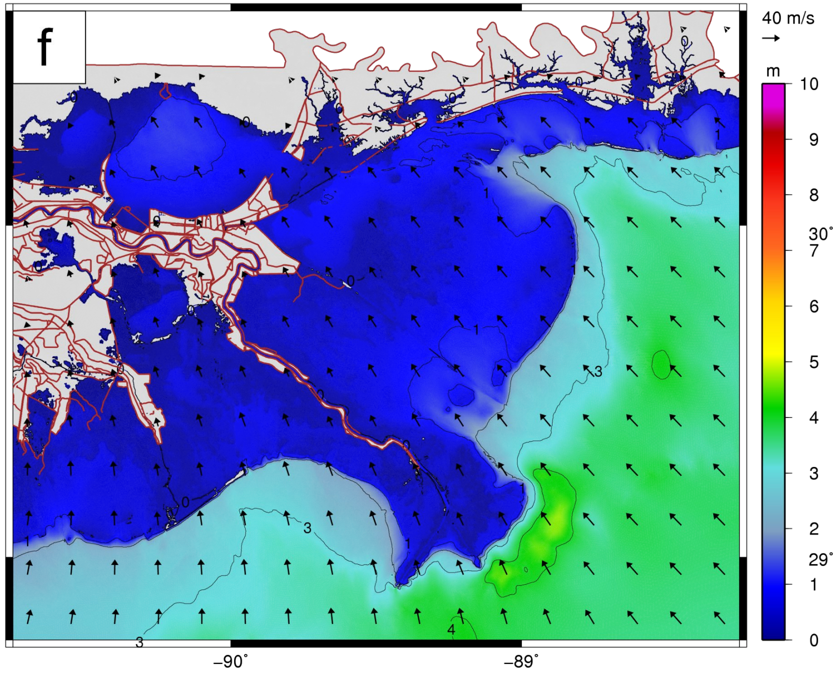
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 02 / 0200 UTC

Winds (m/s)



Waves (m)



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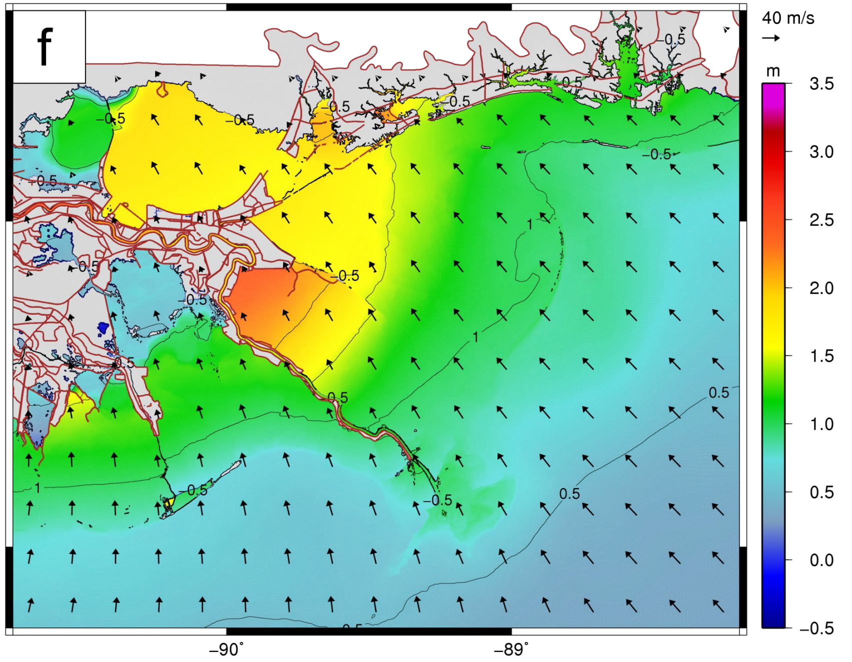


Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Evolution of coastal ocean hydrodynamics models – the recent past

The GOOD

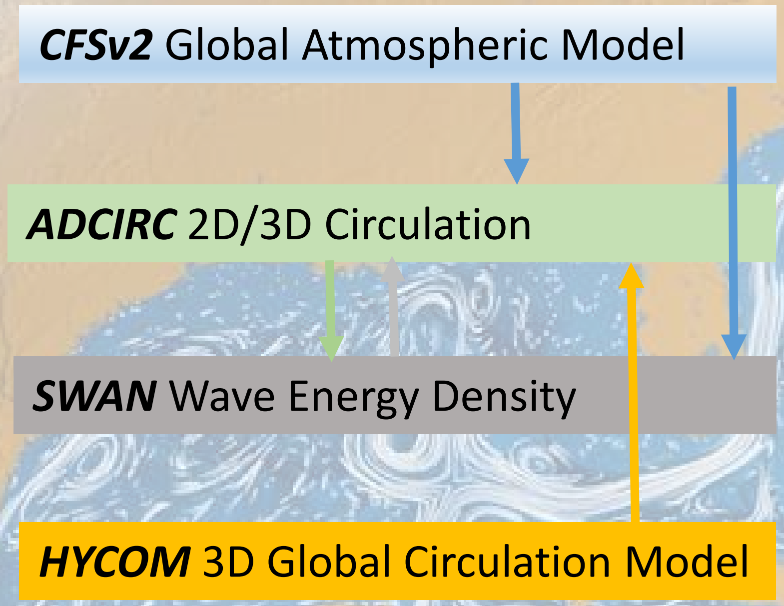
- Unstructured grids focusing on localized resolution
- Better resolution
- Better algorithms
- Better physics of sub-grid scale
- Improving parallelism
- More component interaction

The BAD

- Sub-optimal grids
- Largely second order or lower
- Often inefficient parallel processing
- Largely siloed development with disparate communities

Evolution of coastal ocean hydrodynamic models – the present

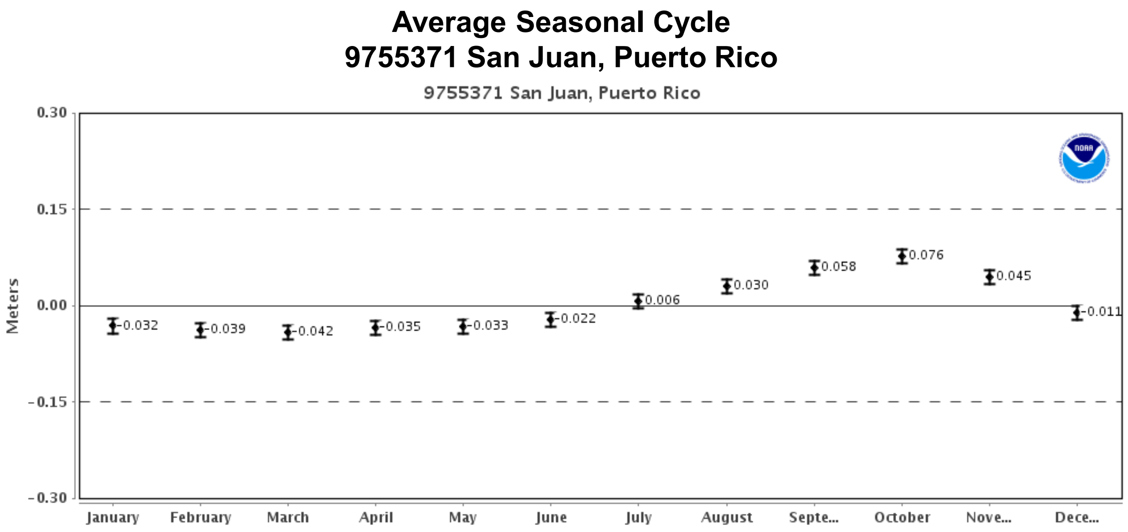
Dynamic *ADCIRC, SWAN & HYCOM* interleafing

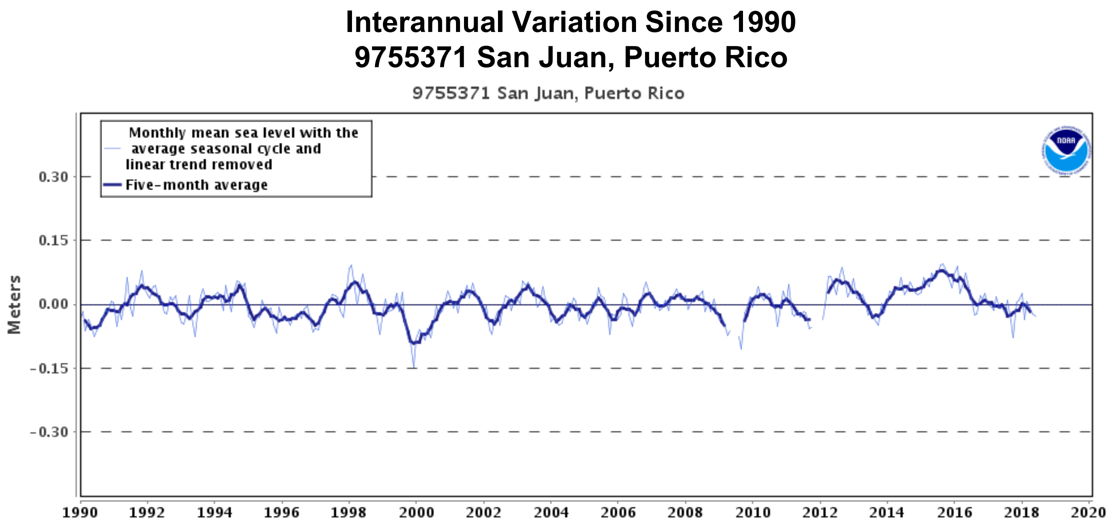


Background

➢ For a certain storm, flooding risks for coastal cities change based on long term, seasonal, and other variabilities in water levels

- Long term warming of the ocean and melting of glaciers
- Seasonal warming and cooling cycles



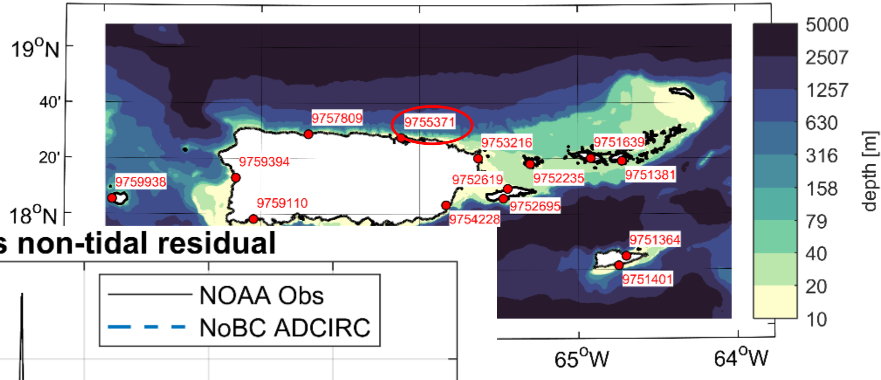


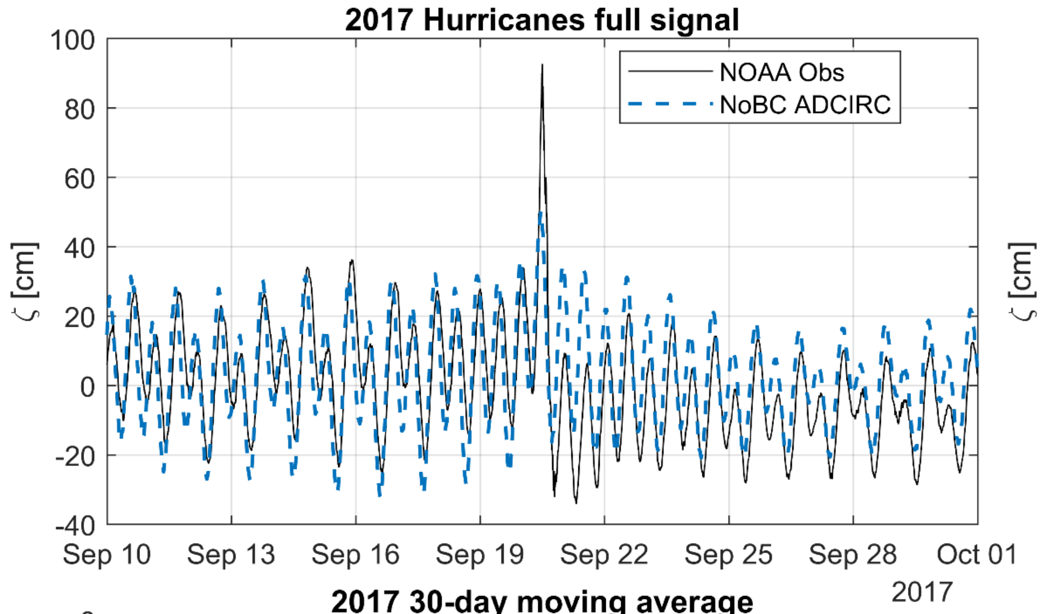
Obtained from: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9755371

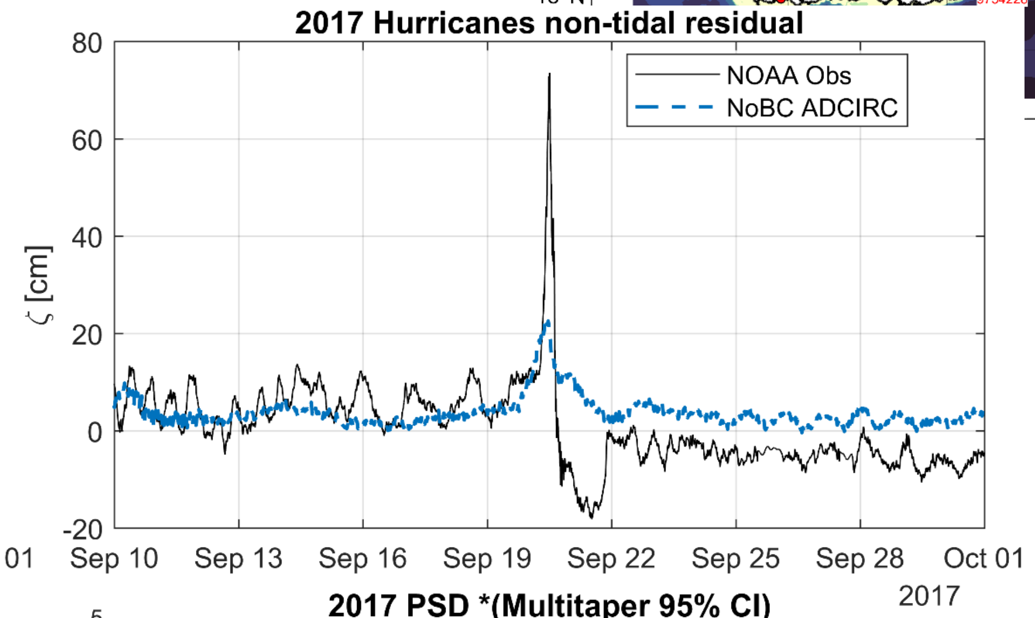
- Changes in ocean current systems
- Changes to freshwater runoff
- Interaction of winds and nearshore stratification

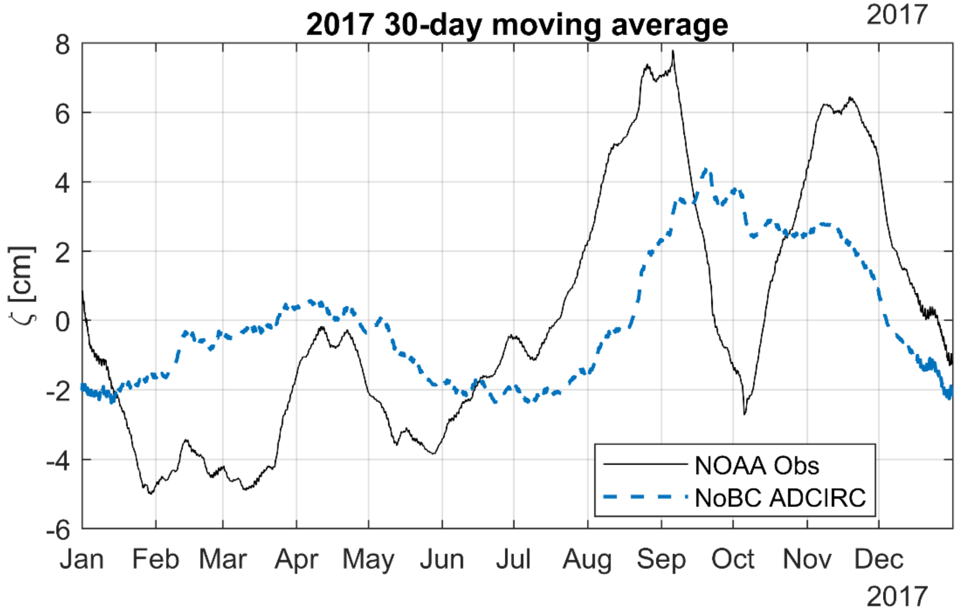
Time Series and Spectral Density –

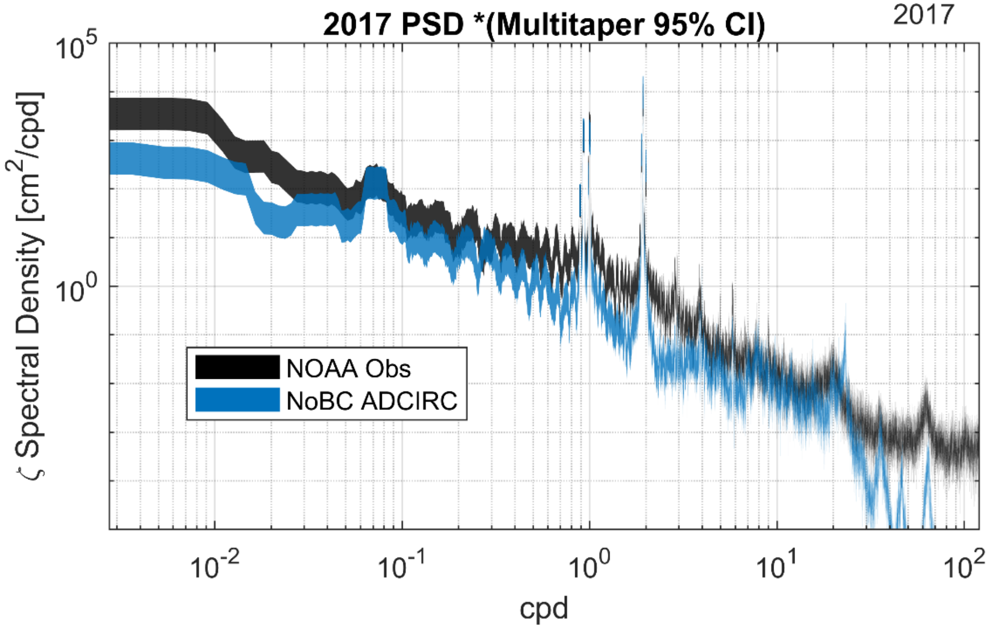
San Juan, La Puntilla, San Juan Bay, PR









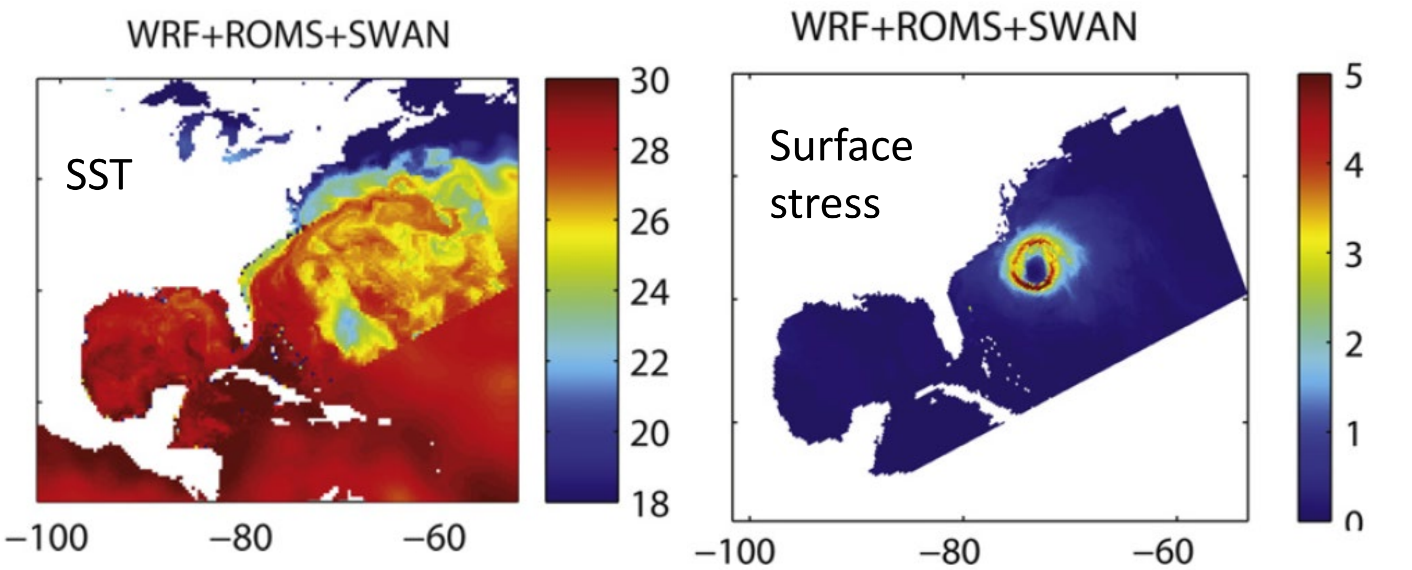


Problem

- Processes that affect background water levels are primarily baroclinic
- Tide + Surge analysis is often conducted using 2D barotropic model
  - Model does not take into account density or vertical velocity structure
- 3D models are being used more for surge analysis but..
  - 3D model is more sensitive and adds a greater degree of freedom compared to 2D
  - Horizontal resolution, temporal resolution, and domain size typically sacrificed

3D baroclinic ROMS coupled system during Hurricane Isabel

J.C., Armstrong, B., He, R., Zambon, J.B., 2010. Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. Ocean Model. 35, 230–244. doi:10.1016/j.ocemod.2010.07.0100



Solution (this Study)

- Feed a 2D barotropic model (ADCIRC) information from an operational and freely available 3D baroclinic ocean model (HYCOM - GOFS3.1)

- Behaves like explicit mode-splitting between two different models
  - 2D barotropic model is the (fast) barotropic external mode
  - 3D baroclinic ocean model is the (slow) baroclinic internal mode

- Preserve the high horizontal and temporal resolution, and numerical stability associated with 2D barotropic models that makes them so useful

- Accounts for the effects of 3D ocean baroclinicity on coastal water levels

- Leverages on the quality of existing widely validated and used ocean models

Method (Internal)

- 3D baroclinic terms ∇B and ∇D are calculated from the density ρ and velocity structure $\boldsymbol{v}$ on the HYCOM grid output and interpolated to 2D ADCIRC model
- Internal tide wave drag parameterization uses buoyancy frequencies N computed and interpolated from HYCOM
- GWS Oceanographic Toolbox converts HYCOM outputs (T and S) to ρ and N

2D Depth-integrated Momentum Equation

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} + f\mathbf{k} \times \boldsymbol{u} = -\nabla \left[\frac{p_s}{\rho_0} + g(\zeta - \zeta_{EQ} - \zeta_{SAL}) \right] + \frac{\nabla M}{H} - \frac{\nabla D}{H} - \frac{\nabla B}{H} + \frac{\boldsymbol{\tau}_s}{\rho_0 H} - \frac{\boldsymbol{\tau}_b}{\rho_0 H} - \mathcal{F}_{IT}$$

- Baroclinic pressure gradient (BPG):

$$\nabla B = \int_{-h}^{\zeta} \left(g \nabla \left[\int_{z}^{\zeta} \frac{\rho - \rho_0}{\rho_0} \right] dz \right) dz$$

- Momentum Dispersion:

$$\nabla D = \nabla \int_{-h}^{0} [(\boldsymbol{v} - \boldsymbol{V}) \cdot (\boldsymbol{v} - \boldsymbol{V})]\, dz$$

- Internal tide induced barotropic energy conversion:

$$\mathcal{F}_{IT} = C_{IT} \frac{[(N_b^2 - \omega^2)(\tilde{N}^2 - \omega^2)]^{1/2}}{\omega} (\nabla h \cdot \boldsymbol{u}) \nabla h$$

Method (Boundaries)

2D Continuity Equation

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot (\boldsymbol{u}H) = -\sigma(\boldsymbol{x})(\zeta - \zeta_c)$$

2D Depth-integrated Momentum Equation

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + f\mathbf{k} \times \boldsymbol{u} = -\nabla \left[\frac{p_s}{\rho_0} + g(\zeta - \zeta_{EQ} - \zeta_{SAL})\right] + \frac{\nabla M}{H} - \frac{\nabla D}{H} - \frac{\nabla B}{H} + \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho_0 H} - \mathcal{F}_{IT} - \sigma(\boldsymbol{x})(\boldsymbol{u} - \boldsymbol{u_c})$$

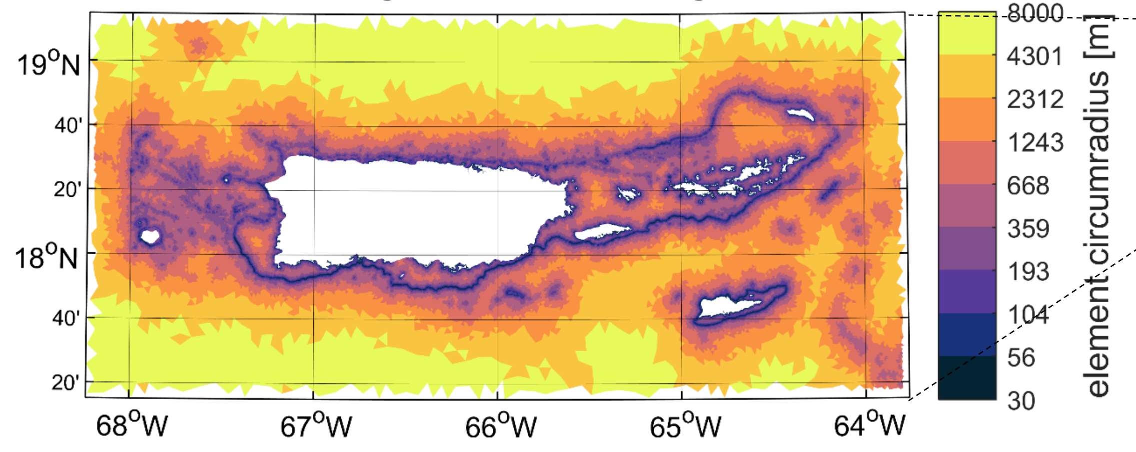
- An absorption-generation sponge layer on the lateral boundary is pretty much *required!*
- $\sigma(x)$ follows quadratic function increasing from zero at beginning of sponge layer
- ζ_c is the sum of tidal elevations and HYCOM elevations
- $\boldsymbol{u_c}$ is the tidal velocities *only*
- $\nabla B, \nabla D, \boldsymbol{\tau}_s = 0$, $p_s = p_{ref}$ inside sponge!

Obtained from TPXO9.1 harmonic constituents

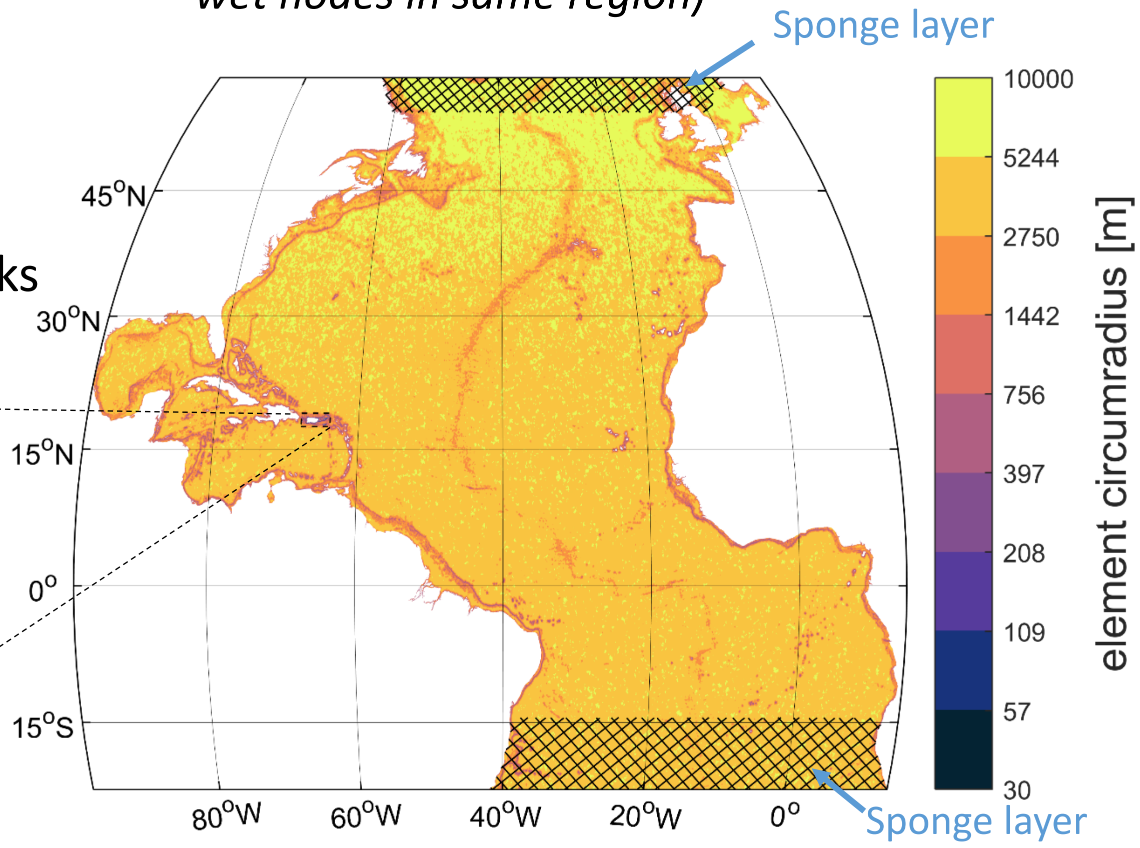
Application to Puerto Rico and US Virgin Islands (PRVI)

- North Atlantic Ocean unstructured mesh generated using state-of-the-art OceanMesh2D MATLAB toolbox (FREE)
  https://github.com/CHLNDDEV/OceanMesh2D/
  User guide doi: 10.13140/RG.2.2.21840.61446/1
- Maximum resolution ~8 km in ocean (same as HYCOM)
- ~30m resolution around PRVI coast and shelf breaks

PRVI high-resolution region



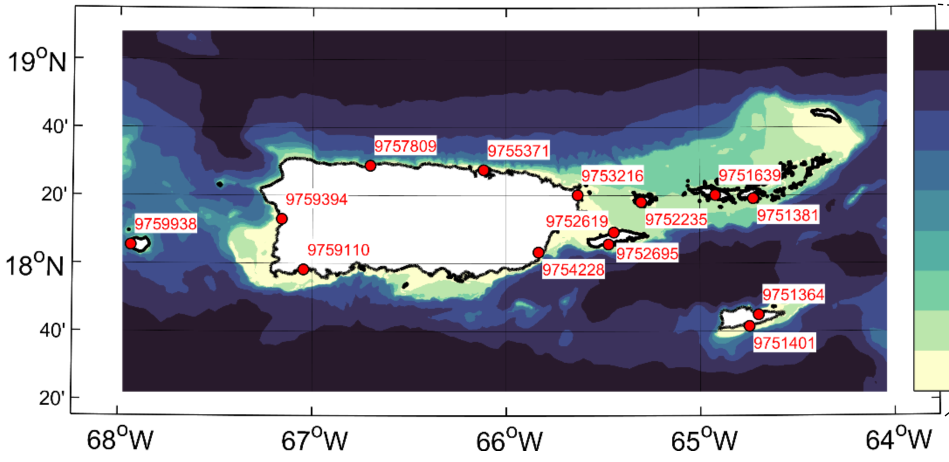
North Atlantic Ocean Domain
~1.5 million nodes (HYCOM has ~30 million wet nodes in same region)

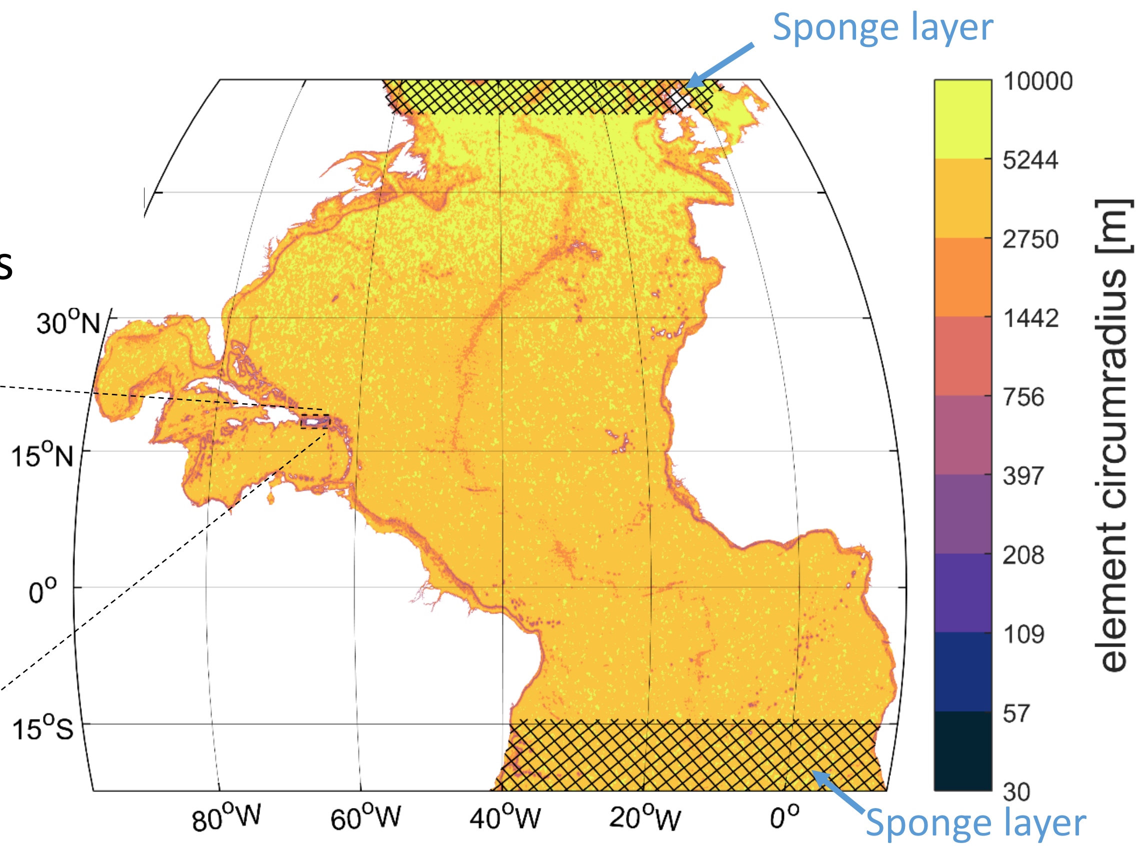


Model Setup

- ➢ CFSv2 hourly winds and sea surface pressures
- ➢ GOFS 3.1 HYCOM 3-hourly oceanographic outputs
- ➢ Simulation over whole year of 2017
- ➢ Compare 2D barotropic ADCIRC, 2D “baroclinic” ADCIRC, and GOFS 3.1 HYCOM at NOAA tide gauges

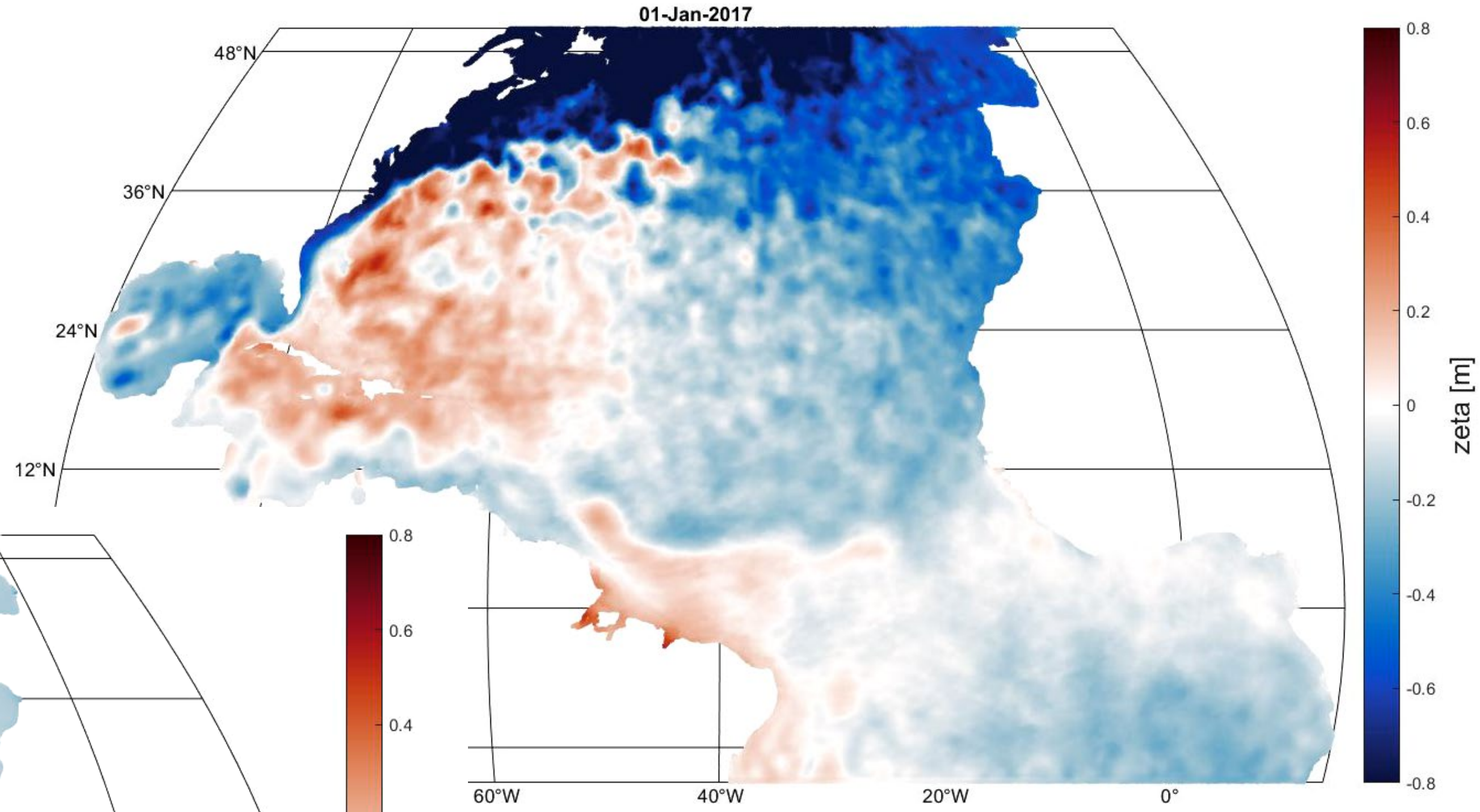
PRVI bathymetry and NOAA tide gauges



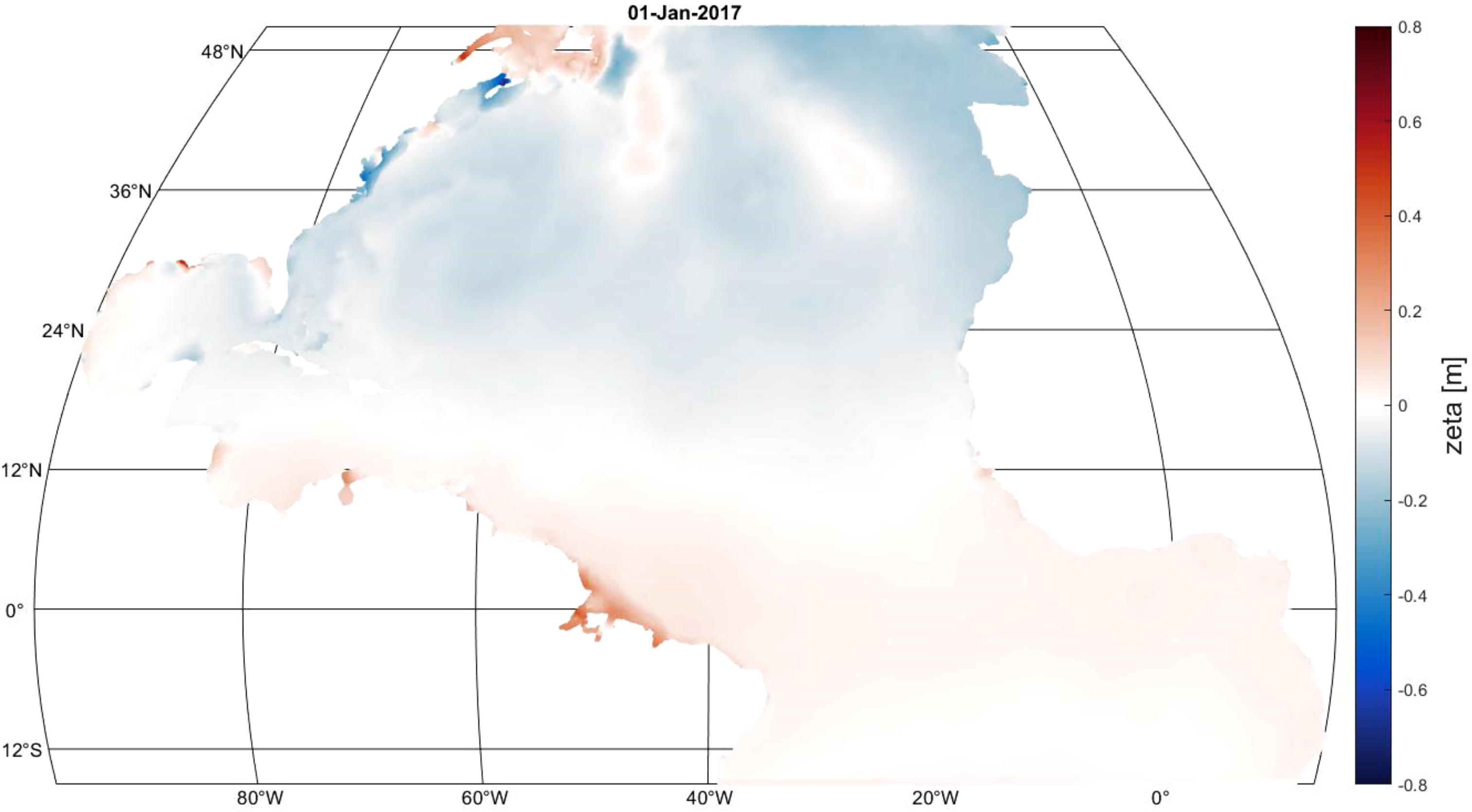


2017
SSH Daily Outputs
(no tides)

2D Baroclinic ADCIRC

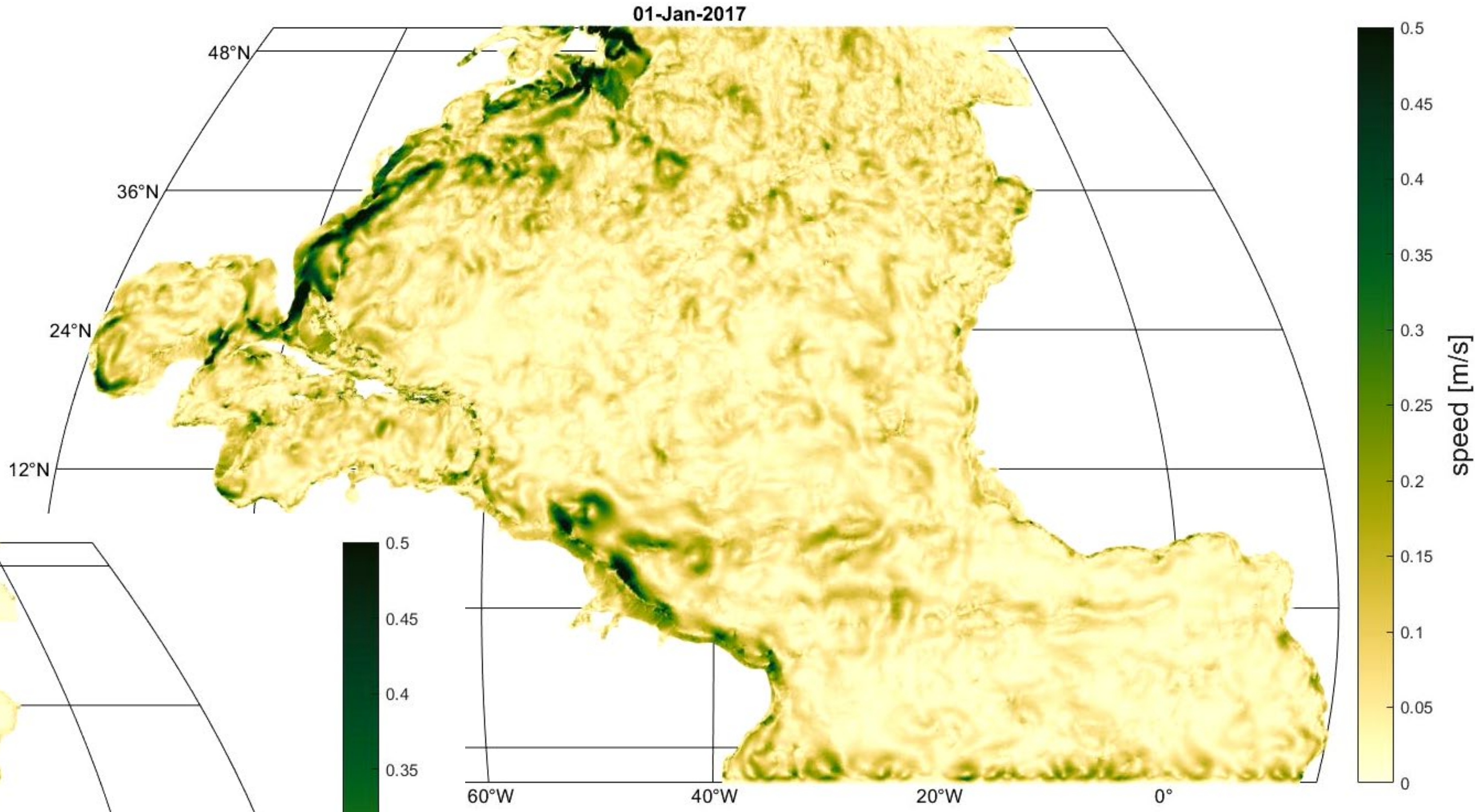


2D Barotropic ADCIRC

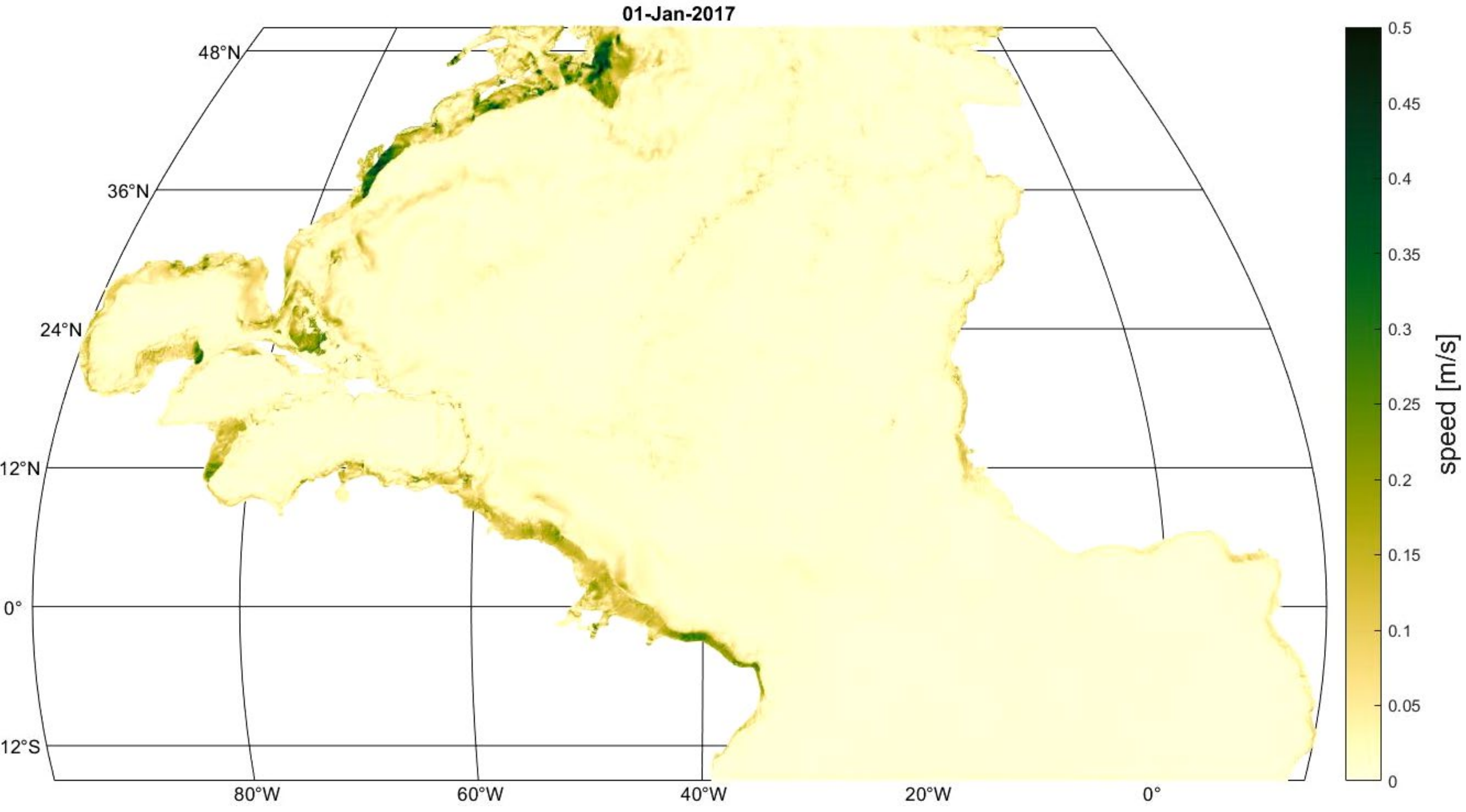


2017
Ocean Currents
Daily Outputs
(no tides)

2D Baroclinic ADCIRC

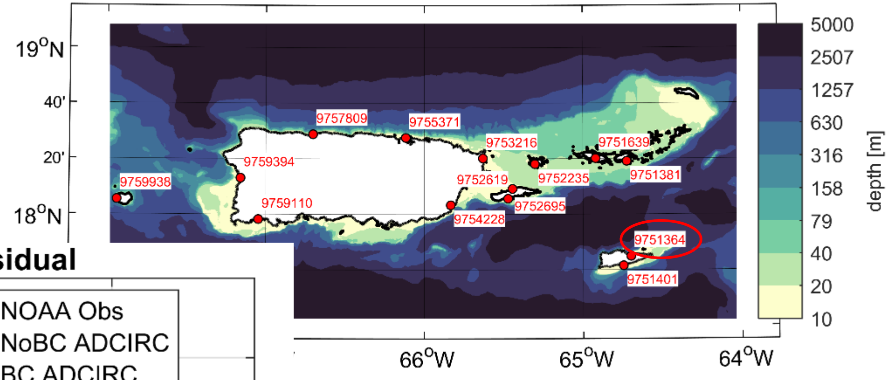


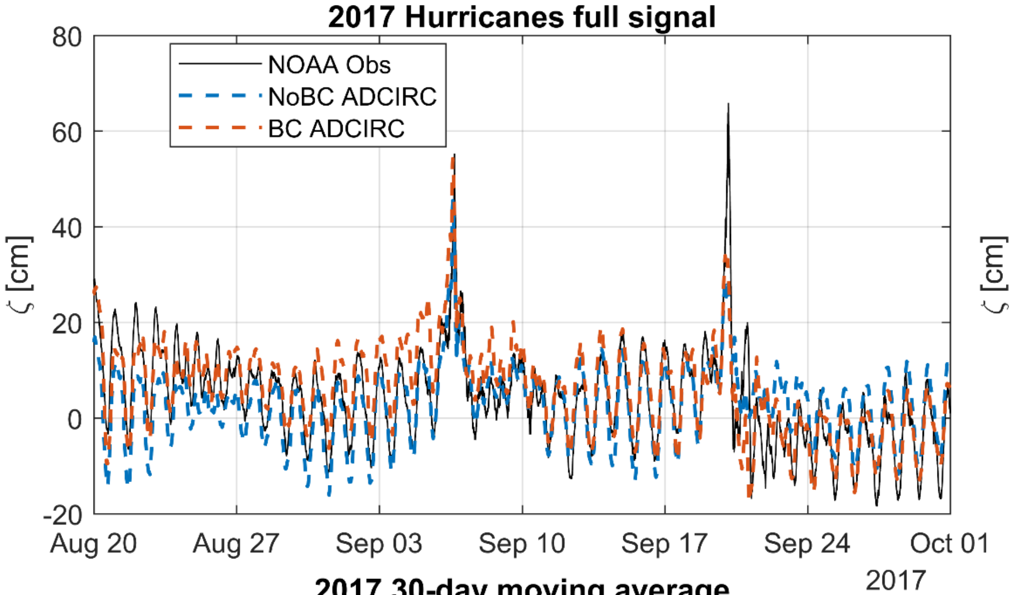
2D Barotropic ADCIRC

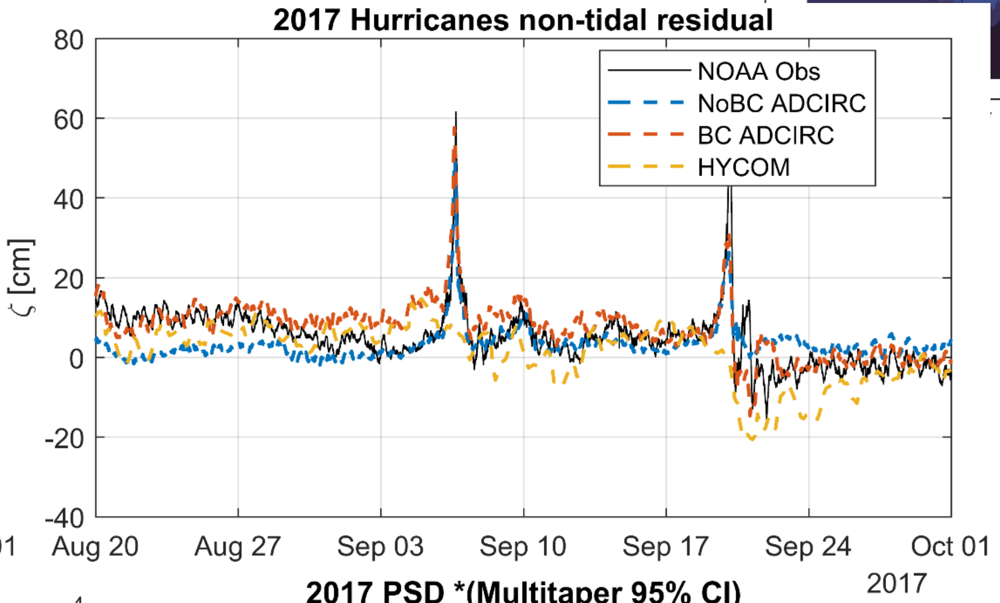


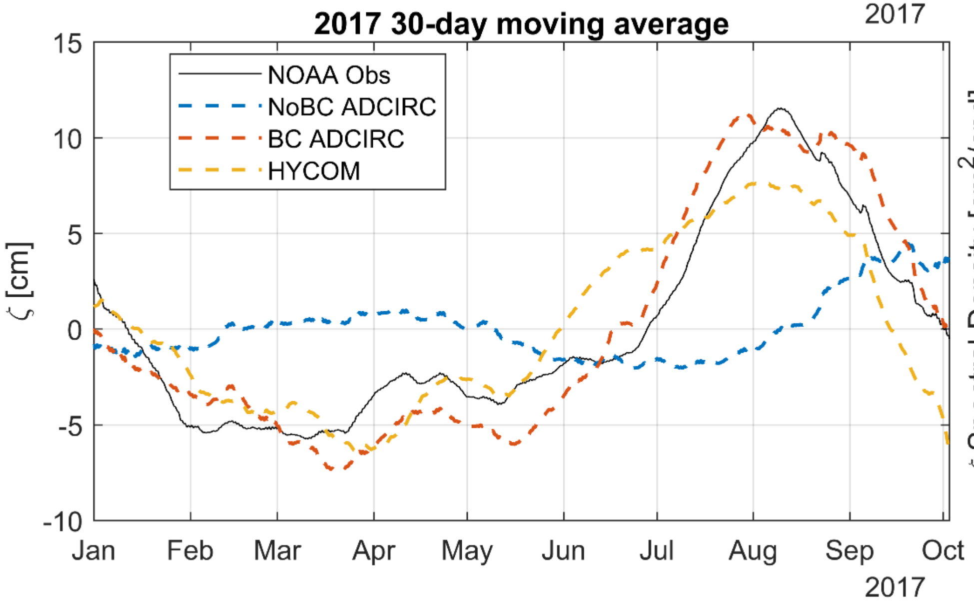
Time Series and Spectral Density -

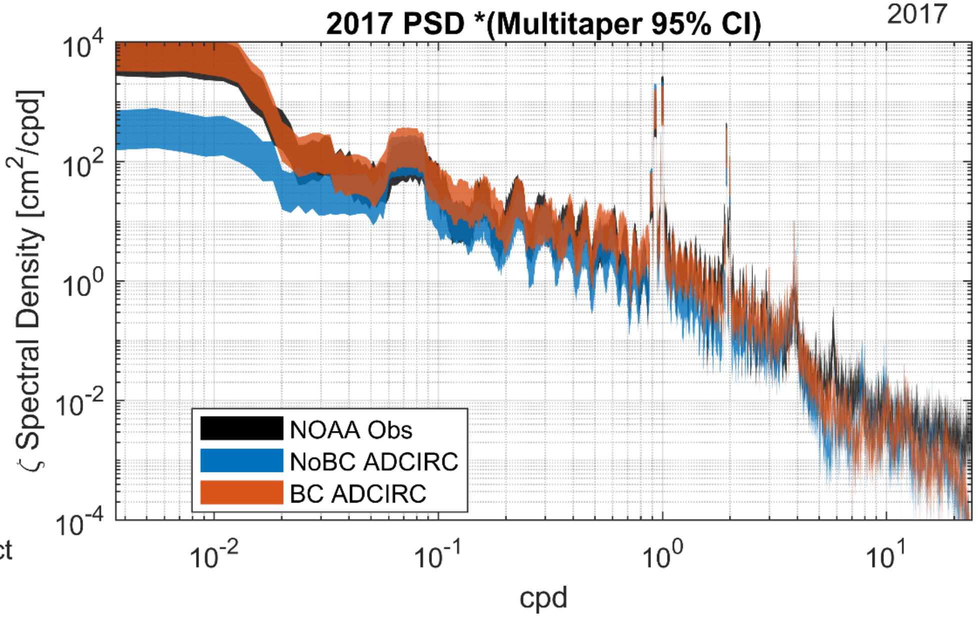
Christiansted Harbor St Croix, VI





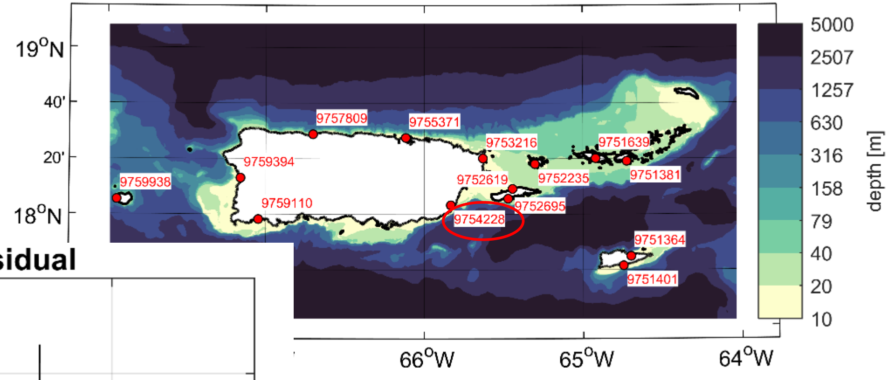


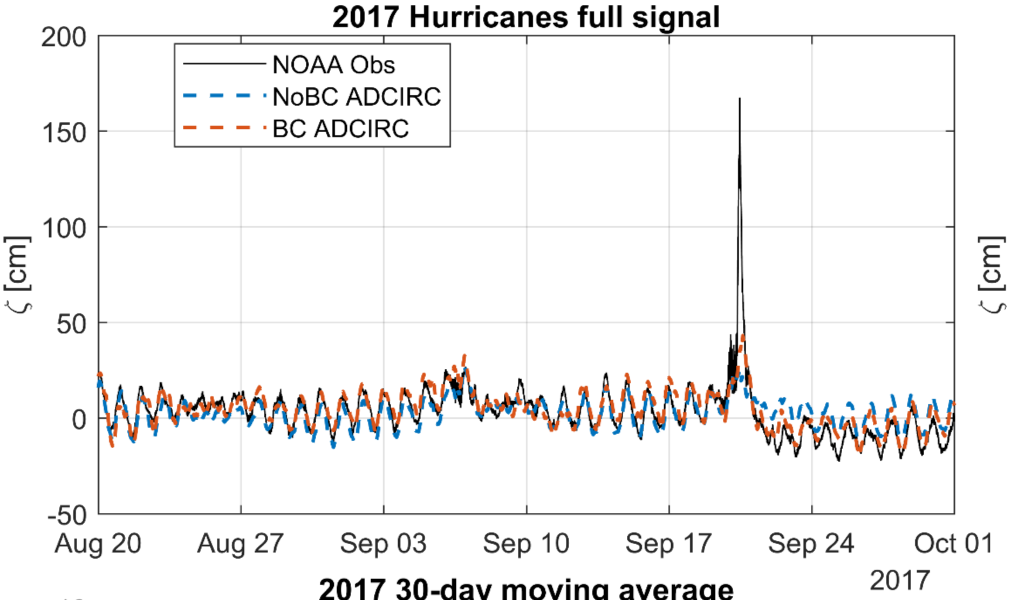


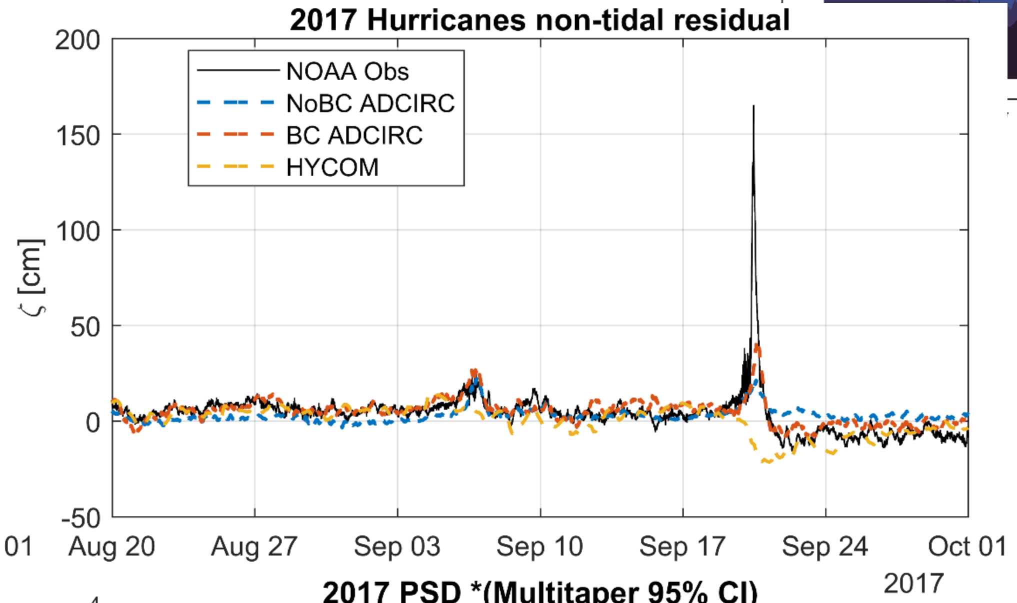


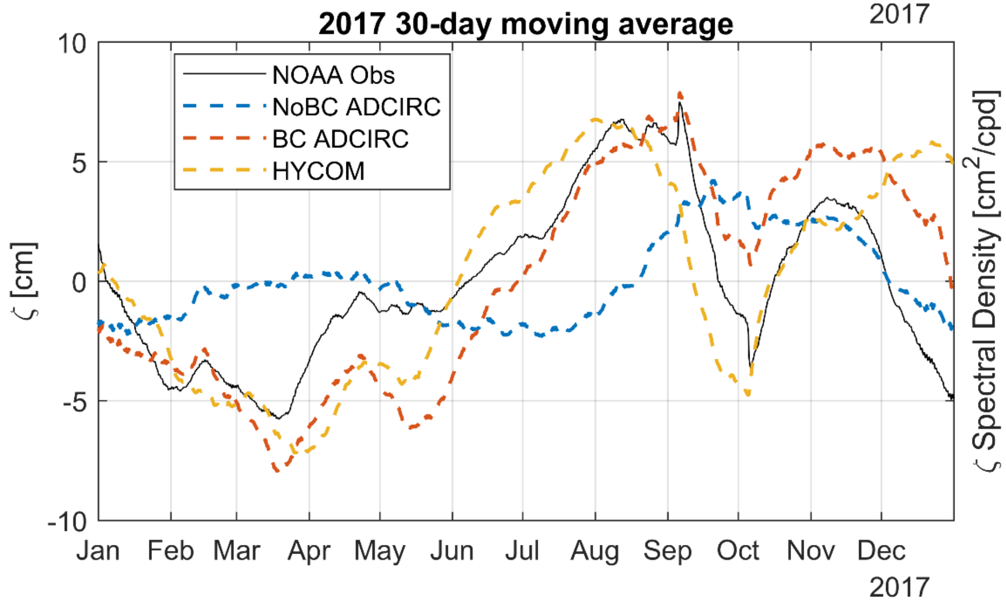
Time Series and Spectral Density -

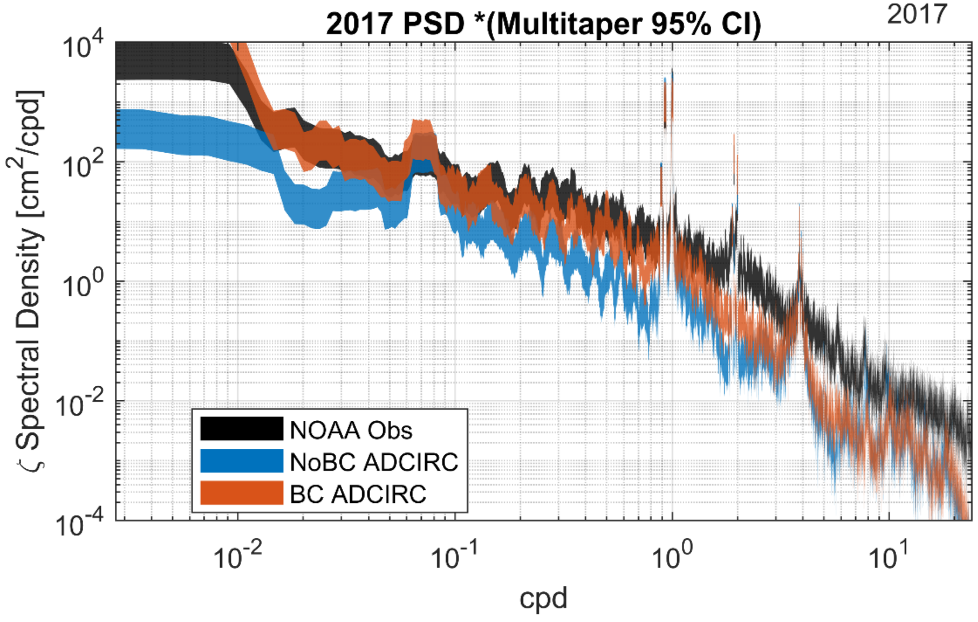
Yabucoa Harbor, PR





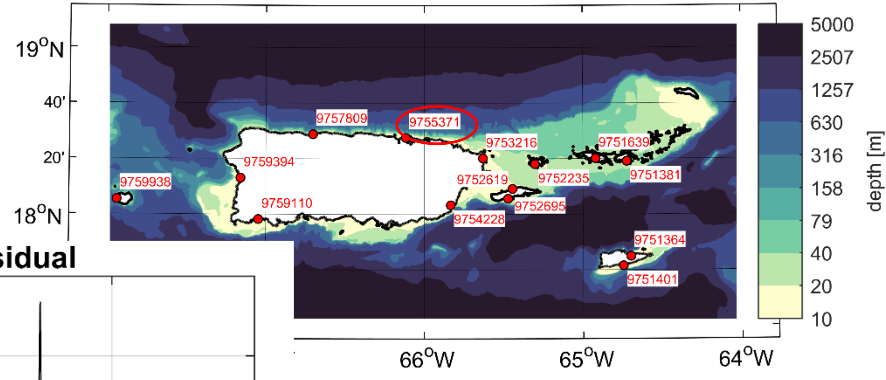


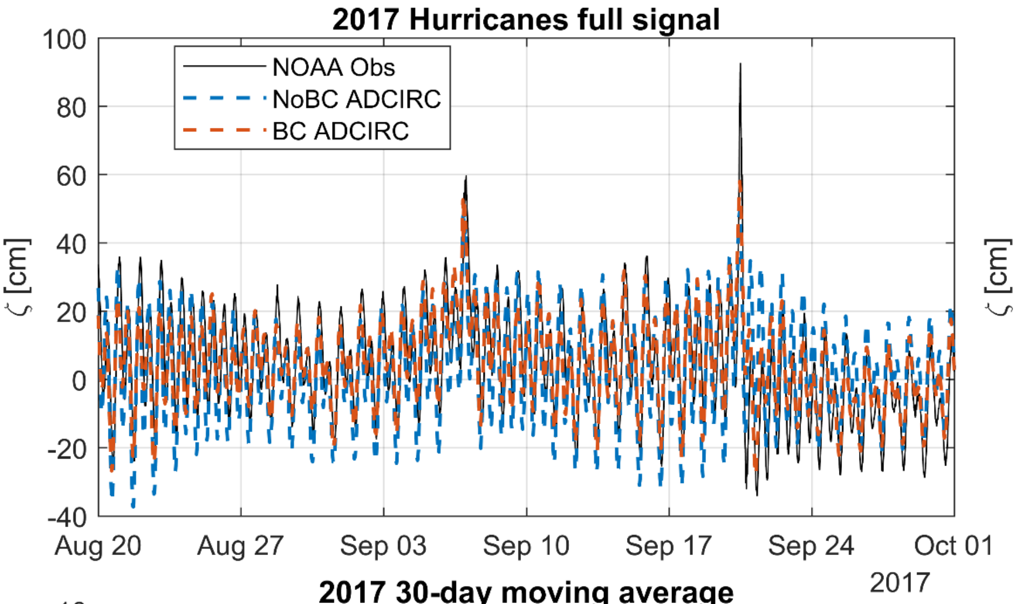


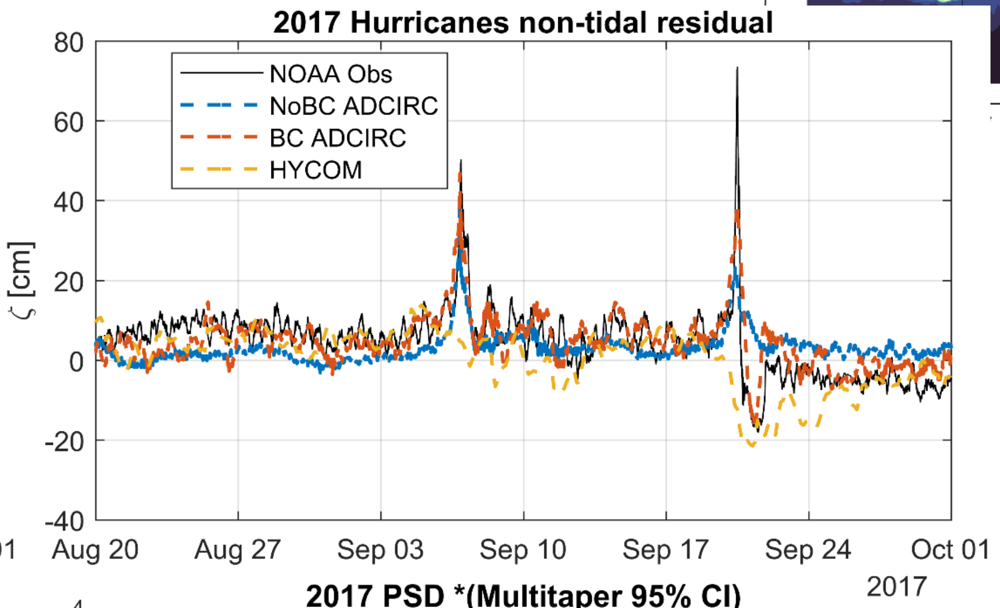


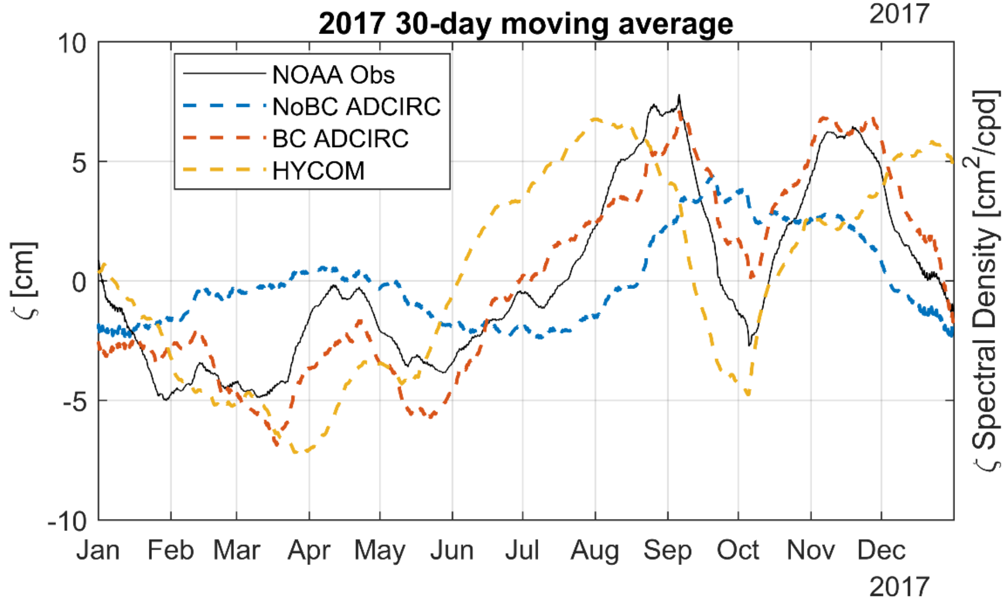
Time Series and Spectral Density –

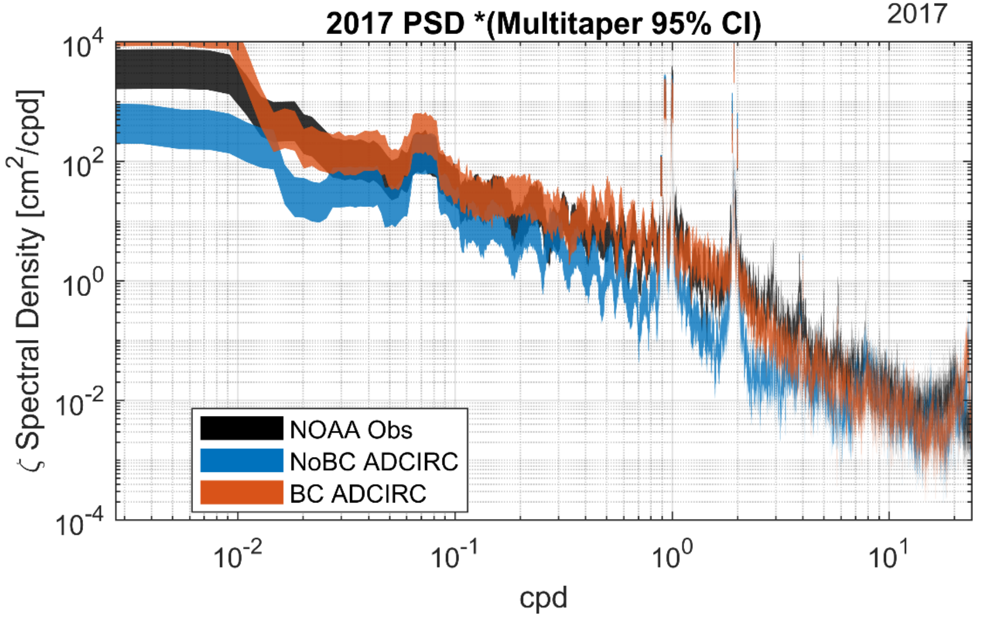
San Juan, La Puntilla, San Juan Bay, PR



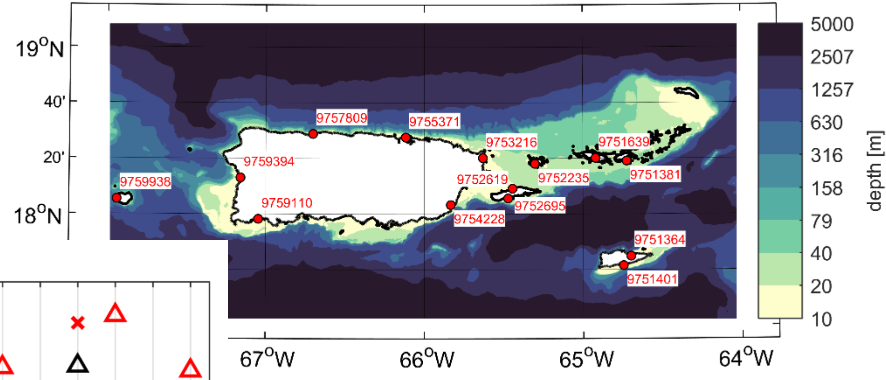


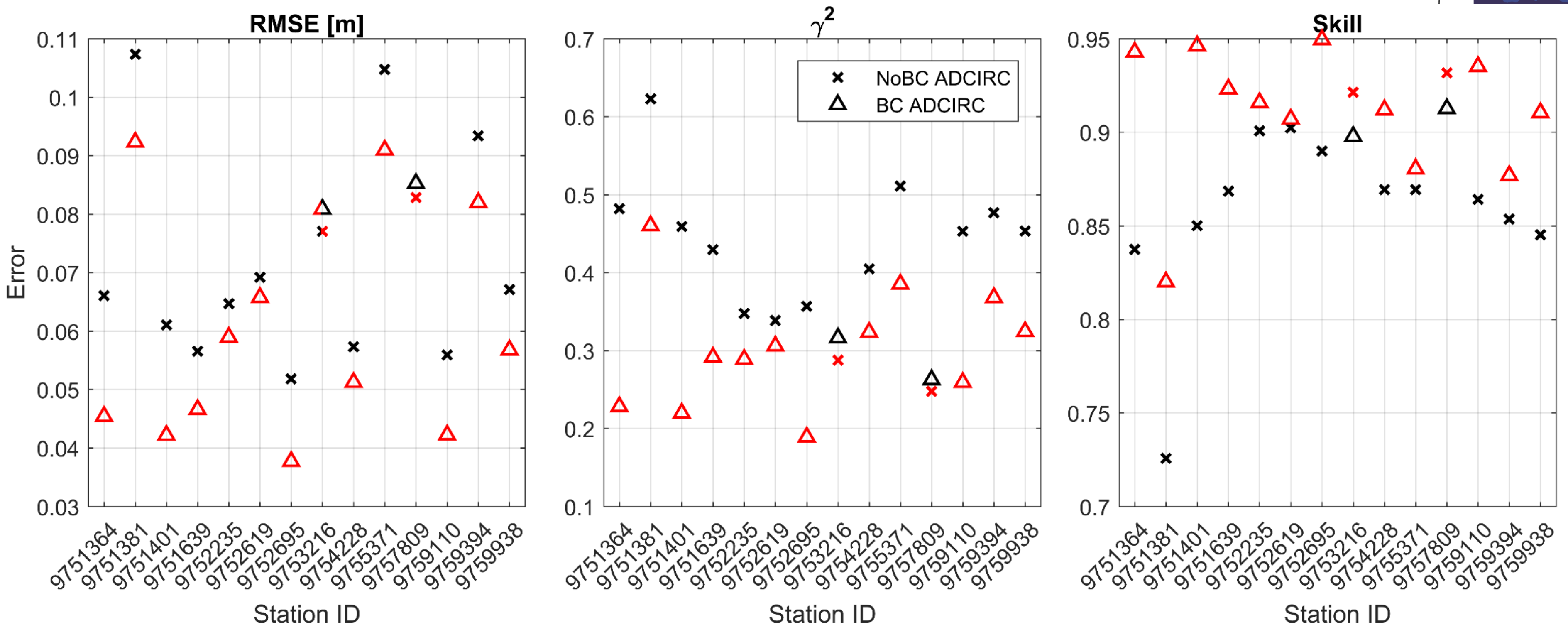






Summary of Model Error/Skill





Red is better

$$RMSE = \left[\frac{1}{T}\int_0^T (\zeta_m - \zeta_o)^2 \; dt\right]^{1/2}$$

$$\gamma^2 = \frac{var(\zeta_m - \zeta_o)}{var(\zeta_o)}$$

$$Skill = 1 - \frac{\int_0^T (\zeta_m - \zeta_o)^2 \; dt}{\int_0^T \left(|\zeta_m - \overline{\zeta_o}| + |\zeta_o - \overline{\zeta_o}|\right)^2 \; dt}$$

ADCIRC-HYCOM Interleafing

- Coupled 2D baroclinic ADCIRC model captures local and large-scale baroclinic effects
  - ✓ Captures local set-down after Hurricane Maria
  - ✓ Follows seasonal variations with similar accuracy to HYCOM

- Model skill was improved at all stations in comparison to barotropic version
  - ✓ Small increase in computational cost (~5%)

- High-resolution 2D ADCIRC model captures tide + surge response to high accuracy in comparison to the coarse HYCOM ocean model as expected

- Coupled 2D baroclinic model could have other applications
  - e.g., *down-scaling* climate-ocean models to get long-term variation in coastal elevations

Evolution of coastal ocean hydrodynamic models – the present

The GOOD

- Advancing heterogeneous model integration and interleafing component interactions
- Advancing higher and more targeted resolution
- High order algorithms using Discontinuous Galerkin non-conforming algorithmic frameworks

The BAD

- Still largely static grids that are costly to generate
- Static physics
- Poor load balance on component computations
- Falling peak processor performance

Evolution of coastal ocean hydrodynamic models – the future

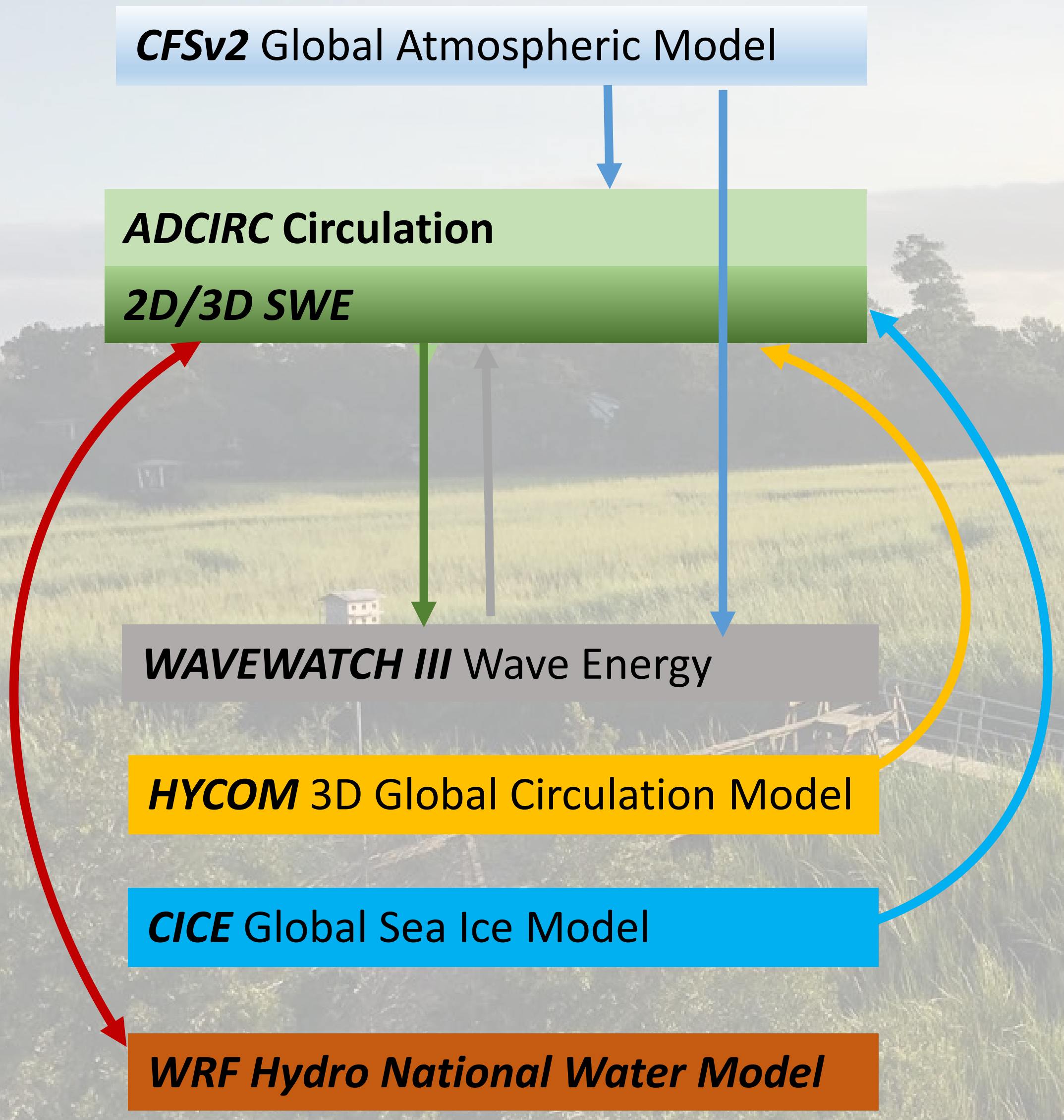
Vision

- Fully dynamic computations that during the simulation select
  - Physics
  - Grid resolution
  - Order of interpolants
  - Load balance

Focus areas

- Develop frameworks that allow dynamic and coupled physics
- Dynamic grid optimization for multi-physics
- High order methods
- Advance engines for load balancing

Advance coupling of multi-physics models

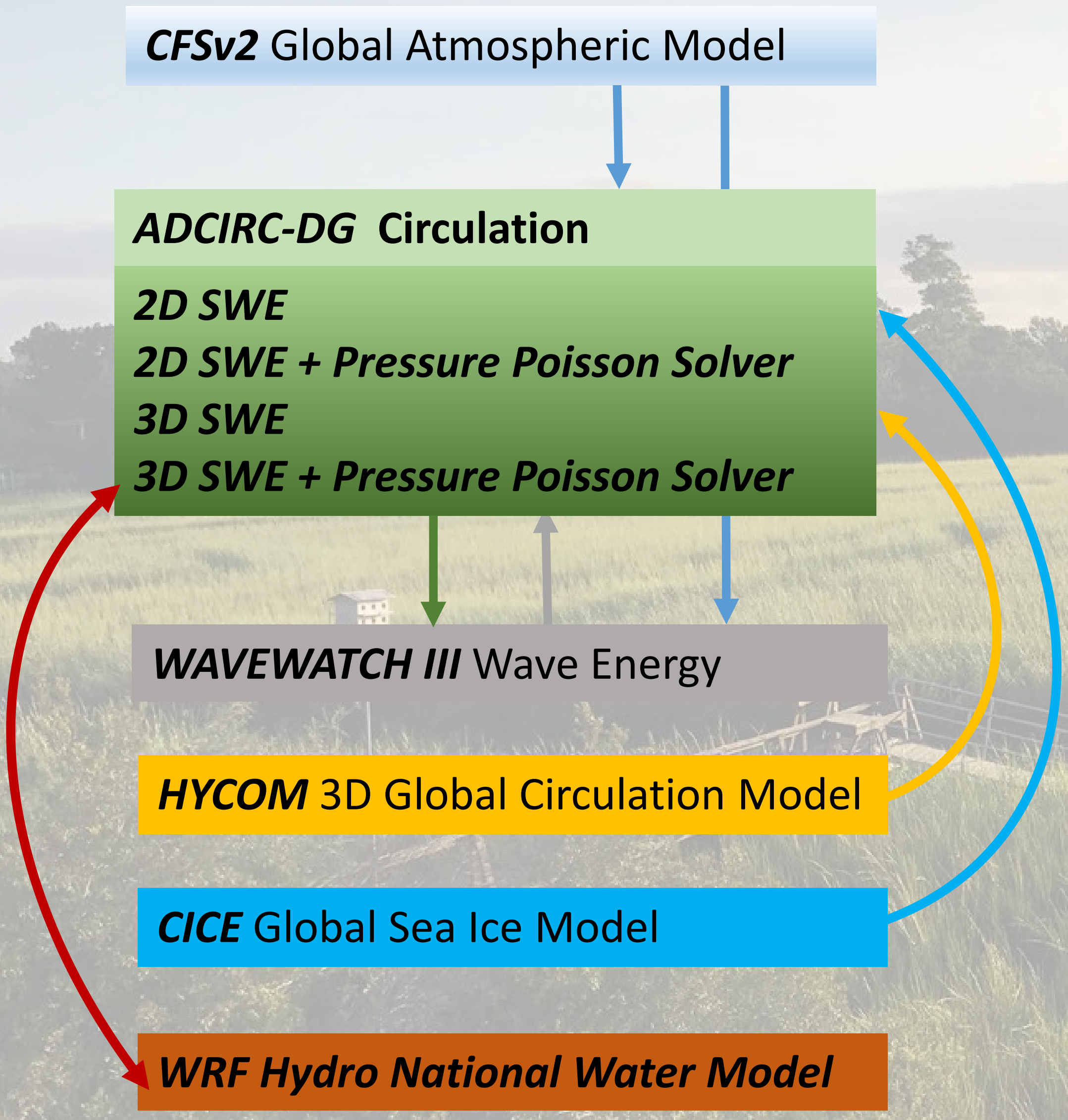


Multi-physics interfacing heterogeneous models over a unified domain

Dynamic coupling of *ADCIRC, WAVEWATCH III, HYCOM* and *CICE* Interleafing over a unified domain on heterogeneous grids communicating through *ESMF/NUOPC*

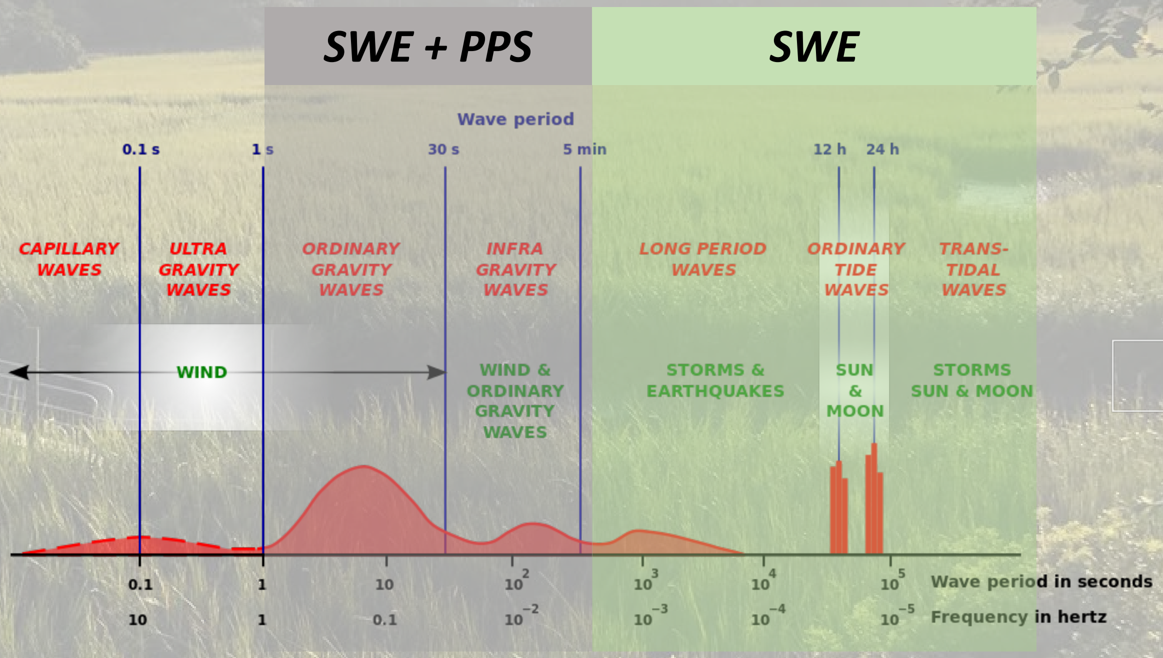
and boundary based two-way coupling to *WRF-Hydro* through *ESMF/NUOPC*

Develop dynamic hydrodynamic equation selection frameworks



Multi-physics within a single algorithmic framework dynamically selecting physics

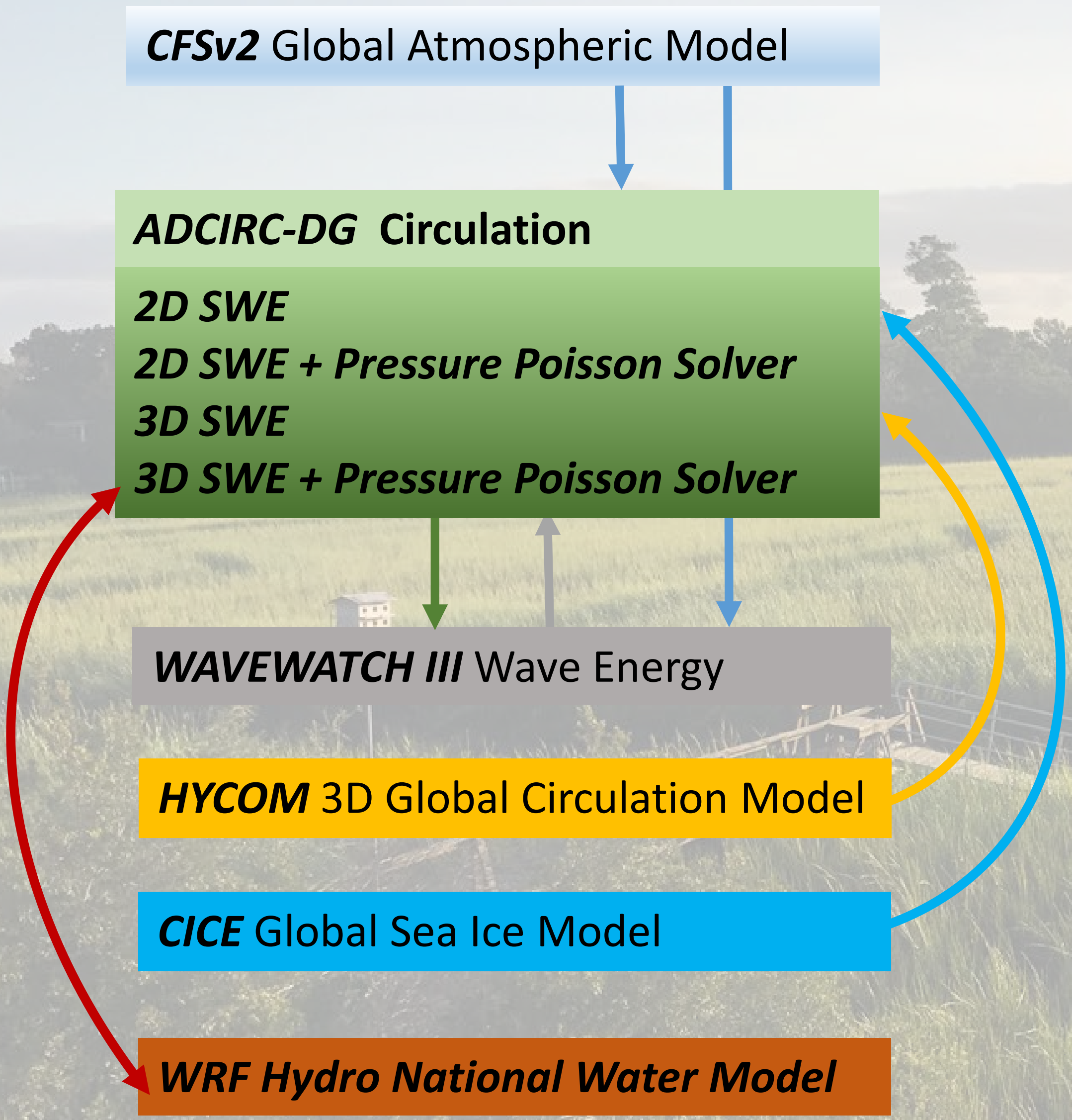
Dynamic equation selection within *ADCIRC-DG* to accommodate Boussinesq type solutions (in shallow water)



***WWIII, HYCOM, CICE* interleafing**
***WRF-Hydro* interfacing**

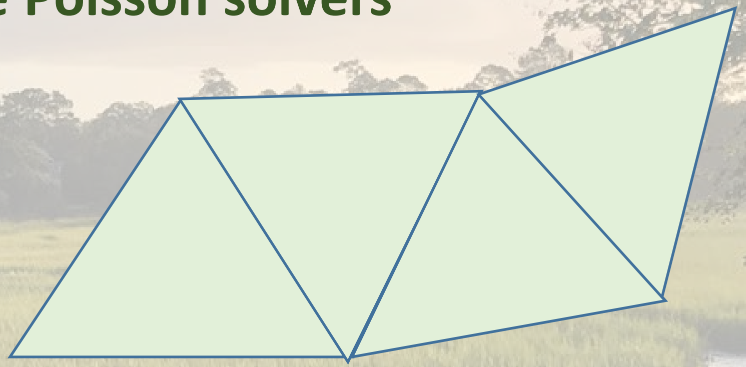
Donahue et al., *Coastal Engineering*, 114, 61-74, 2016.

Develop dynamic hydrodynamic equation selection frameworks

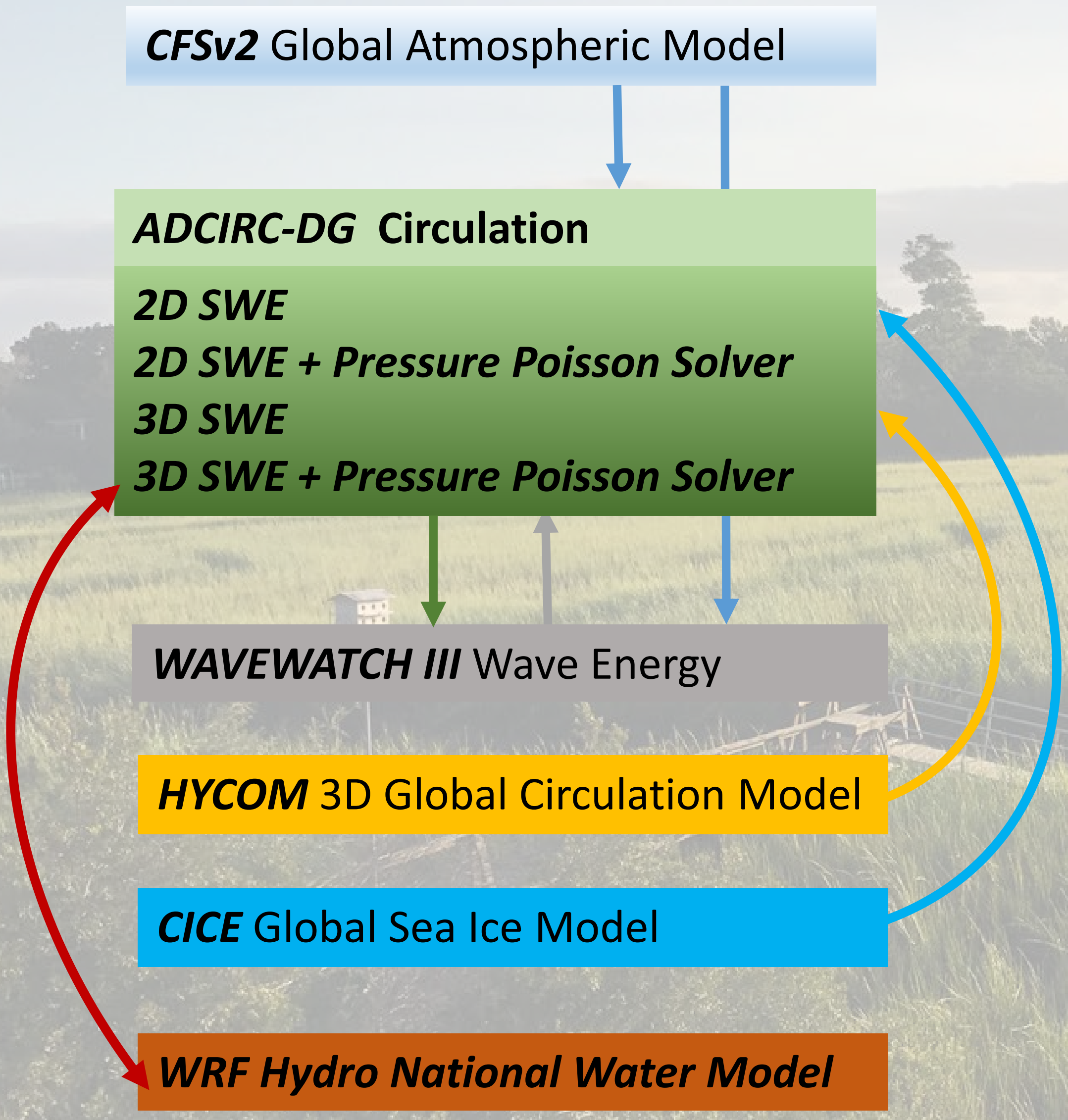


Multi-physics within a single algorithmic framework dynamically selecting physics

Pressure Poisson solvers

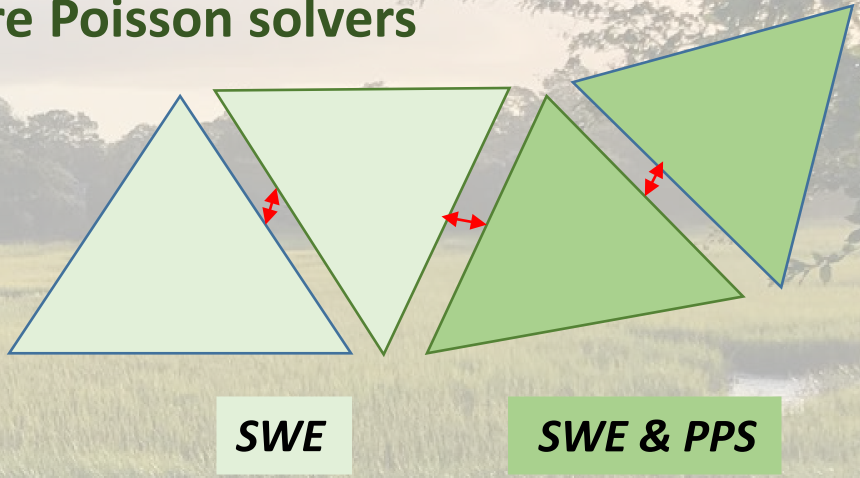


Develop dynamic hydrodynamic equation selection frameworks



Multi-physics within a single algorithmic framework dynamically selecting physics

Pressure Poisson solvers

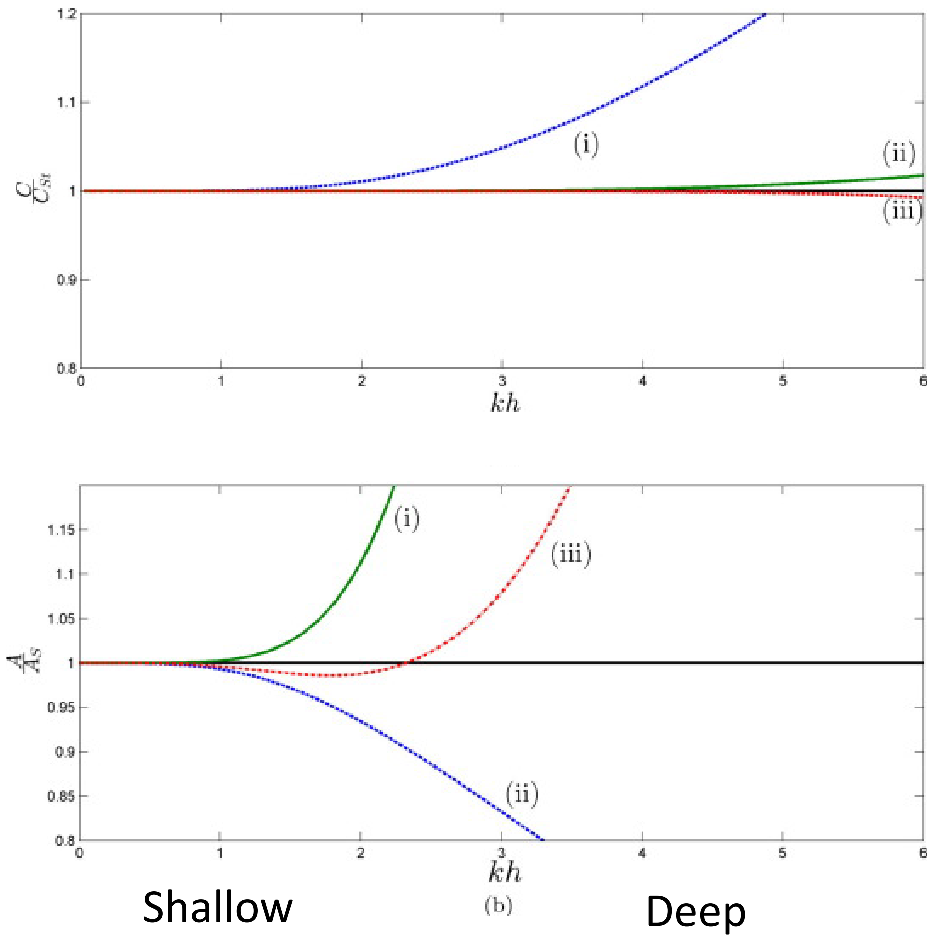


Pressure-Poisson based simulations

- **Extend Shallow Water Equations to include non-hydrostatic terms using Pressure-Poisson-type (PP) perturbation solutions**
  - **Manipulate error terms using asymptotic rearrangement to improve properties**
  - **From the class of Boussinesq wave models**

- **This gives increased accuracy for phase-resolving simulations of wave propagation and runup in the nearshore**
  - **But need to resolve ~15 points/wavelength: only over a small region**

- **End goal is to embed PP solutions into larger-scale models using the same general solvers and grids**

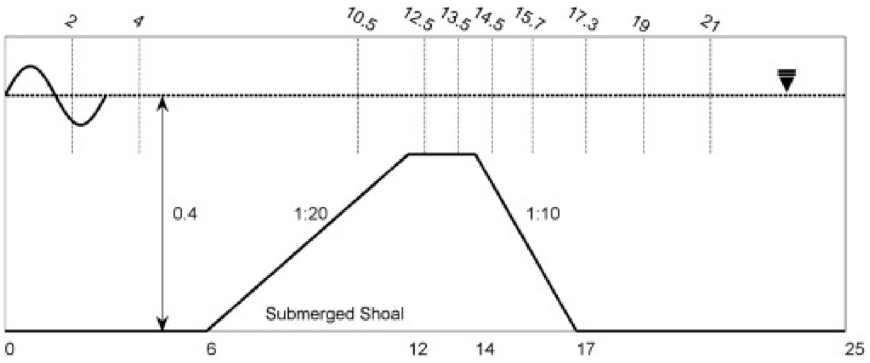


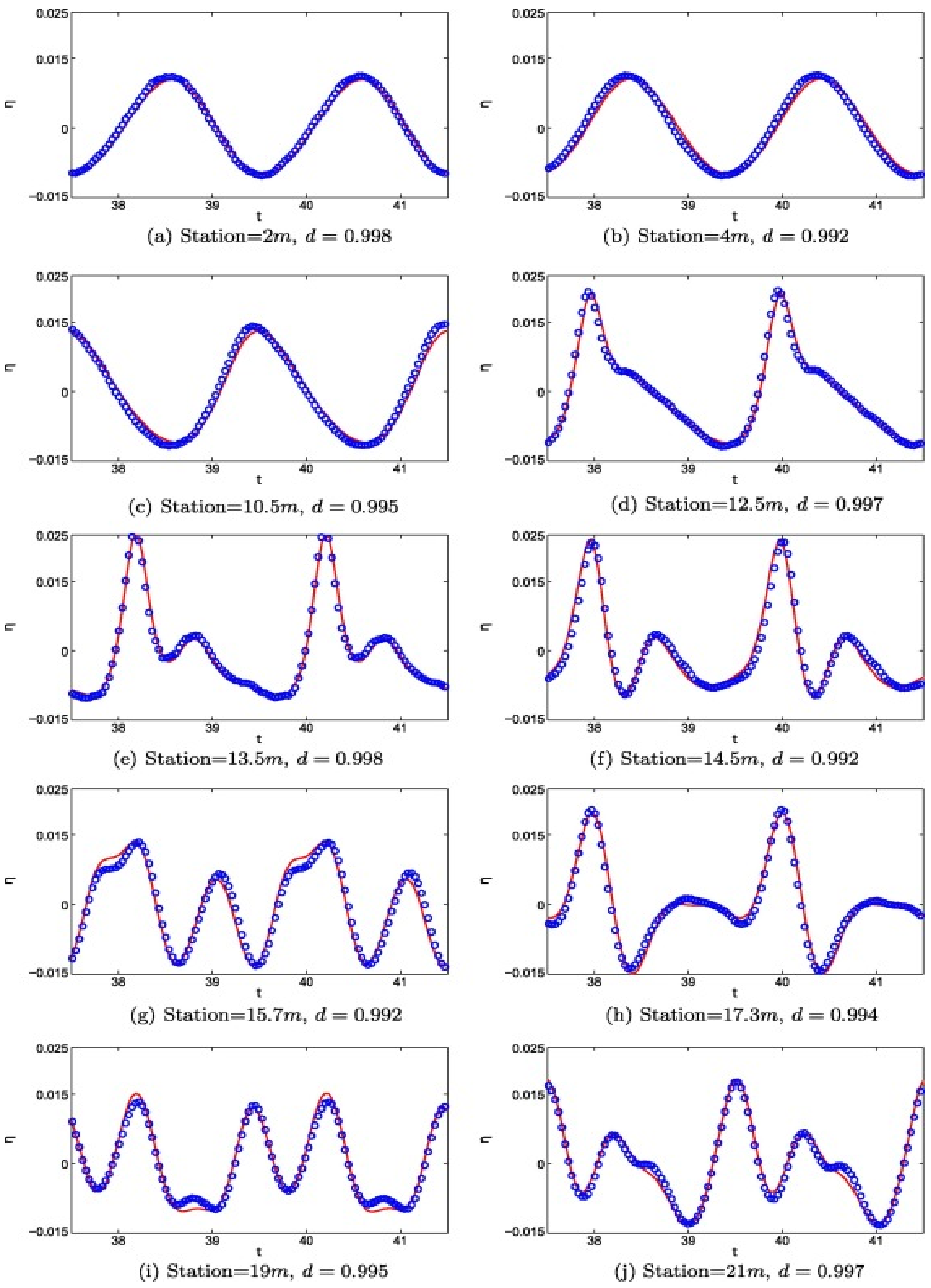
Frequency Dispersion (top); and Shoaling (bottom) accuracy for PP-models compared to linear analytical solutions

Donahue et al., ***Ocean Modeling,*** 86, 36-57, 2016.
Donahue et al., ***Coastal Engineering***, 114, 61-74, 2016.

Pressure-Poisson based simulations

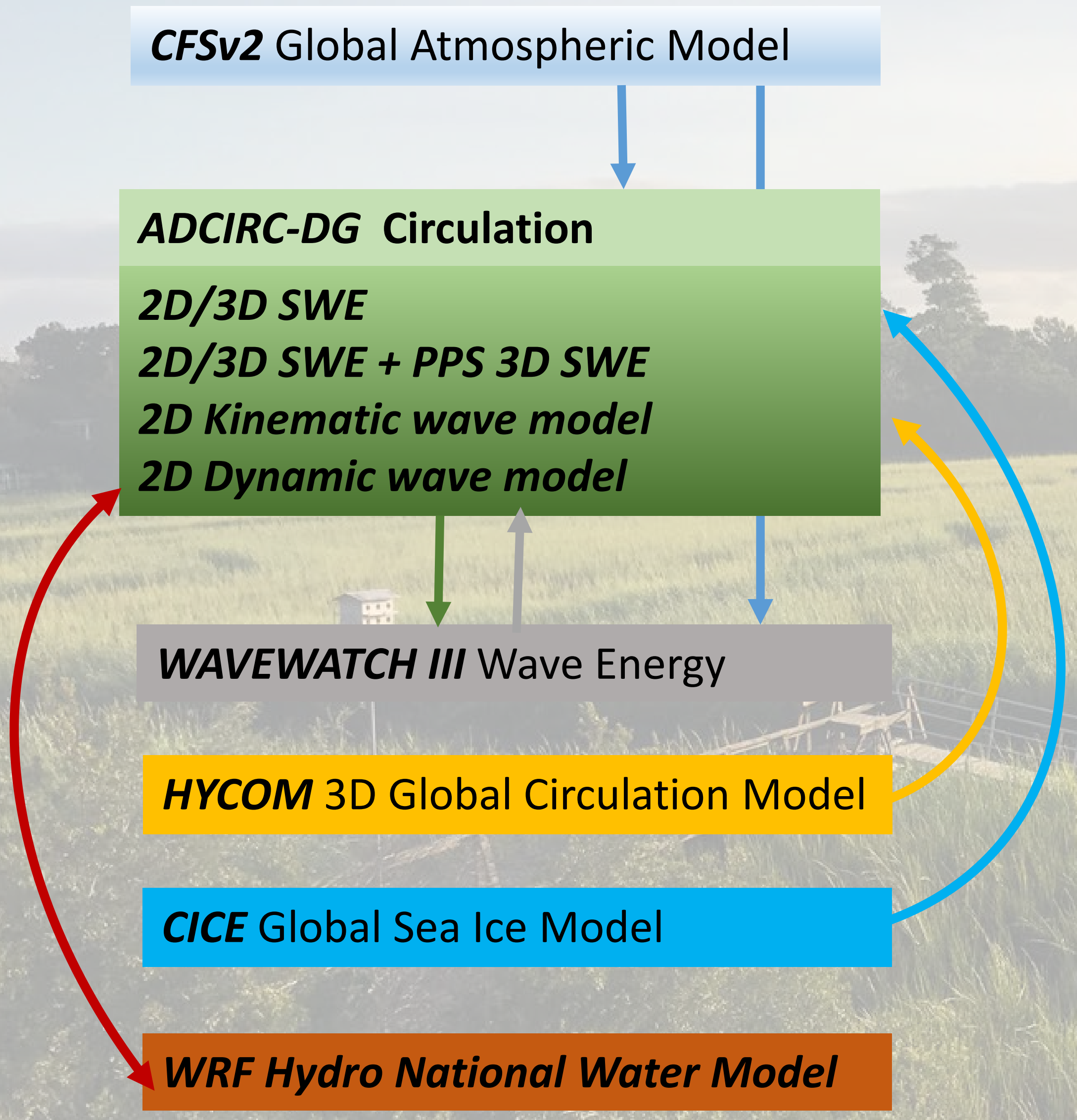
- **Can simulate highly nonlinear waves approaching the coastline, and through to the shoreline**
  - Only in finite depths
- **Different levels of model can provide different levels of accuracy, with corresponding cost increases**
- **Remaining hurdles are largely implementational rather than theoretical**
  - Coding and testing for operational-type problems have not yet been implemented





(a) Station=2m, $d = 0.998$ (b) Station=4m, $d = 0.992$ (c) Station=10.5m, $d = 0.995$ (d) Station=12.5m, $d = 0.997$ (e) Station=13.5m, $d = 0.998$ (f) Station=14.5m, $d = 0.992$ (g) Station=15.7m, $d = 0.992$ (h) Station=17.3m, $d = 0.994$ (i) Station=19m, $d = 0.995$ (j) Station=21m, $d = 0.997$

Develop dynamic hydrodynamic equation selection frameworks

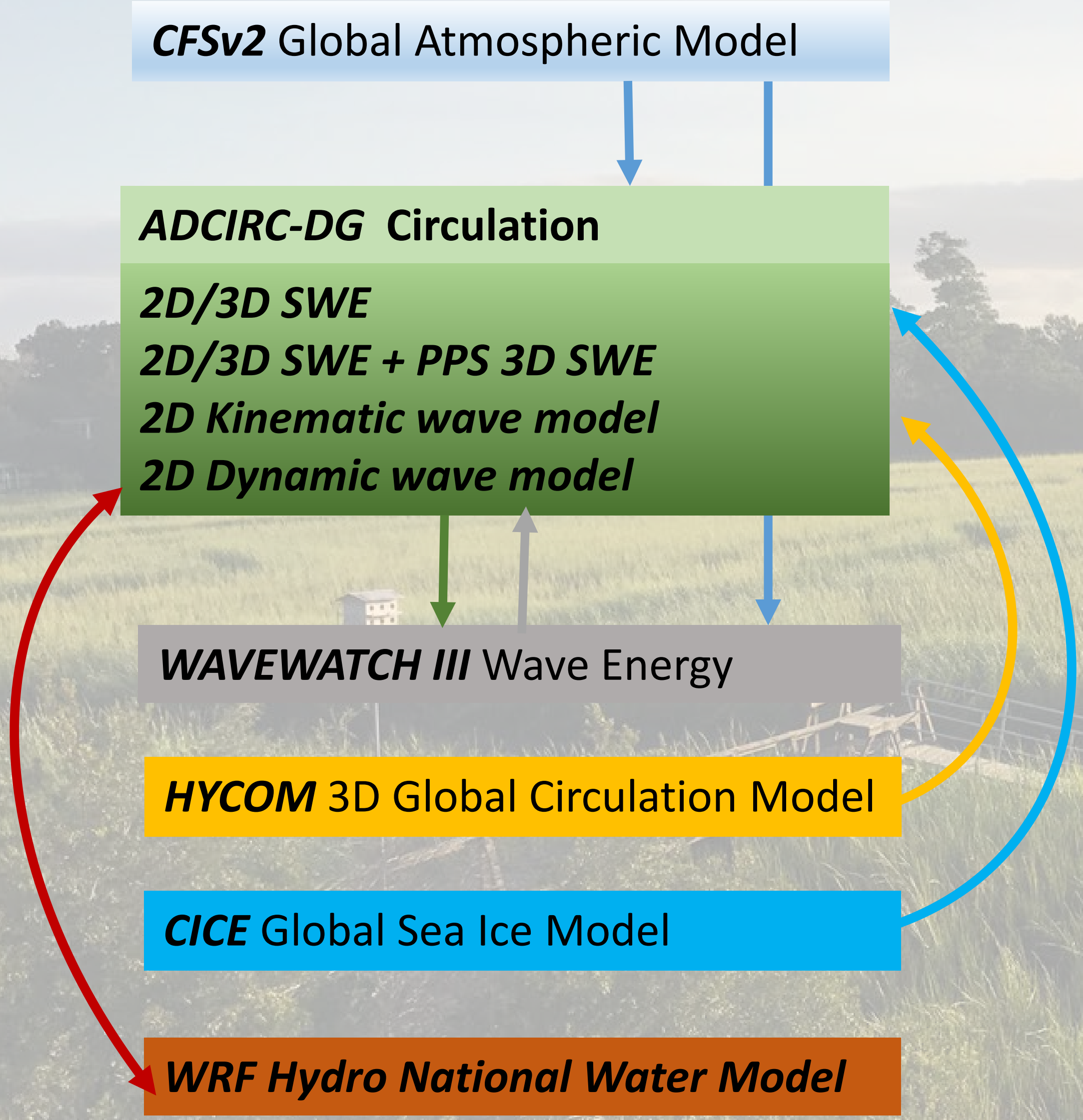


Multi-physics within a single algorithmic framework dynamically selecting physics

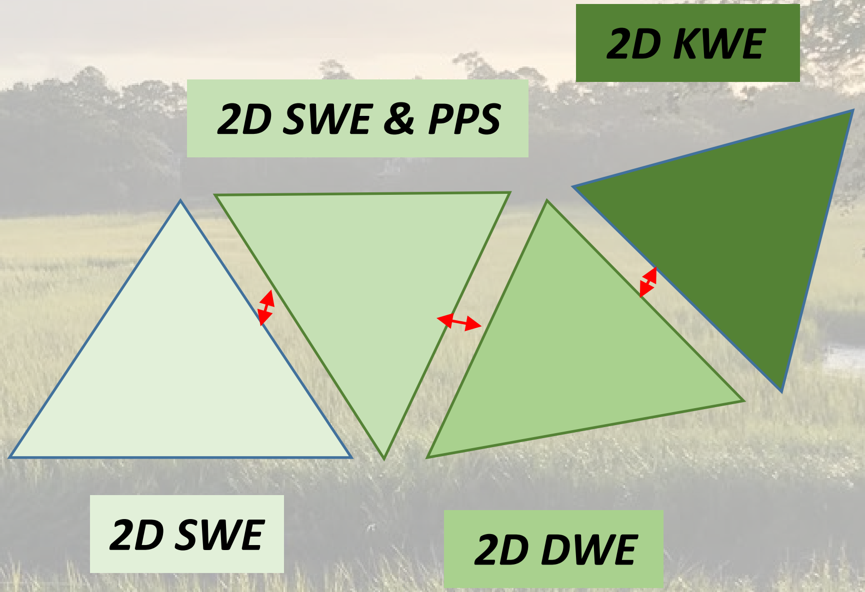
Dynamic equation selection within ADCIRC-DG to accommodate Boussinesq type solutions as well as the Kinematic and Dynamic Wave Equations solution

***WWIII, HYCOM, CICE* interleafing**
***WRF-Hydro* interfacing**

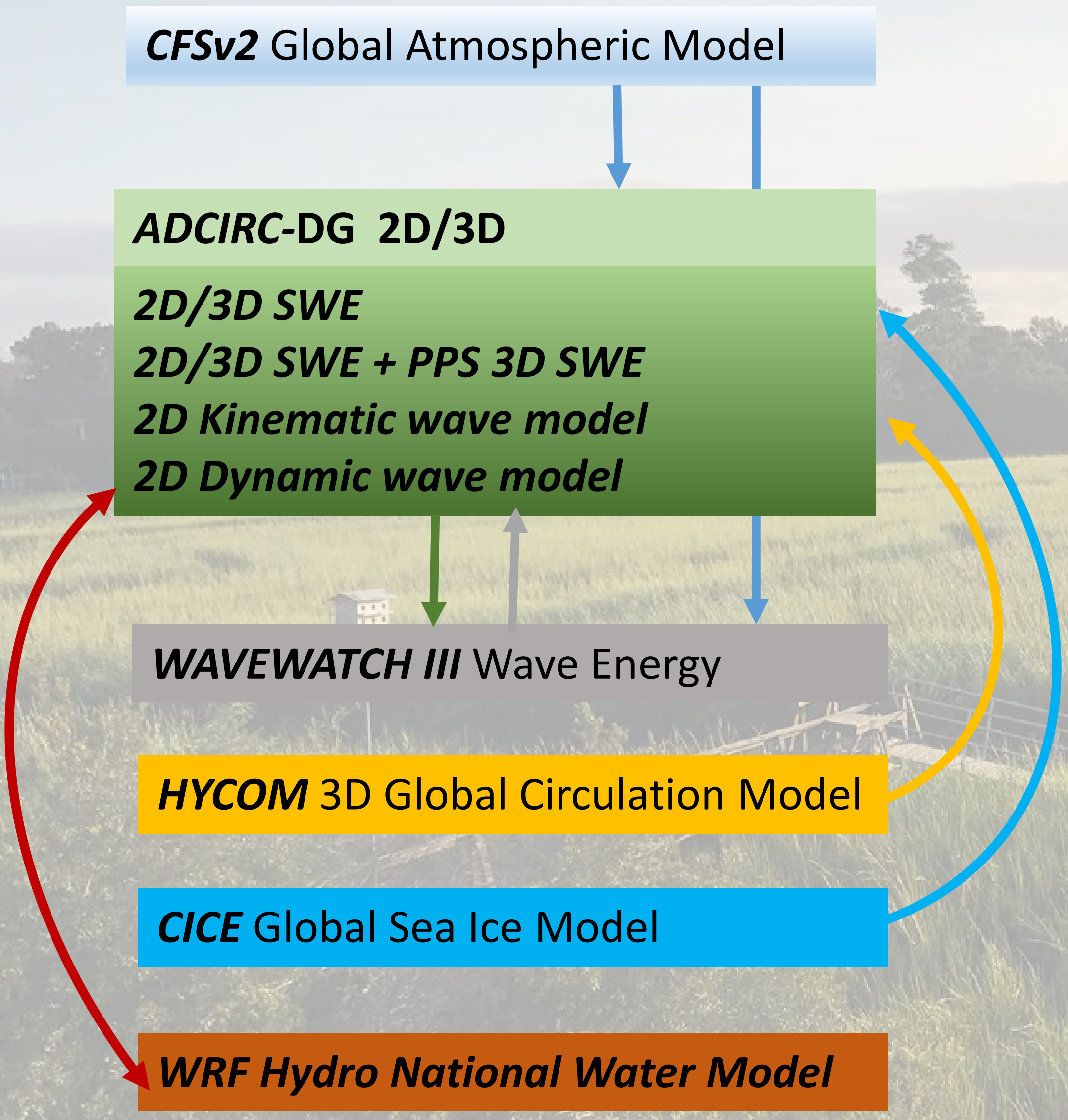
Develop dynamic hydrodynamic equation selection frameworks



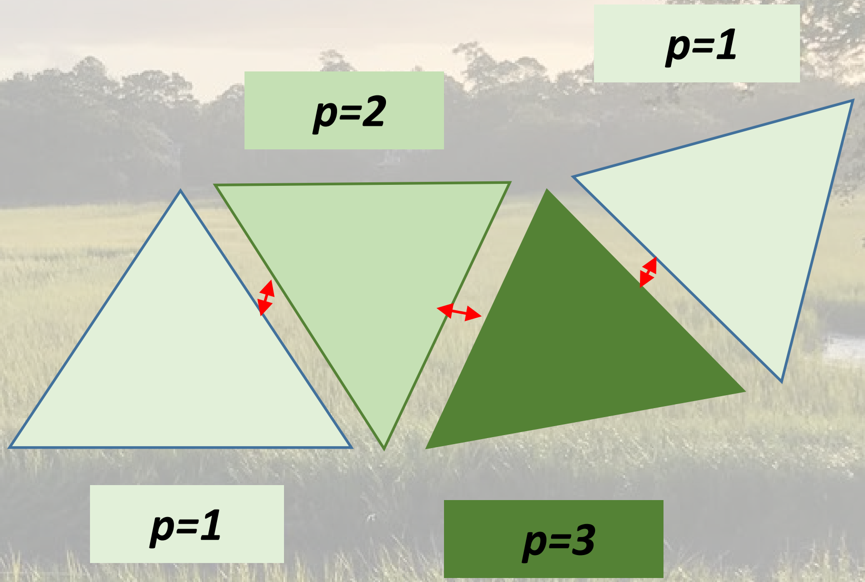
Multi-physics within a single algorithmic framework dynamically selecting physics



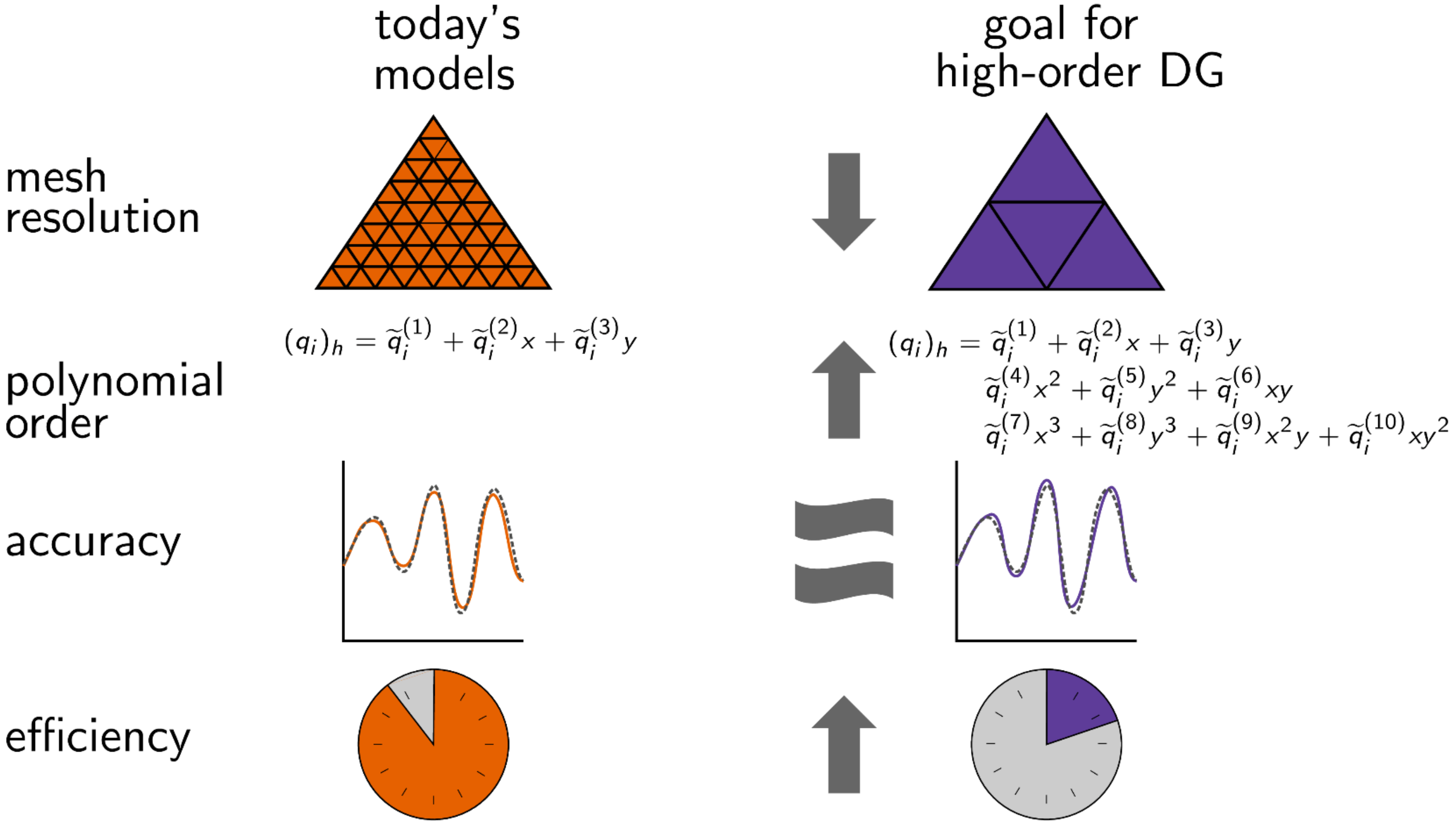
Develop dynamic high order interpolation (*p*-adaptive) frameworks



Dynamic selection of interpolant order
p adaptation



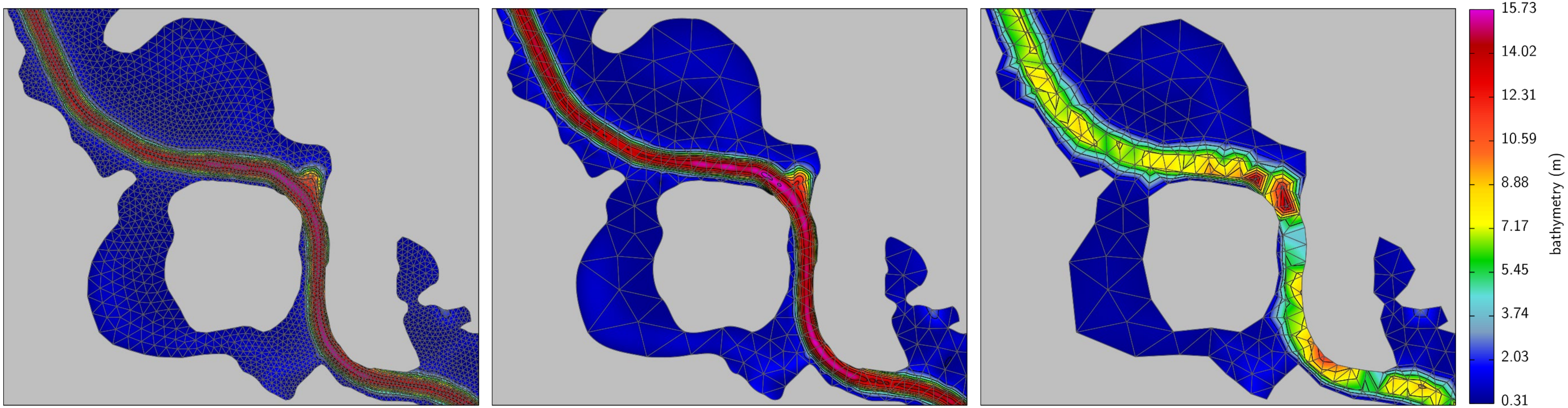
High order interpolants



High order interpolants

- **Discontinuous Galerkin (DG) allows for non-conforming h-p dynamic adaptation**

High-resolution ADCIRC | **High-order DG (*p*=3)** | **Low-resolution ADCIRC**

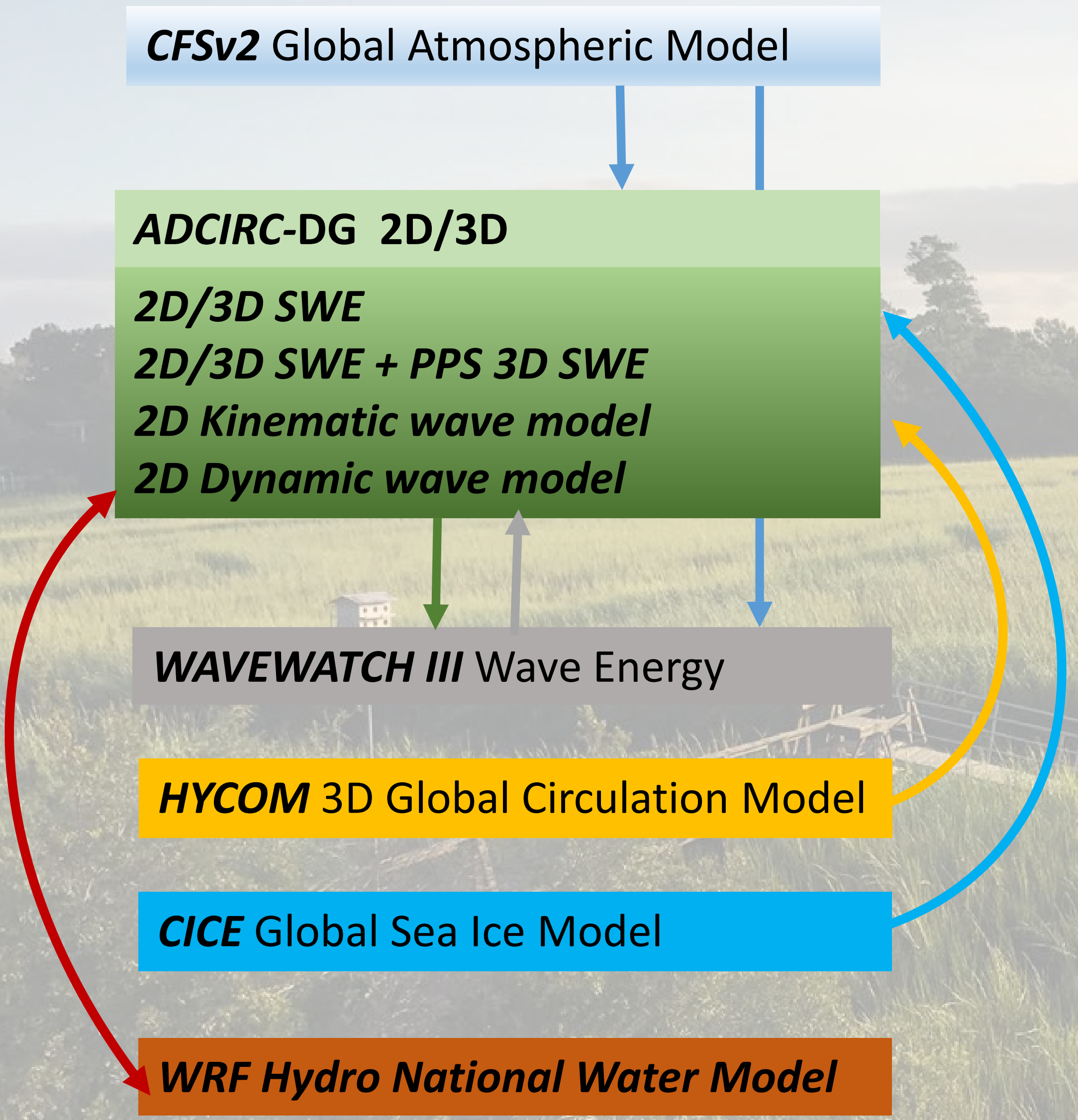


Runs 4 x faster

Poor solutions

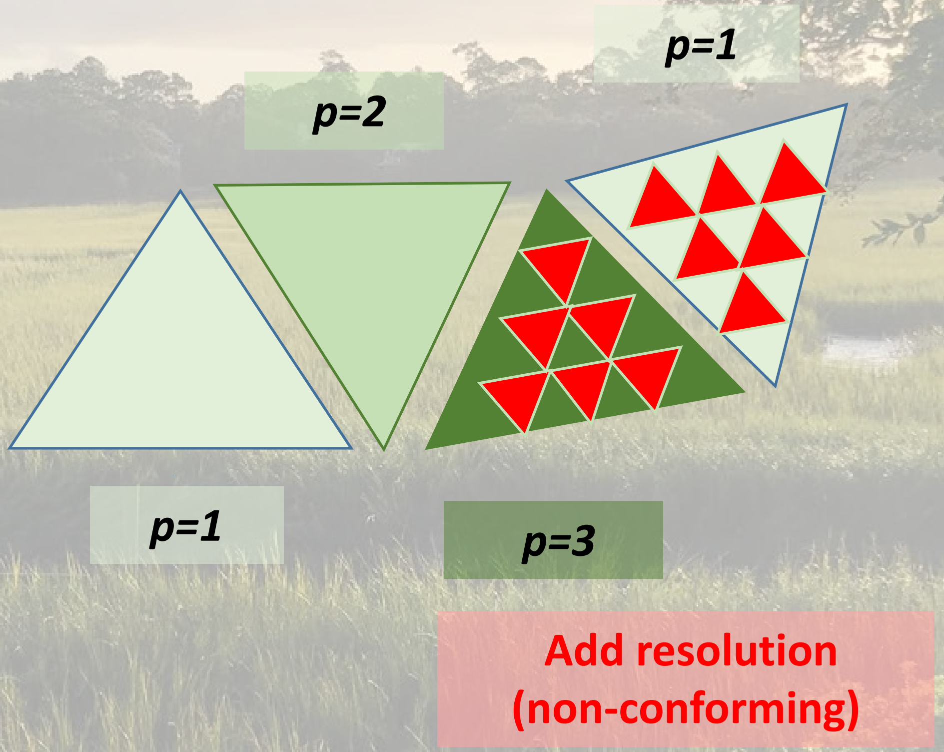
Wirasaet et al., ***Journal of Computational Physics, 299,***, 579-612, 2015.
Brus et al.., ***Journal of Scientific Computing***, **70**, 210-242, 2017.

Develop adaptive gridding (*h*-adaptive) frameworks



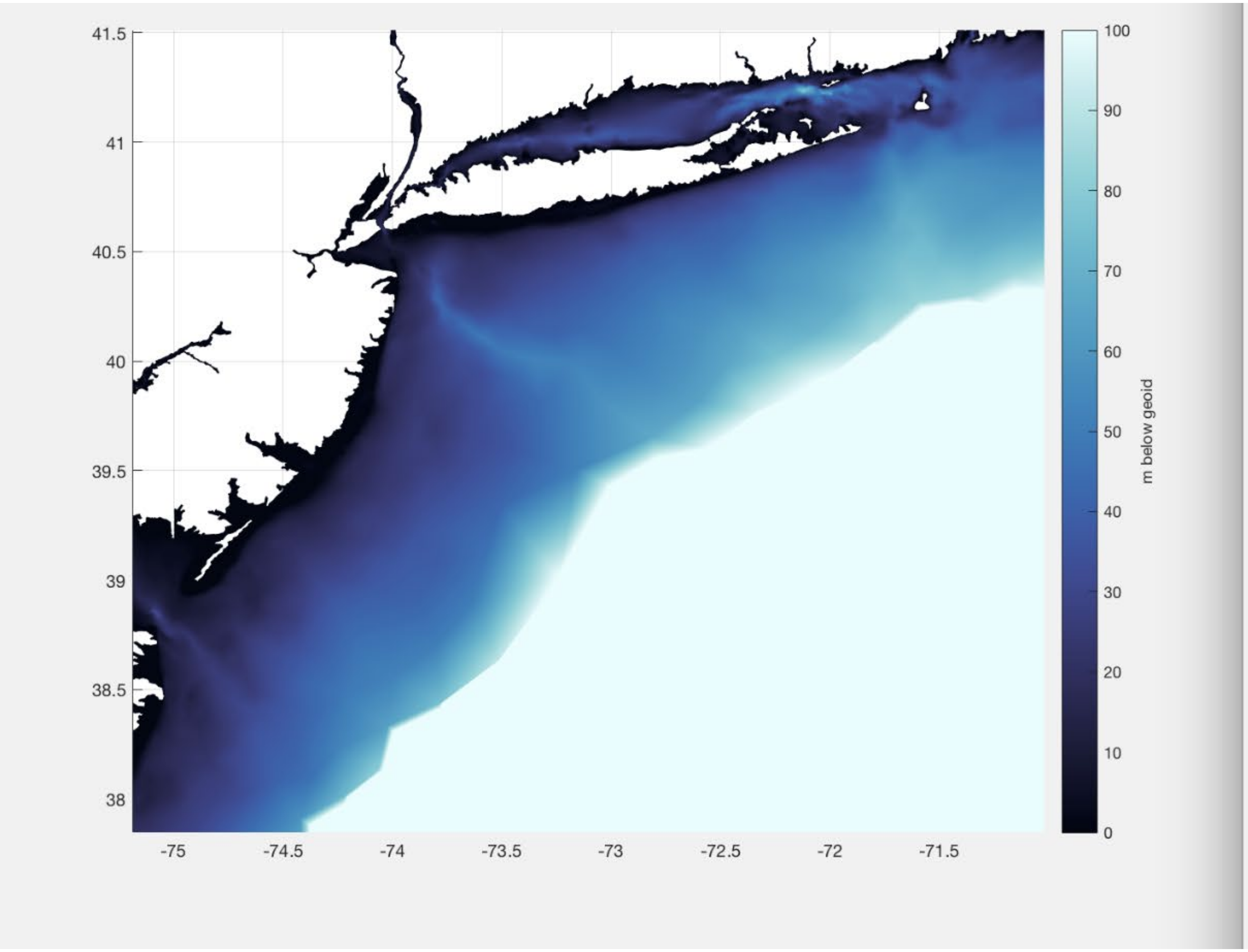
Dynamic selection of grid resolution

***h* adaptation**

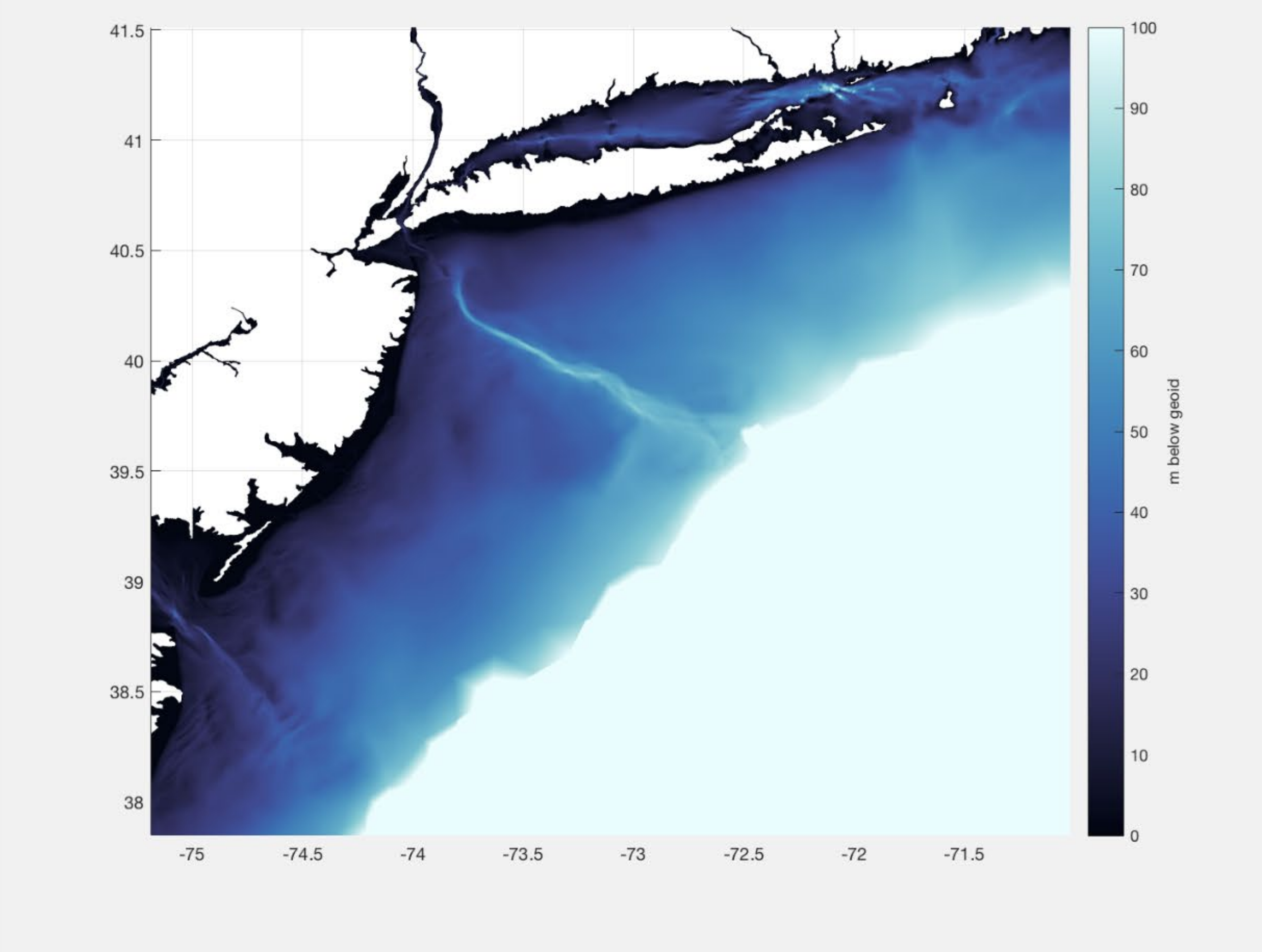


Dynamic grid optimization for evolving physics

Lower energy tides

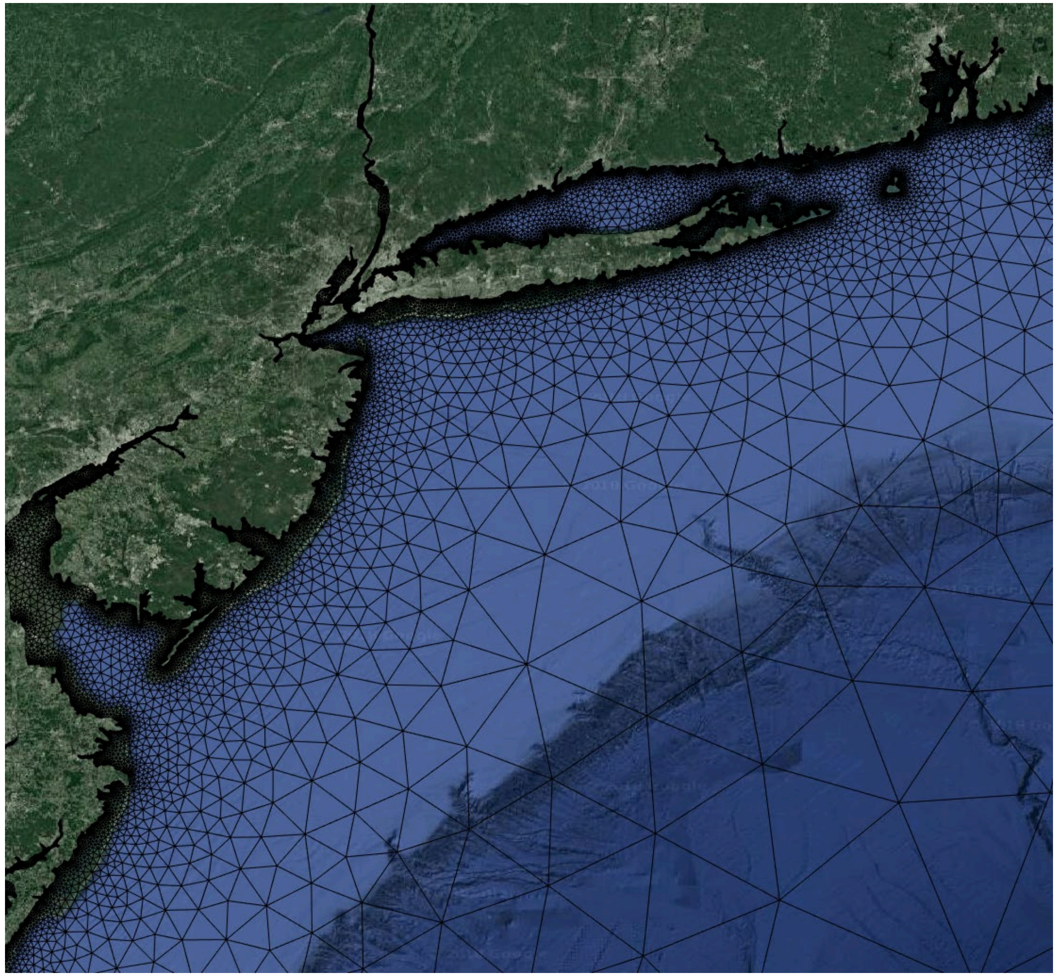


High energy storm driven circulation

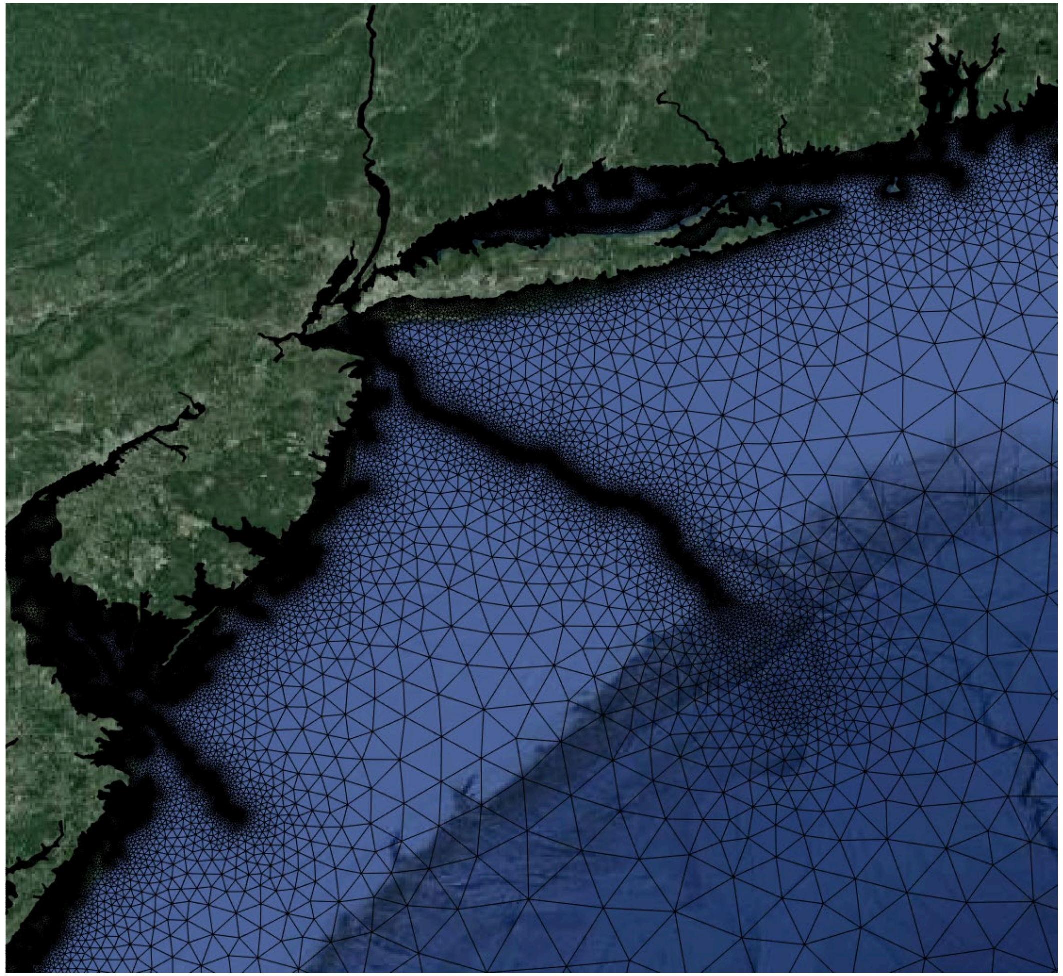


Dynamic grid optimization for evolving physics

Lower energy tides



High energy storm driven circulation

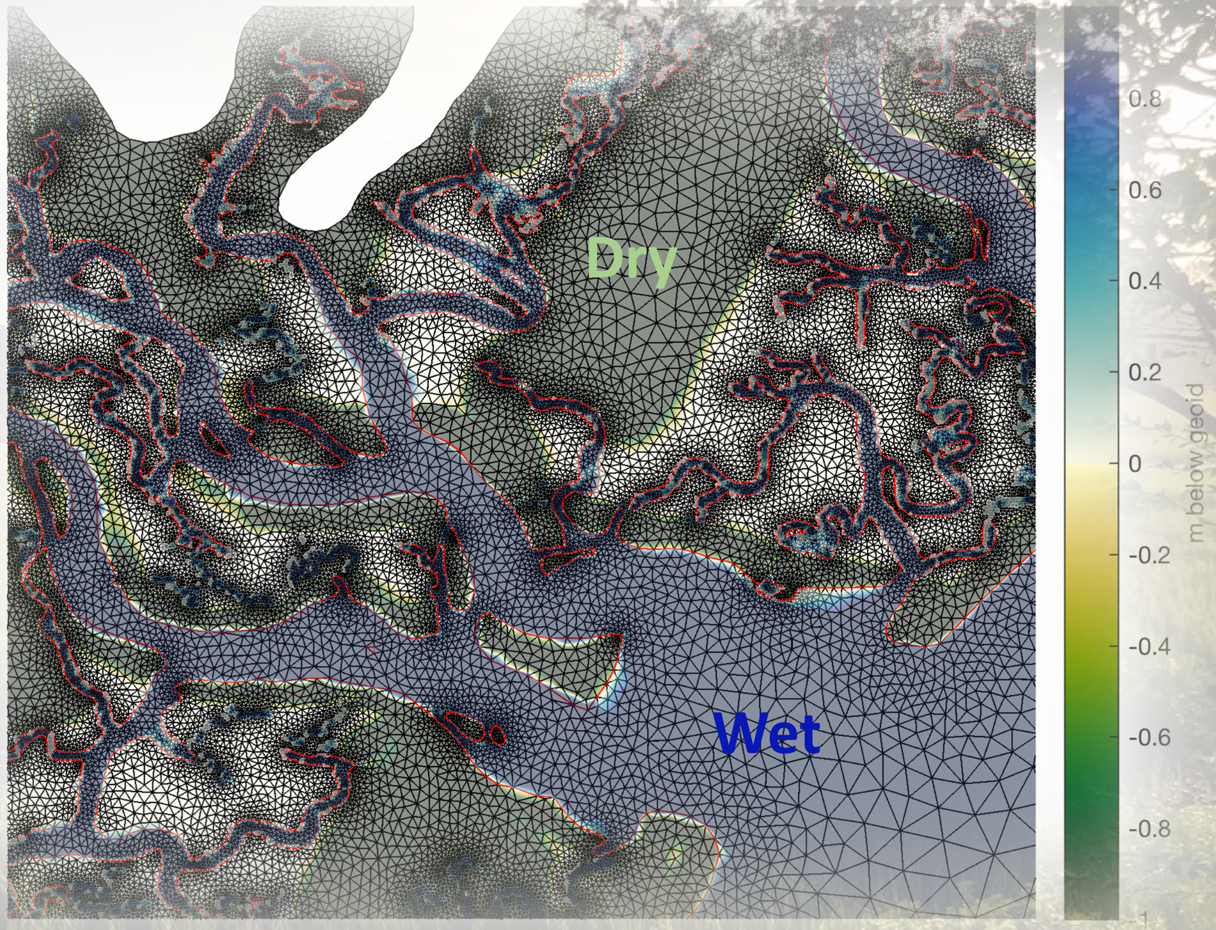


Dynamic load balancing

Eliminating dry element from the computation through loop clipping will reduce total cycle costs

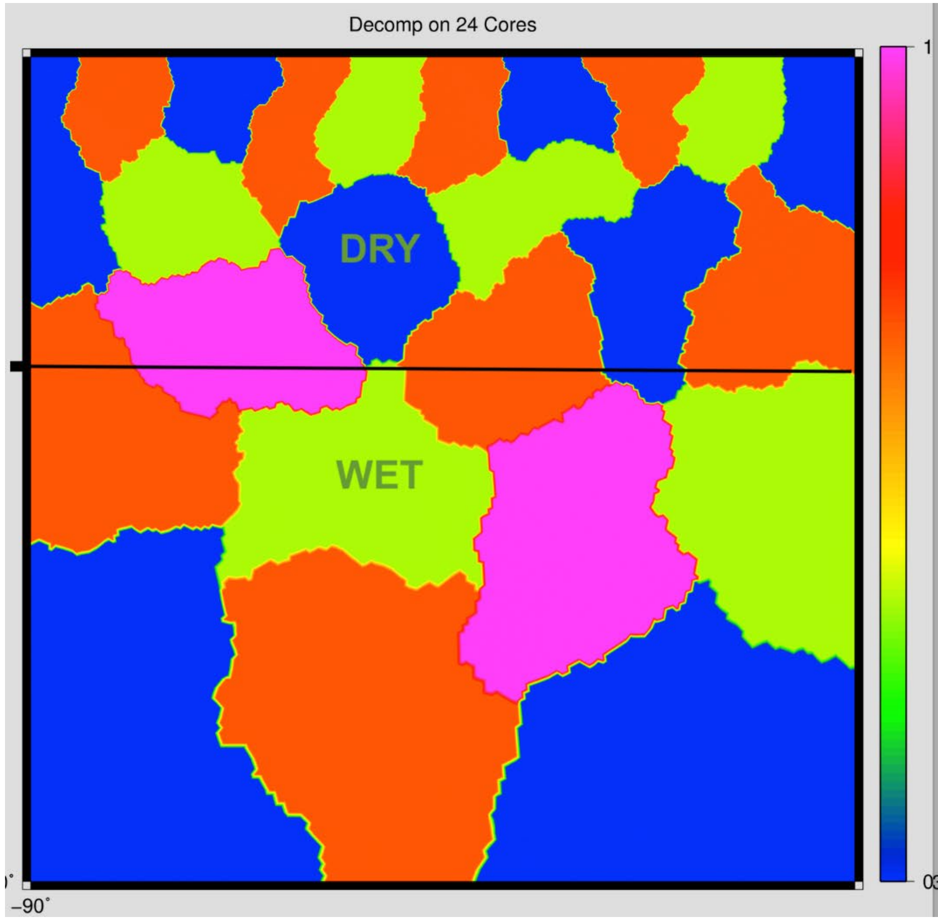
Dynamic rebalancing of the sub-domain loads will reduce total wall clock time

MPI/Zoltan
HPX

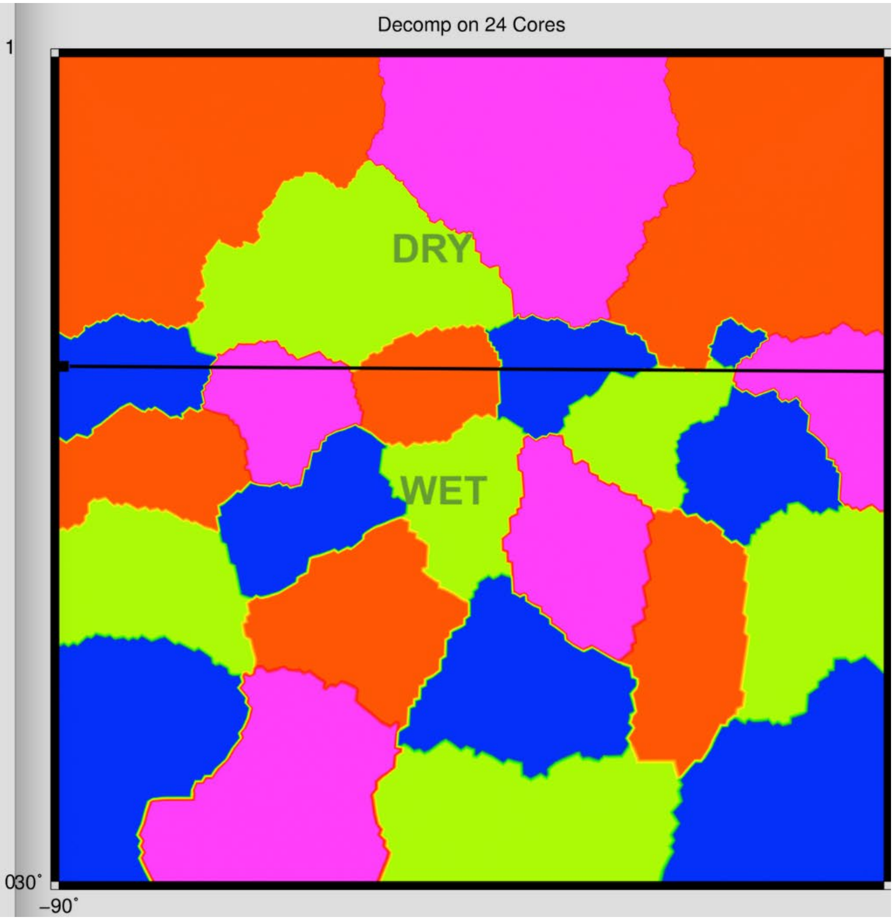


Dynamic load balancing: MPI/Zoltan

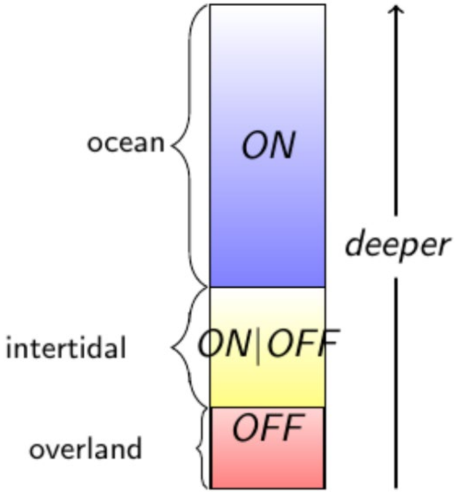
Equal node distribution

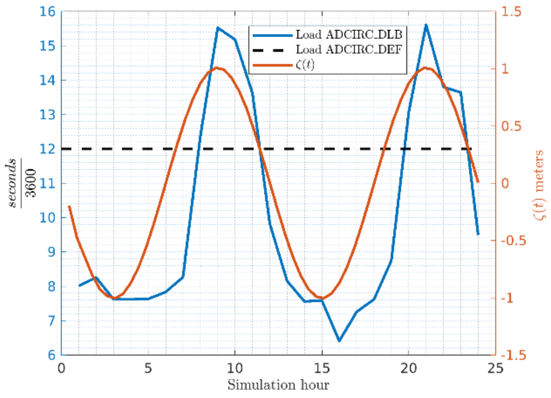


Weighted node distribution



Nodal data structure



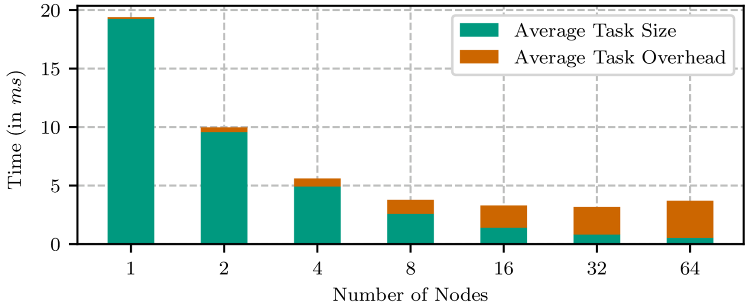


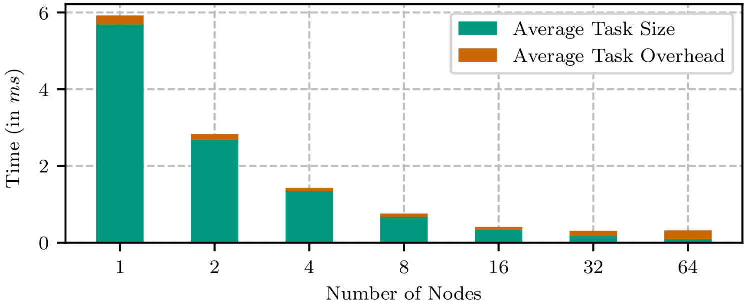
Dynamically redistributing dry elements improves parallel efficiency 45% for 50% average dry nodes

Dynamic load balancing: HPX – load balancing beyond MPI

- Motivation: Exa-scale, heterogeneous architectures, post Moore's Law computing
- General purpose C++ runtime system for parallel and distributed applications
- Exposes C++11 standard conforming API
- Innovative mixture of:
  - A global system-wide address space (AGAS)
  - Fine-grain parallelism and lightweight synchronization
  - Implicit, work queue based, message driven computation

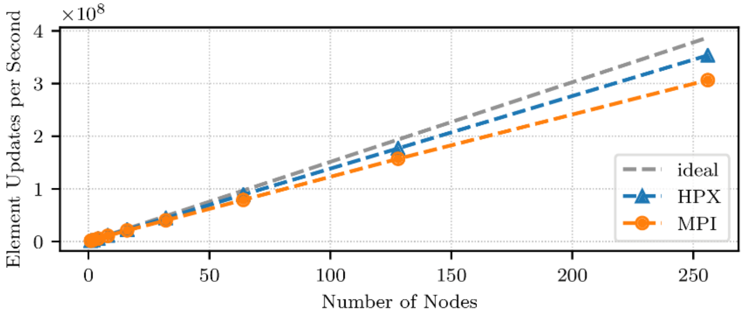
HPX Task Composition

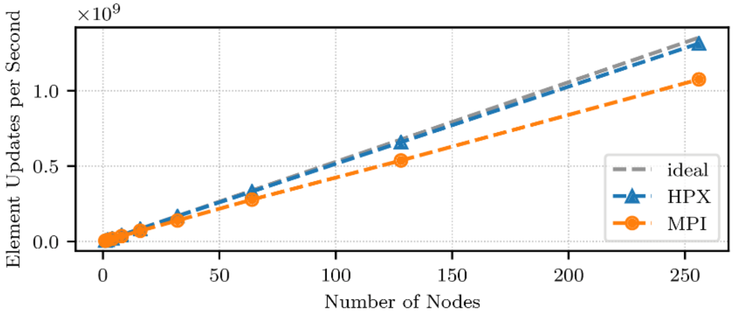




- HPX task scheduling is more expensive on KNL.

Weak Scaling

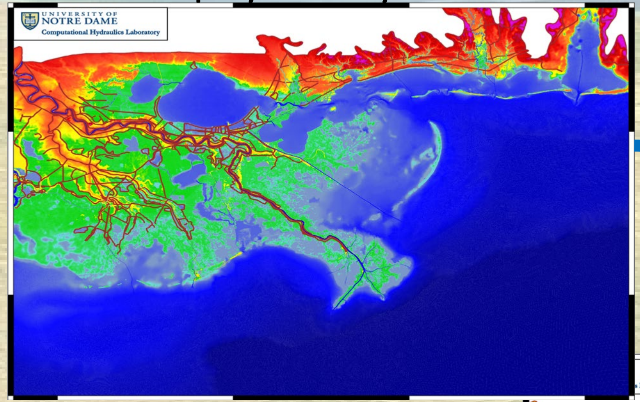




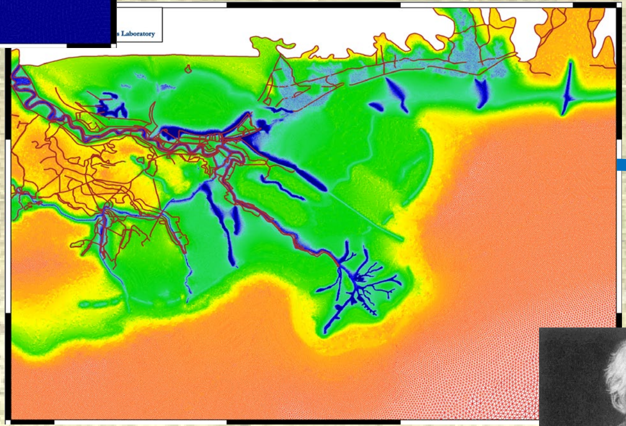
- HPX achieves a 1.25x – 1.21x speedup over MPI

Evolution of coastal ocean hydrodynamic models – the past

Geophysical systems

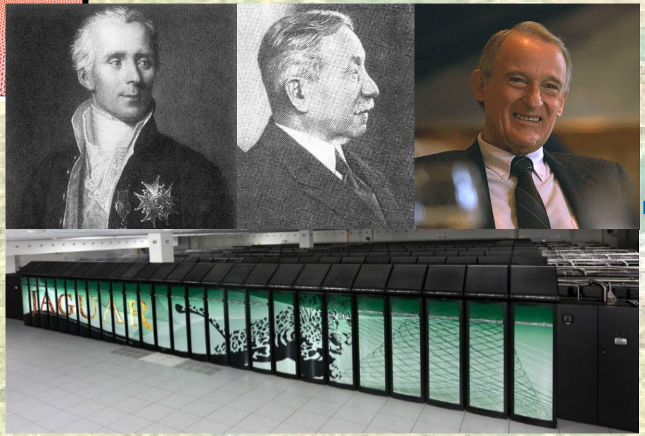


Unstructured grids

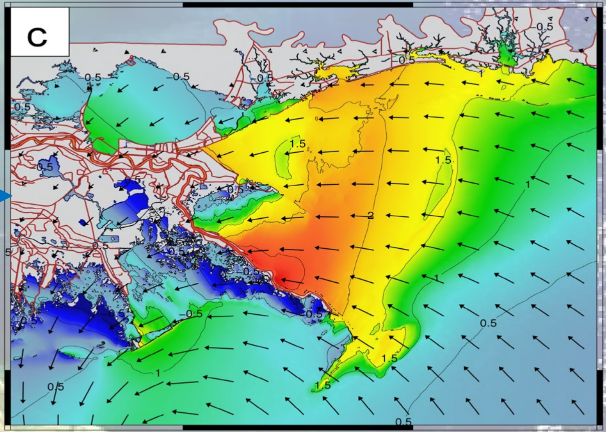


Physics & forcing functions
Model interfacing and interleafing

Pde's + FEM + HPC



Ocean Responses



Evolution of coastal ocean hydrodynamic models – the future