The Evolution of Process and Scale Coupling in Coastal Ocean Hydrodynamic Modeling

Joannes Westerink[1], Rick Luettich[2], Clint Dawson[3], Dam Wirasaet[1], Andrew Kennedy[1]

[1]University of Notre Dame, [2]University of North Carolina at Chapel Hill,
[3]University of Texas at Austin

Geoprocesses, Geohazards – CSDMS 2018
May 22-24, 2018

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

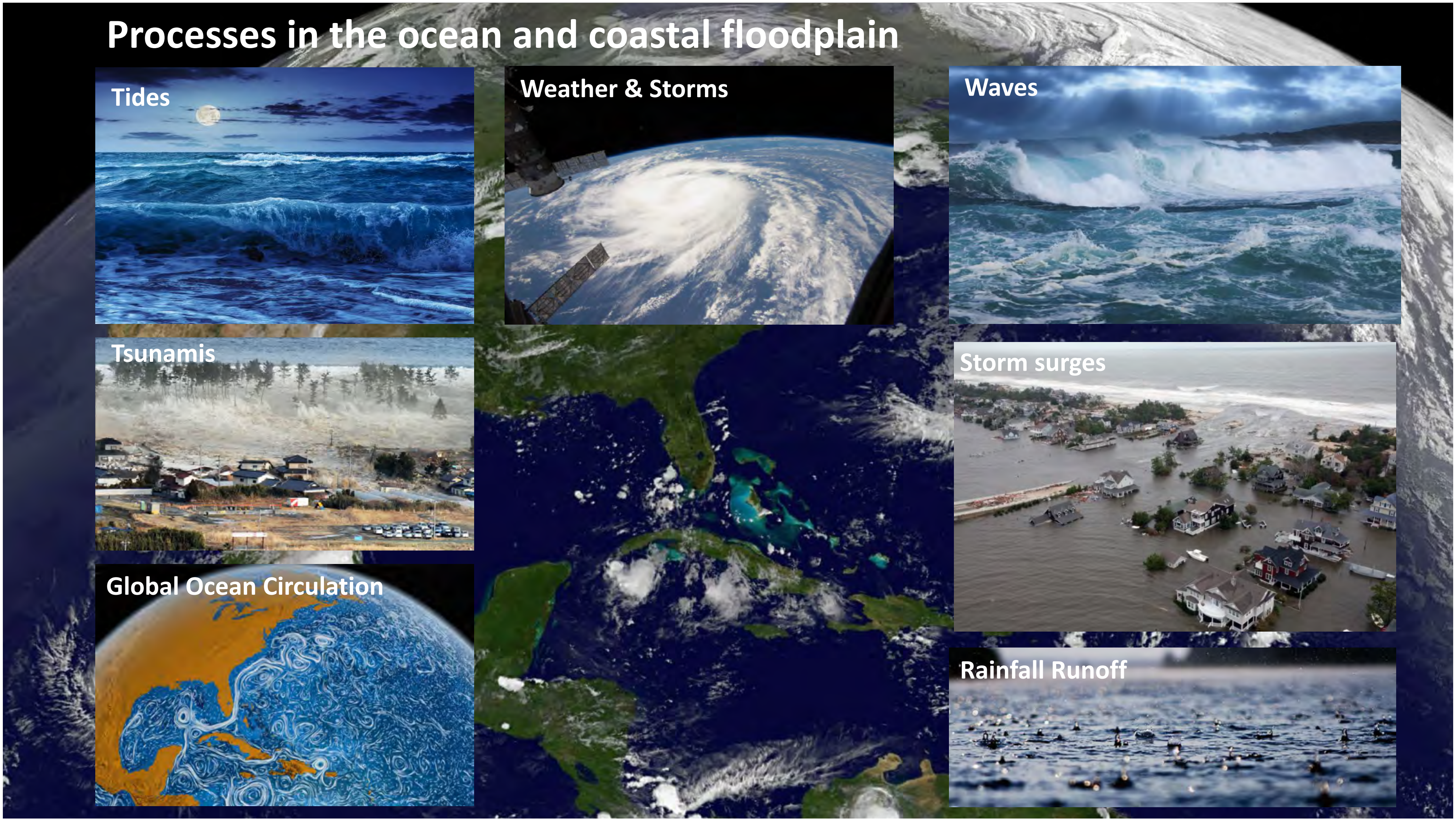
Wave forces

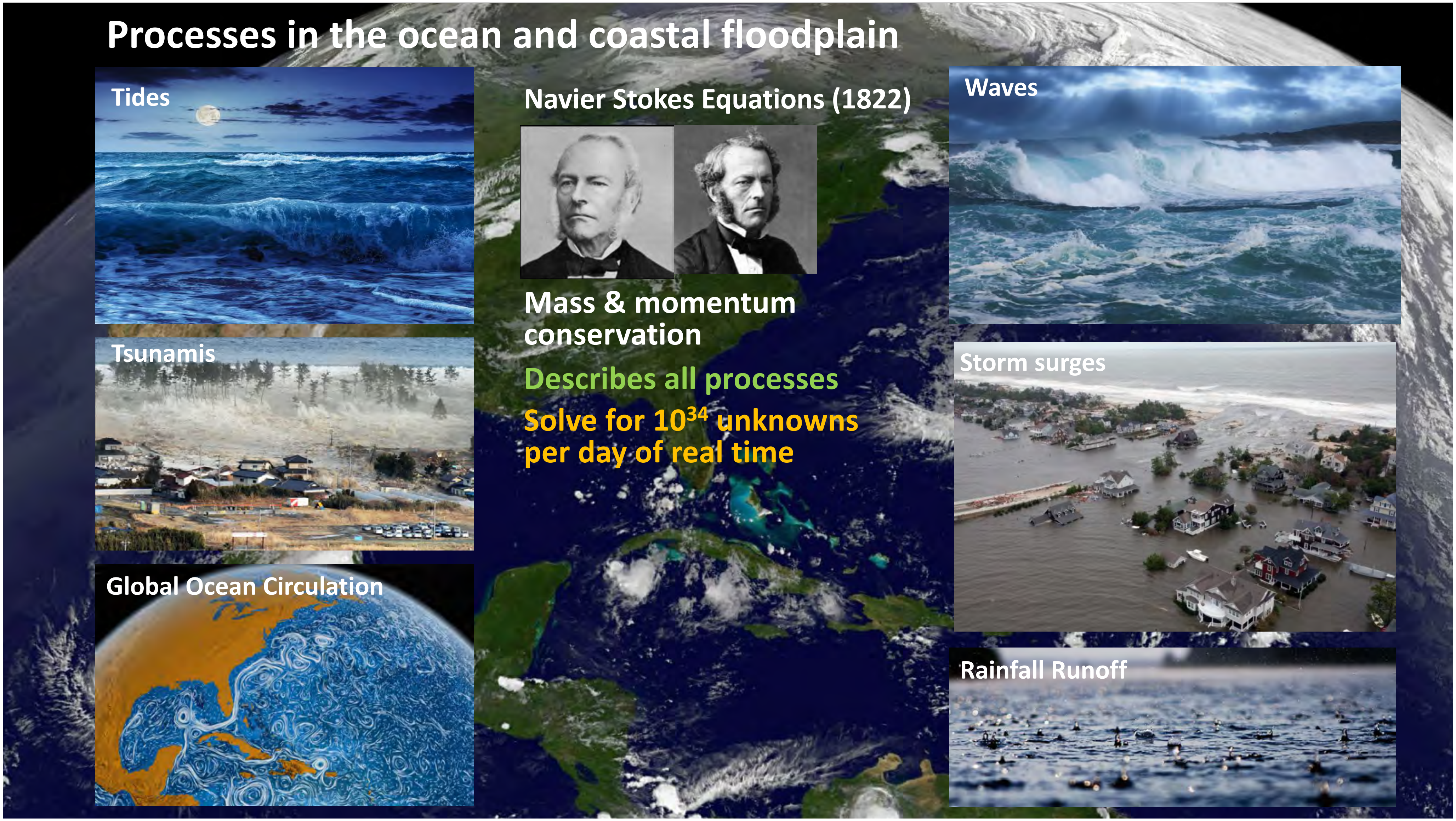
Sinking deltas

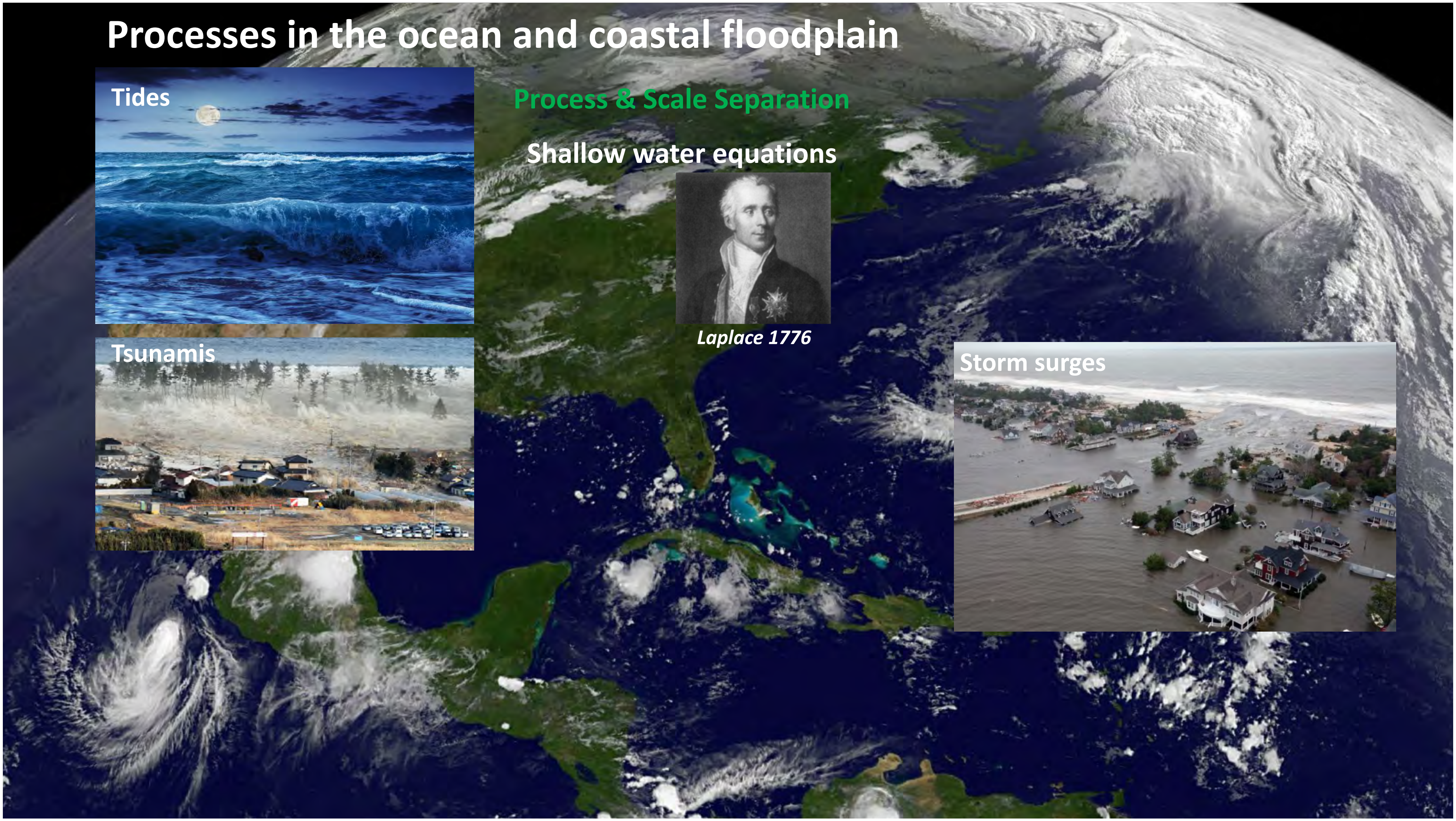
Wetland degradation

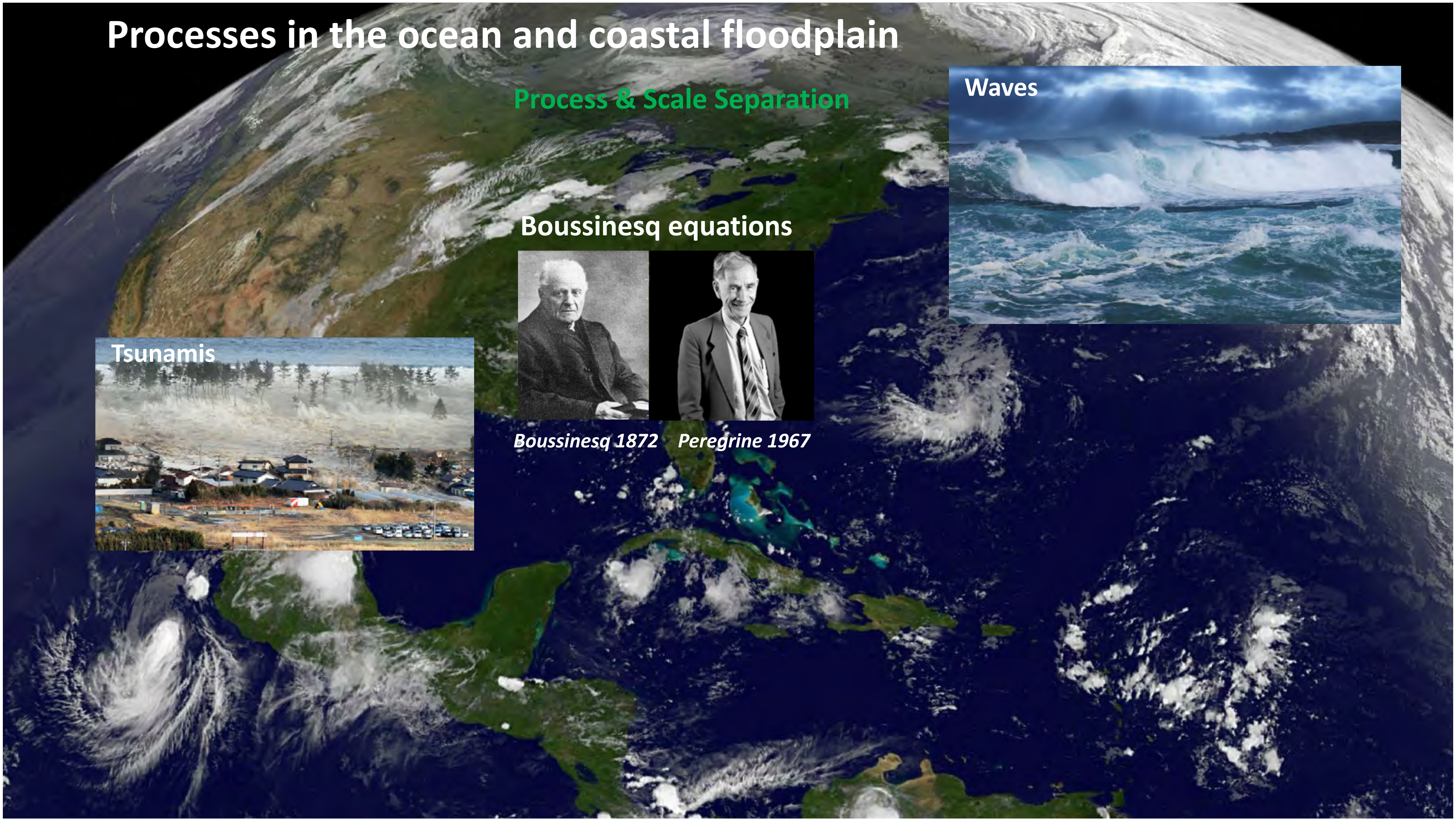
Coastal dead zones

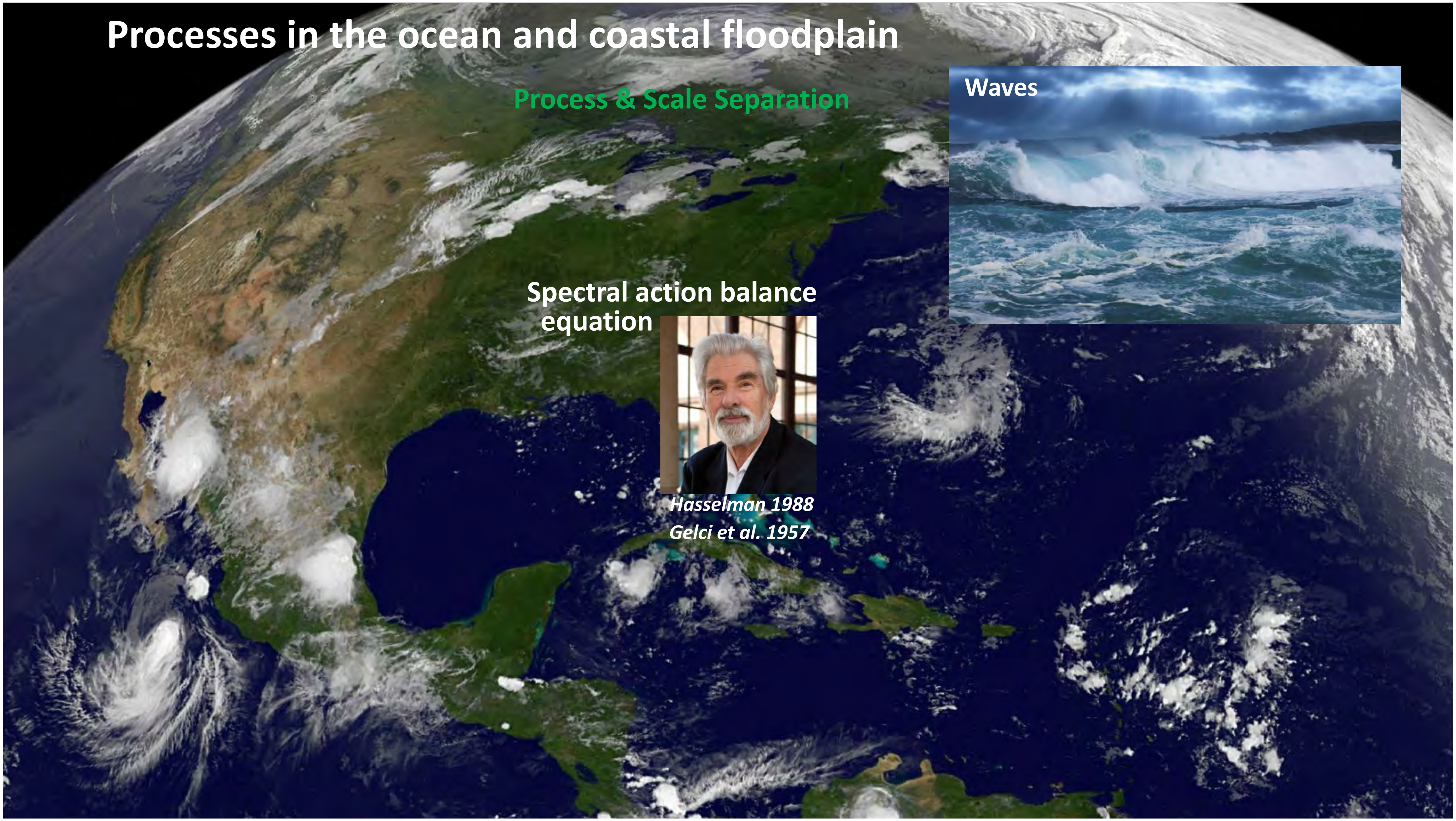
Marine larval transport


Processes in the ocean and coastal floodplain
Tides
Weather & Storms
Waves
Tsunamis
Storm surges
Global Ocean Circulation
Rainfall Runoff

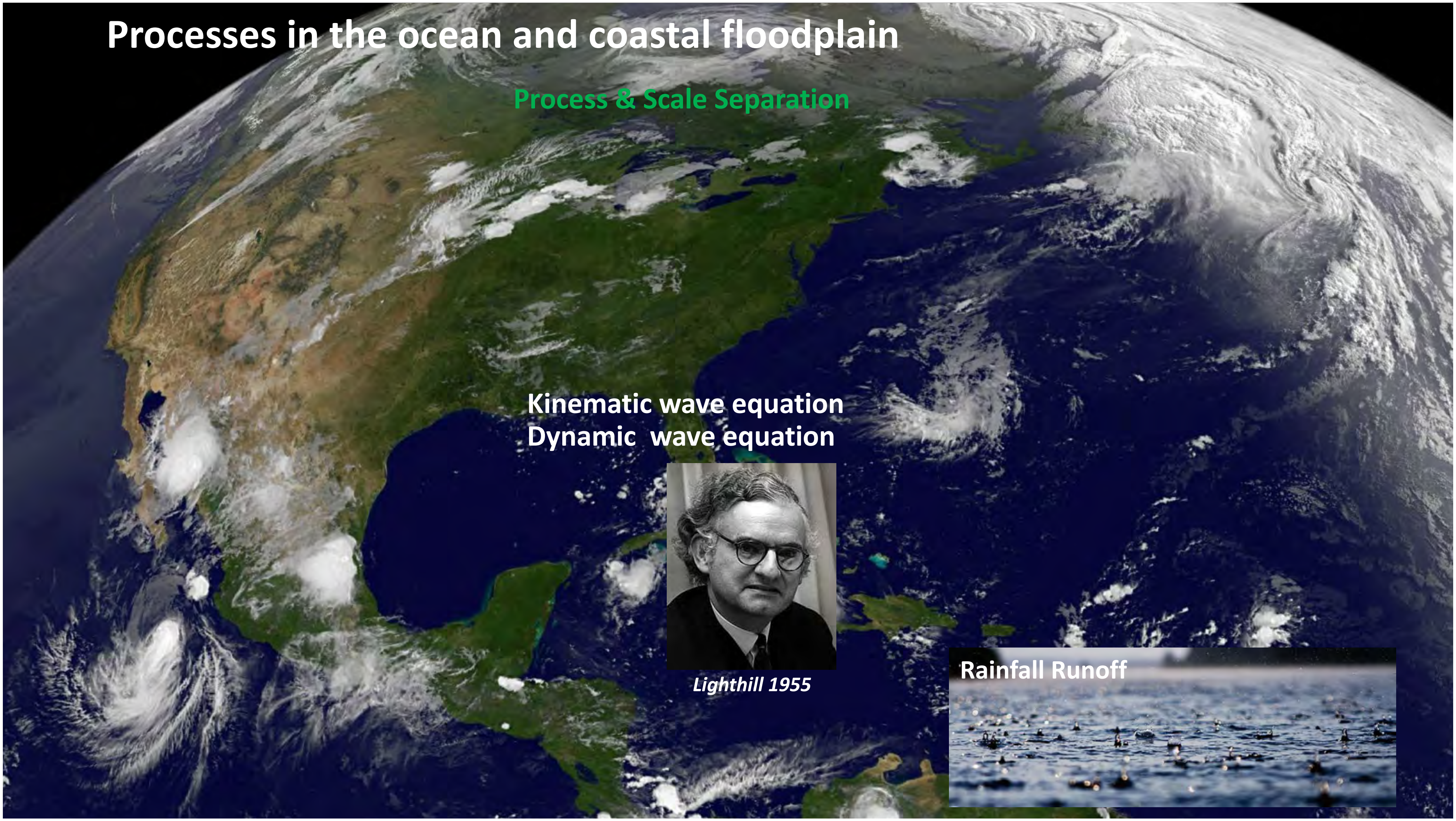

Processes in the ocean and coastal floodplain
Tides
Tsunamis
Global Ocean Circulation
Navier Stokes Equations (1822)
Mass & momentum conservation
Describes all processes
Solve for 10^34 unknowns per day of real time
Waves
Storm surges
Rainfall Runoff


Processes in the ocean and coastal floodplain
Tides
Process & Scale Separation
Shallow water equations
Laplace 1776
Tsunamis
Storm surges


Processes in the ocean and coastal floodplain
Process & Scale Separation
Waves
Boussinesq equations
Tsunamis
Boussinesq 1872
Peregrine 1967


Processes in the ocean and coastal floodplain
Process & Scale Separation
Waves
Spectral action balance equation
Hasselman 1988
Gelci et al. 1957

Processes in the ocean and coastal floodplain

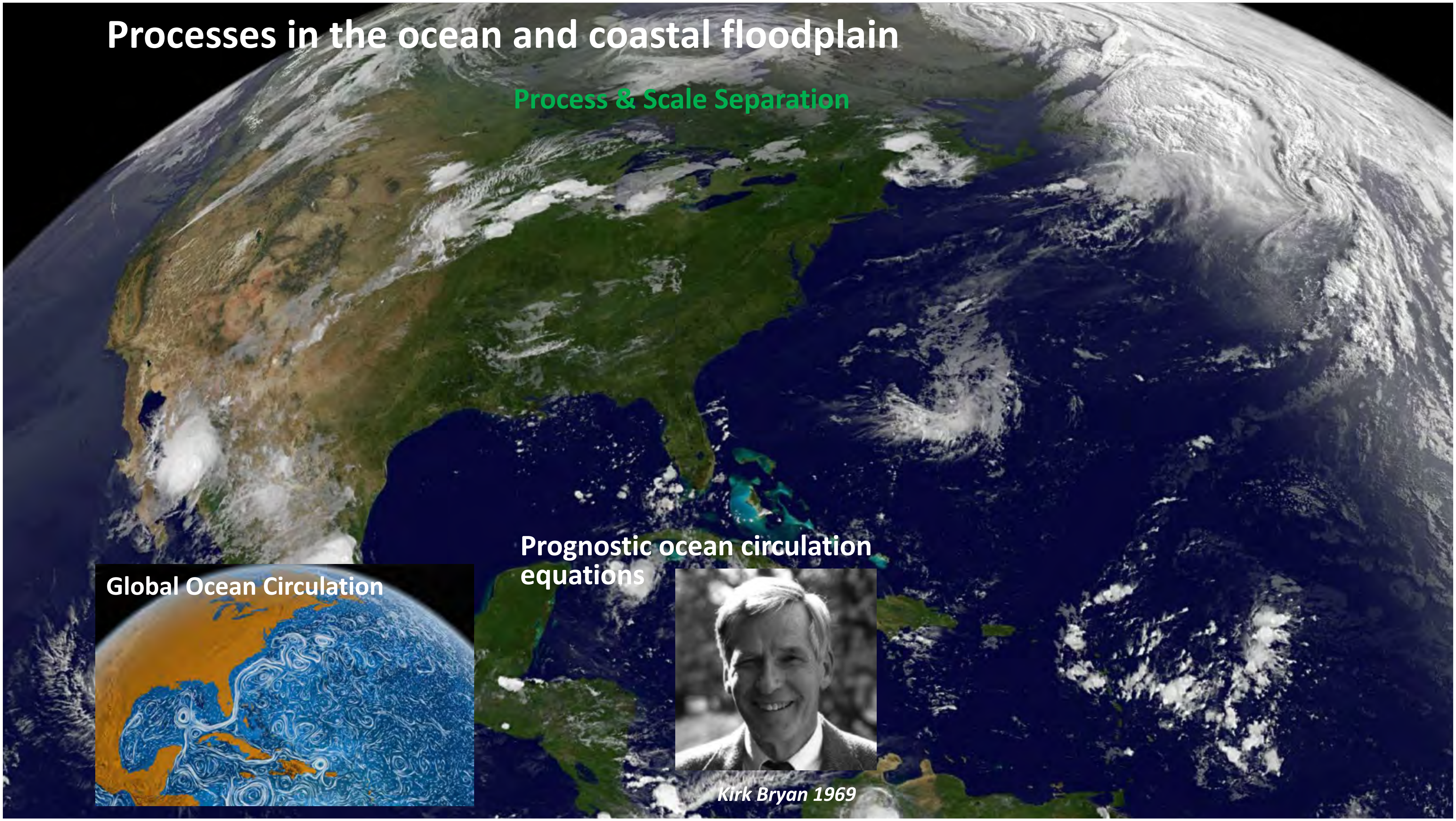


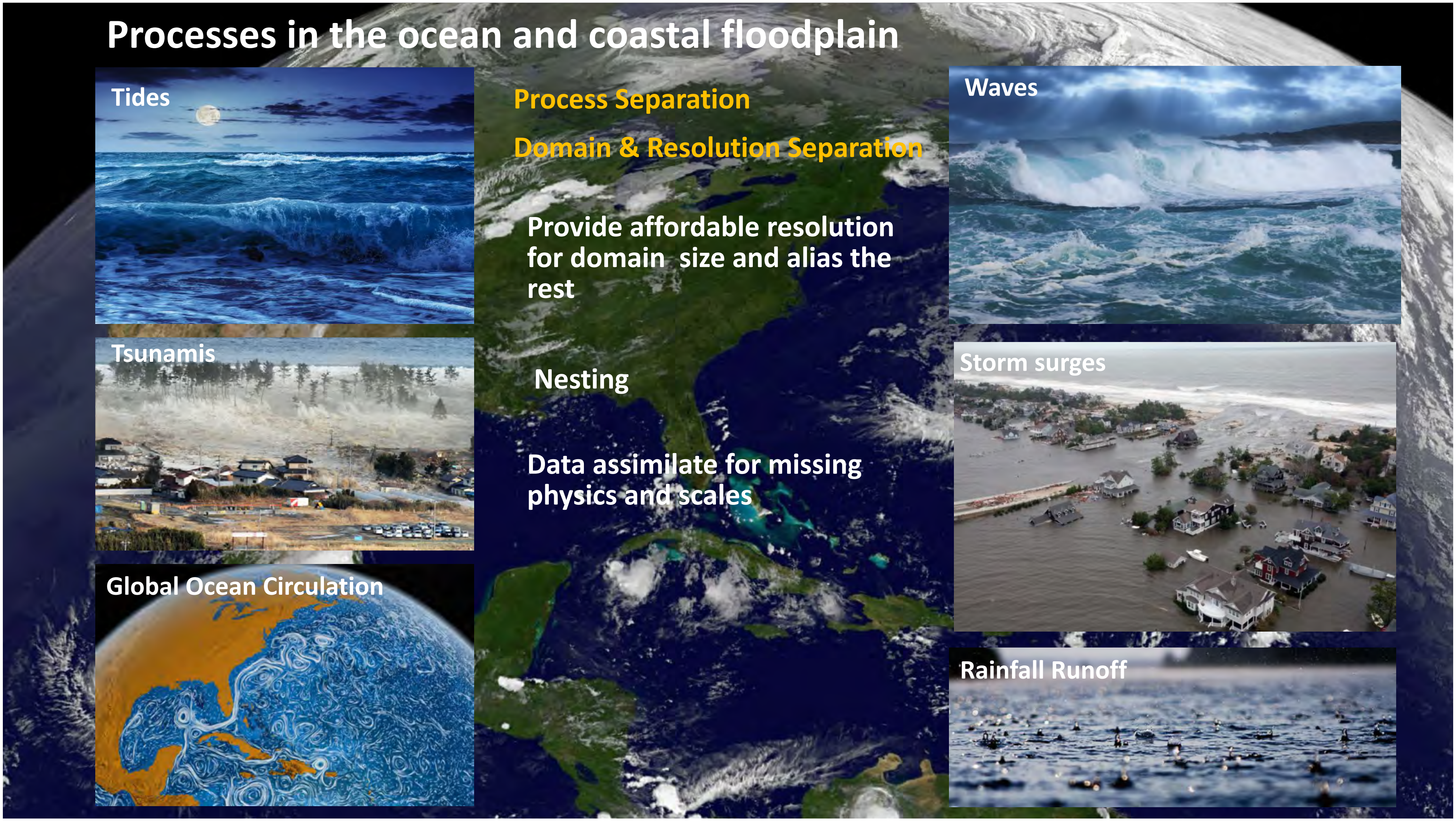
Process & Scale Separation

Kinematic wave equation
Dynamic wave equation

Lighthill 1955

Rainfall Runoff


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
Tides
Tsunamis
Global Ocean Circulation
Process Separation
Domain & Resolution Separation
Provide affordable resolution for domain size and alias the rest
Nesting
Data assimilate for missing physics and scales
Waves
Storm surges
Rainfall Runoff

Evolution of coastal ocean hydrodynamics models – the past

The GOOD

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

The BAD

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

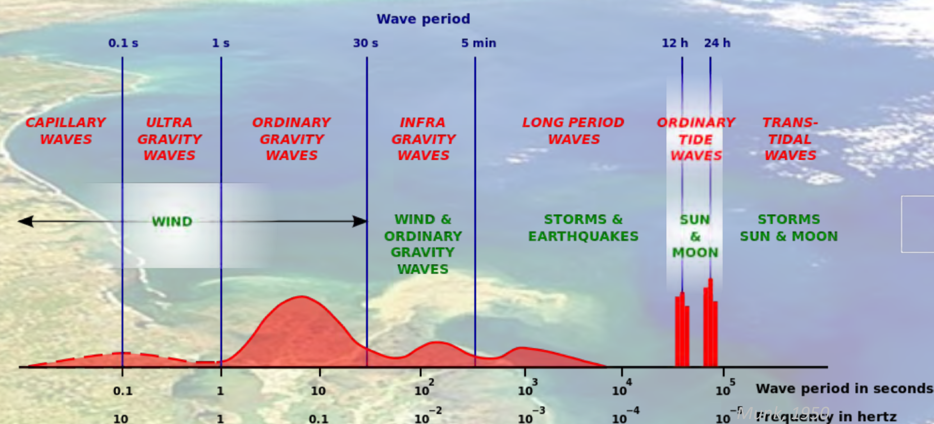
Evolution of coastal ocean hydrodynamics models – the past

Dynamic ADCIRC & SWAN Coupling

CFSv2 Global Atmospheric Model

ADCIRC 2D SWE

SWAN Wave Energy Density



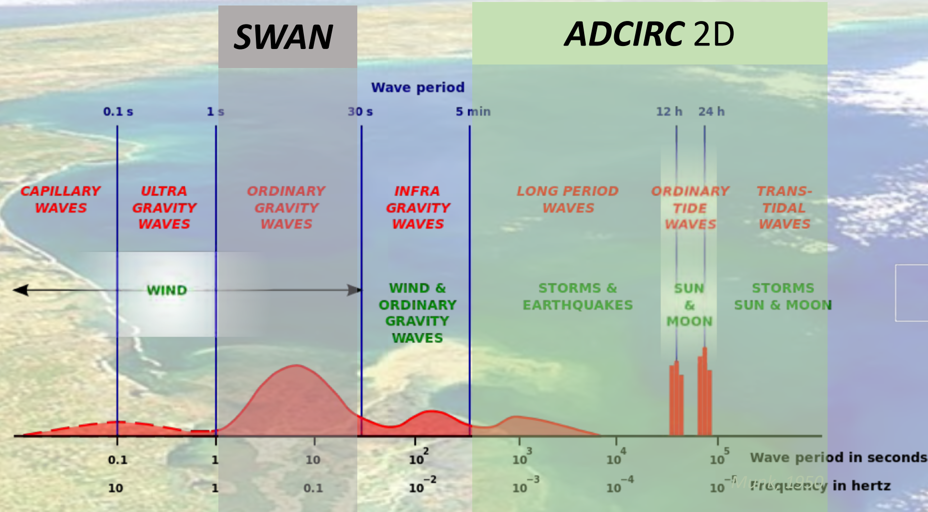
Evolution of coastal ocean hydrodynamics models – the past

Dynamic ADCIRC & SWAN Coupling

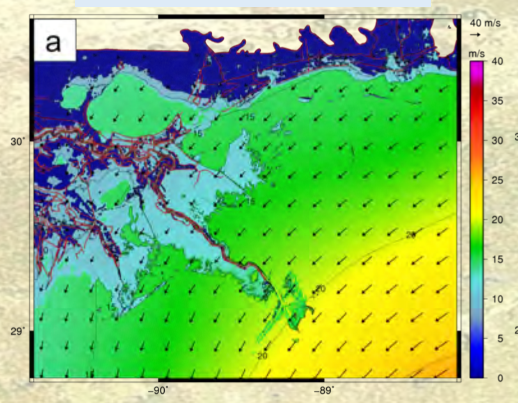
CFSv2 Global Atmospheric Model

ADCIRC 2D SWE

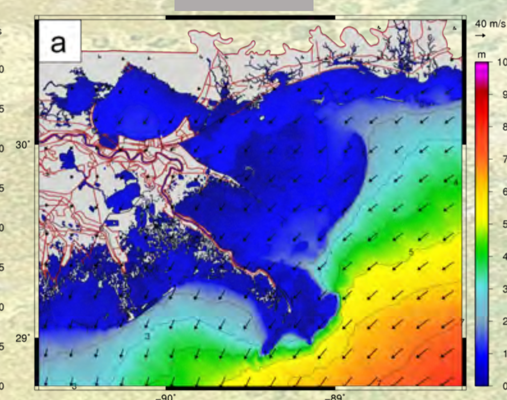
SWAN Wave Energy Density



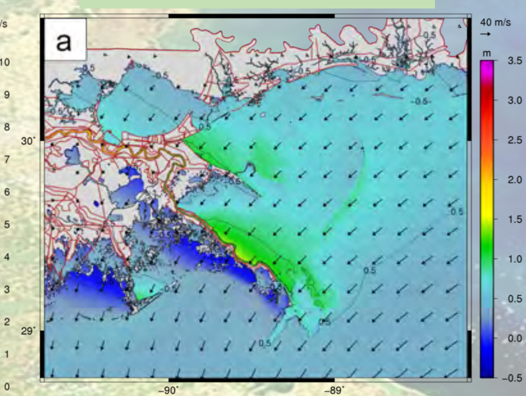
CFSv2



SWAN



ADCIRC 2D

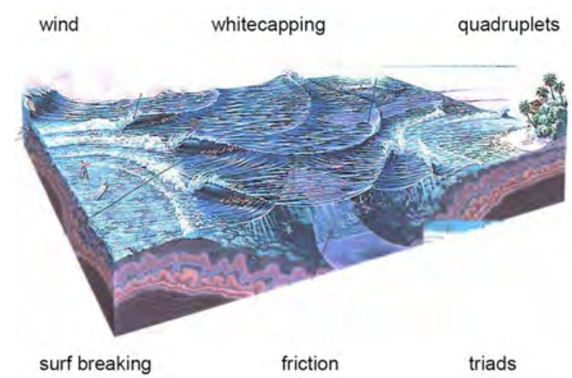


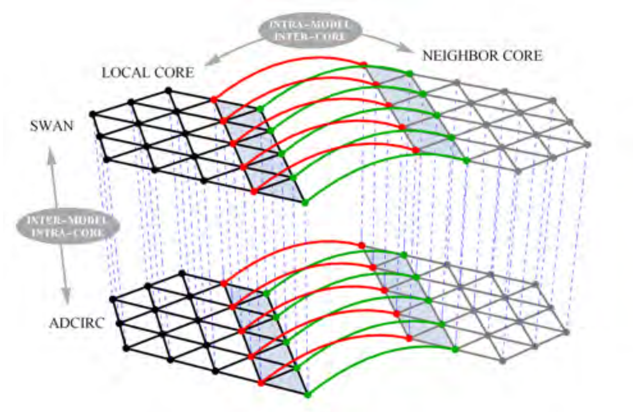
ADCIRC+SWAN: Coastal ocean circulation and wave models – the past

- 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

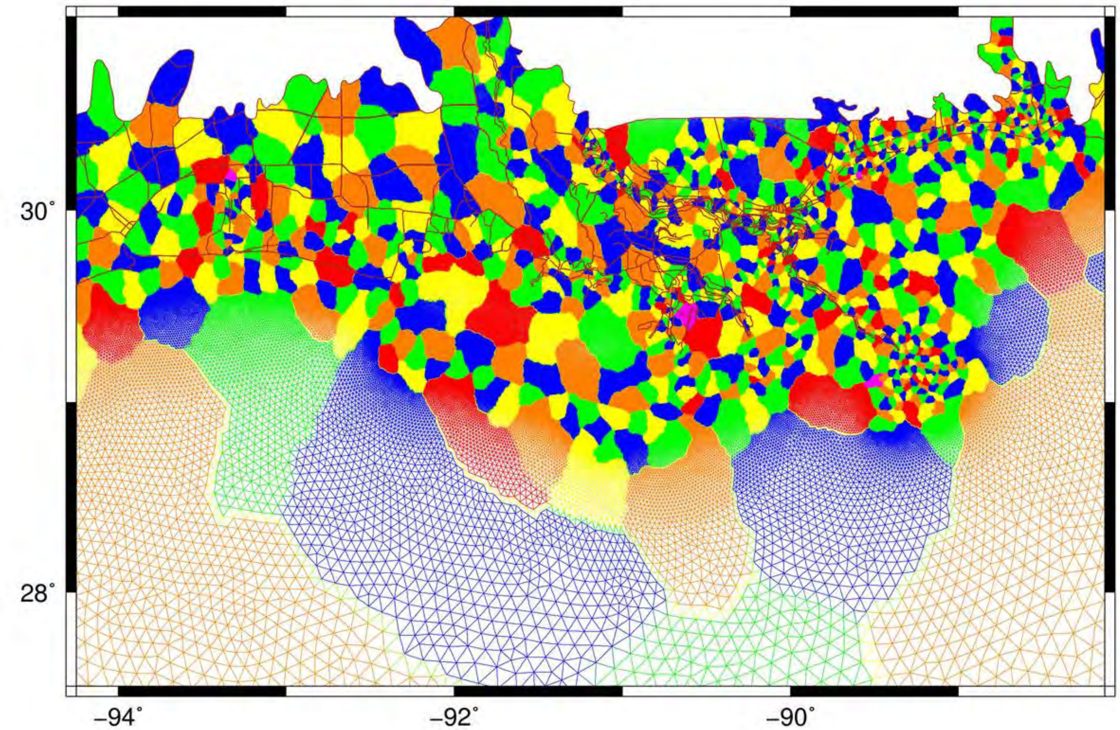




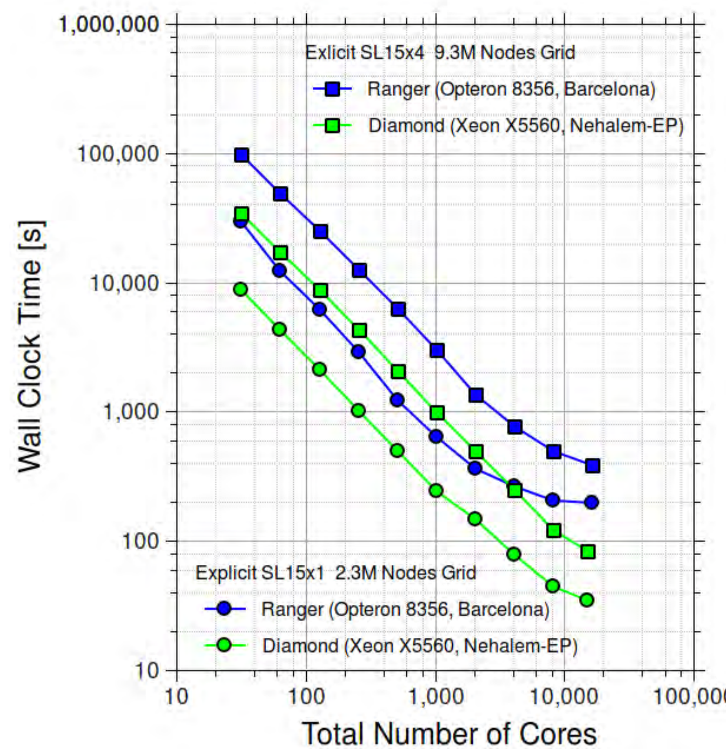
Dietrich et al., ***Coastal Engineering***, **58**, 45-65, 2011.
Dietrich et al., ***Journal of Scientific Computing***, **52**, 468-497 2012.

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

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

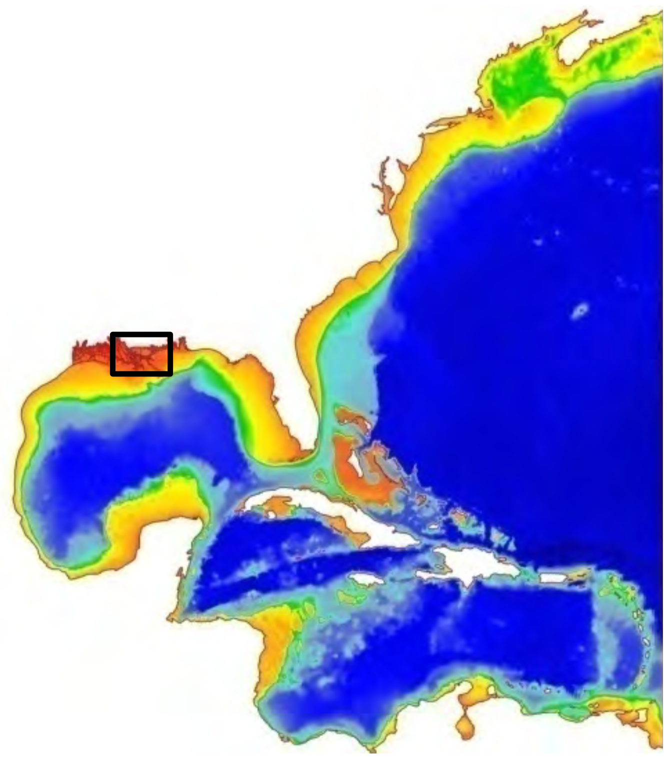


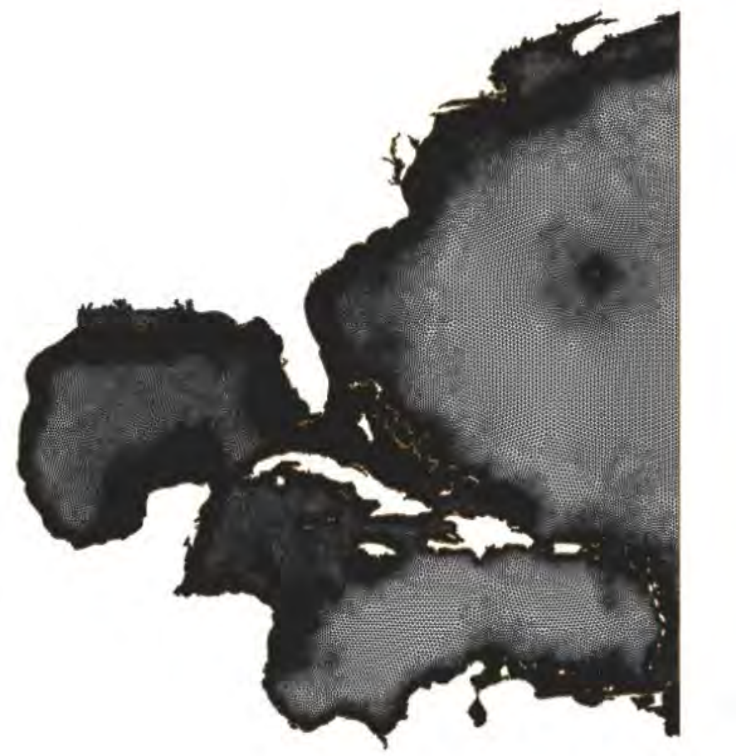
HPC: Parallel Performance



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

SL16v18 model bathymetry and topography and unstructured mesh

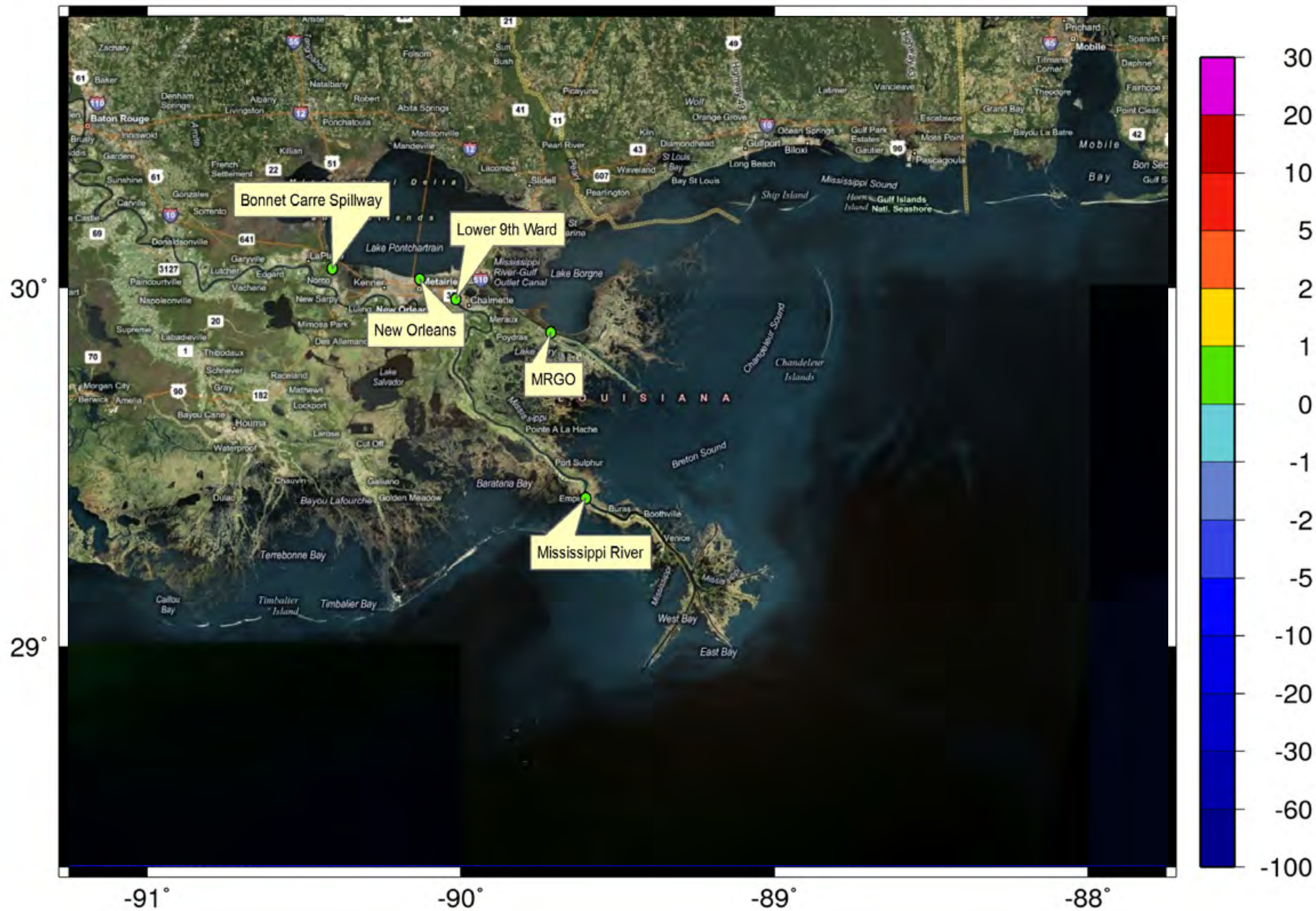




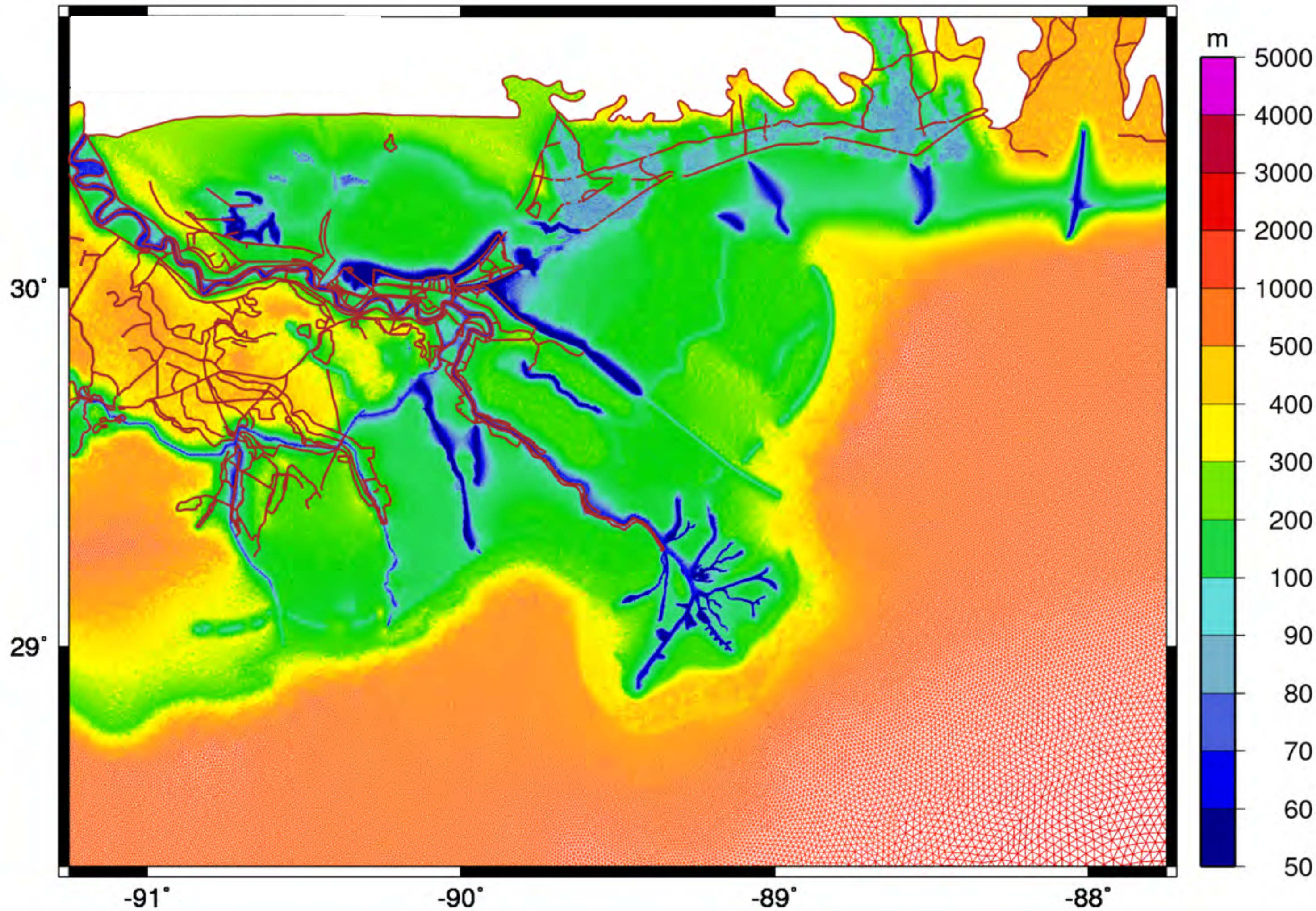
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.
Kennedy et al., ***Geophysical Research Letters***, **38**, L08608, 2011.
Kerr et al., ***Journal of Waterway, Port, Coastal, and Ocean Engineering***, **139,** 326-335, 2013.

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

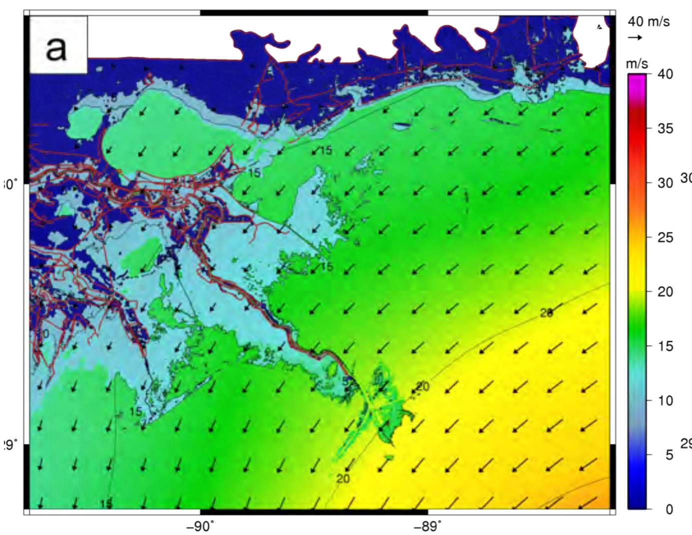


Models: SL16v18 mesh size in SE Louisiana

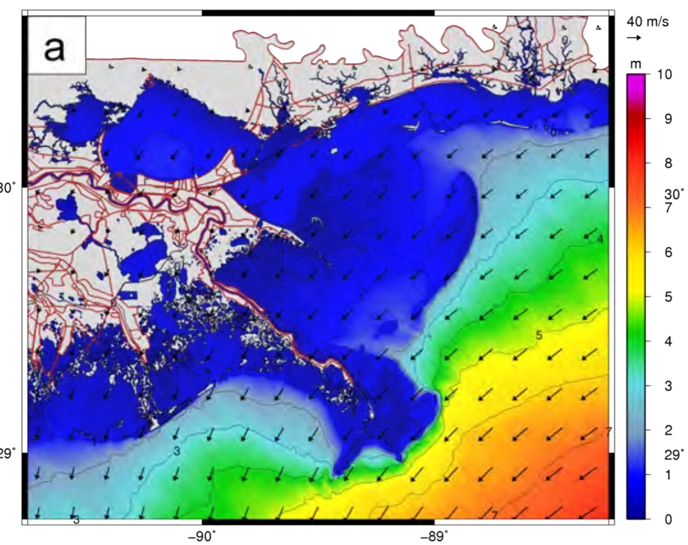


Hurricane Gustav: 2008 / 09 / 01 / 0200 UTC

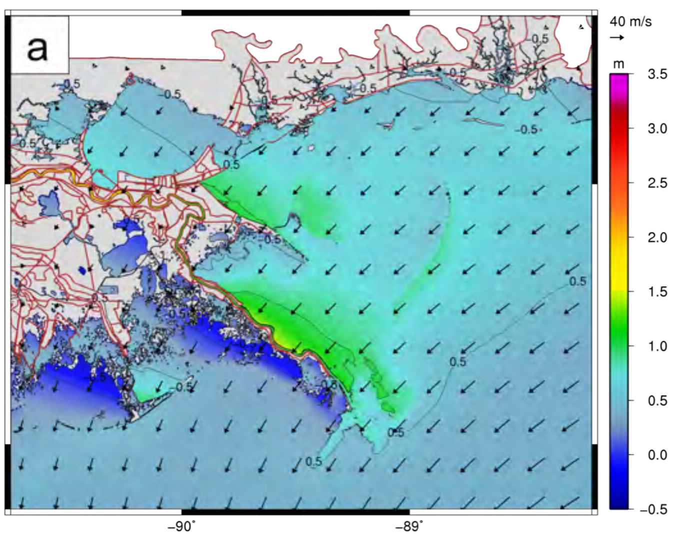
Winds (m/s)



Waves (m)



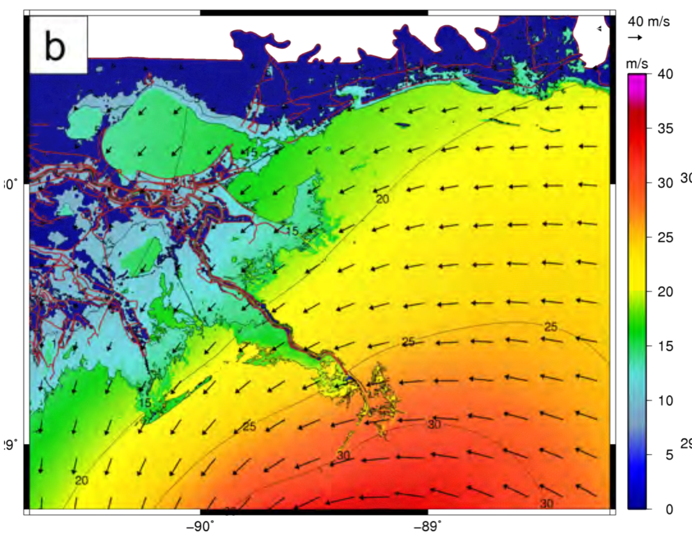
Water Elevations (m)



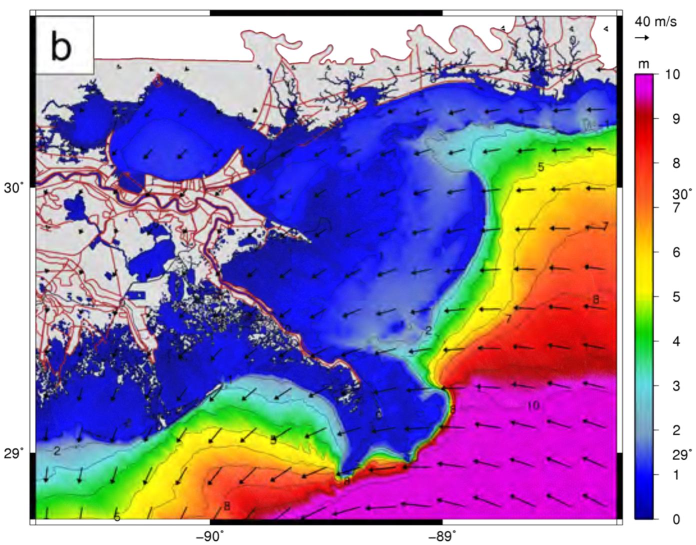
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 0800 UTC

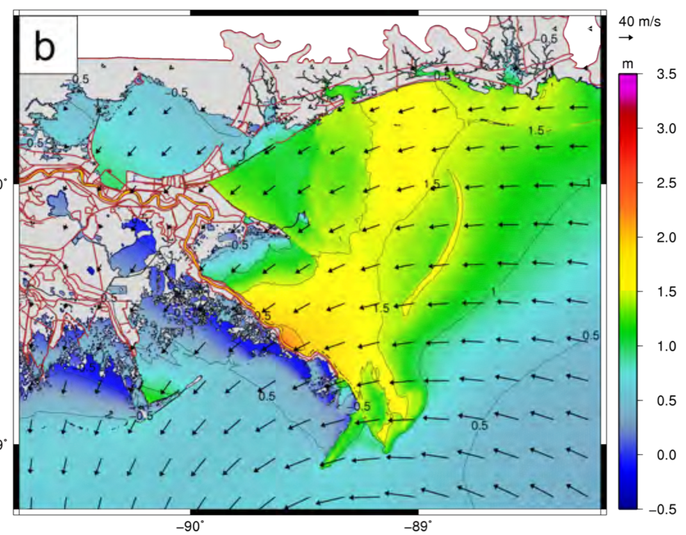
Winds (m/s)



Waves (m)



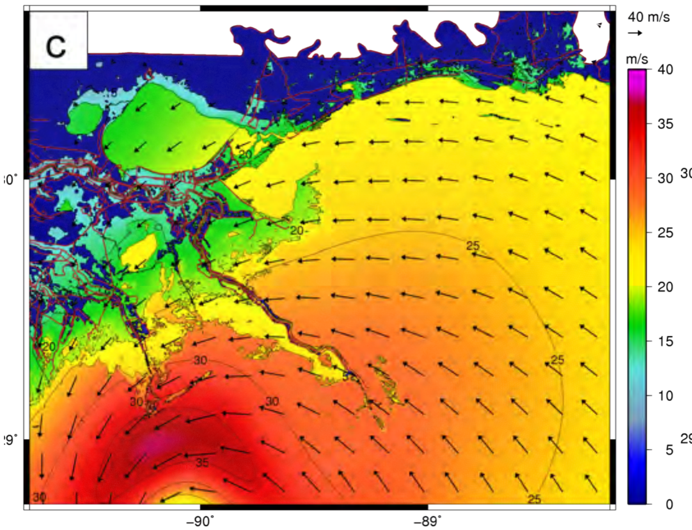
Water Elevations (m)



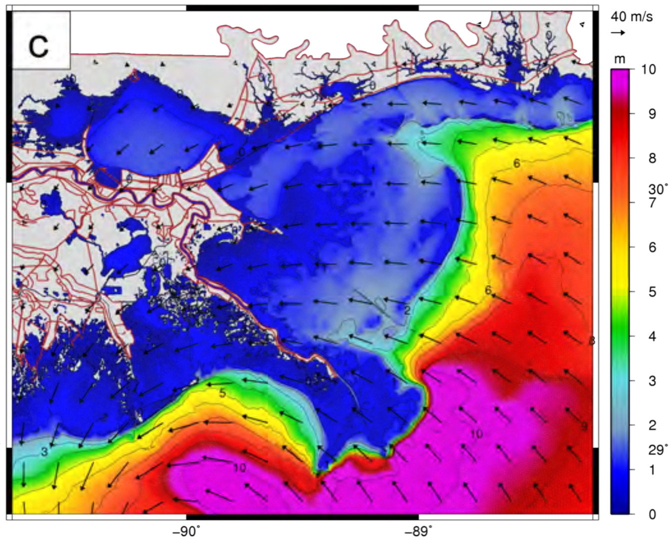
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 1100 UTC

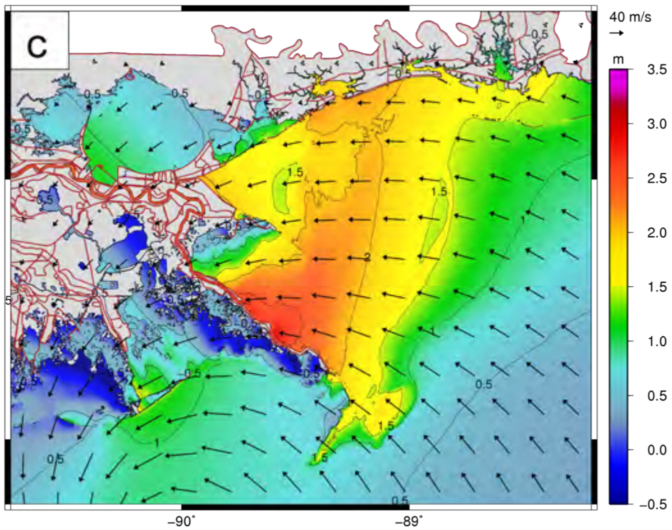
Winds (m/s)



Waves (m)



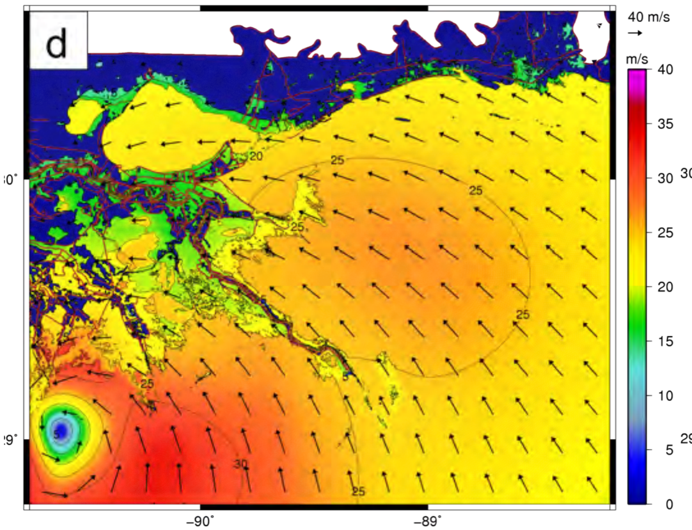
Water Elevations (m)



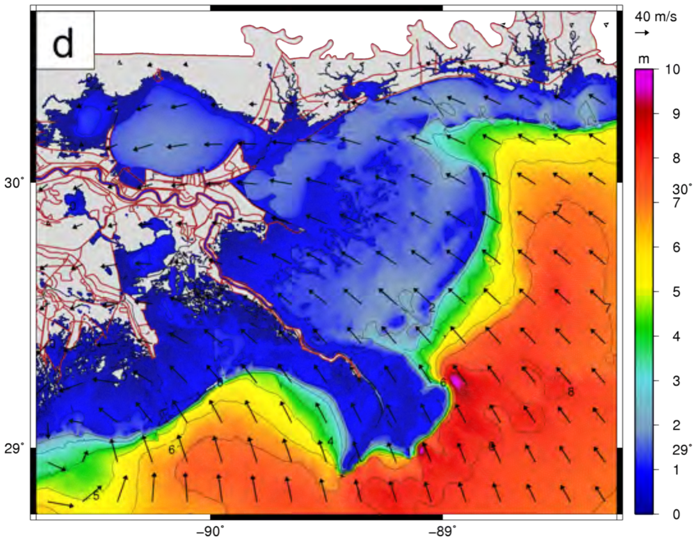
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 1400 UTC

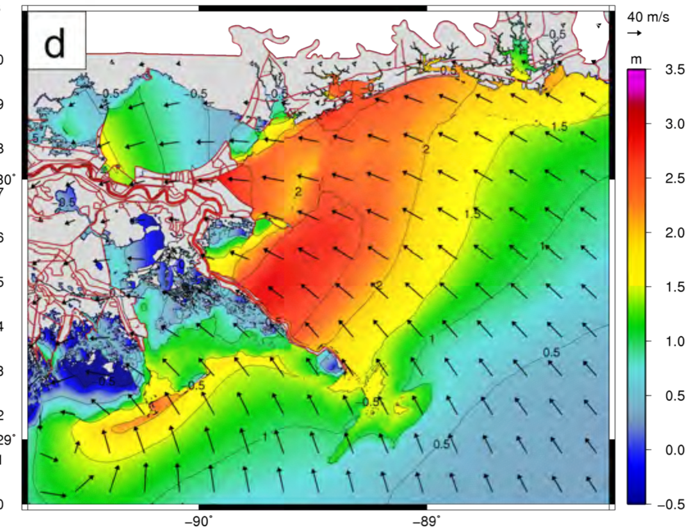
Winds (m/s)



Waves (m)



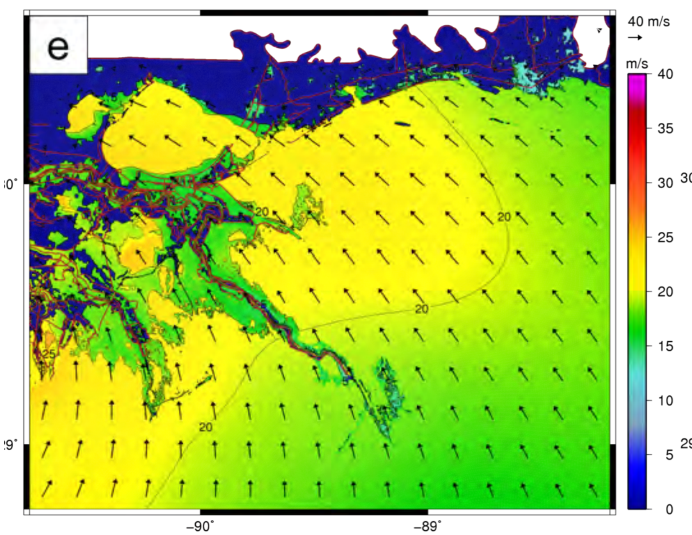
Water Elevations (m)



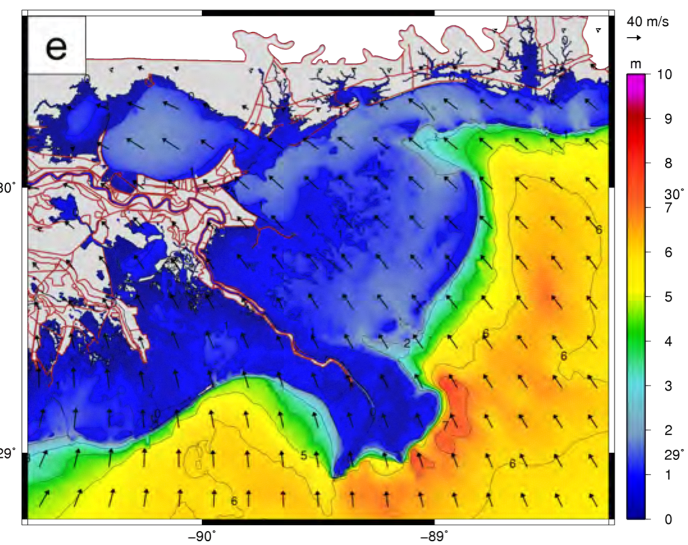
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 01 / 1700 UTC

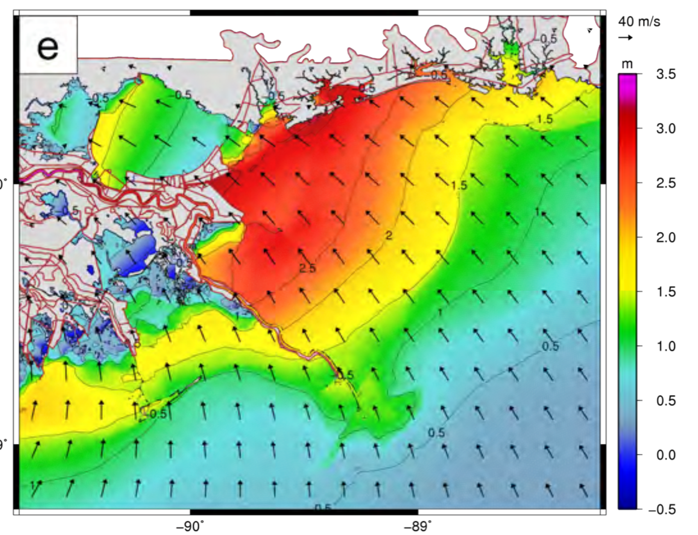
Winds (m/s)



Waves (m)



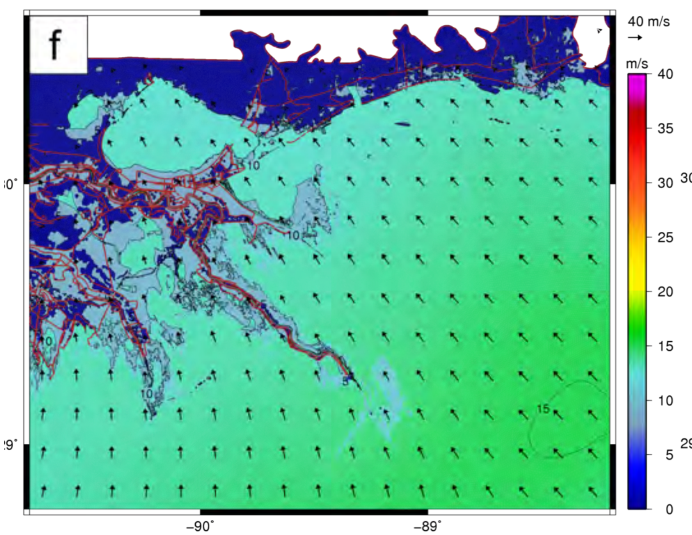
Water Elevations (m)



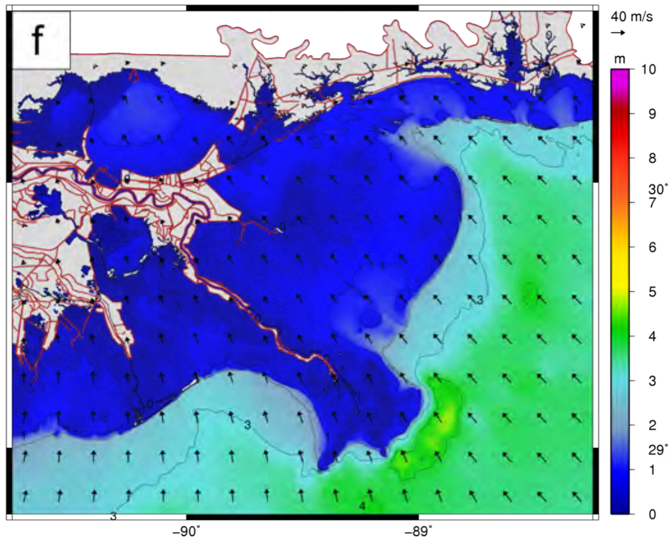
Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.

Hurricane Gustav: 2008 / 09 / 02 / 0200 UTC

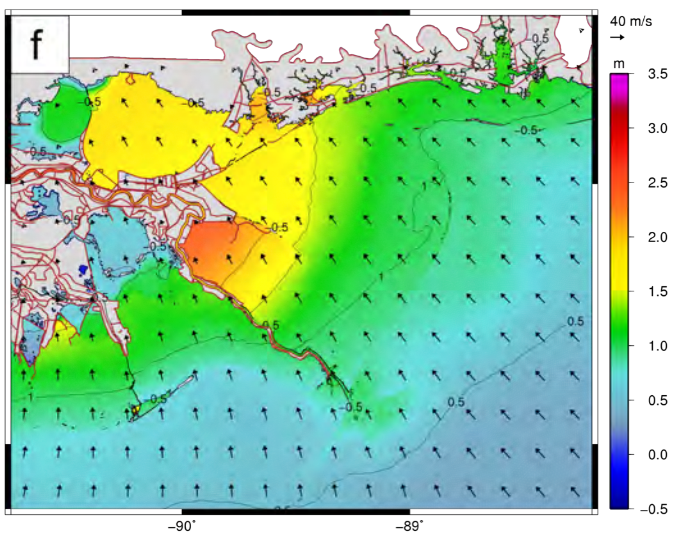
Winds (m/s)



Waves (m)



Water Elevations (m)



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

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

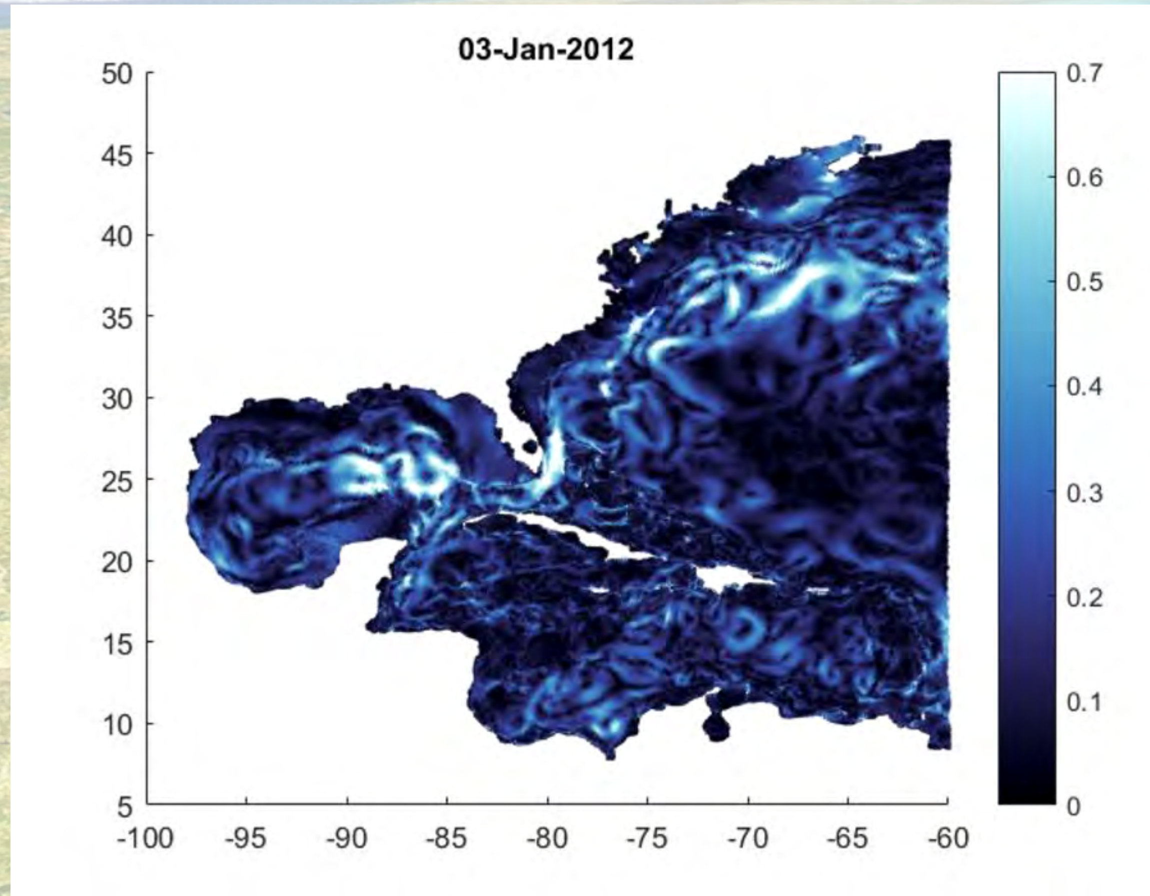
The BAD

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

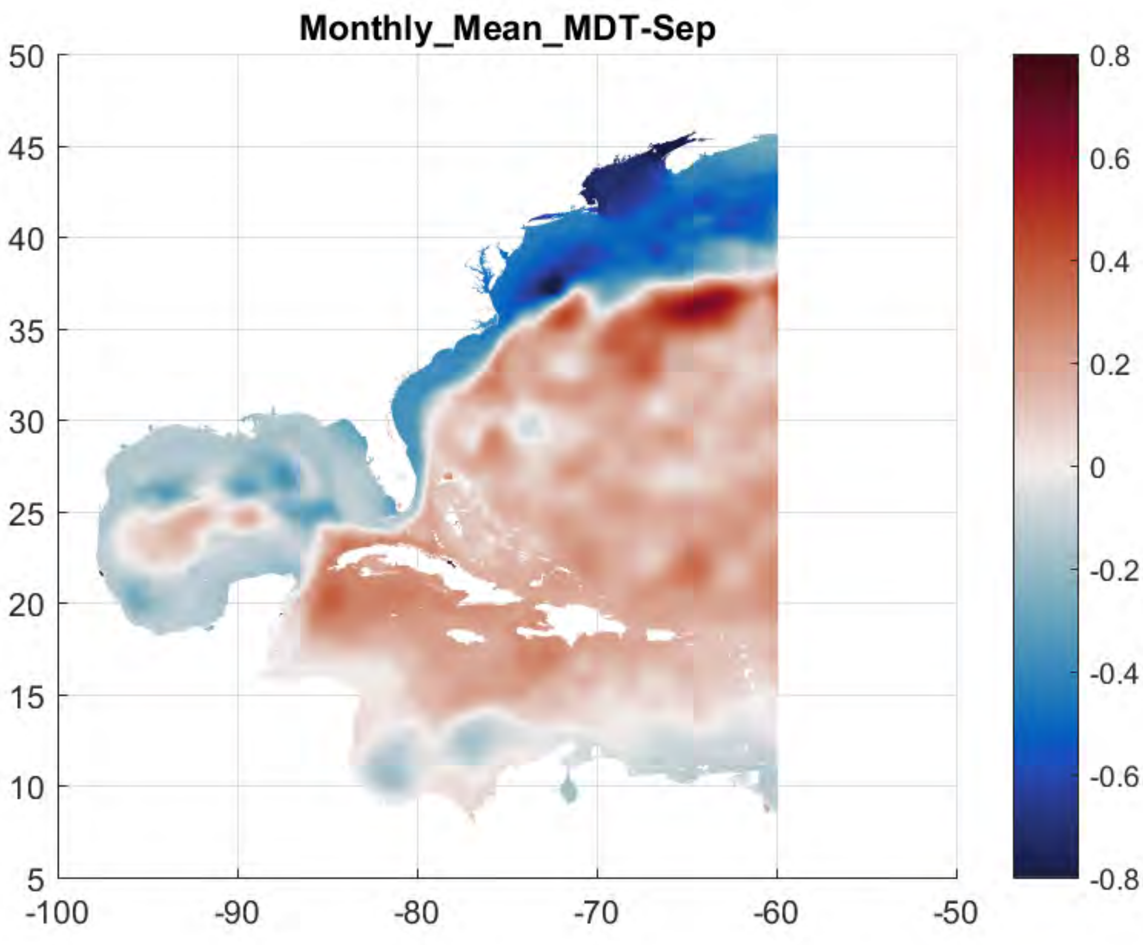
Evolution of coastal ocean hydrodynamic models – the present

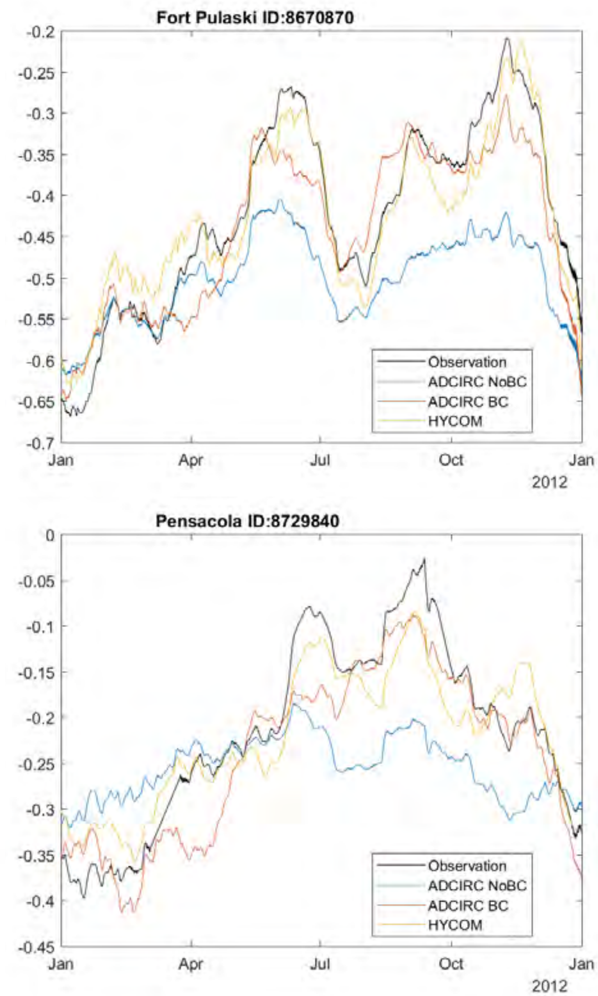
Dynamic *ADCIRC, SWAN & HYCOM* interleafing

- ***CFSv2*** Global Atmospheric Model
- ***ADCIRC*** 2D/3D Circulation
- ***SWAN*** Wave Energy Density
- ***HYCOM*** 3D Global Circulation Model



Evolution of coastal ocean hydrodynamic models – the present





Evolution of coastal ocean hydrodynamic models – the future

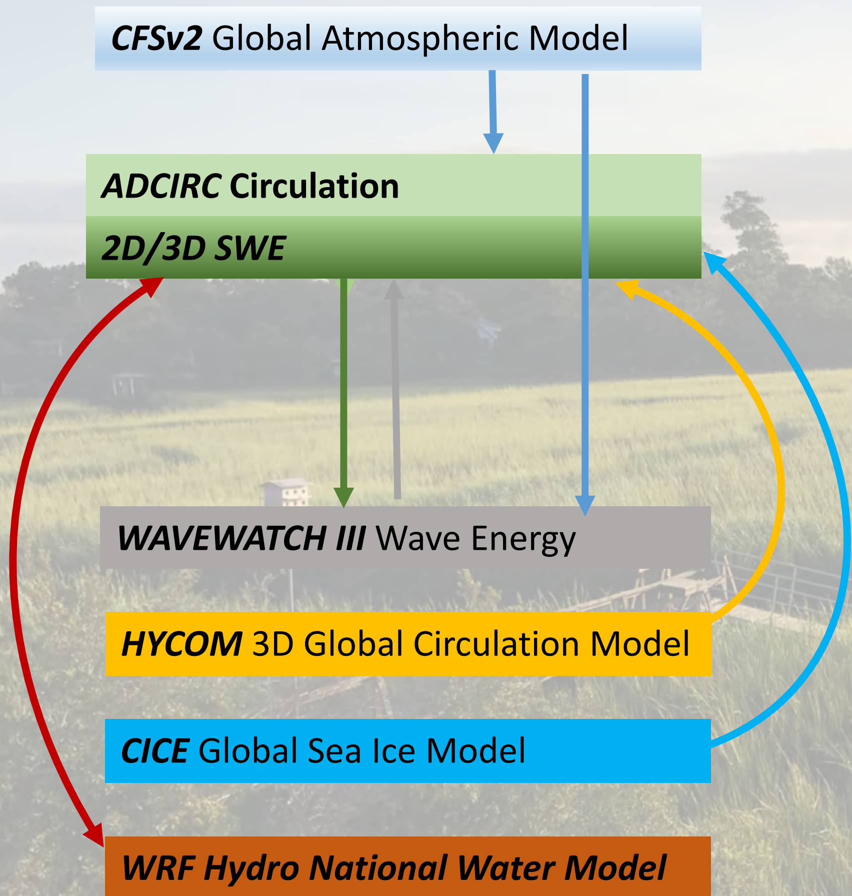
Vision

- 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

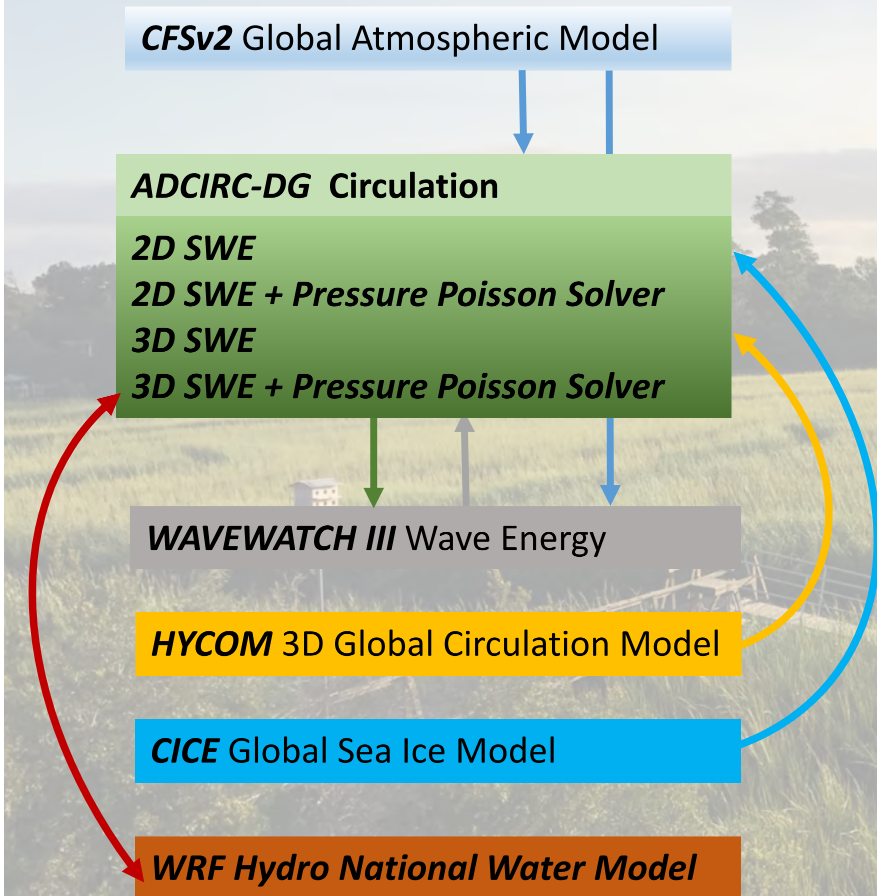


Multi-physics interfacing heterogeneous models over a unified domain

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

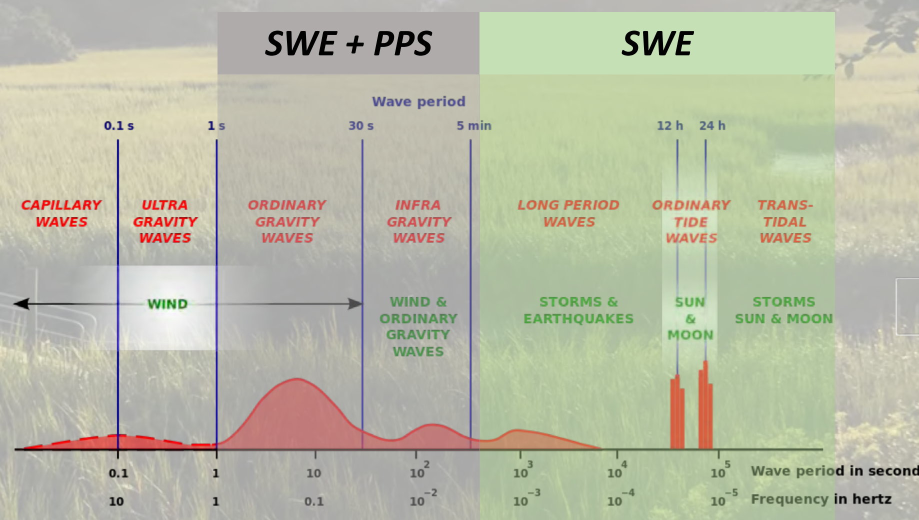
and boundary based two-way coupling to *WRF-Hydro* through *ESMF/NUOPC*

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)

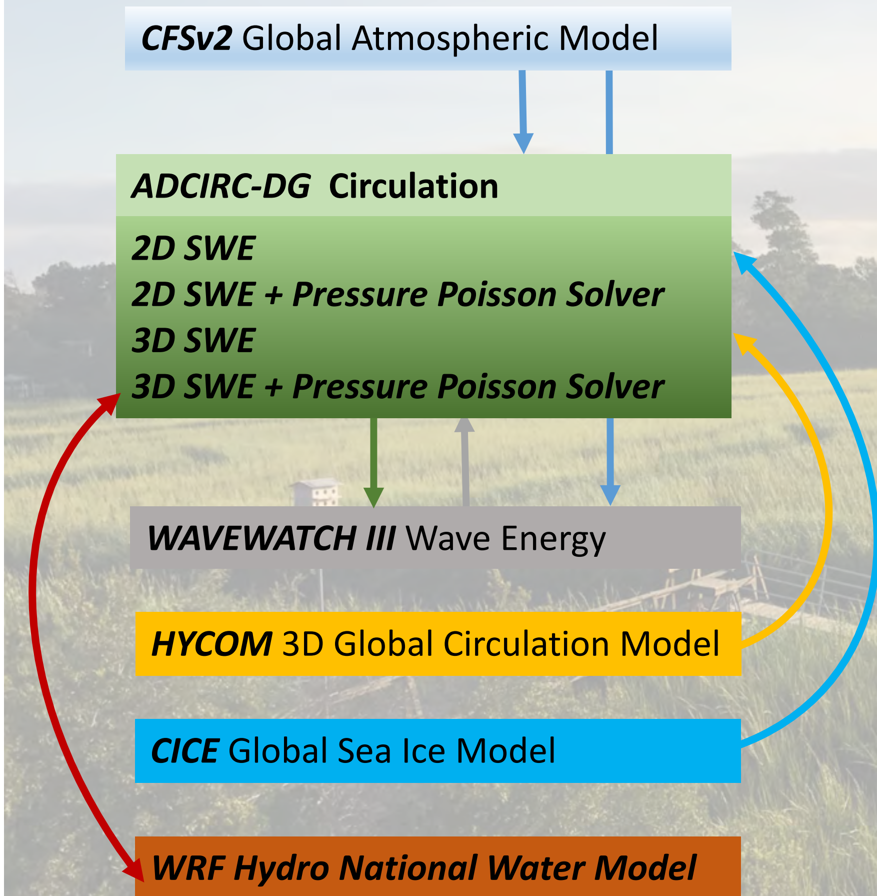


***WWIII, HYCOM, CICE* interleafing**

***WRF-Hydro* interfacing**

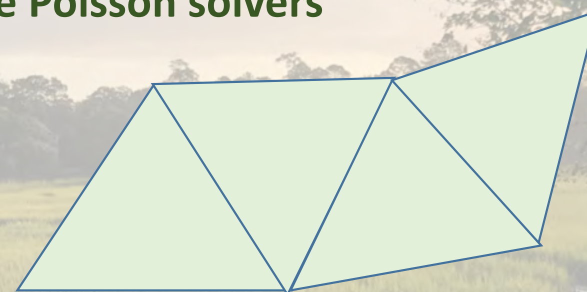
Donahue et al., *Coastal Engineering*, 114, 61-74, 2016.

Develop dynamic hydrodynamic equation selection frameworks

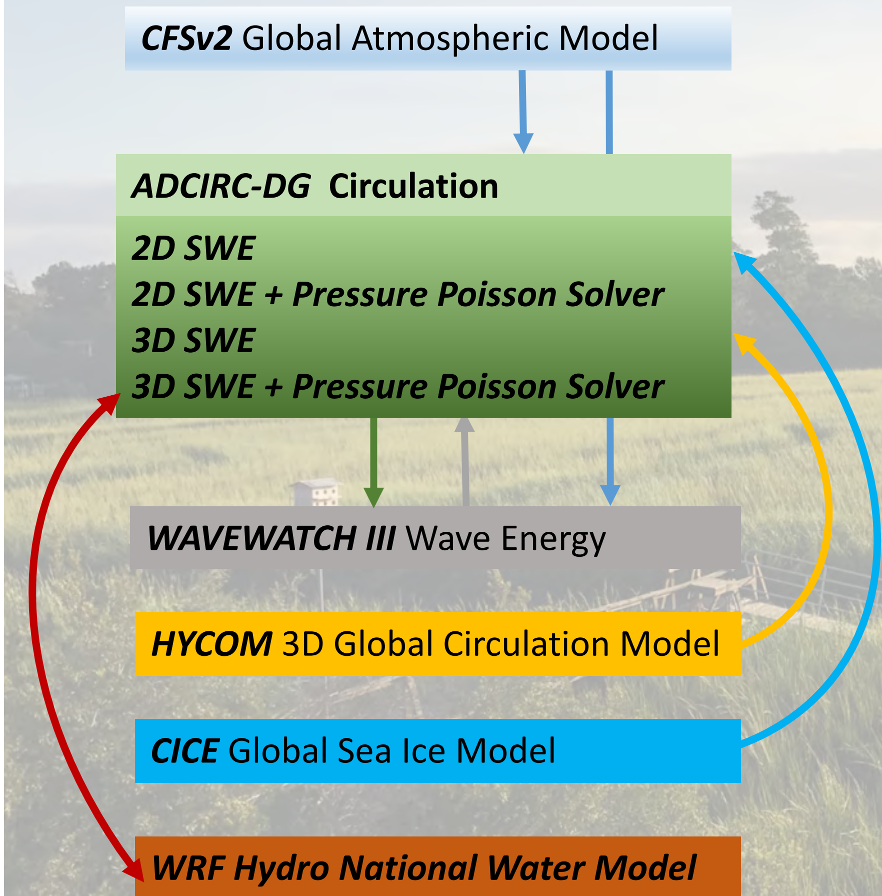


Multi-physics within a single algorithmic framework dynamically selecting physics

Pressure Poisson solvers

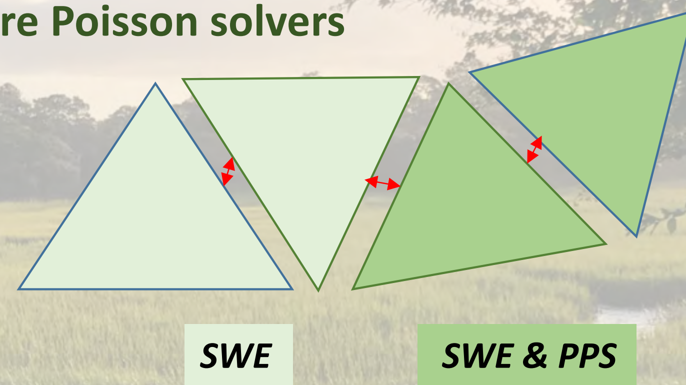


Develop dynamic hydrodynamic equation selection frameworks



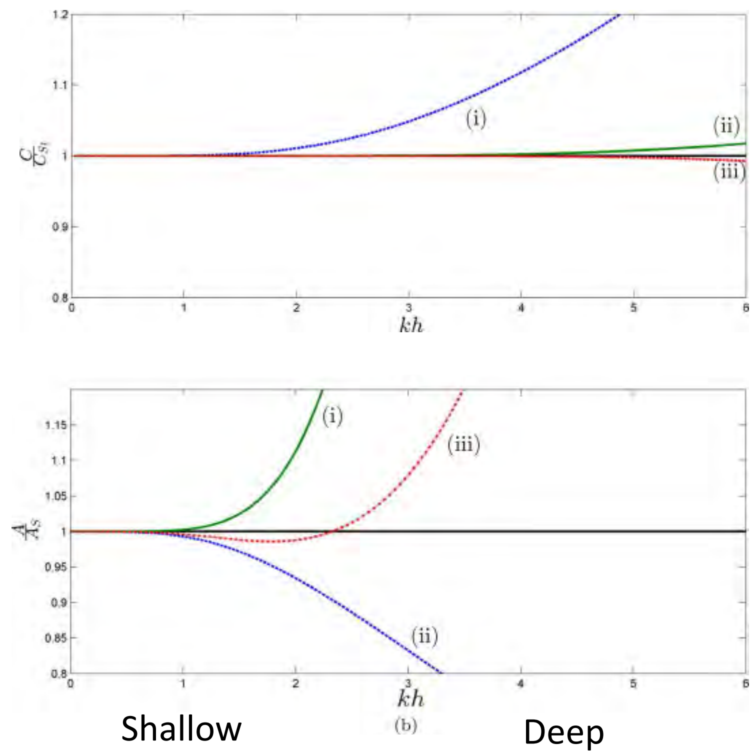
Multi-physics within a single algorithmic framework dynamically selecting physics

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**

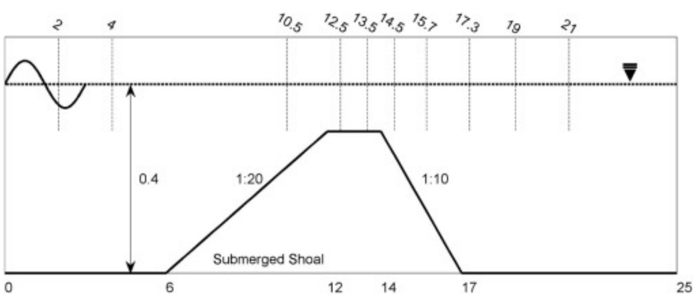


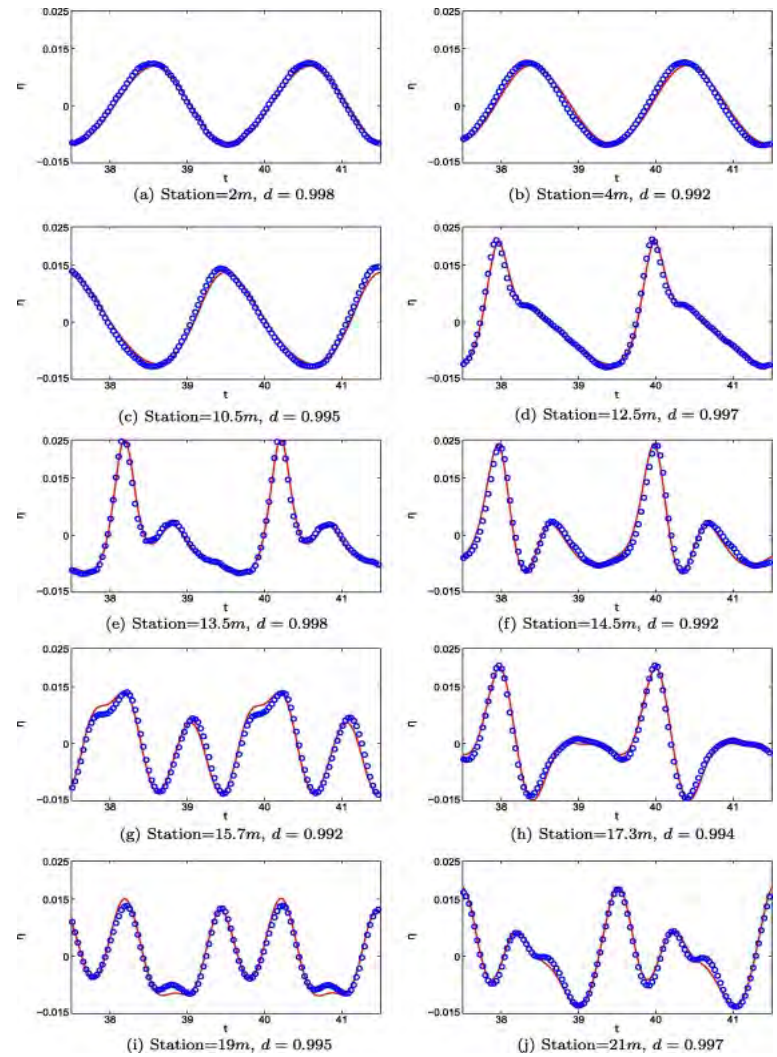
Frequency Dispersion (top); and Shoaling (bottom) accuracy for PP-models compared to linear analytical solutions

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

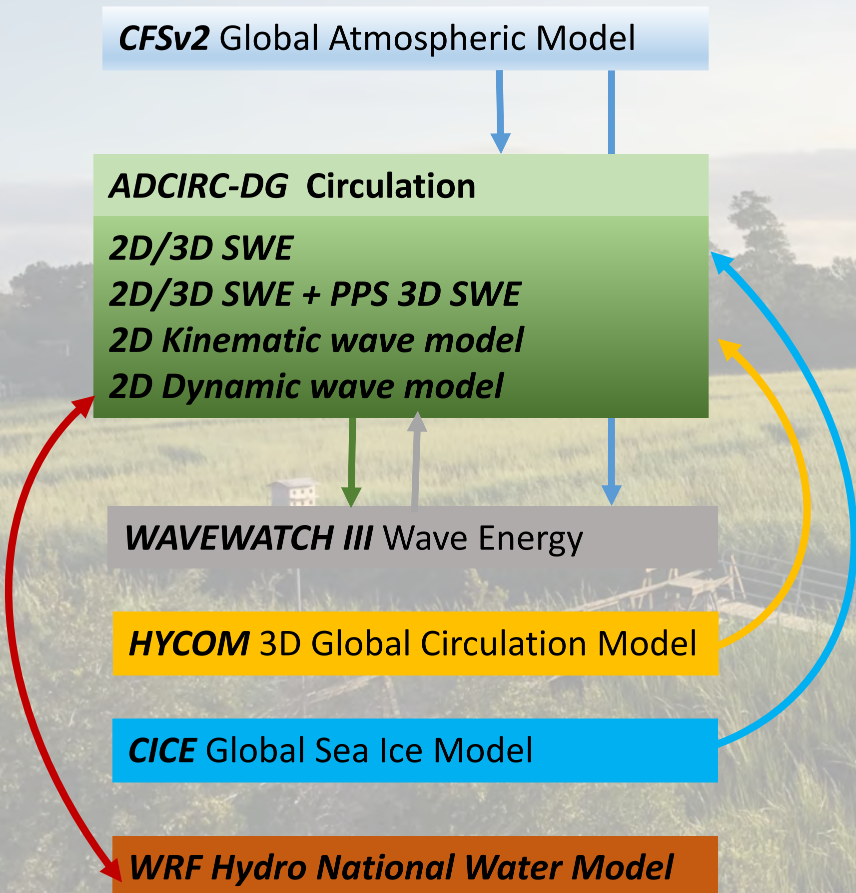
Pressure-Poisson based simulations

- **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





Develop dynamic hydrodynamic equation selection frameworks

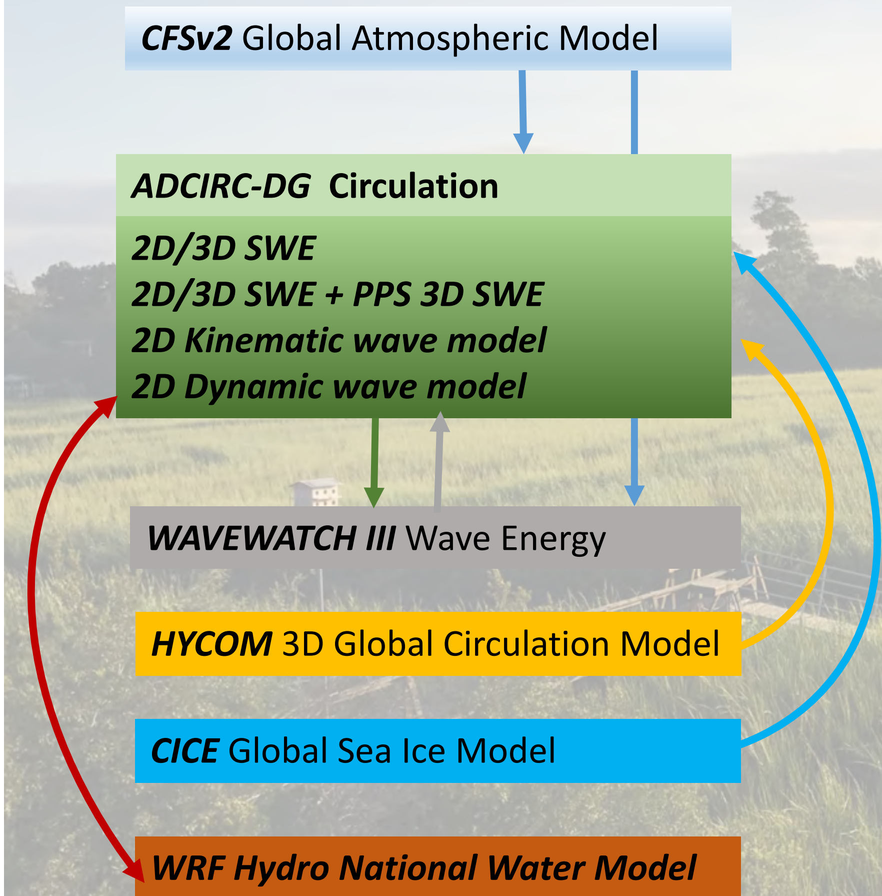


Multi-physics within a single algorithmic framework dynamically selecting physics

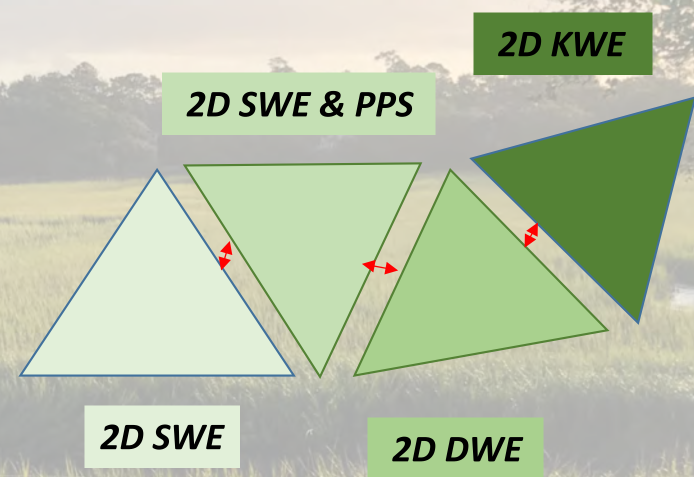
Dynamic equation selection within ADCIRC-DG to accommodate Boussinesq type solutions as well as the Kinematic and Dynamic Wave Equations solution

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

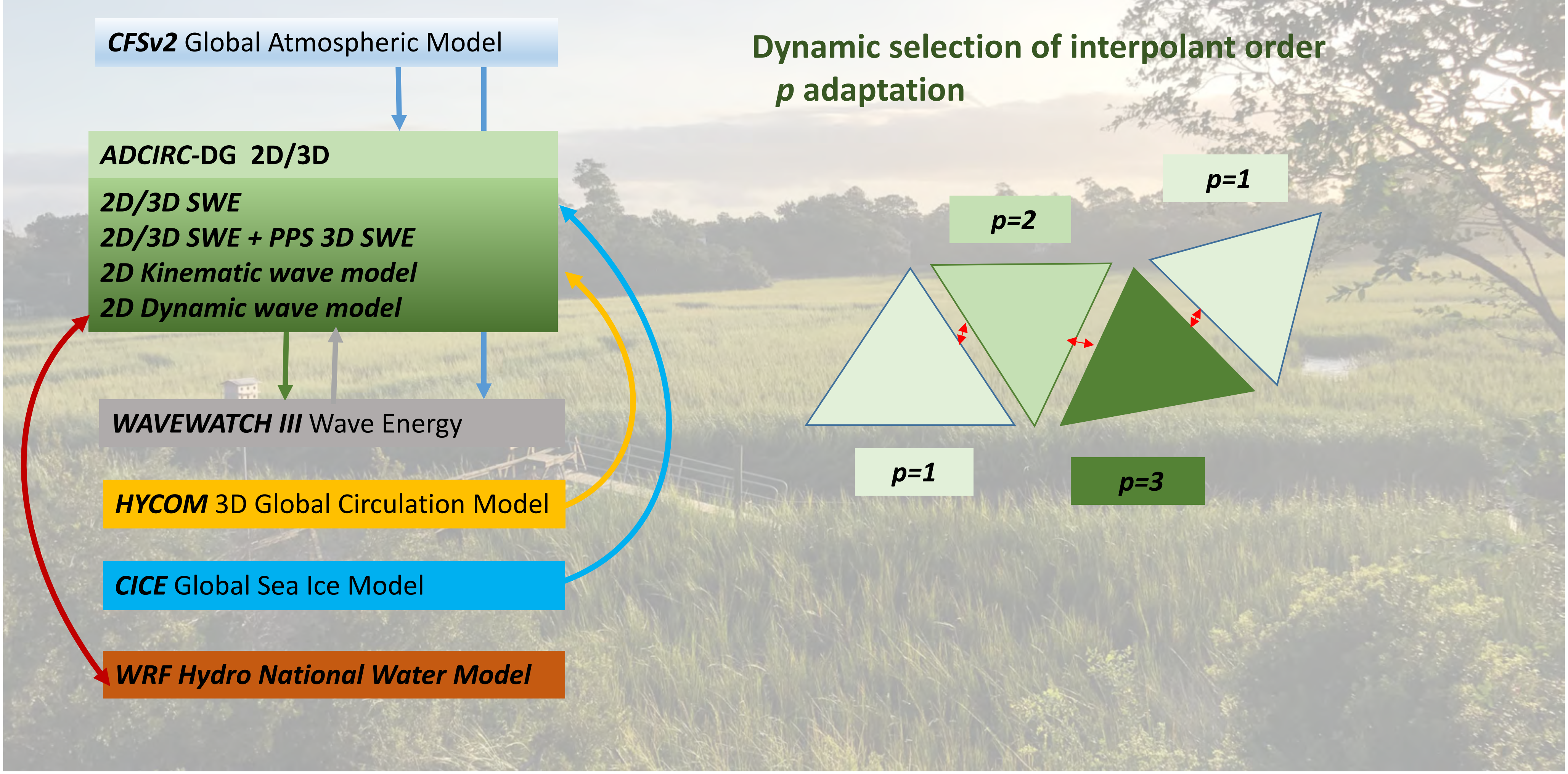
Develop dynamic hydrodynamic equation selection frameworks



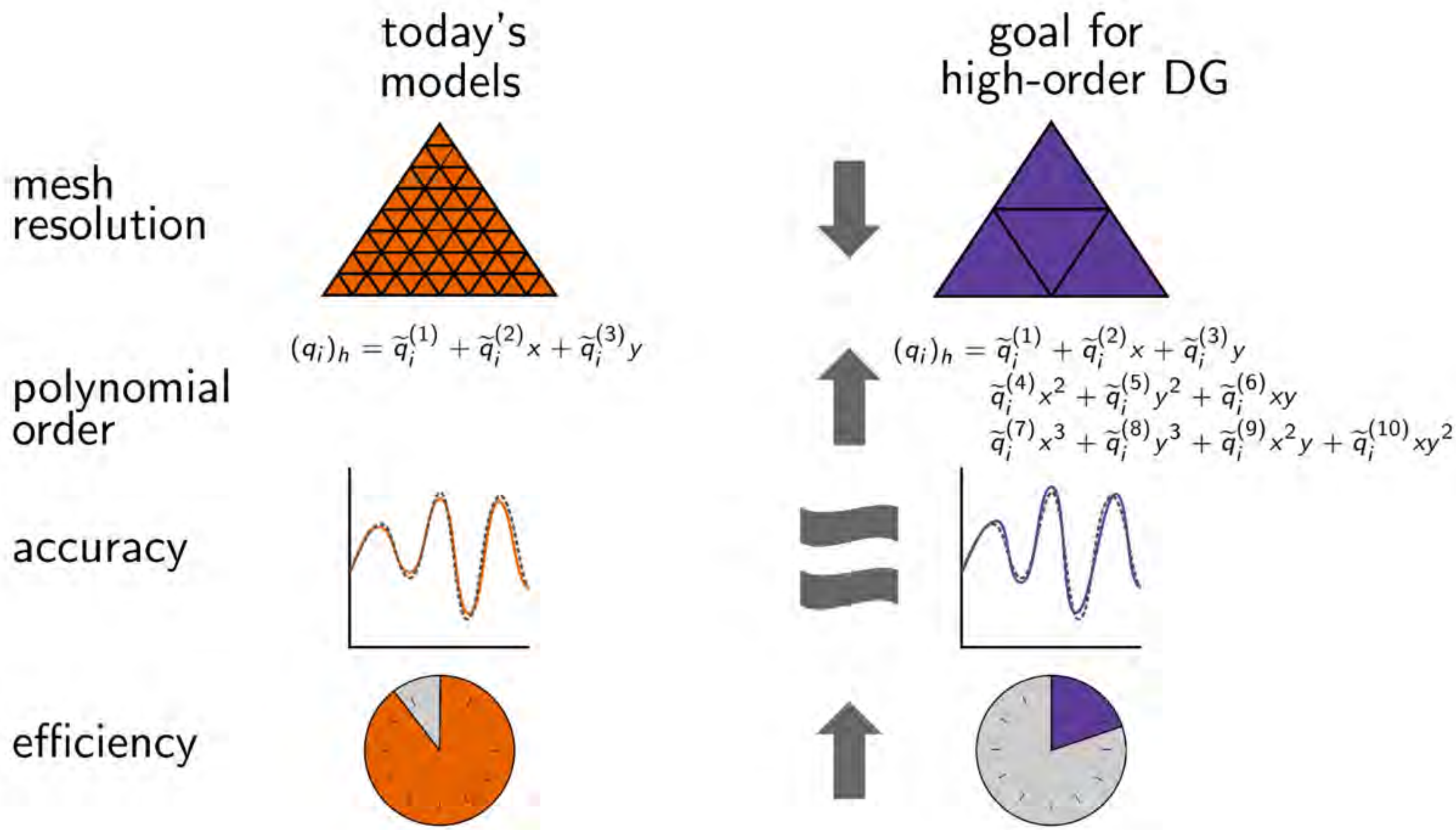
Multi-physics within a single algorithmic framework dynamically selecting physics



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



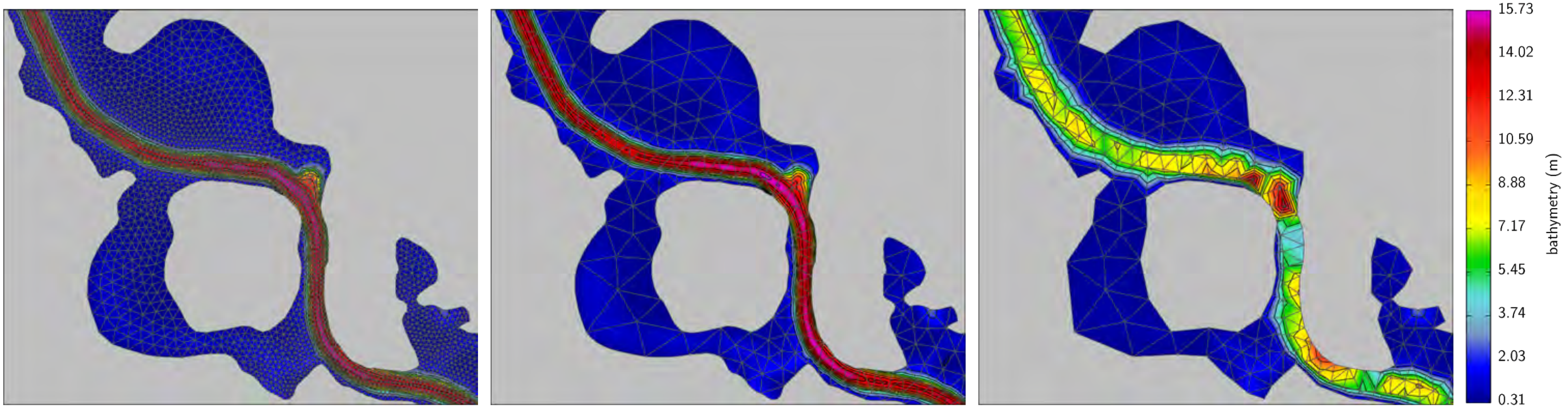
High order interpolants



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**

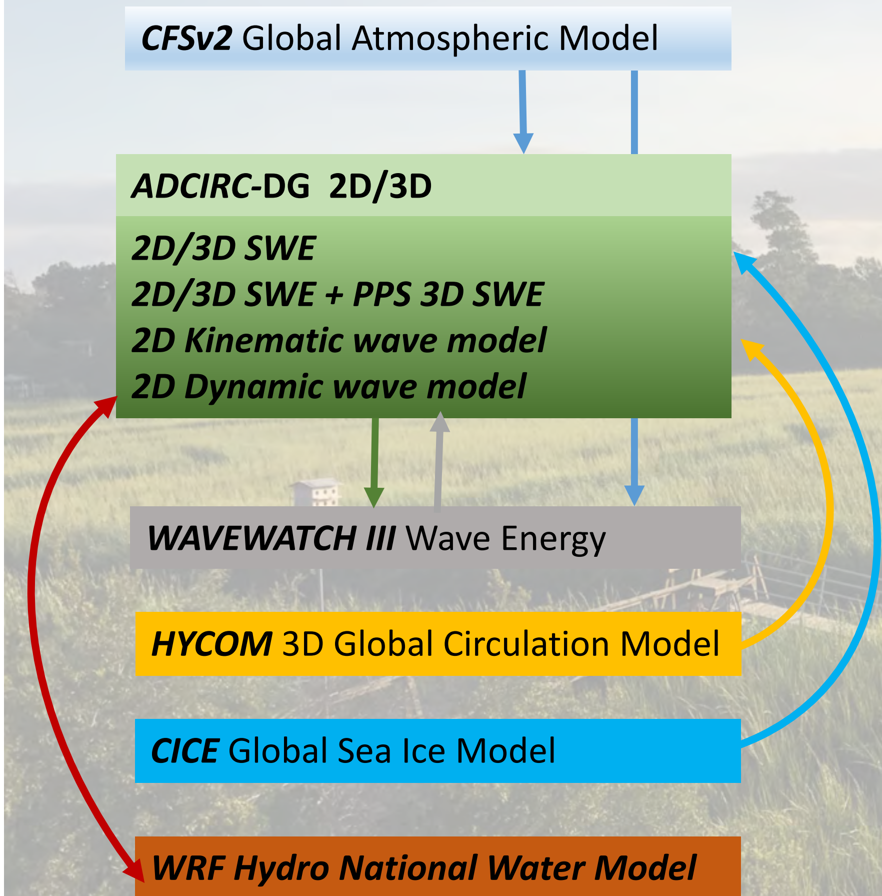


Runs 4 x faster

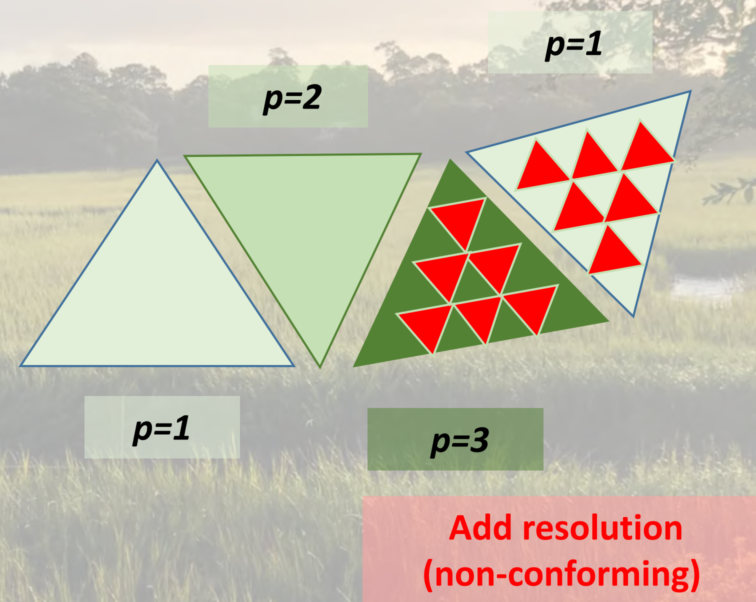
Poor solutions

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

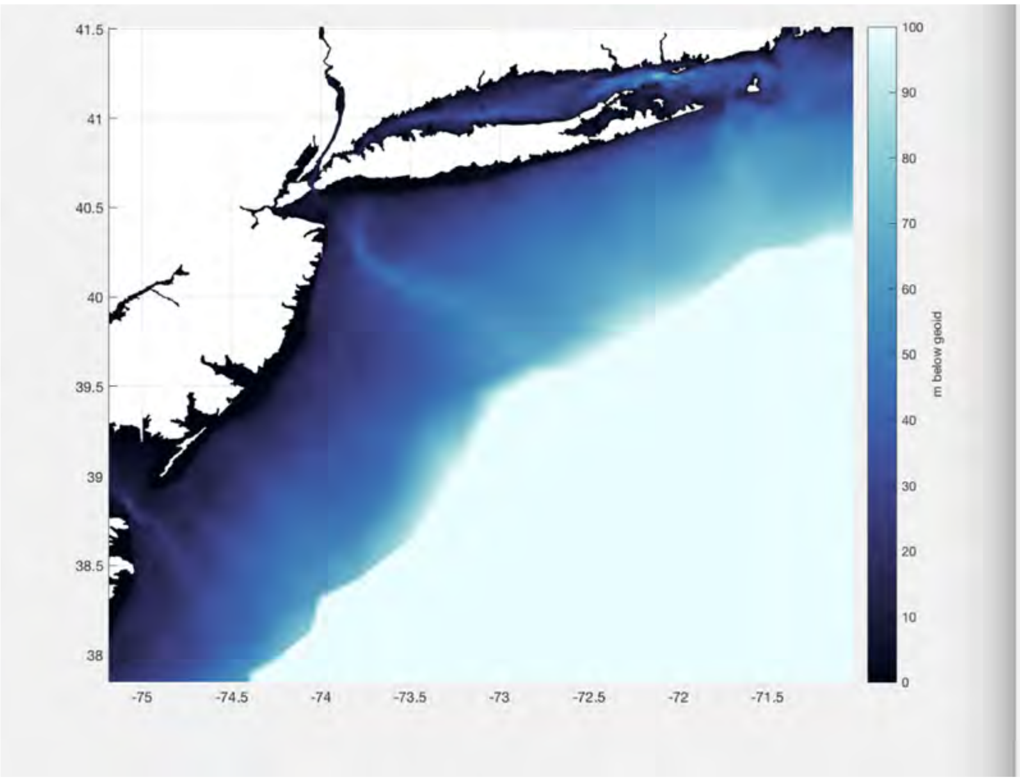


Dynamic selection of grid resolution
***h* adaptation**

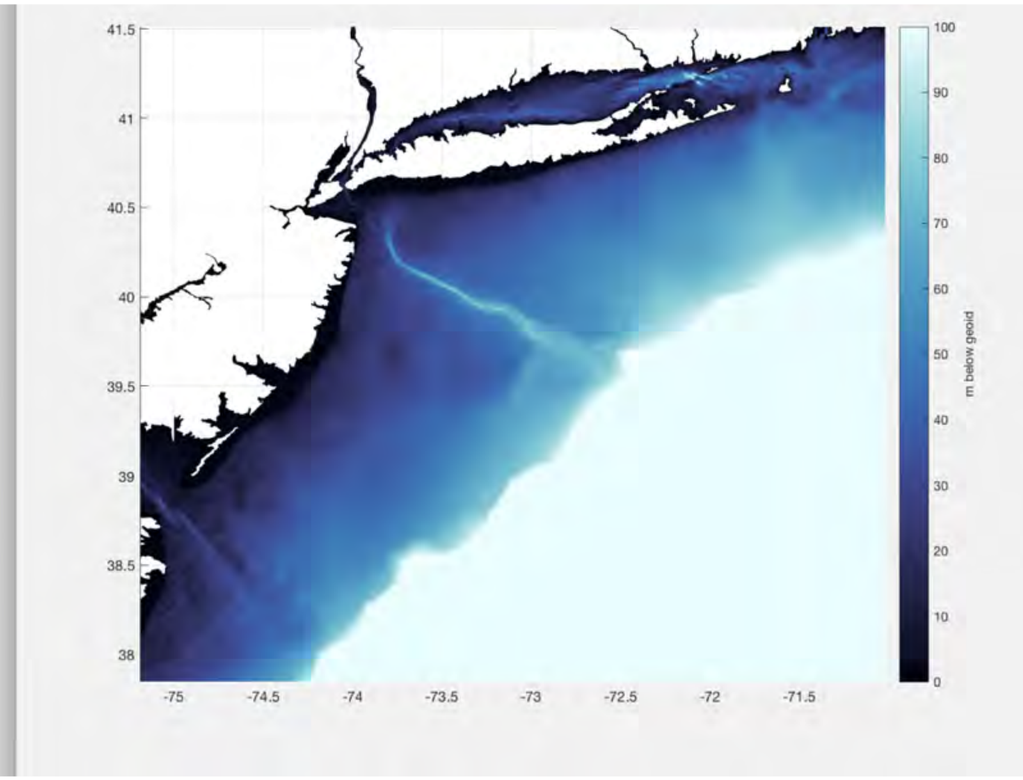


Dynamic grid optimization for evolving physics

Lower energy tides

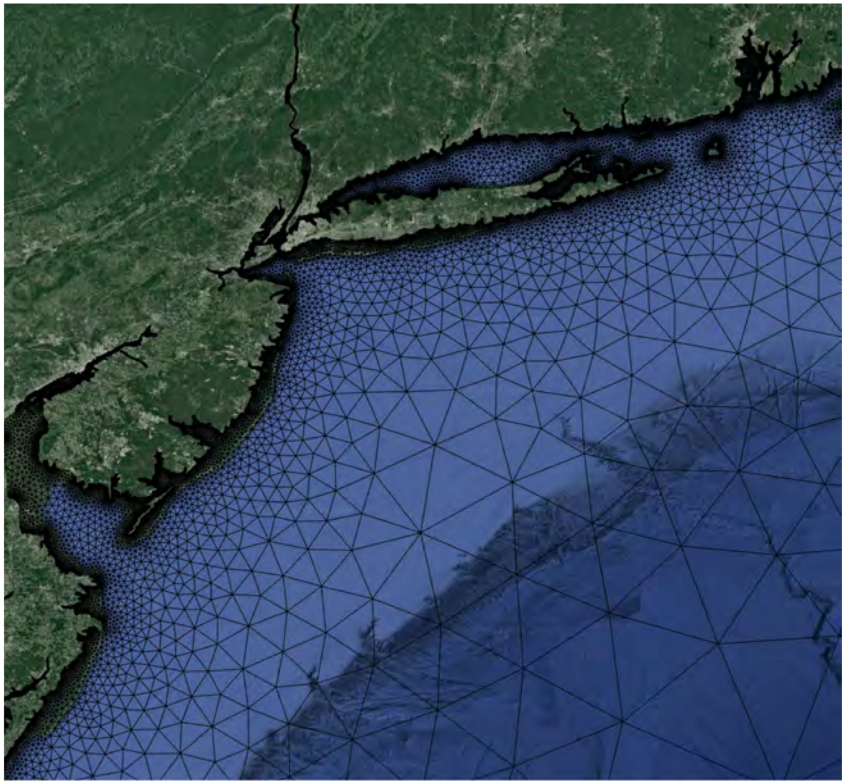


High energy storm driven circulation

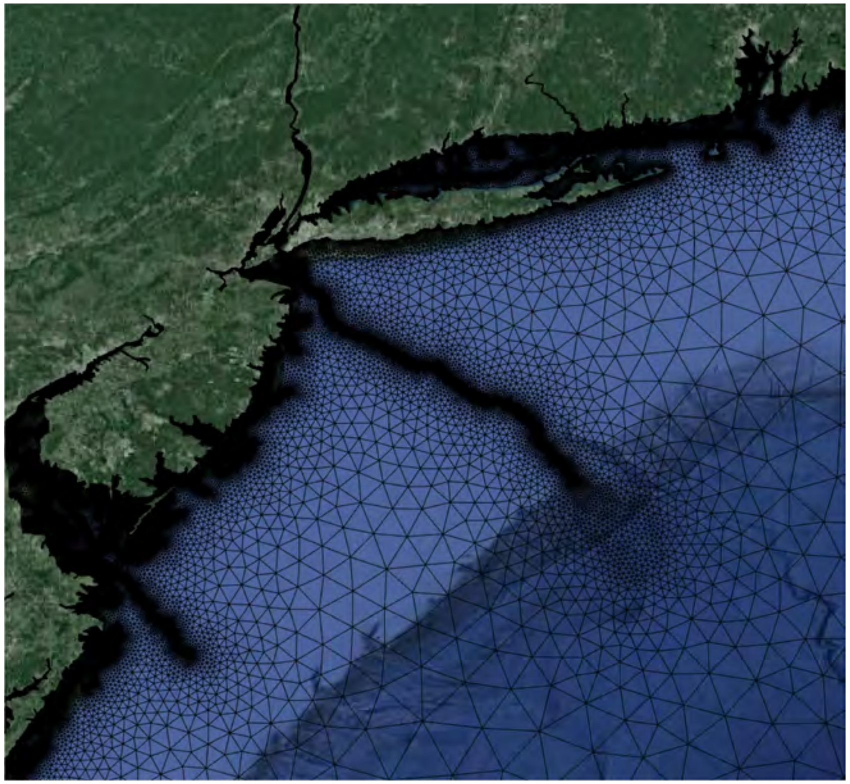


Dynamic grid optimization for evolving physics

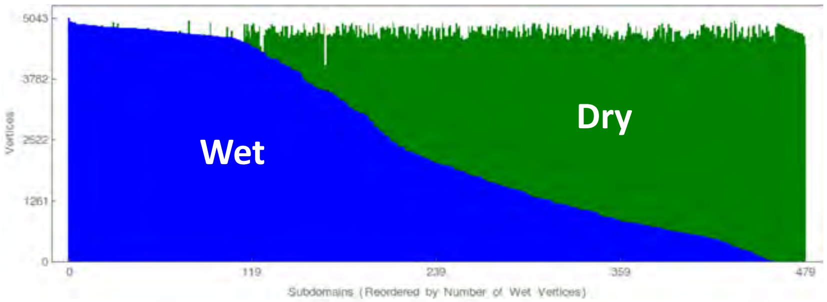
Lower energy tides

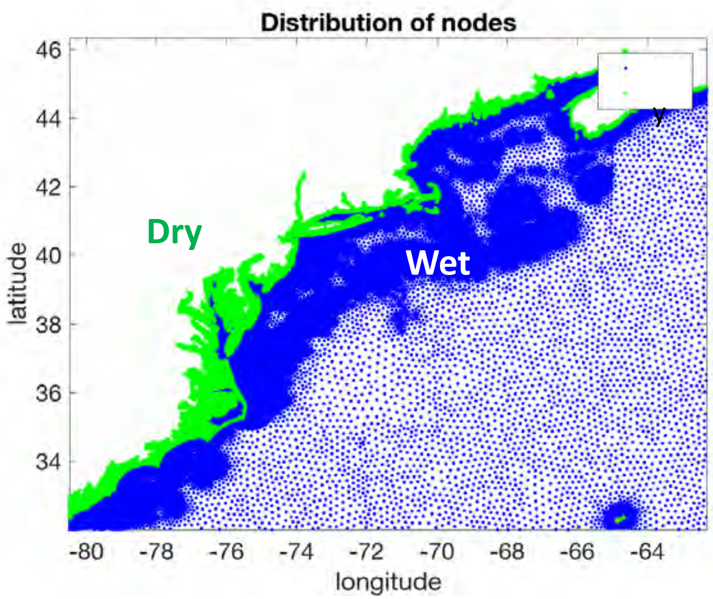


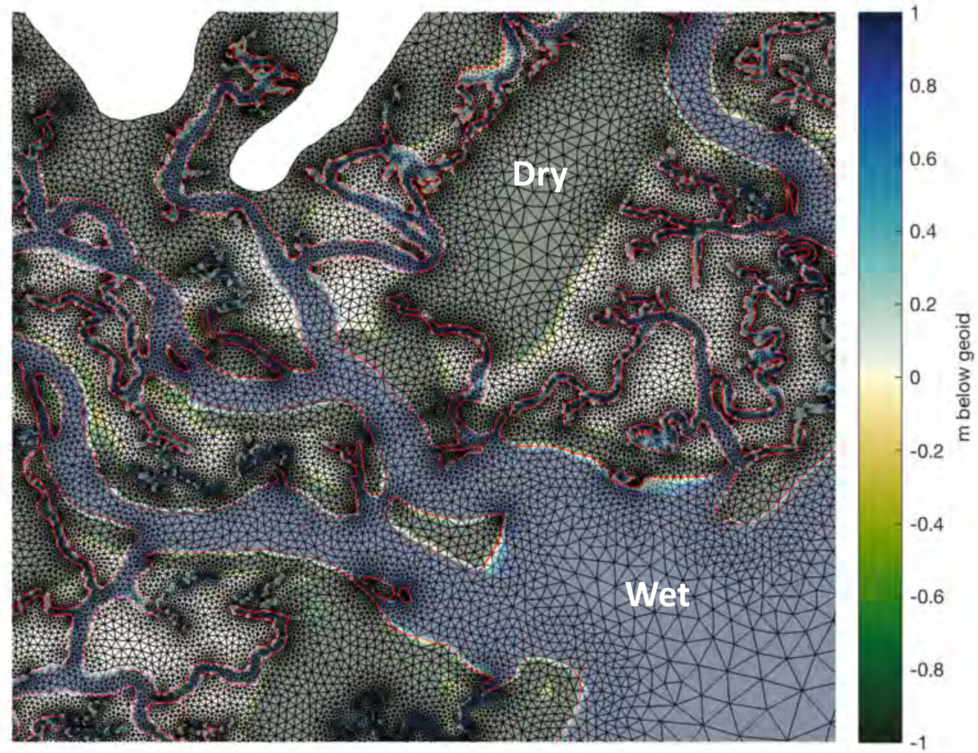
High energy storm driven circulation



Dynamic load balancing: MPI/Zoltan

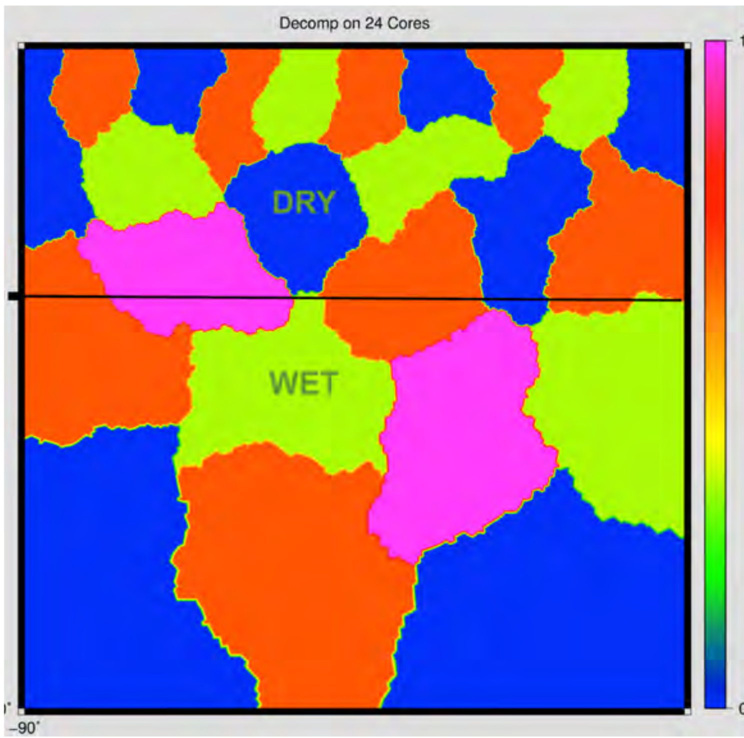




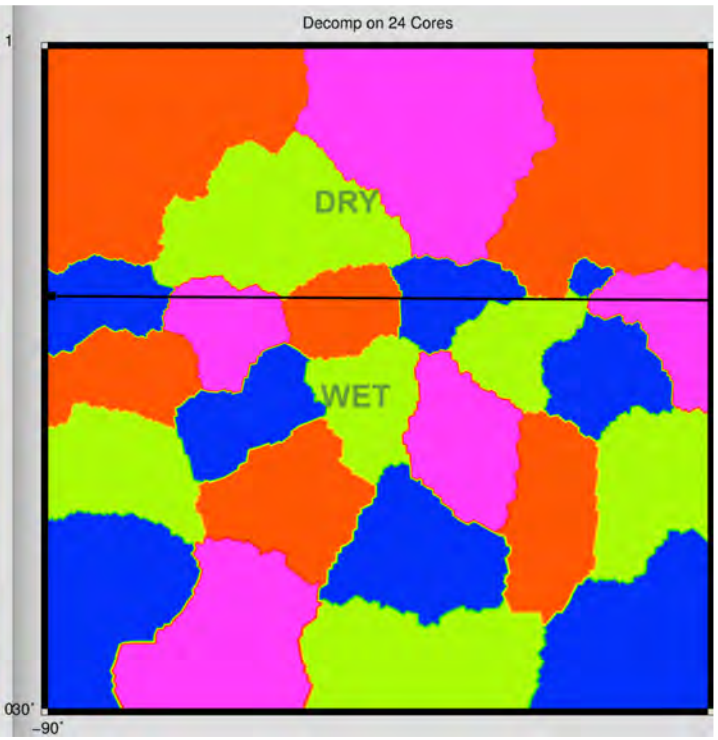


Dynamic load balancing: MPI/Zoltan

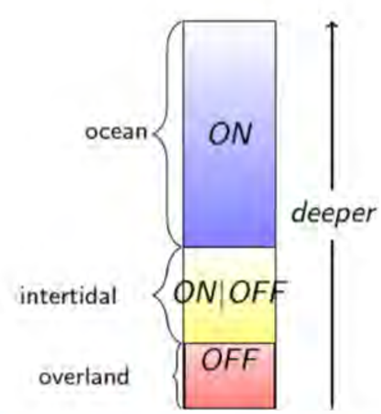
Equal node distribution

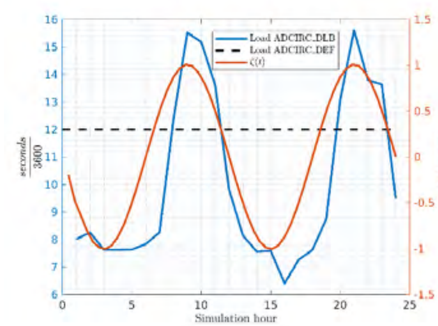


Weighted node distribution



Nodal data structure



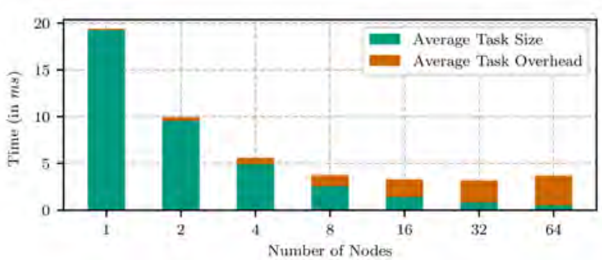


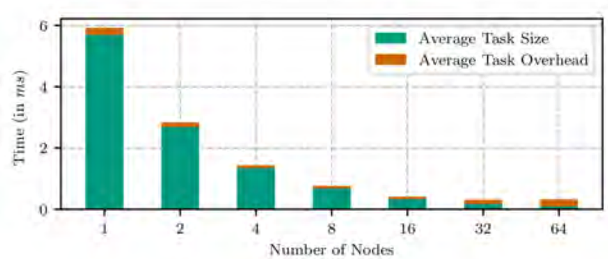
Dynamically redistributing dry elements improves parallel efficiency 45% for 50% average dry nodes

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**

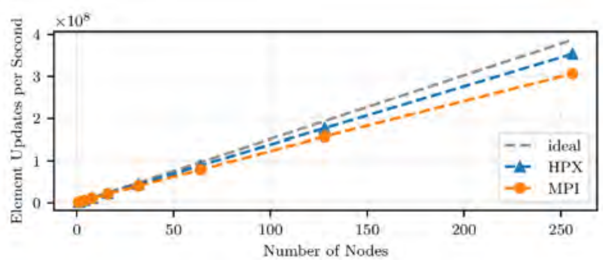
HPX Task Composition

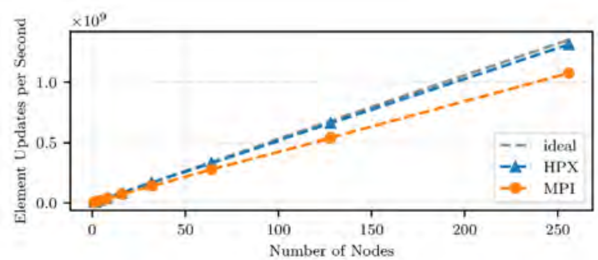




- **HPX task scheduling is more expensive on KNL.**

Weak Scaling





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

Evolution of coastal ocean hydrodynamic models – the future