The University of Texas at Austin
Oden Institute for Computational Engineering and Sciences

Frontera User Meeting
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LEVERAGING FRONTERA IN EXTREME FIDELITY MODELING OF STORM SURGE IN TEXAS AND ACROSS THE GLOBE

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Outline

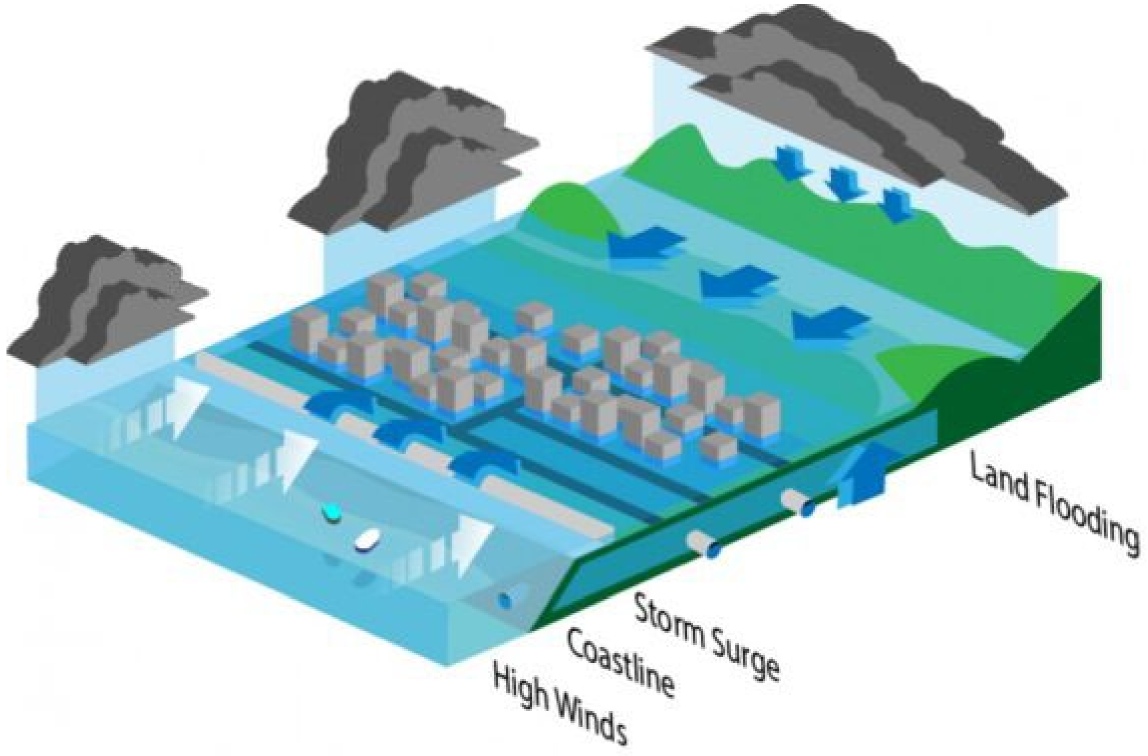
- Motivation and Background
- Mathematical Model
- Development of Computer Model(s)
- Results
- Concluding Remarks

Background

Source: https://www.weather.gov/hgx/projects_ike08_bolivar2

- Storm surge from tropical cyclones (hurricanes) can lead to extensive material and human damages
- Texas and the other gulf states are particularly vulnerable due to the frequency of storms in the Gulf of Mexico
- 1000s of deaths and billions in damage since record keeping began in 1829

Background



- Recent storms are accompanied by heavy rains

-> “Compound flooding” :

- Interaction between two or more sources of floodwaters
- Example: Hurricane Harvey (2017) - (minor) storm surge in Galveston Bay blocked drainage of rainfall runoff and amplified inundation

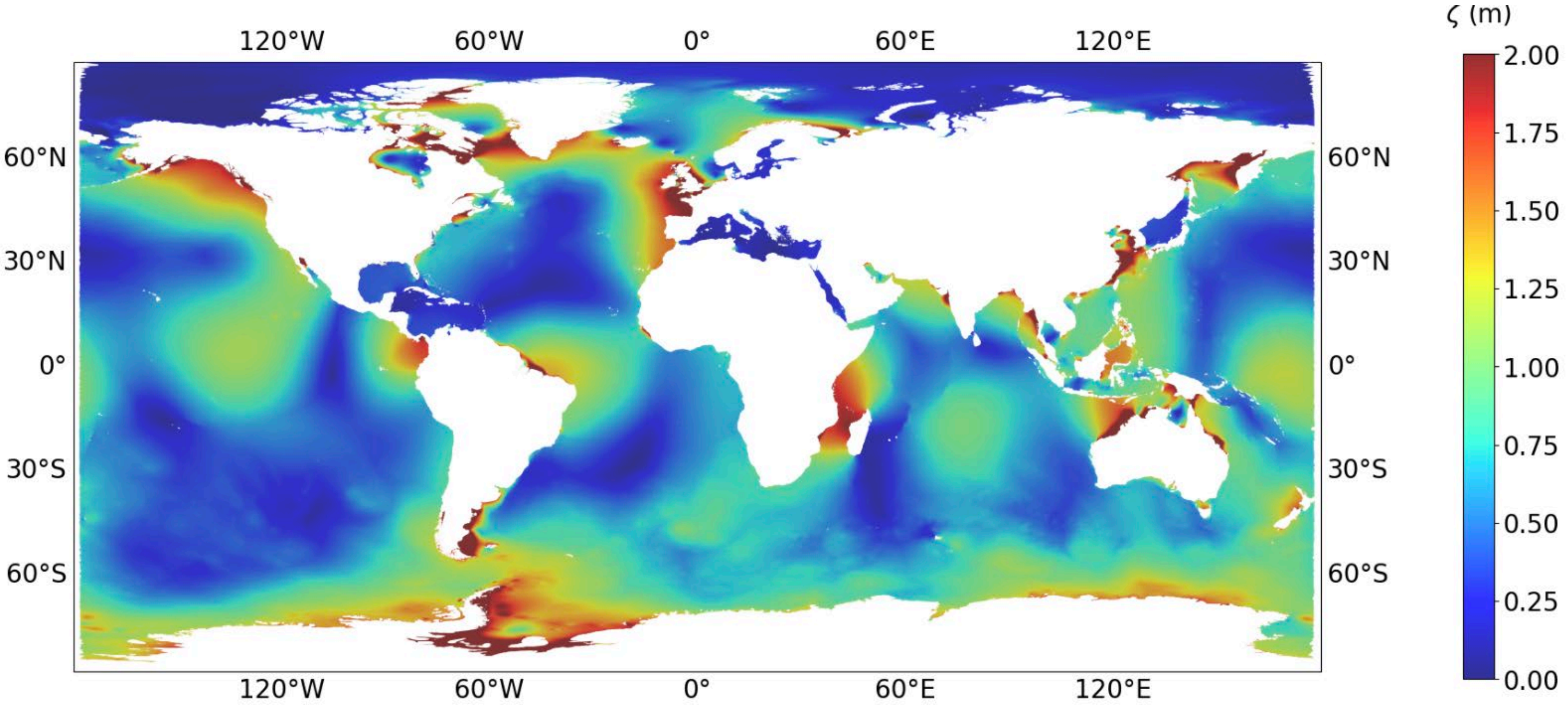
Source:http://sites.utexas.edu/climatesecurity/2020/03/25/
flooding-from-all-directions-how-compound-flooding-threatens-urban-areas-in-oceania/

Motivation / Project 1

- Develop computer models that cover the entire Texas coastline area:
  - Rivers
  - Floodplains
  - Ocean
- Identify past hurricane events
- Data collection and processing of inputs to the model, including:
  - Meteorology
  - River flows
- Perform computations for each identified event:
  - Storm surge only
  - River flooding only
  - Compound
- Post process results to identify the transitional zones between the 3 types of floods

Motivation / Project 2

- Develop computer models for operational forecasting of storm surge in Texas and all oceans in the world



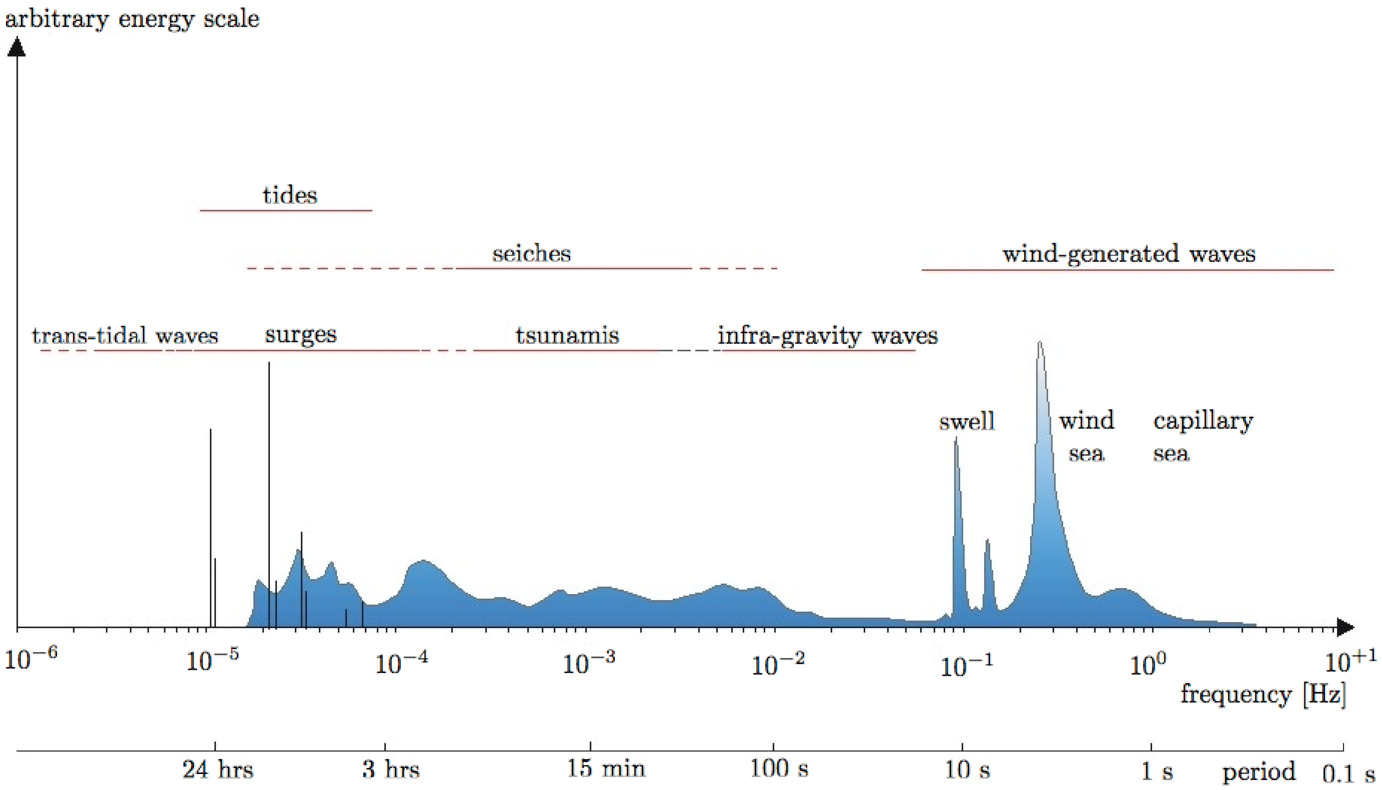
Why Frontera?

- When a disturbance in the ocean becomes well-enough formed, the National Hurricane Center begins issuing ”guidance.” These are issued every 6 hours and give predictions about the future track and intensity of the storm.
- Once a storm forms, the ADCIRC real-time forecaster group led by our colleague Jason Fleming in Louisiana starts doing simulations. The forecast system is automated (ADCIRC Surge Guidance System or ASGS)
- When a storm approaches the coast, fast and accurate predictions of surge is critical for emergency management and planning.
- Current storm surge forecasting model currently used on Stampede2 takes about 2 hours on 2496 skx cores
- The same model runs in less than 1 hour on 2240 cores on Frontera

Mathematical Model

- “Shallow water”—a body of water where the horizontal length scale is much larger than the depth. Much of the ocean is “shallow.”
- Shallow water mathematical models date back to Laplace in 1775.
- Computer modeling of shallow water bodies goes back 40-50 years. These were limited in scope by computer power and algorithms.
- Supercomputers and improved algorithms made large-scale modeling possible in the late 1990’s.
- Ocean and coastal models are now used worldwide for a variety of studies. Each model has its strengths and weaknesses.

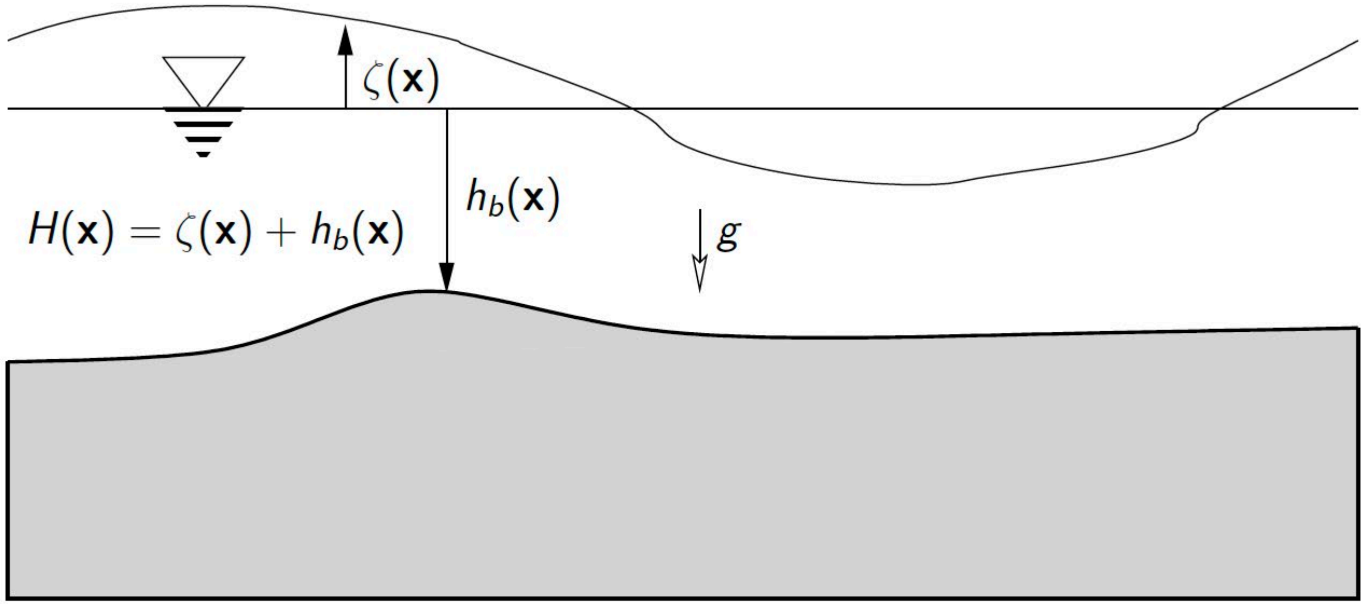
The Physics and Mathematics: Long and Short Waves



- Long waves
- Short waves (wind driven)

Refn: L.H. Holthuijsen, *Waves in Oceanic and Coastal Water,* Cambridge

Shallow Water Quantities



ζ = surface elevation (positive above geoid)
h_b = bathymetric depth (positive below geoid)
H = total water depth (strictly positive)

Long Waves: (2D) Shallow Water Equations

The Shallow Water Equations

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0$$

$$\frac{\partial (Hu)}{\partial t} + \frac{\partial (Hu^2 + \frac{1}{2}g(H^2 - h_b^2))}{\partial x} + \frac{\partial (Huv)}{\partial y} = g\zeta \frac{\partial h_b}{\partial x} + F_x$$

$$\frac{\partial (Hv)}{\partial t} + \frac{\partial (Huv)}{\partial x} + \frac{\partial (Hv^2 + \frac{1}{2}g(H^2 - h_b^2))}{\partial y} = g\zeta \frac{\partial h_b}{\partial y} + F_y$$

where
$u, v =$ depth-averaged horizontal velocities
$F_x, F_y =$ external forcing, including: bottom friction, winds/pressure, Coriolis, waves ...

Modeling Issues

- Driving forces: wind and atmospheric pressure, Coriolis, tides
- Complex coastlines: large, rough domains and complex boundaries
- Highly varying bathymetry and overland topography
- Wetting and drying (shallow water equations invalid for H->0)
- Bottom friction/drag
- Interaction of water with levees and other structures
- Shallow water equations must be solved using numerical methods

Advanced Circulation Computer Model (ADCIRC)

- Developed for tidal flows by Luettich and Westerink in the early 1990's based on earlier work by Lynch, Gray and Kinnmark[1]
- Parallelized in mid 1990's (MPI parallelization)
- First applied to hurricanes for a hindcast study of Hurricane Betsy (1968) for the US Army Corps of Engineers to develop a flood protection system in New Orleans
- Hurricane Katrina (2005) led to extensive post-Katrina development and validation
- Used for FEMA flood insurance studies
- Used for hurricane protection studies in response to Katrina, Sandy, and Ike
- Now used operationally for hurricane forecasting

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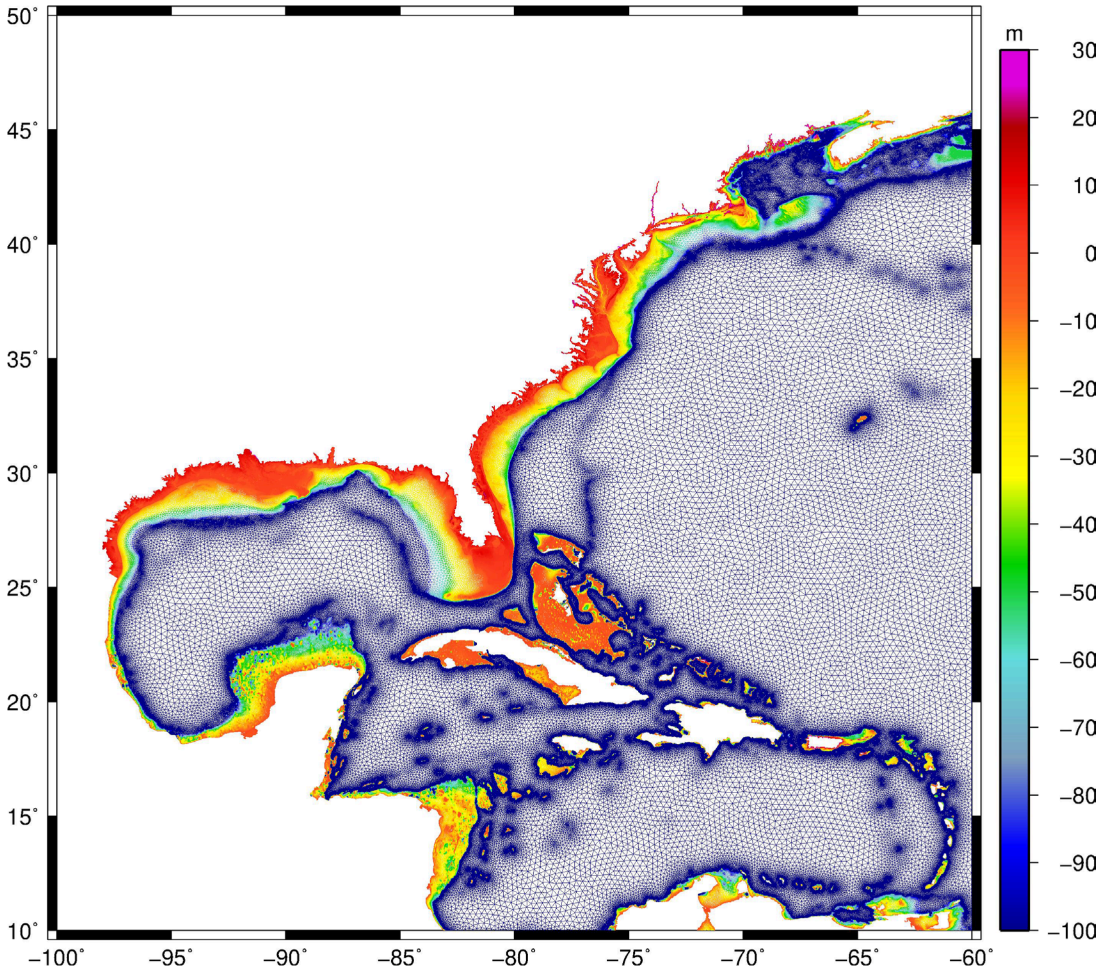
[1] R. A. Luettich, J. J. Westerink, and N. W. Scheffner. "ADCIRC: an advanced three-dimensional circulation model for shelves, coasts, and estuaries. Report 1, Theory and methodology of ADCIRC-2DD1 and ADCIRC-3DL". In: *Coastal Engineering Research Center (US)* (1992).

Advanced Circulation Computer Model (ADCIRC)

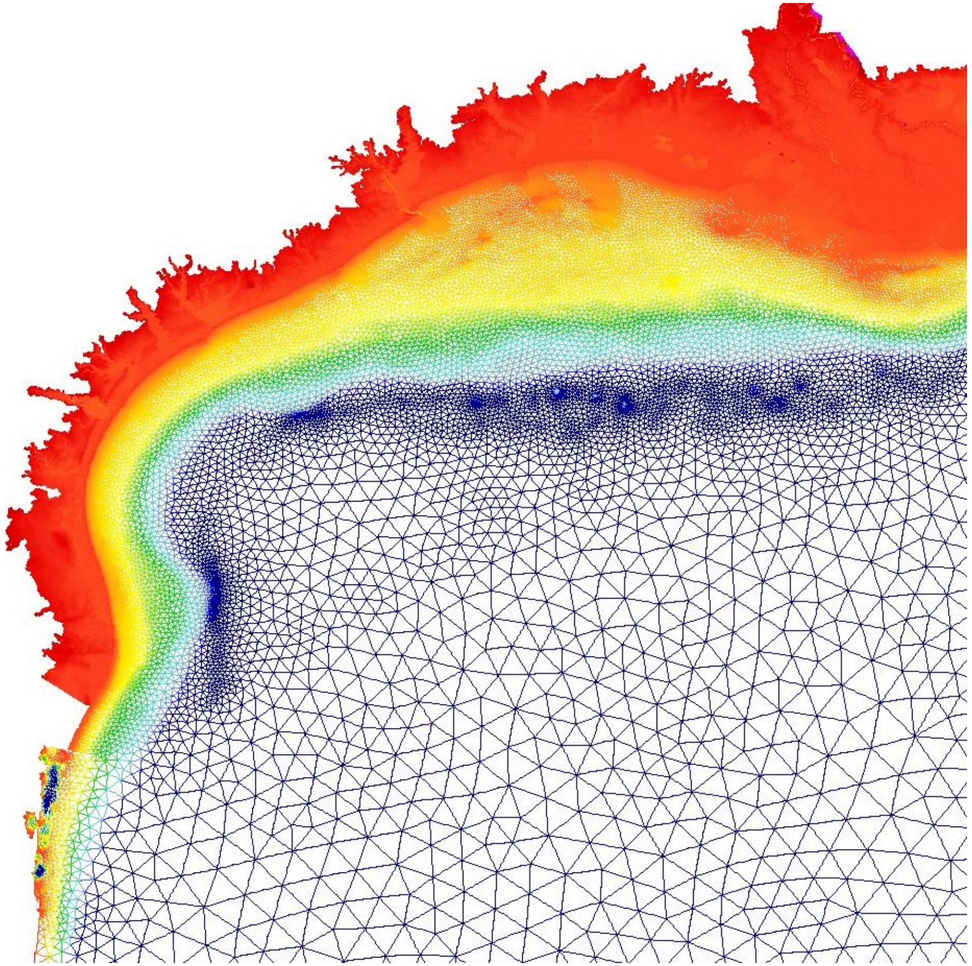
- Spatial discretization of the shallow water equation using the finite element method on unstructured triangular meshes
  - Bubnov-Galerkin method with linear polynomial basis functions
- Temporal discretization using implicit-explicit finite difference methods
  - Nonlinear terms all handled explicitly
- Executes on large-scale High-Performance Computing platforms with scaling beyond 10,000+ cores
- Takes into account man-made coastal protection structures such as levees using the weir formula
- Actively developed by a large community of users

Project 1 – New Compound Flooding Texas Mesh



- Extreme resolution of the Texas coast (rivers and floodplains)
- 8 million nodes, 16 million triangular finite elements
- Validated for storm surge during past hurricanes (focus on Ike 2008)
- Flooding from rain induced runoff is modeled using river flows from major watersheds

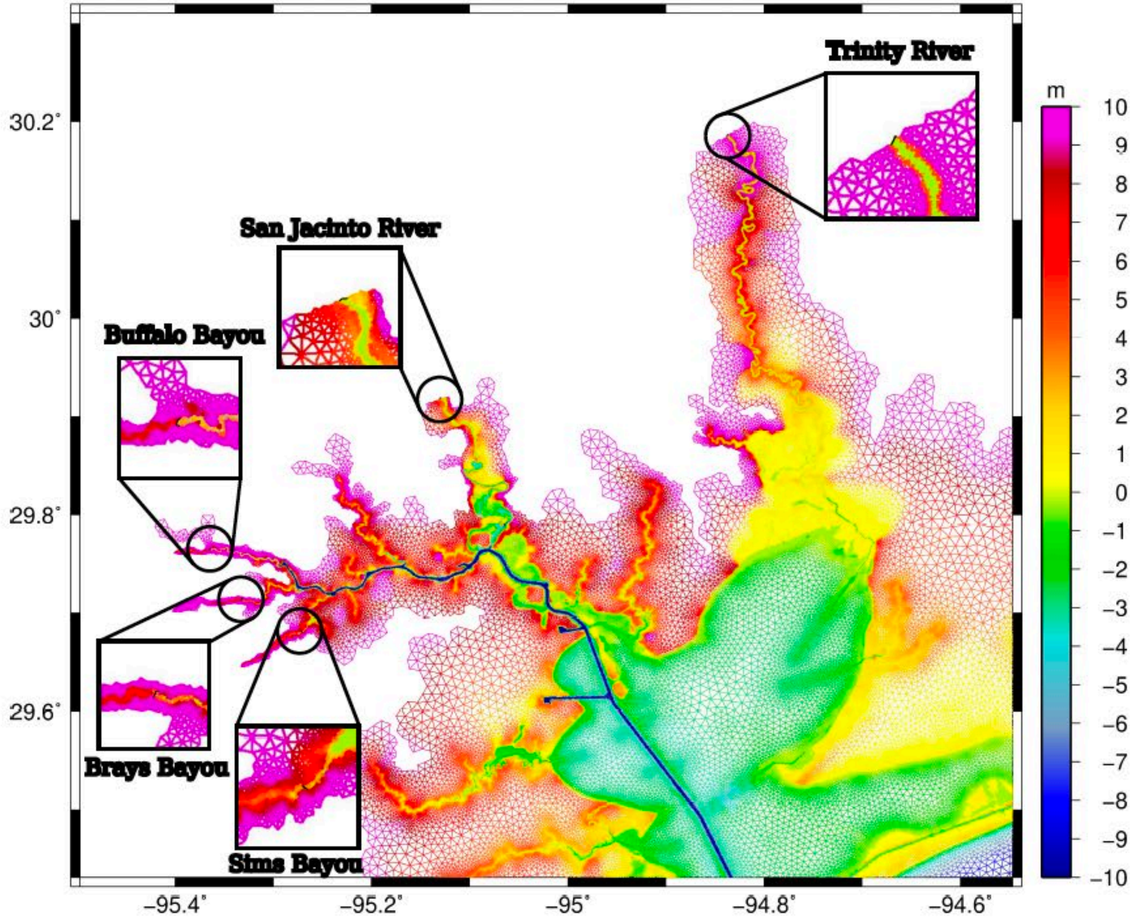
Project 1 – New Compound Flooding Texas Mesh



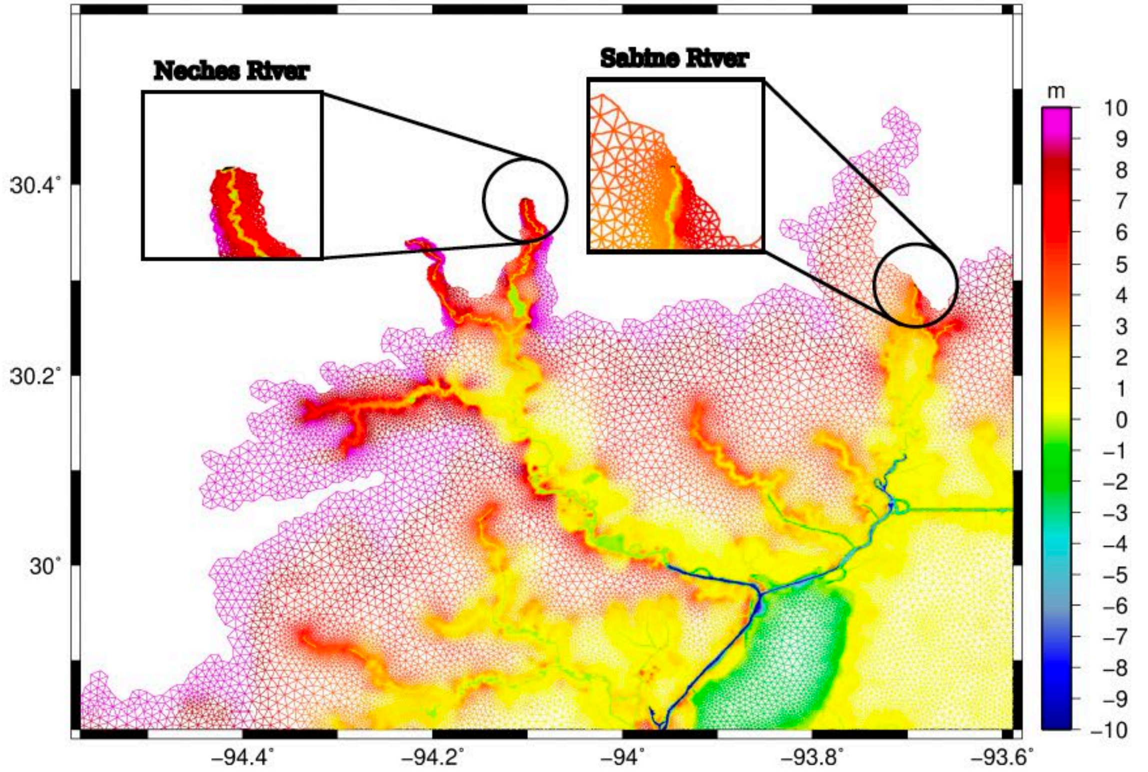
Mesh contains:

- Bathymetry and topography
- Spatially variable distribution of land and sea floor characterization (Manning's n parameter)
- Tree cover information
- Levees and other build protection structures

Project 1 – Mesh Details



(a) Houston-Galveston



(b) Beaumont

Project 1 – Boundary Conditions

- **Open boundary condition**: nodes on the boundary specifying time-dependent water elevation, such as tides
- **Zero-flux boundary condition**: used for land and islands
- **Normal flux boundary condition**: nodes on the boundary or inside the domain specifying time-dependent flow rates, i.e., rivers:
  - 45 rivers in Texas are added as normal flux boundary conditions, including major ones like Sabine, Neches, Trinity, etc.
  - Most of the data obtained from USGS time series records and converted to ADCIRC format
  - Missing data is handled using trend analysis of gauges as well as TxRR model results provided by TWDB and interpolation in time

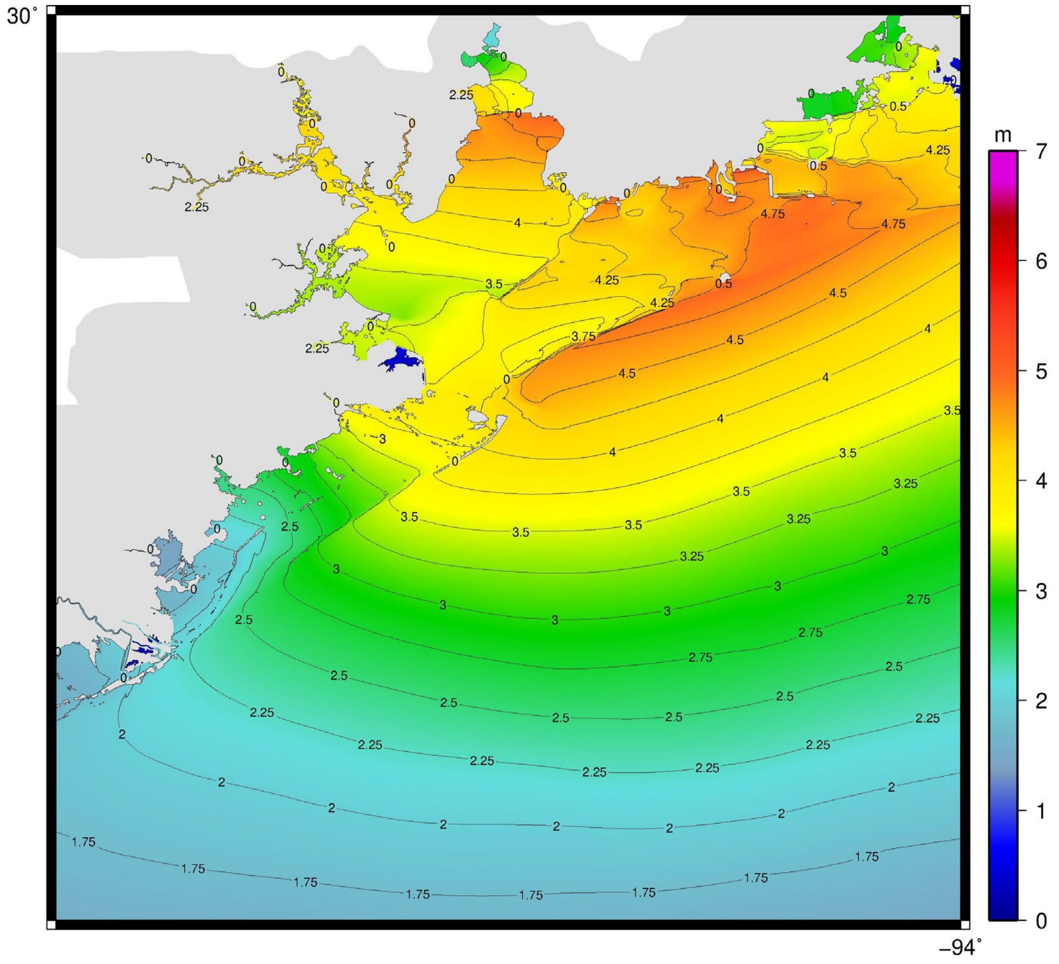
Project 1 – Validation of Hurricane Ike (2008)

- Strong category 2 storm, made landfall at Galveston, TX
- Produced 10-20 ft. of surge along the upper Texas coast and inland 16 km.
- Simulation is a 10 day hindcast using data-assimilated winds provided by Ocean Weather, Inc.
- Simulations performed at the Texas Advanced Computing Center using the Frontera Machine
  - Highly resolved in TX: 8M nodes, 16M elements, 2 second time step (2 hrs)
- Benchmark for validation are results obtained using the current operational forecasting ADCIRC mesh:
  - Highly resolved in TX and LA: 9M nodes, 18M elements, 1 second time step (5 hrs on Stampede2)

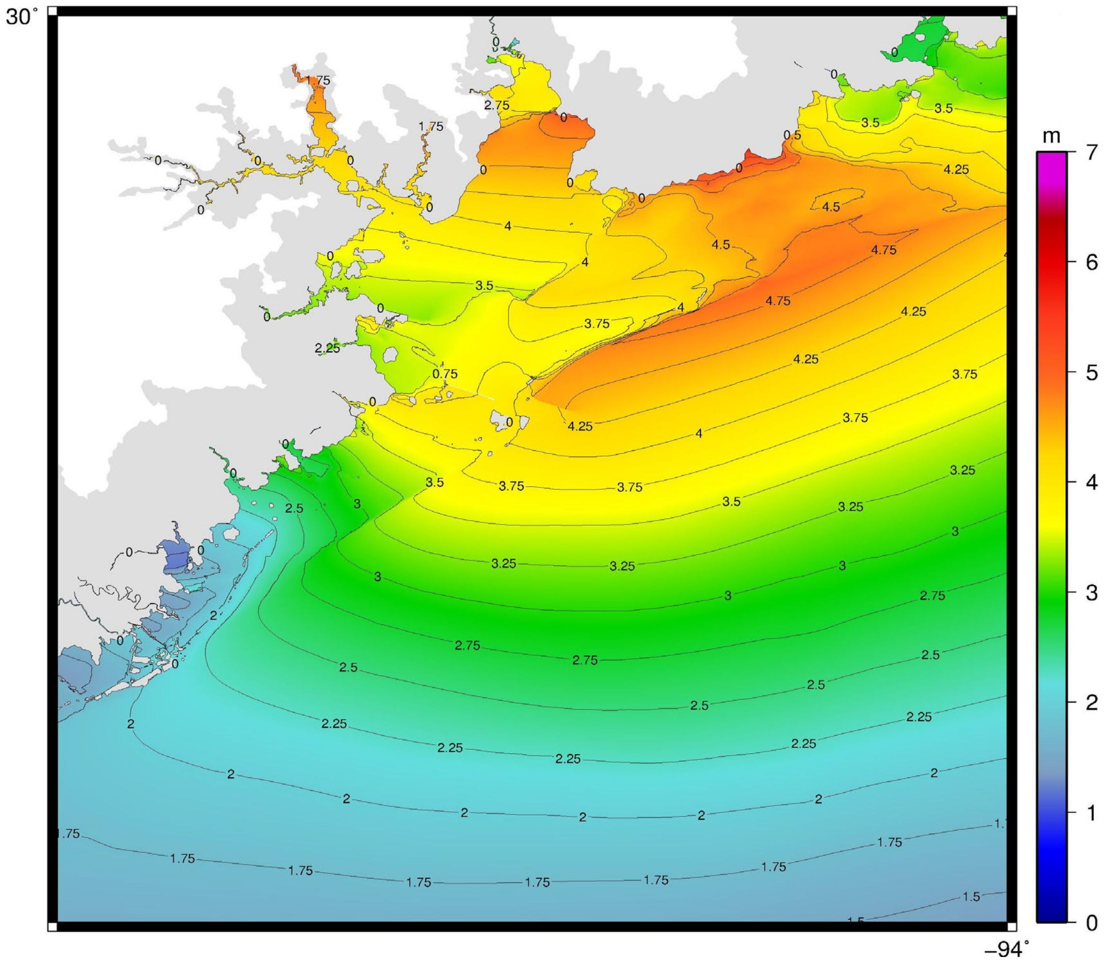
Current forecasting mesh

New mesh

Project 1 – Validation of Hurricane Ike (2008)



Current forecasting mesh



New mesh

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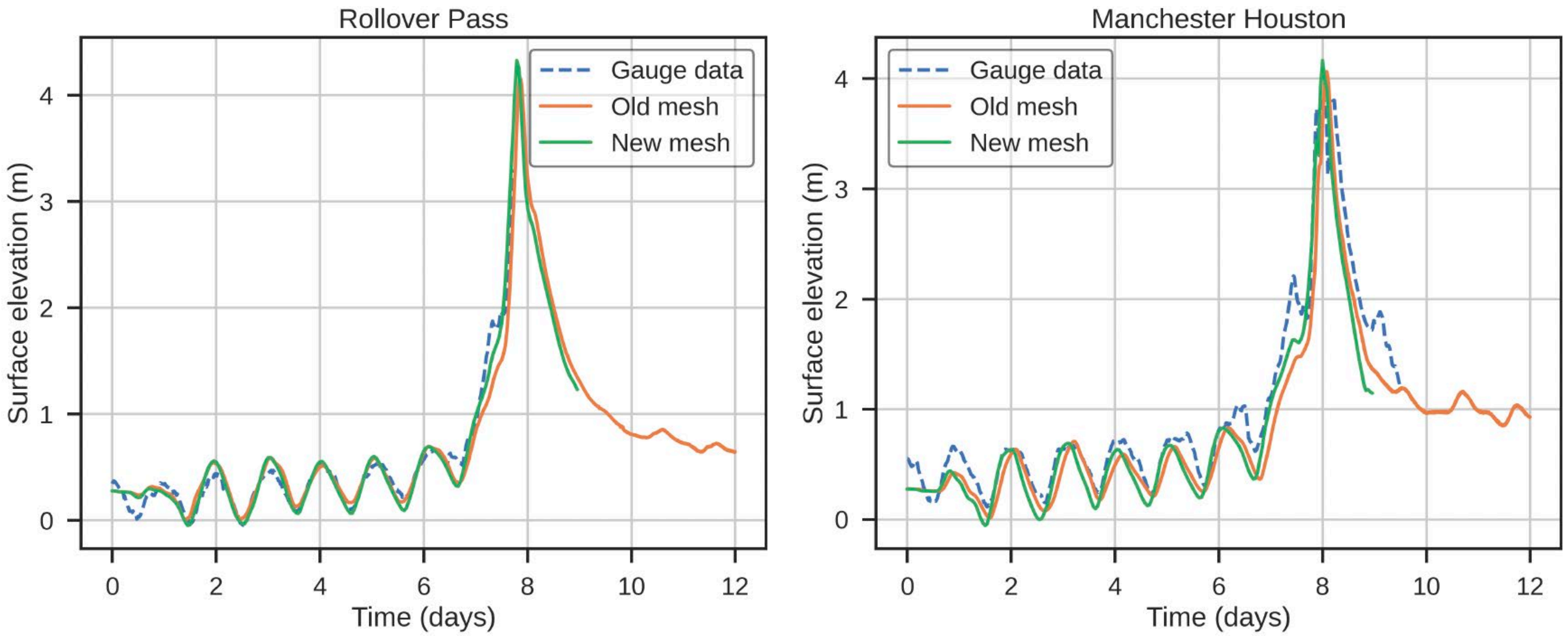

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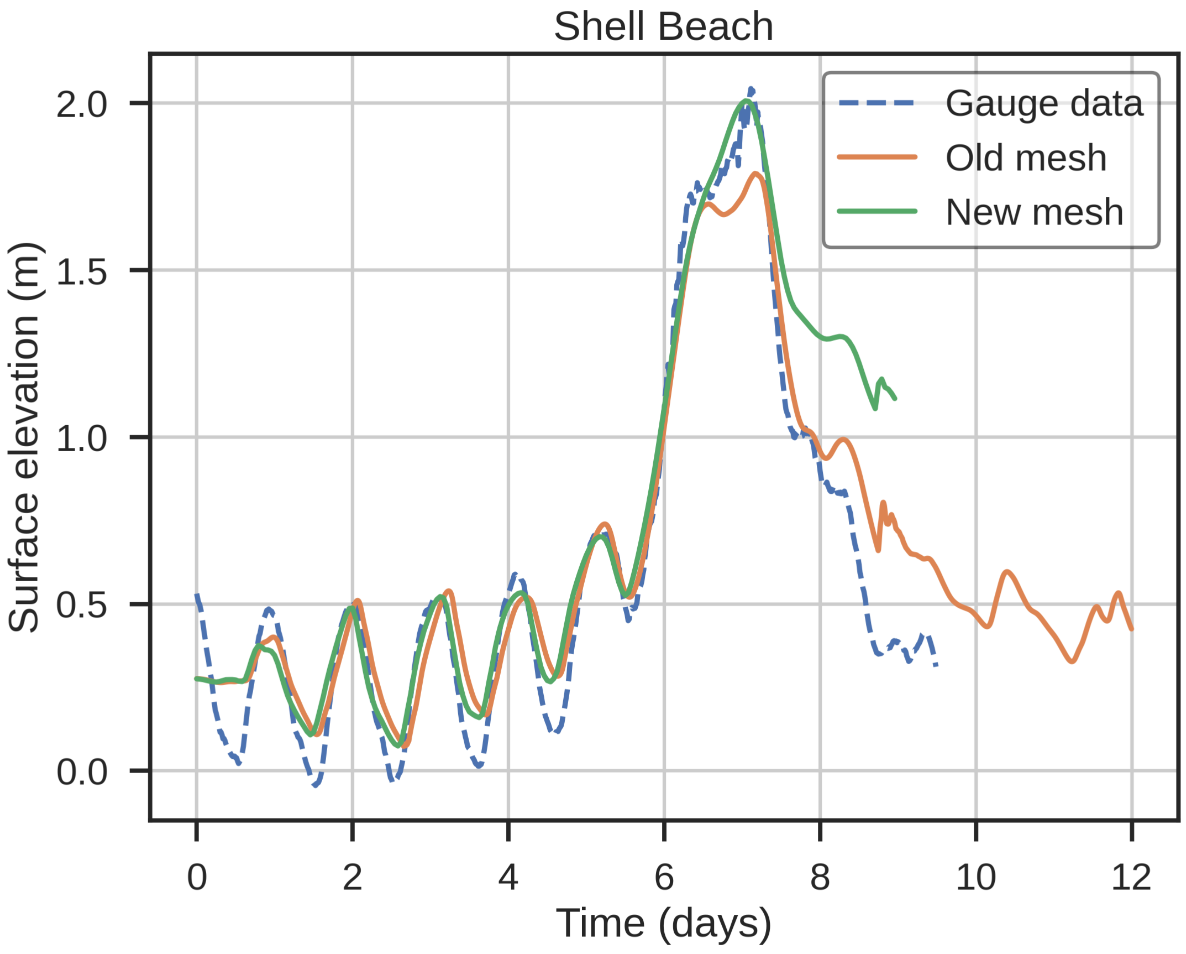
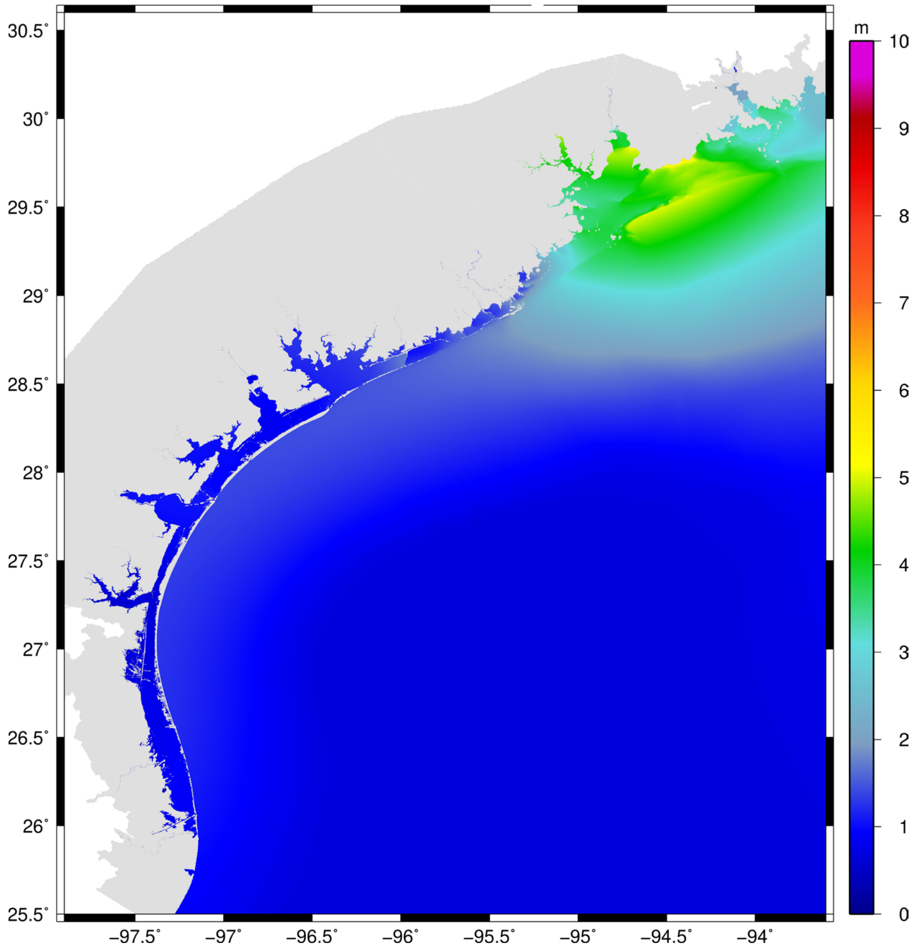
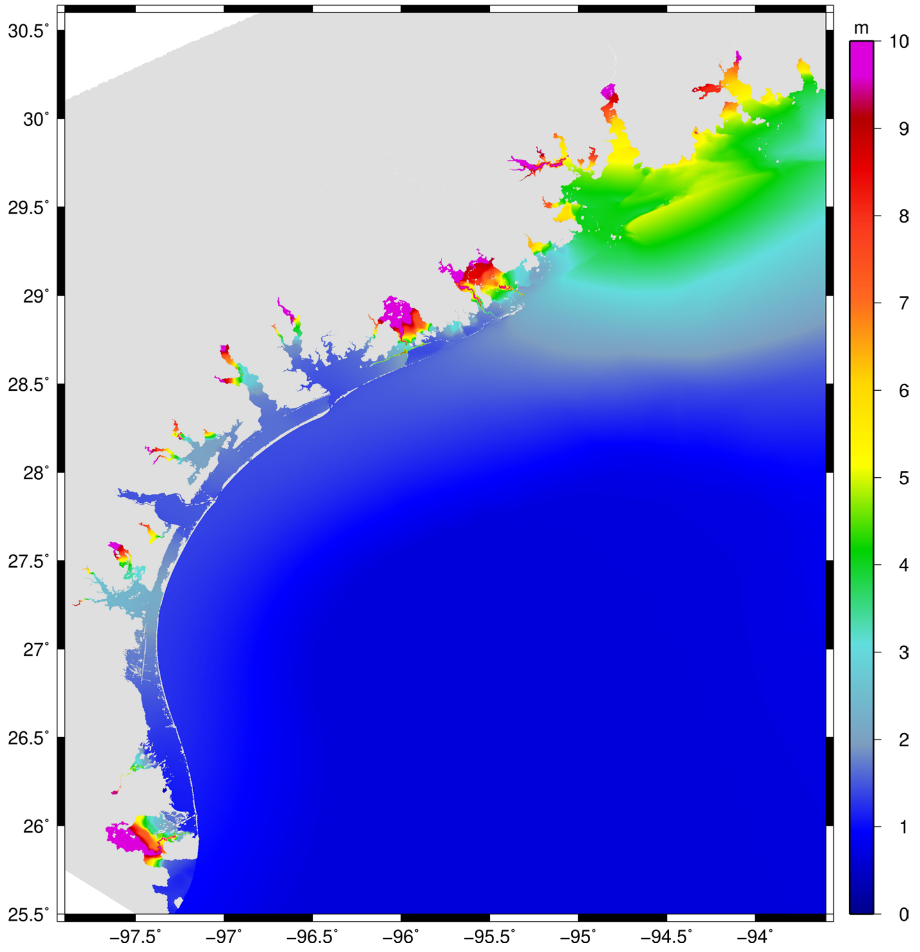


Project 1 - Stress Test of the Model

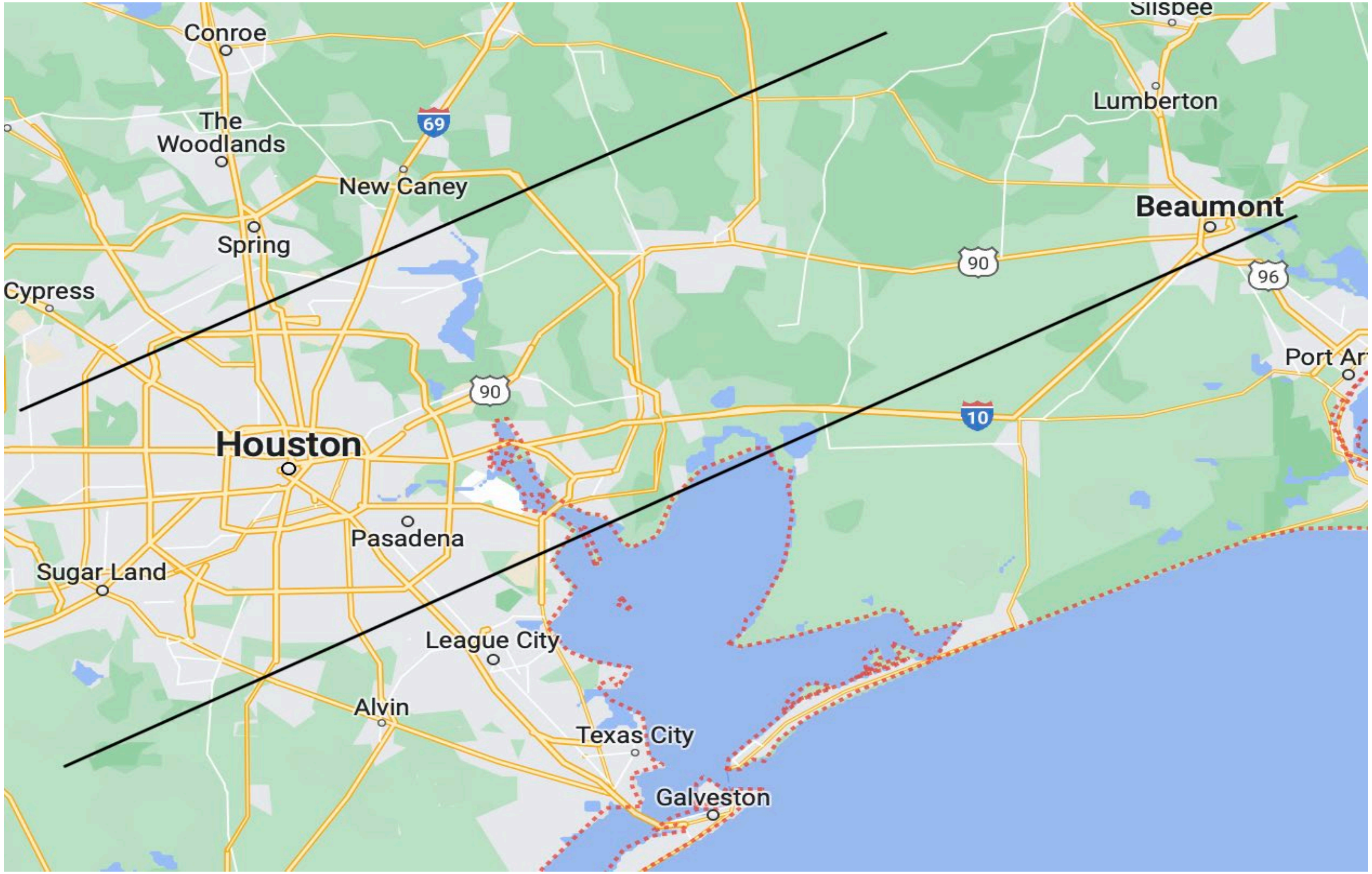


Hurricane Ike surge

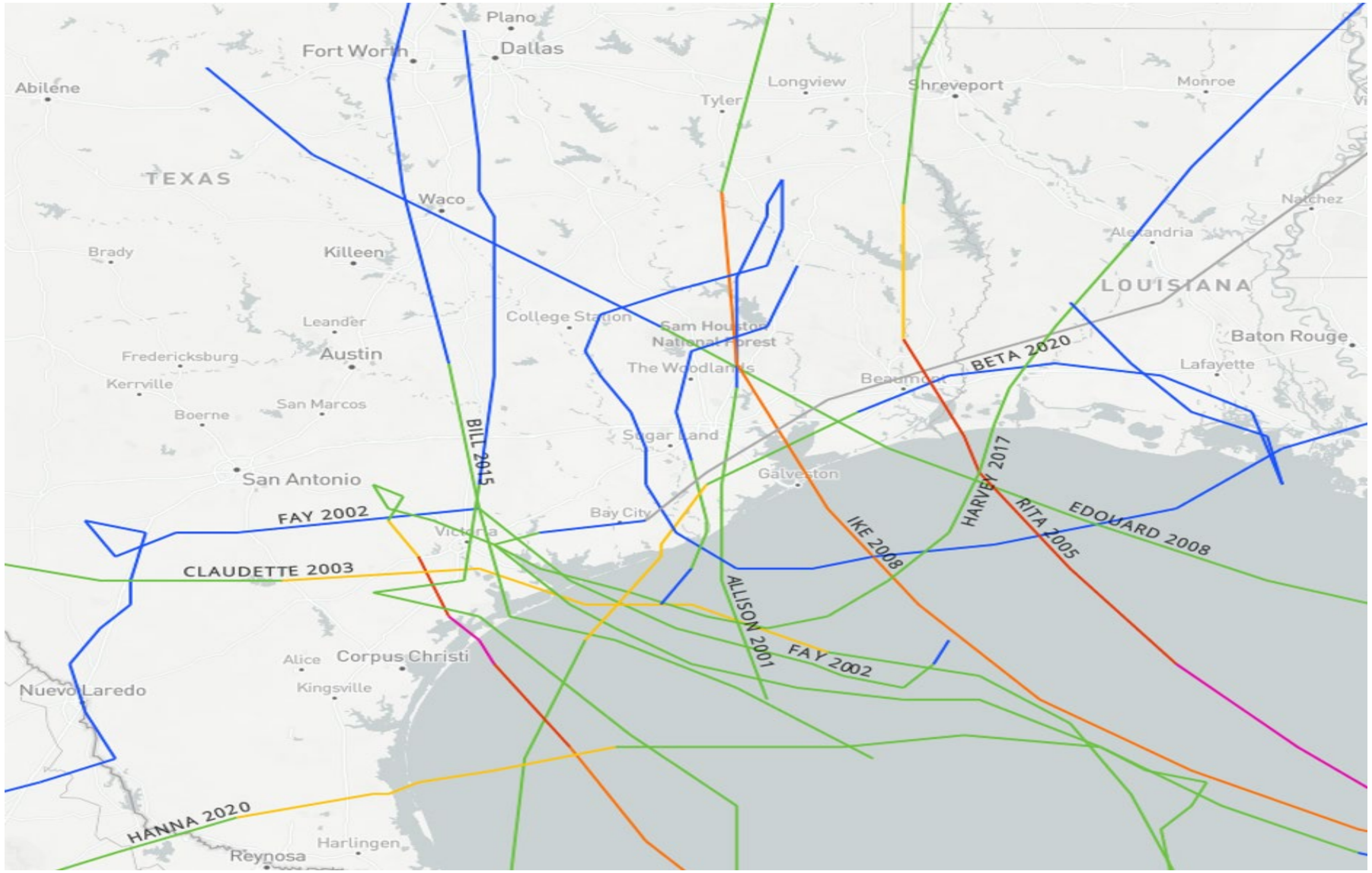


Hurricane Ike surge + 500,000cfs in all rivers (breaks old mesh)

Project 1


Silsbee
Conroe
Lumberton
The Woodlands
69
New Caney
Beaumont
Spring
90
96
Cypress
Port Ar
90
10
Houston
Pasadena
Sugar Land
League City
Alvin
Texas City
Galveston

Project 1 – Past events



Tracks of 14 historic hurricanes

Project 1 – Forcing data

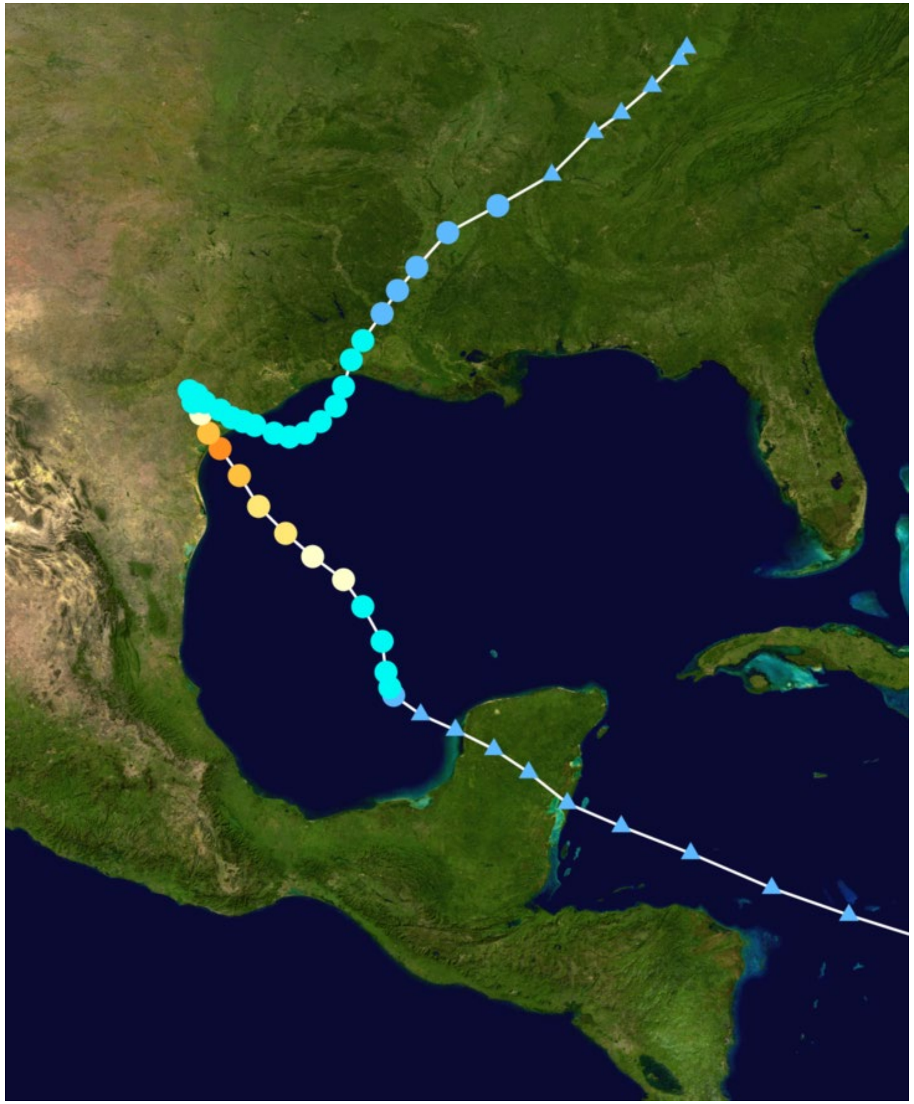
- Winds and pressure are generated using a parametric hurricane vortex model, Generalized Asymmetric Holland model, e.g. for pressure:

$$P(r) = P_c + (P_n - P_c)e^{-A/r^B}$$

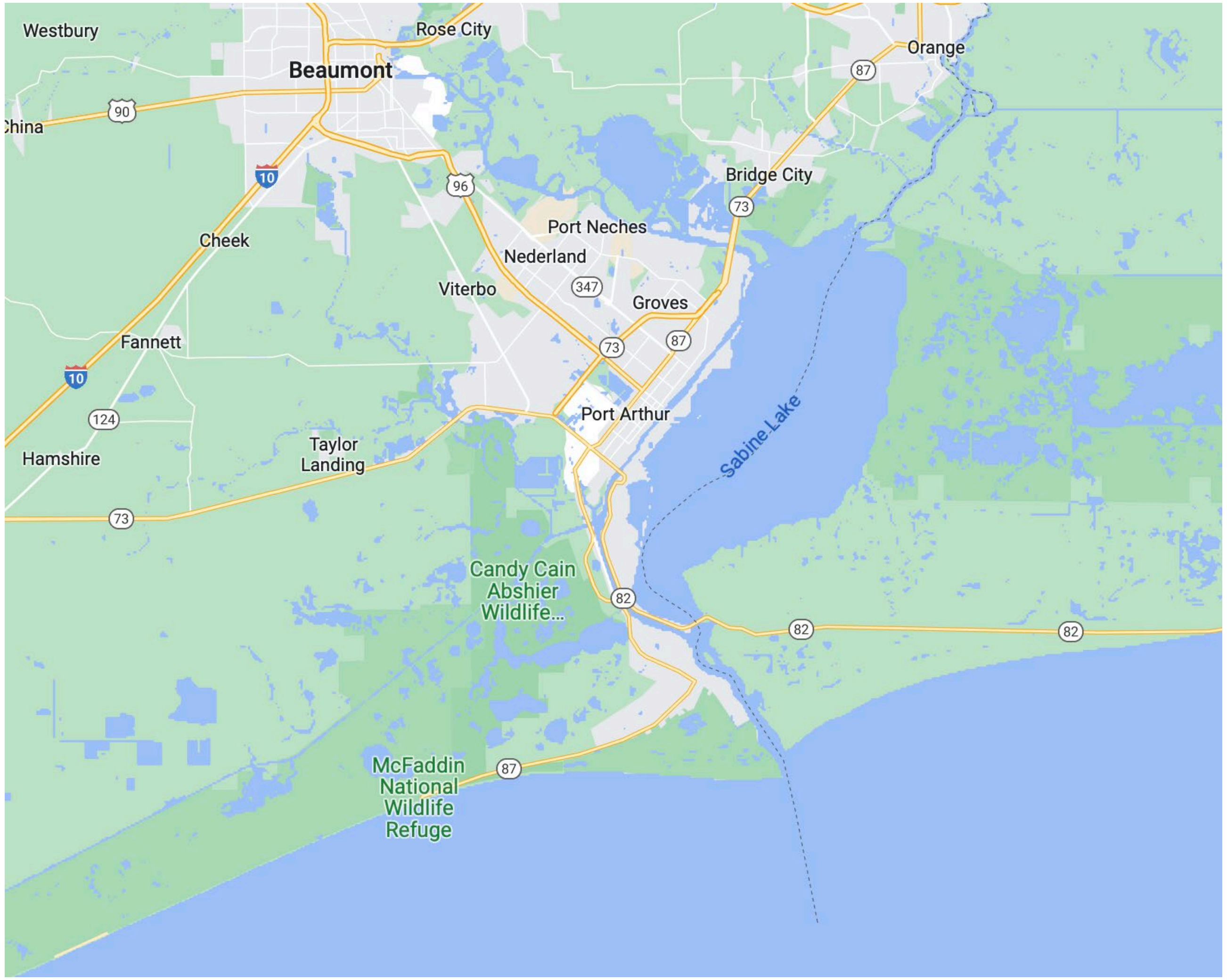
- Parameters are all taken from the National Hurricane Center "Best Track" hindcast from the Revised Hurricane Database
- River flow data is obtained from NOAA and USGS gauges in the 45 rivers

Results – Hurricane Harvey (2017)

- Costliest hurricane on record (tied with Katrina)
- Maximum storm surge: 8 ft. near Port Aransas
- Rainfall in Houston up to ~50 inches
- Simulation dates: August 17 - September 2, 2017



Results – Hurricane Harvey (2017)



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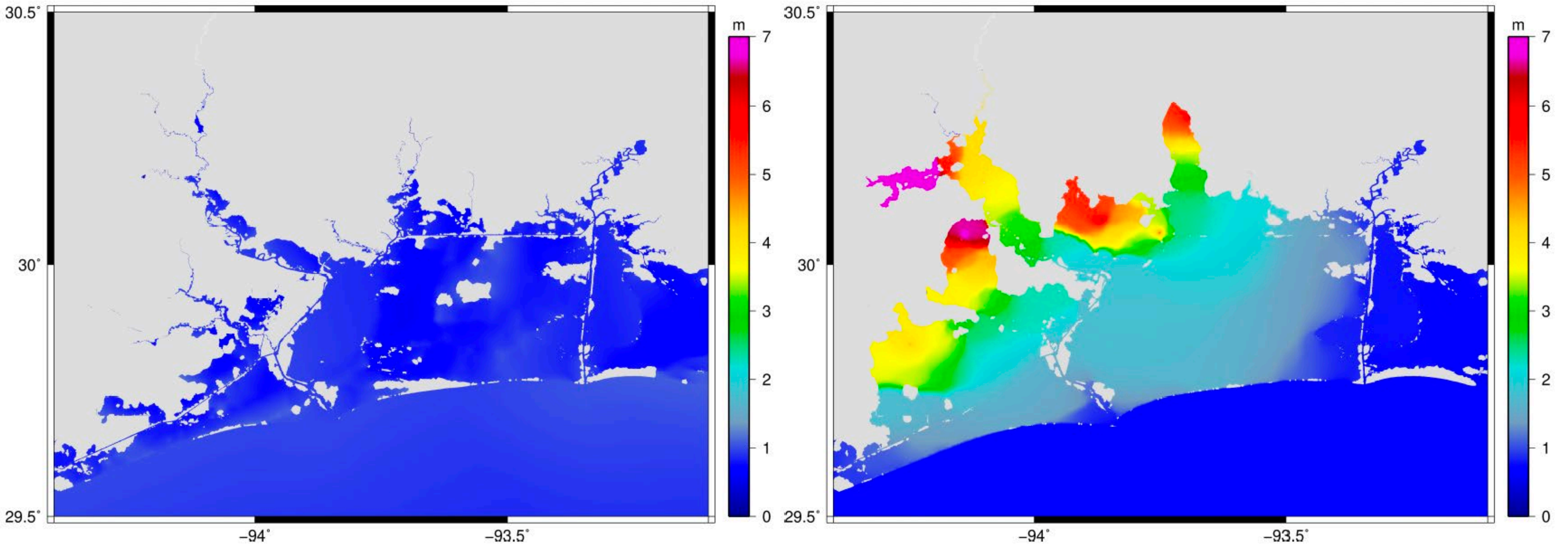
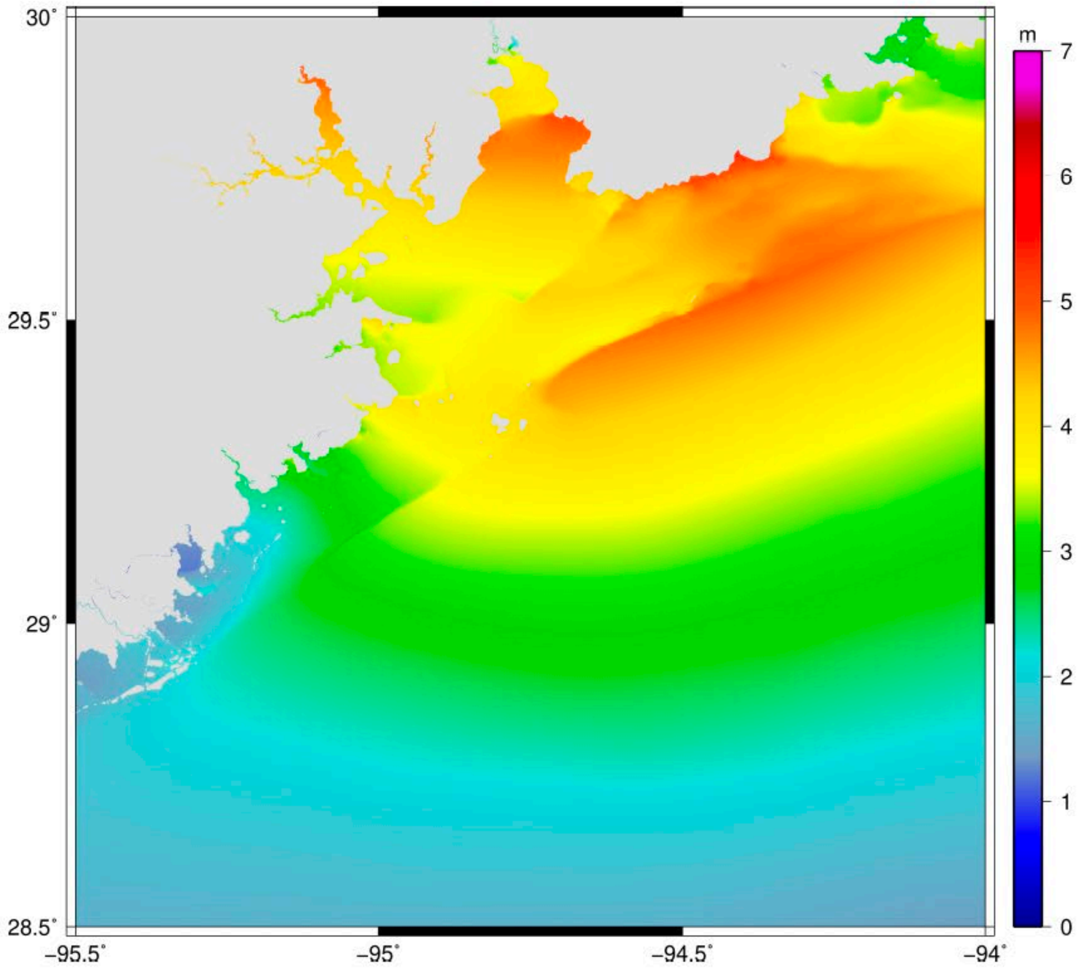


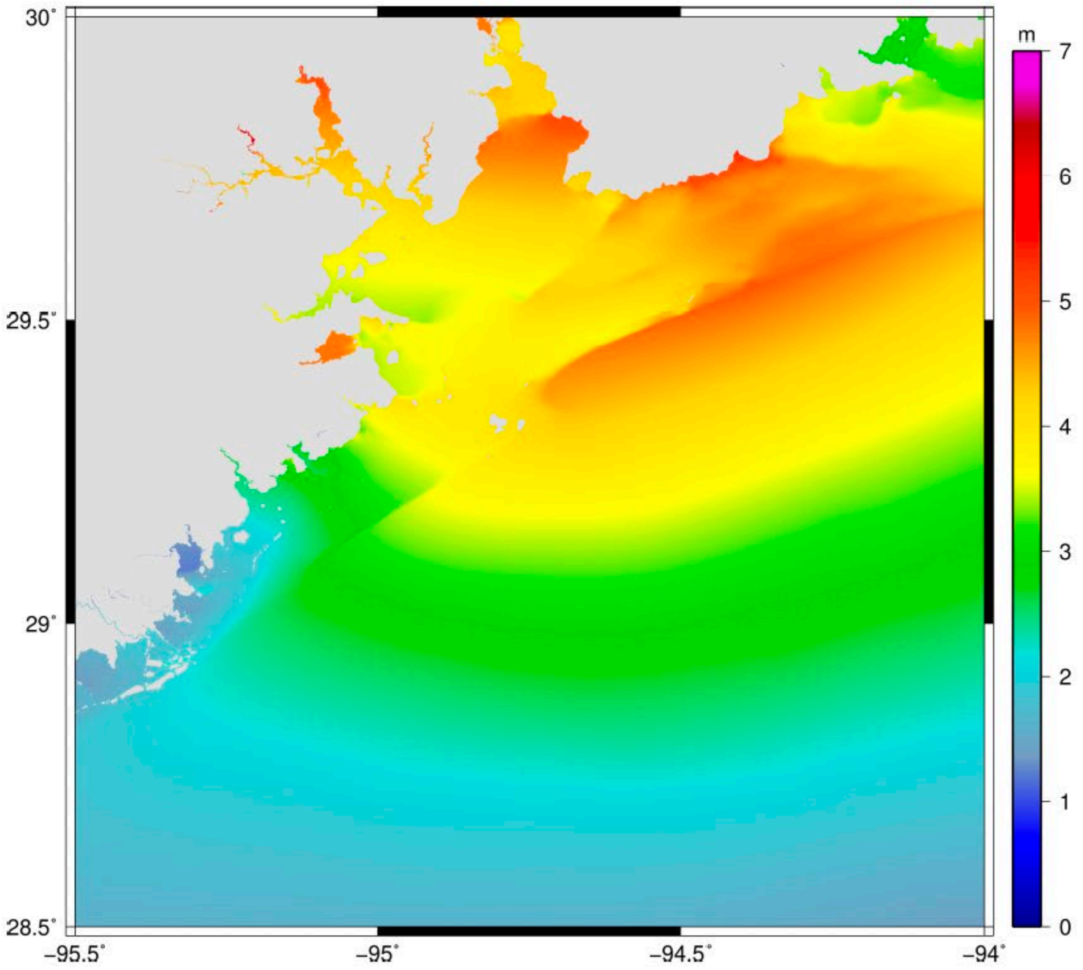
(a) Storm surge only

(b) Storm surge + river flows

Results – Hurricane Ike (2008)

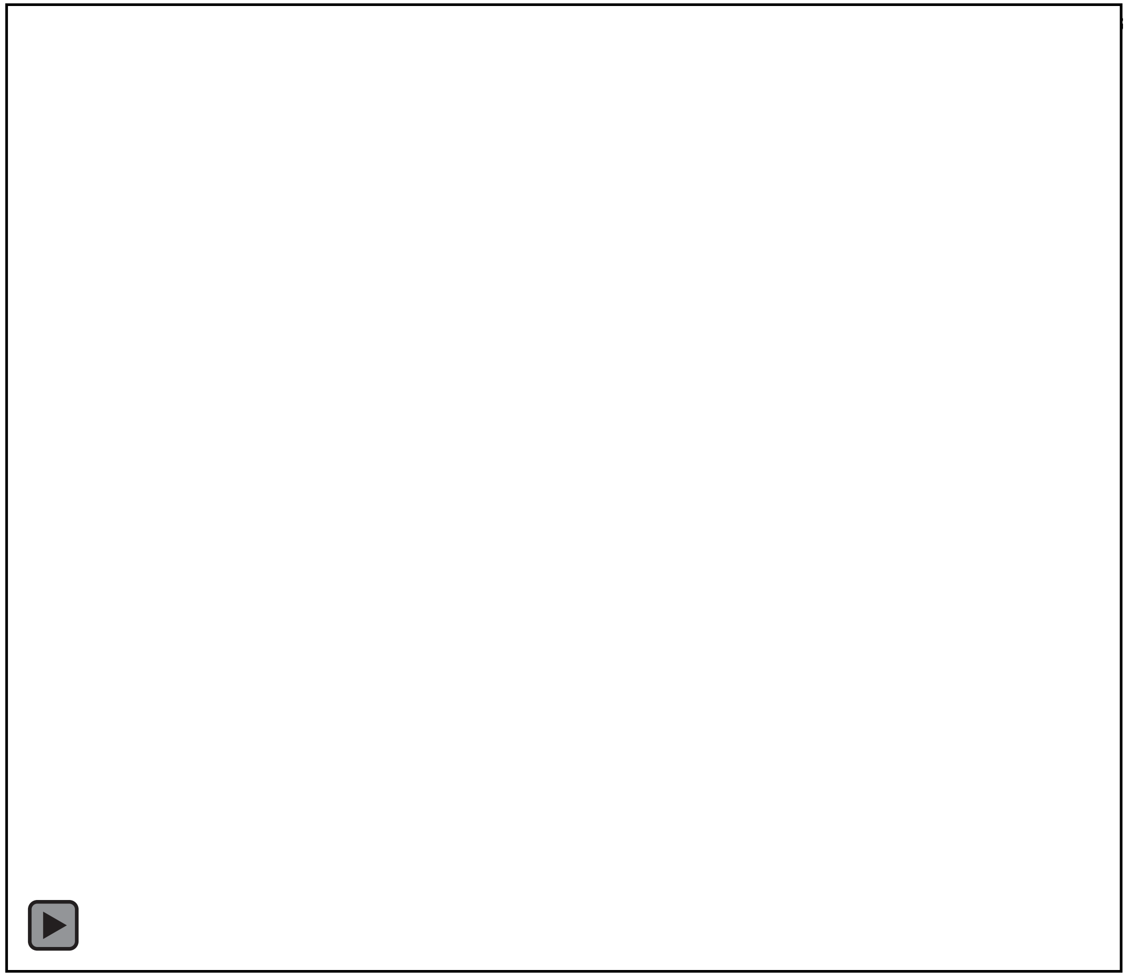


(a) Storm surge only

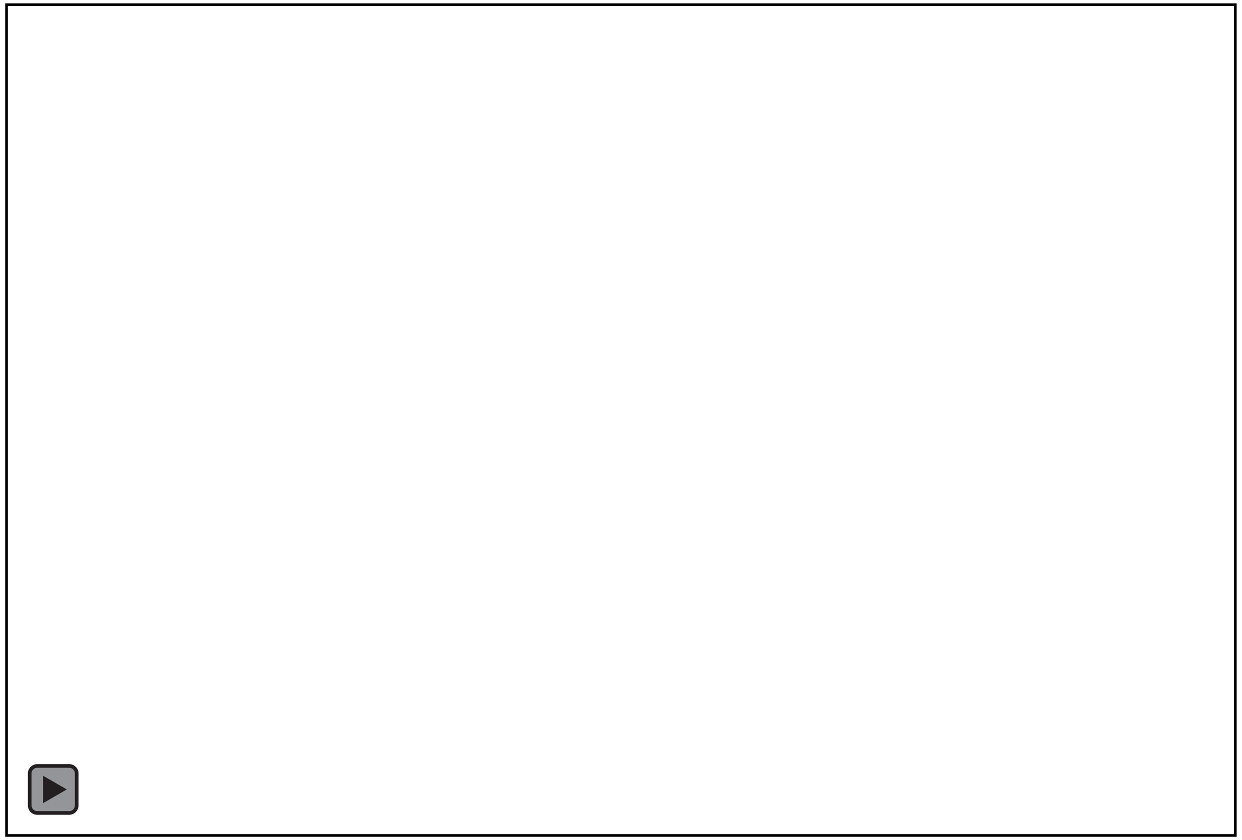


(b) Storm surge + river flows

Results



Hurricane Ike



Hurricane Harvey

Project 1 Takeaways

- New ADCIRC mesh capable of incorporating riverine runoff in hindcasting and studies
- New ADCIRC mesh to be used for operational forecasting of storm surge
- Currently post-processing the results to ascertain the locations of the transitional zones
- At present state, we have performed ~ 150 hurricane simulations for this project (hundreds more to come
- Without Frontera, using these meshes and methods would be impractical due to the high computational burden

Project 2 - Global Surge Modeling

- Currently working with The University of Notre Dame and US National Oceanographic and Atmospheric Administration (NOAA) to develop and provide global ocean storm surge forecasts
- “Global Storm and Tide Operational Forecast System” (GSTOFS) https://dylnwood.github.io/GESTOFS-develop/
- Model is run operationally at 2am (EST) on Frontera and produces a 5-day hindcast and a 7-day forecast (takes ~1.25 hours vs. ~10 hours previously on Notre Dame cluster)
- Hindcast data is validated against tide and water level gauges from NOAA (US coast) and UNESCO (rest of the world)

Project 2 - Global Model Data

- 12.7 million nodes, 24.8 million triangular elements
- Resolution: 40km in the oceans, floodplains: ~100m, US floodplains ~80m
- 13 km resolution Global Forecast System (GFS) wind and air pressure forcing
- Sea ice coverage also from GFS
- Model is initialized with two-day data assimilated measurements
- 12 second time step (fully explicit)

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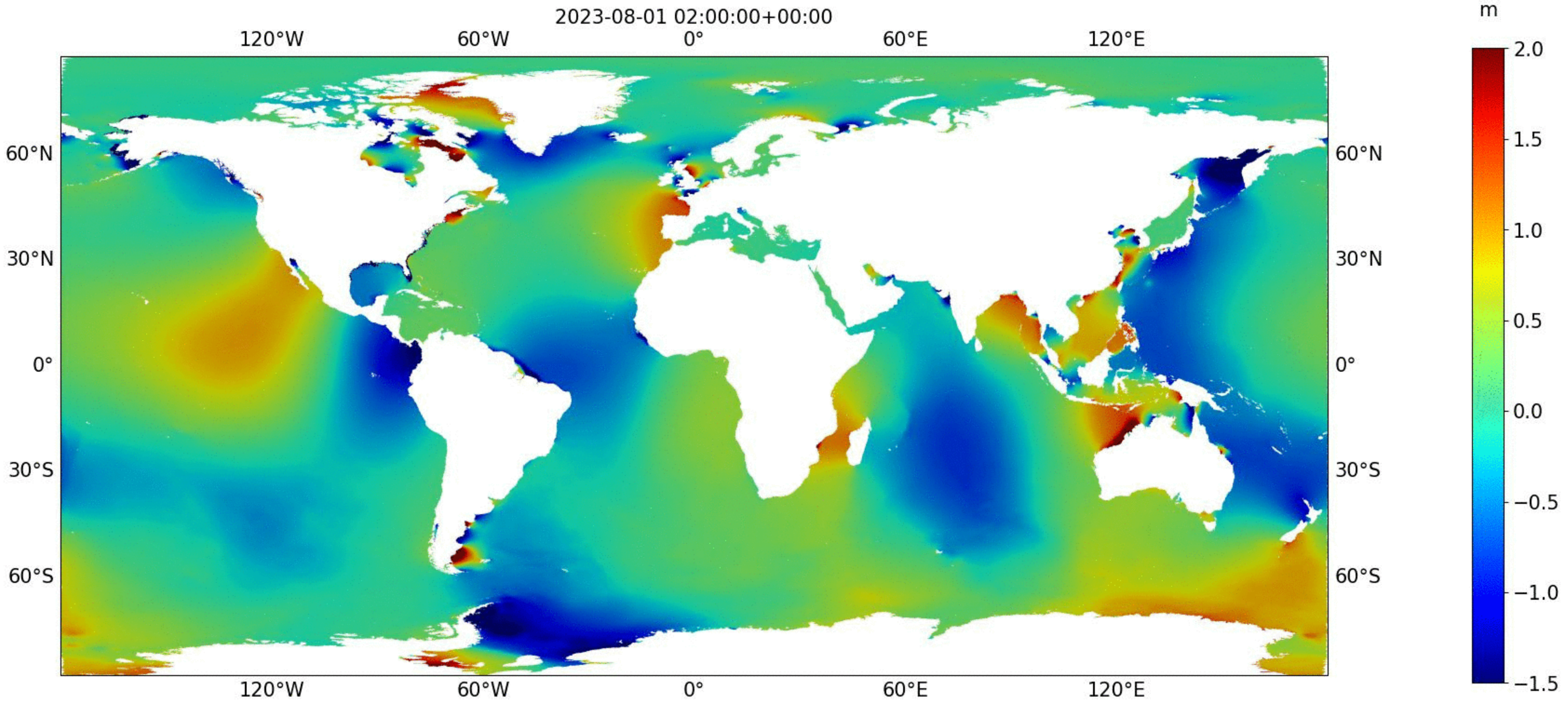
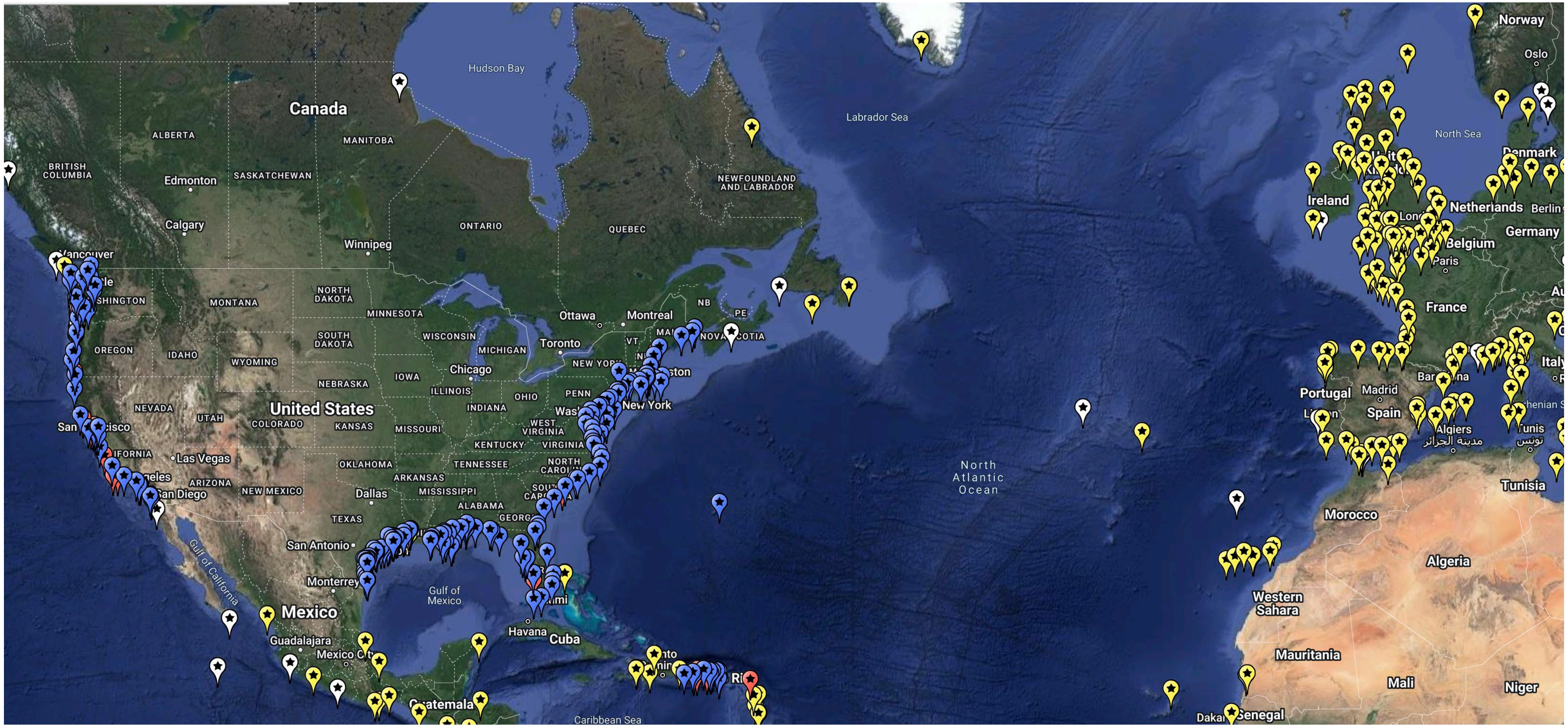
Project 2 - Global Model Elevation Forecast



Project 2 - Global Model Elevation Gauges



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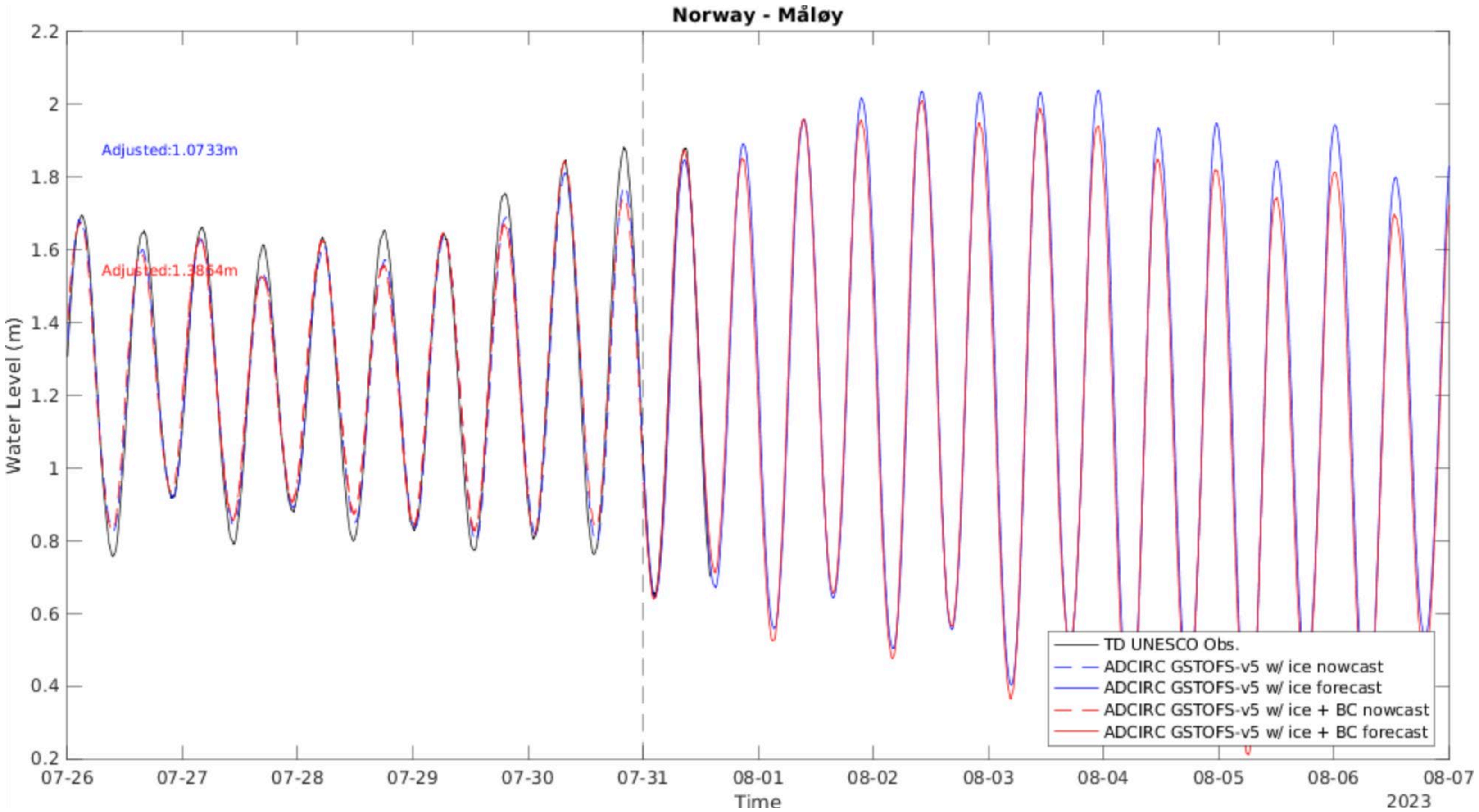

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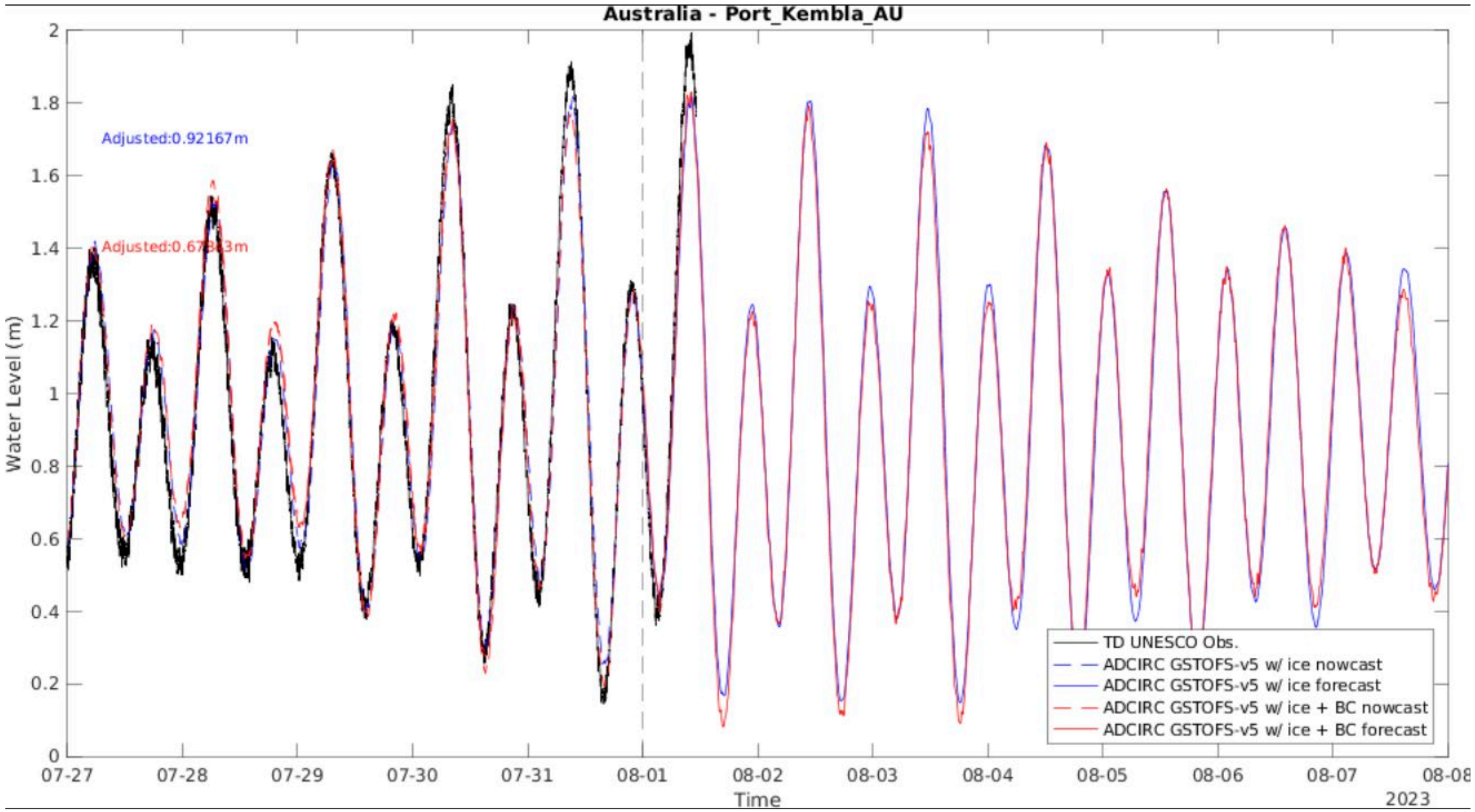

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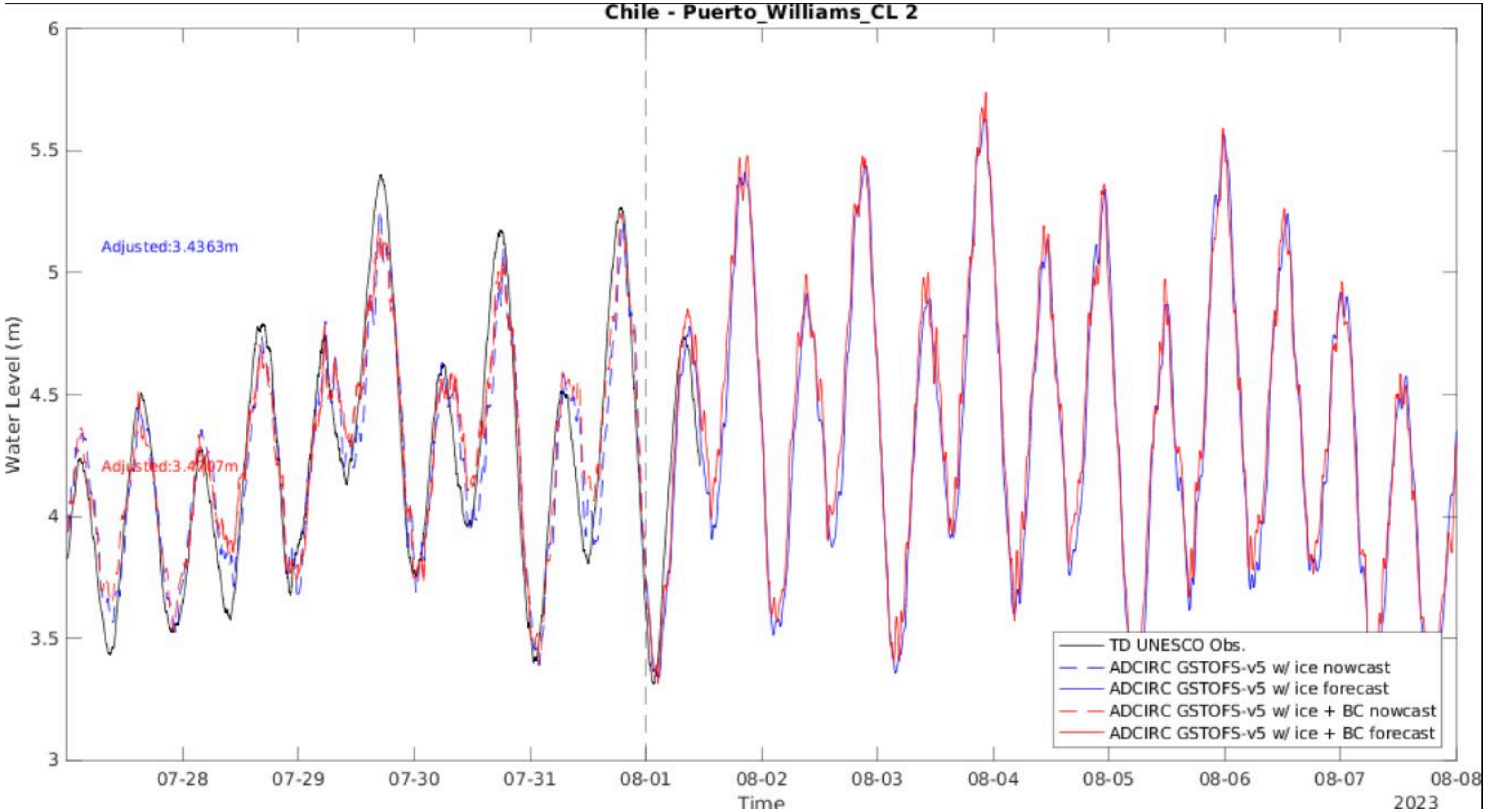

Concluding Remarks

- Frontera is a vital resource in the development and operation of both local and global storm surge models
- Frontera has allowed us to develop models that cover larger areas than ever before with unprecedented detail and resolution
- For future hurricane seasons, we plan to use the newly developed mesh of Texas in operational storm surge forecasting using Frontera
- Frontera allows us to perform forecasts in about half the time needed in the recent past -> An hour extra for emergency planners and managers during storm events

Acknowledgements

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