Storm Surge Modeling in Support of Response and Recovery Efforts

Clint Dawson

Dept. of Aerospace Engineering and Engineering Mechanics
Computational Hydraulics Group (CHG)
Oden Institute for Computational Engineering and Sciences
University of Texas (UT) at Austin

March 2019

Funding

- National Science Foundation ACI and DMS
- Houston Endowment: Severe Storm Prediction, Education and Evacuation from Disasters (SSPEED) Center
- Department of Homeland Security Center for Coastal Resilience
- Texas Advanced Computing Center and NSF XSEDE Program
- Department of Defense High Performance Computing Modernization Office PETTT program
- National Hazards Engineering Research Infrastructure DesignSafe

Computational Hydraulics Group

Jennifer Proft, Amin Kiaghadi, Babak Poursartip, Kyle Steffen, Max Bremer, Chen Chen, Gajanan Choudhary, Samuel Estes, Kazbek Kazhykhen, Wei Li, Yuxiang Lin, Mark Loveland, and Kenton Wu.

Collaborators

- Rick Luettich and Jason Fleming, UNC Chapel Hill
- Joannes Westerink, Notre Dame
- Phil Bedient and the SSPEED Center, Rice

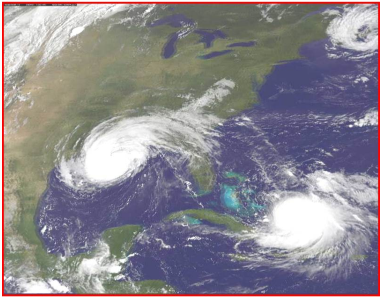
Motivation and Outline

Flooding due to hurricanes causes billions of dollars in damage and can result in tremendous loss of life and livelihood. We need models that can both **forecast** hurricane flooding as they approach land for emergency management, and **predict** impacts of hurricane flooding in the future for planning purposes. Flooding occurs due to both **storm surge** and **rainfall**.

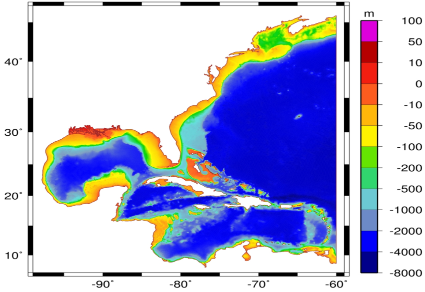
Outline

- How we simulate storm surge on the computer
- Response and recovery efforts
    - Flood Insurance
    - Structural protection: Houston Galveston Area Protection System (HGAPS)
    - Forecasting
- Current and future challenges

A typical domain



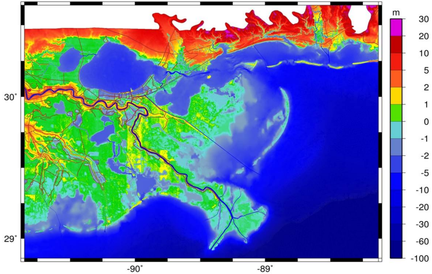
Western North Atlantic



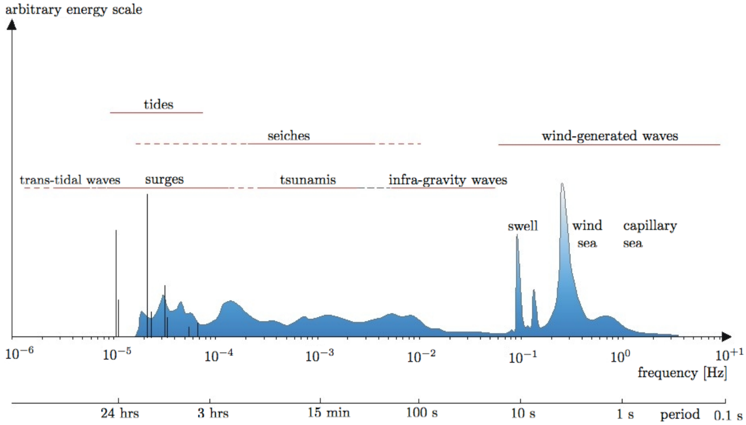
Western North Atlantic model domain

The Model Must Include Coastal Regions

New Orleans after Hurricane Katrina (2005)



Louisiana/Mississippi/Alabama model



- Long waves
- Short waves (wind-driven)

Ref: L.H. Holthuijsen, *Waves in Oceanic and Coastal Waters*, Cambridge.

Additional Modeling Issues

- Driving forces: wind, pressure, Coriolis, tides
- Complex coastlines–rough domains and complex boundary conditions
- Highly varying bathymetry and topography
- Wetting and drying
- Bottom friction/drag
- Interaction of water with structures

Advanced Circulation (ADCIRC) Computer Simulator

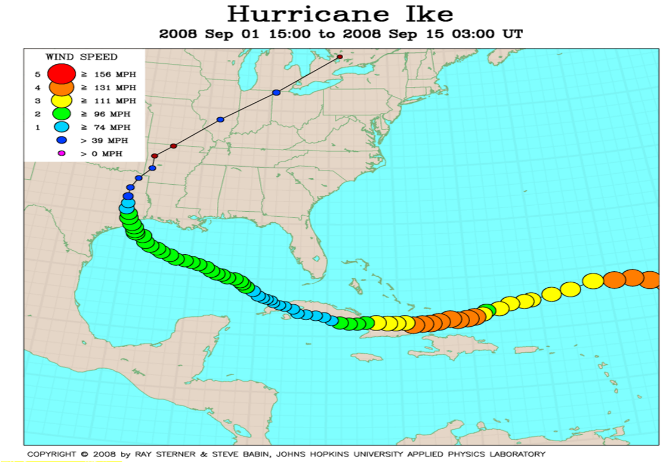
Some history:

- Initial development by Luettich and Westerink in early 1990's
- Parallelized in mid 1990's.
- First applied to hurricanes for a hindcast study of Hurricane Betsy (1968) for the USACE to develop a flood protection system in New Orleans
- Hurricane Katrina (2005) happened and led to extensive post-Katrina development and validation
- FEMA Flood Insurance Studies (DFIRMs)
- Hurricane Protection Studies in response to Katrina, Sandy and Ike.
- Now used in production mode for hurricane forecasting.

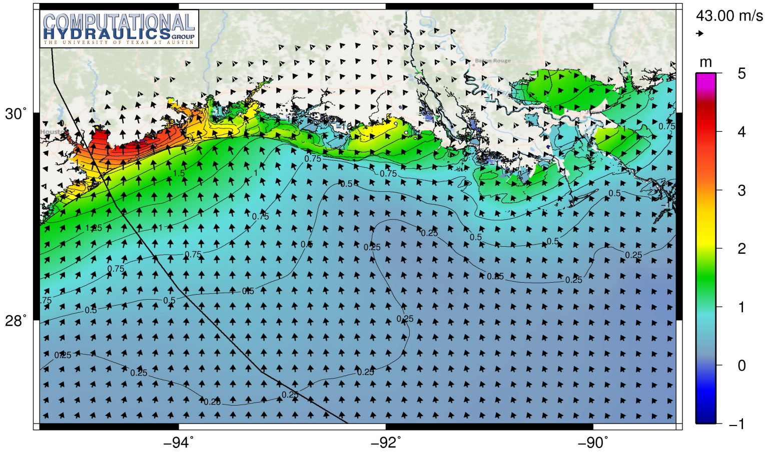
ADCIRC Framework

- Triangular and prismatic (3D) meshes
- Finite element approximation
- Semi-implicit time stepping
- Executes on large-scale HPC platforms with scaling beyond 10,000+ cores
- Coupled with wave models, most notably SWAN (Simulating Waves Nearshore, Holthuijsen *et al* TU Delft) $\Rightarrow$ **ADCIRC+SWAN**

Hurricane Ike Study

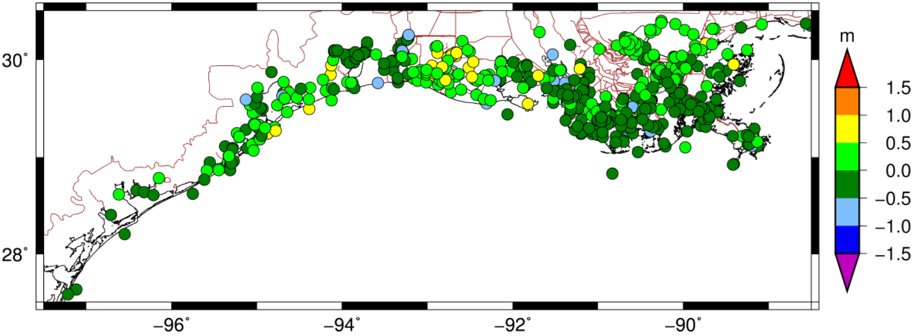


Hurricane Ike Storm Surge



Hurricane Ike Water Levels Day 8.0

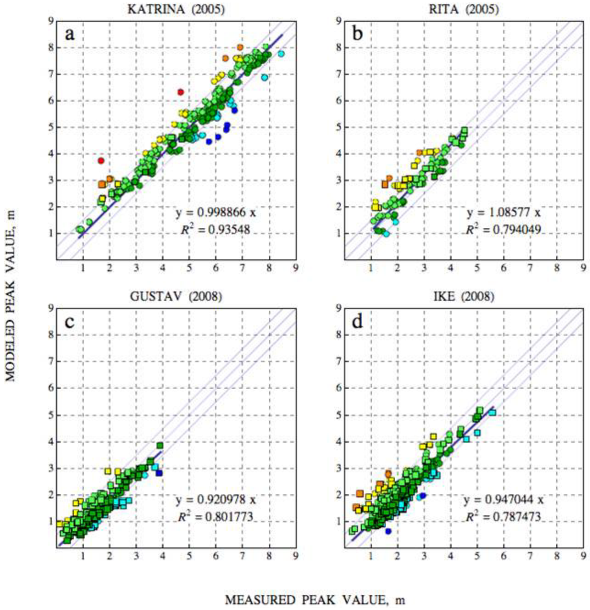
Model Validation: Peak Surge



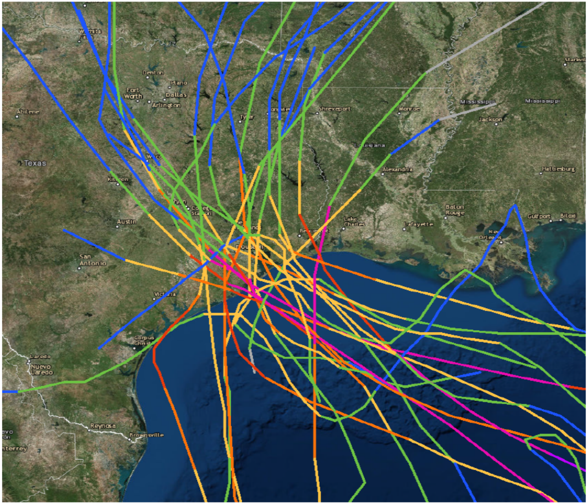
Modeled peak surge vs. measurements. Green and light green indicate error within $\pm$ .5 meter

Refn: Hope *et al* , JGR Oceans

Other Validation Studies



Insurance rates are based on statistics: what is the probability of a property being damaged by a 1:100 year event?



Probablistic Storm Generation

- Synthetic storms generated based on the historical record
- Hurricanes are characterized by track, pressure deficit, maximum wind velocity, radius-to-maximum winds, and forward speed
- Storm characteristics are generated using the Joint Probability Method with Optimal Sampling (JPMOS) $\Rightarrow$ 446 storms for Texas
- Hurricane winds computed using the Planetary Boundary Layer (PBL) method (proprietary software of the USACE).

Synthetic Storm Tracks:SE to NW

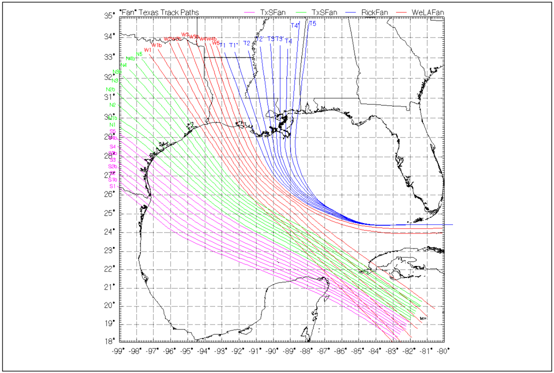


Figure 89: Tracks used to define the synthetic storms. Hurricane parameters vary along the tracks and provide the input to the OceanWeather, Inc., PBL wind/pressure field model. This provides the storm forcing required for each production system simulation.

Synthetic Storm Tracks: S to N

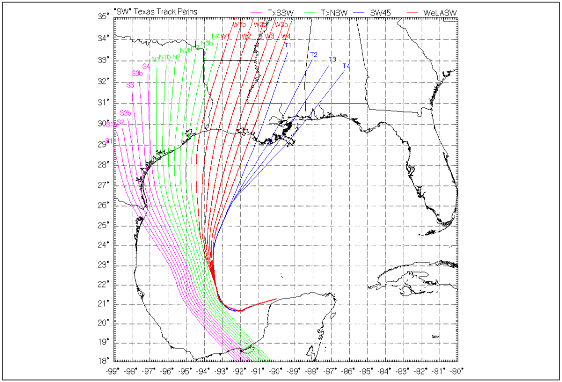


Figure 87: Tracks used to define the synthetic storms. Hurricane parameters vary along the tracks and provide the input to the OceanWeather, Inc., PBL wind/pressure field model. This provides the storm forcing required for each production system simulation.

Synthetic Storm Tracks: E to W

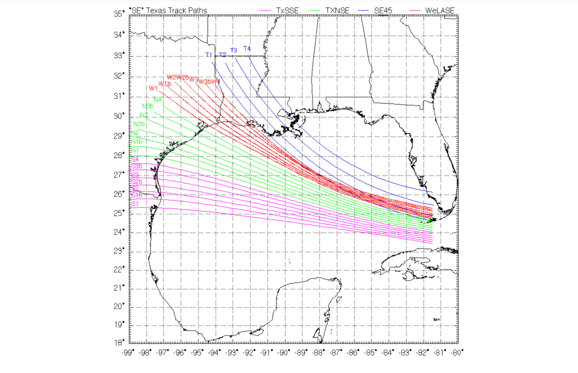
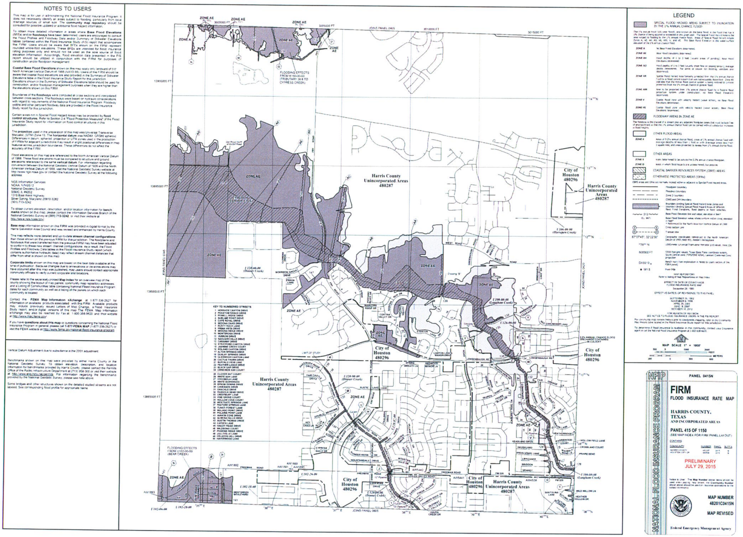


Figure 88: Tracks used to define the synthetic storms. Hurricane parameters vary along the tracks and provide the input to the OceanWeather, Inc., PBL wind/pressure field model. This provides the storm forcing required for each production system simulation.

Flood Insurance Study Process

- Run ADCIRC+SWAN for each storm
- Generate statistics of surge probablities
- Generate a flood insurance rate map
- Send out for review/comment
- Must be accepted by each county/district. Usually is challenged.
- Once accepted, it is used to determine eligibility for flood insurance
- Texas map generated in 2007-2010 time frame, still undergoing review and challenges for most counties. Harris County has been accepted and is in force, insurance rates went up dramatically.

A Typical FIRM for Harris County, TX



Storm Protection: Houston Galveston Area Protection System (HGAPS)

- Developed Proxy Storms which represent “worst-case” scenarios based on Ike and similar storms. These are based on FEMA storms and historical storms.
- In collaboration with SSPEED researchers, developed some possible structural mitigation strategies
- Testing and refining mitigation strategies

Acknowledge: Jennifer Proft, Jacob Torres, Ben Bass and Nick Irza

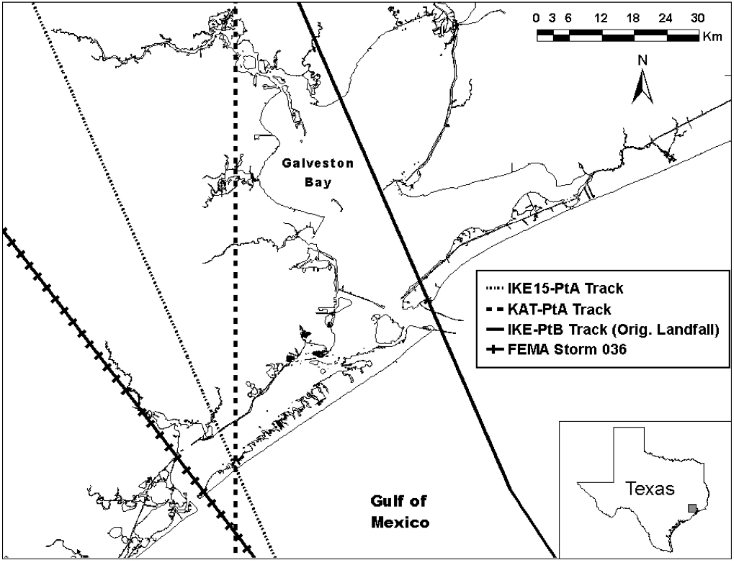
Notable Historical Storms

Storm	Year	Category	MCP (mb)	MSW (km/h)	MST (m)
Unnamed	1900	4	936	209 to 225	6.1
Unnamed	1915	4	940	217	4.9
Rita	2005	3	930	185	3.0 to 4.6
Ike	2008	2	951	175	3.9

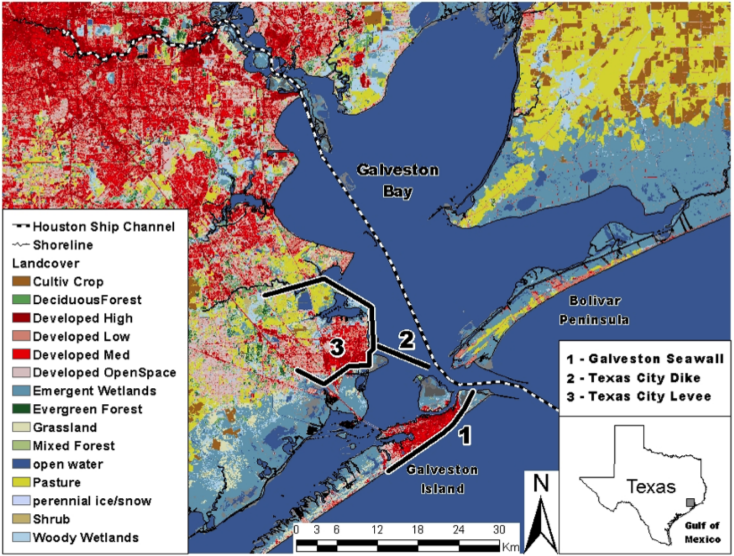
Proxy Storms for Evaluation

Storm	StormID	Type	Category	MCP (m
Ike	Ike00-PtB	Historical	2	951
Ike+15%	Ike15-PtA	Pseudo-synthetic	3	951
Katrina-shifted	KAT00-PtA	Pseudo-synthetic	3	920
FEMA Storm 036	Storm 036	Synthetic	4	916

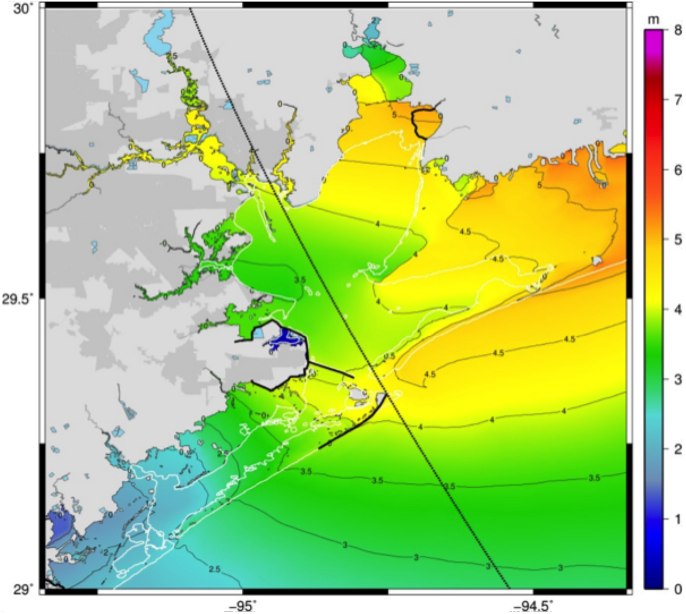
Proxy storm tracks



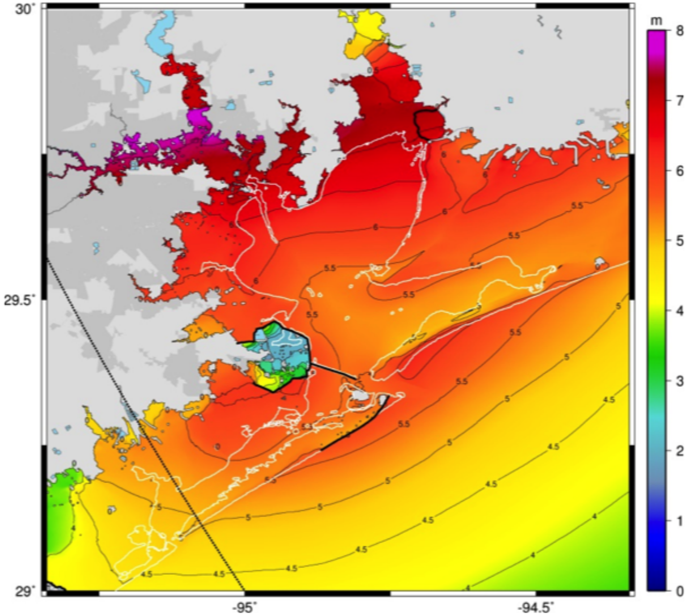
Galveston Bay study region



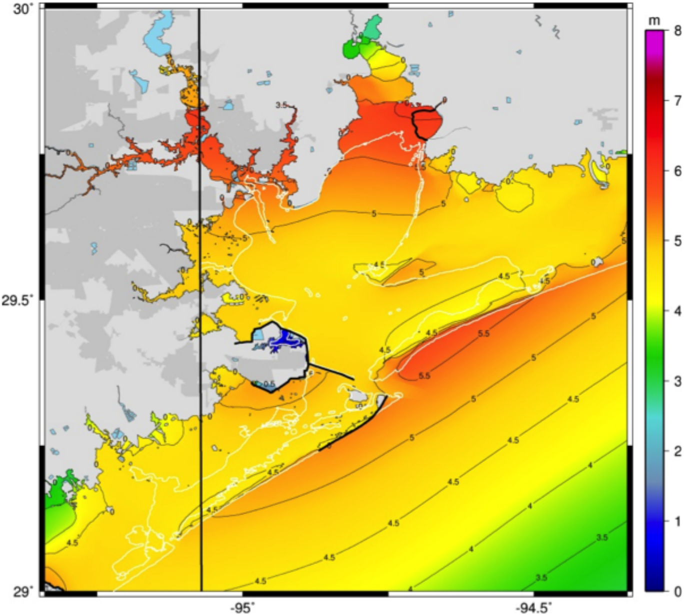
Ike00PtB Baseline



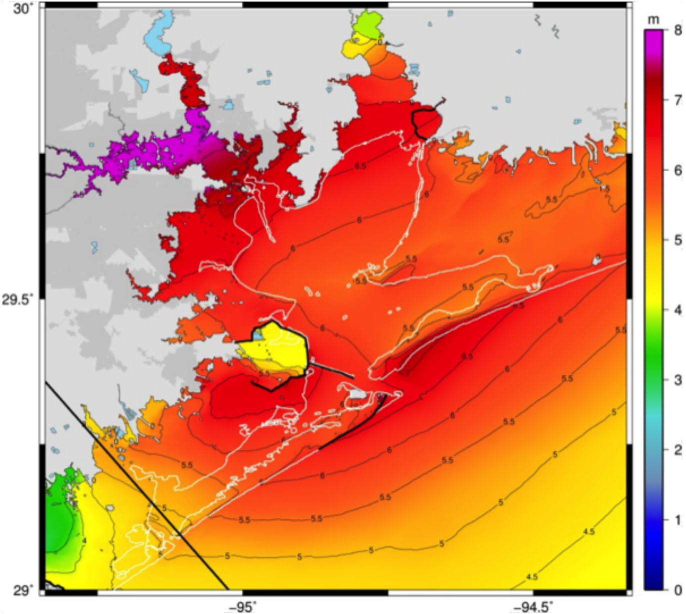
Ike15PtA Baseline



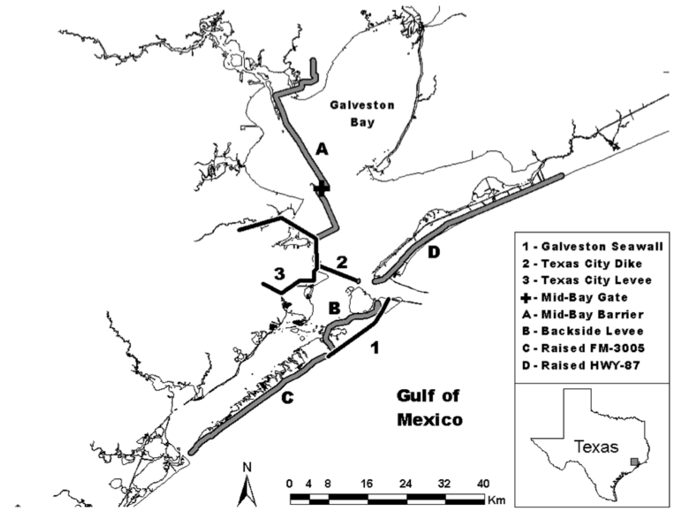
Katrina Shifted Baseline



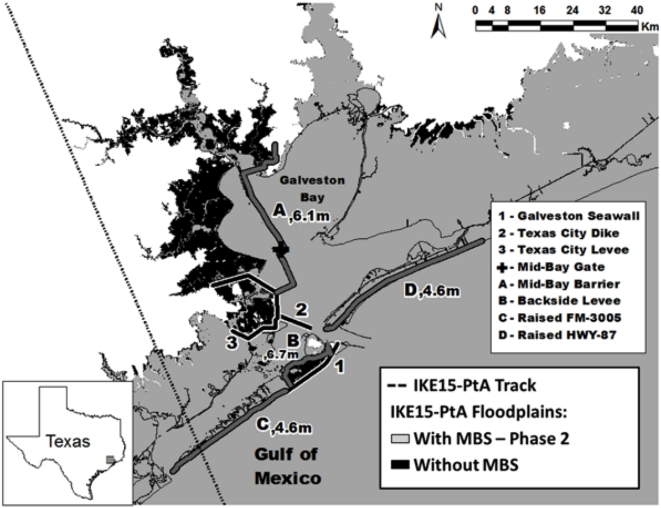
Storm 036 Baseline



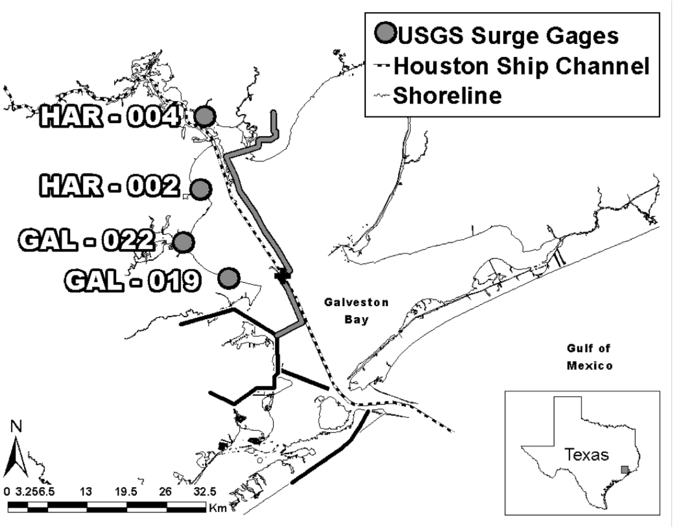
Mid Bay Strategy



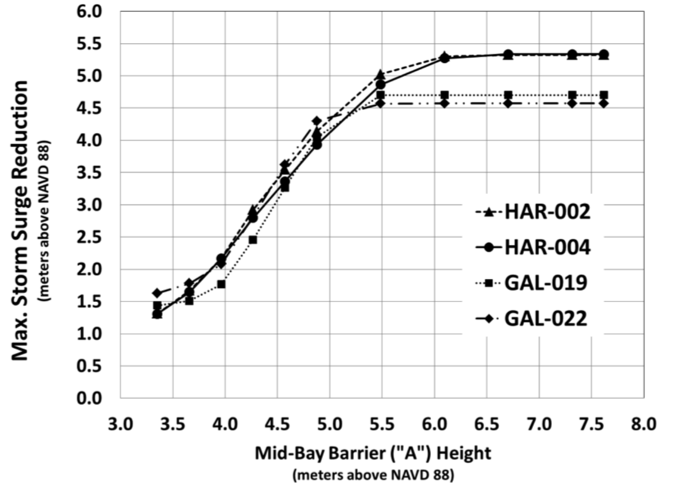
Mid Bay: Surge Reduction



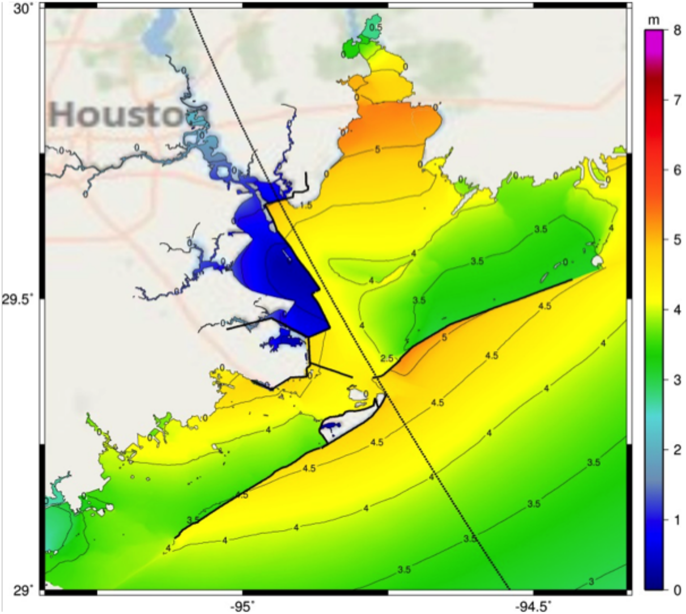
USGS Gauges


USGS Surge Gages
Houston Ship Channel
Shoreline
HAR - 004
HAR - 002
GAL - 022
GAL - 019
Galveston Bay
Gulf of Mexico
Texas
N
0 3.25 6.5 13 19.5 26 32.5
Km

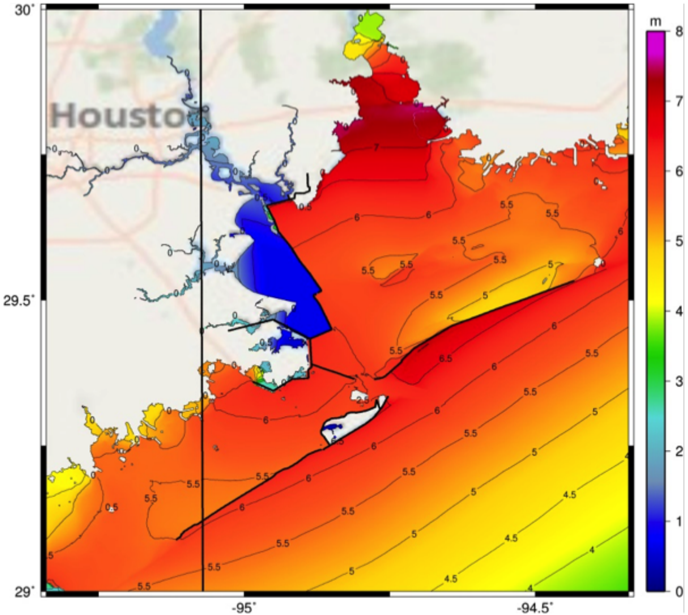
Surge at USGS Gauges



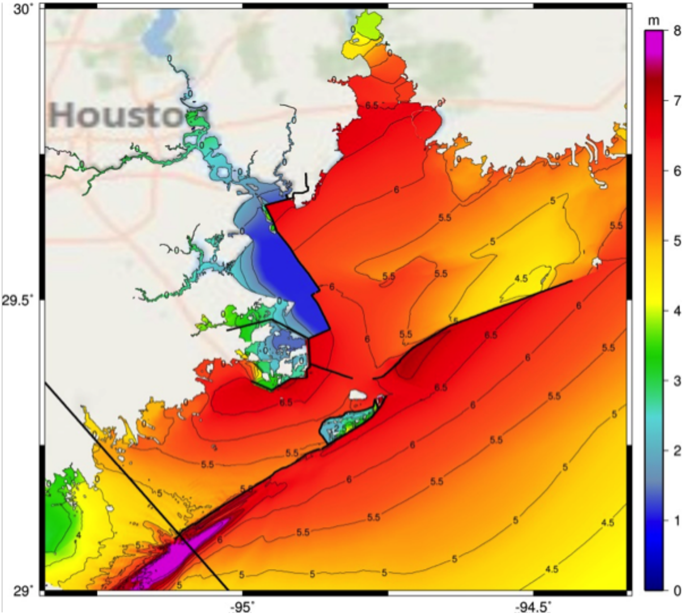
Mid Bay: Ike00PtB



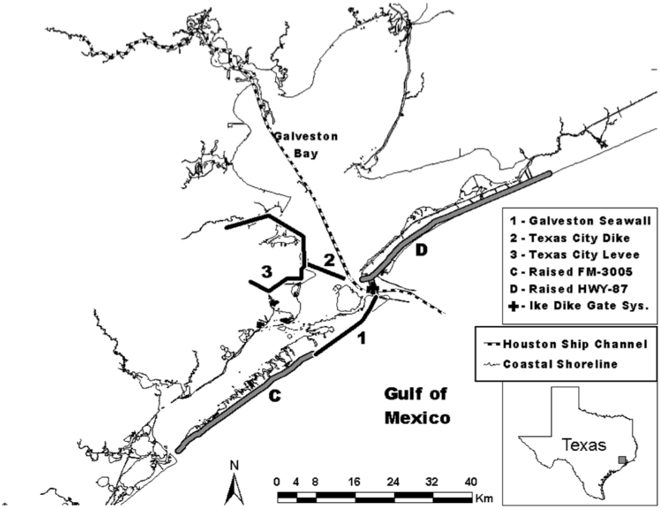
Mid Bay: Katrina Shifted



Mid Bay: Storm 36

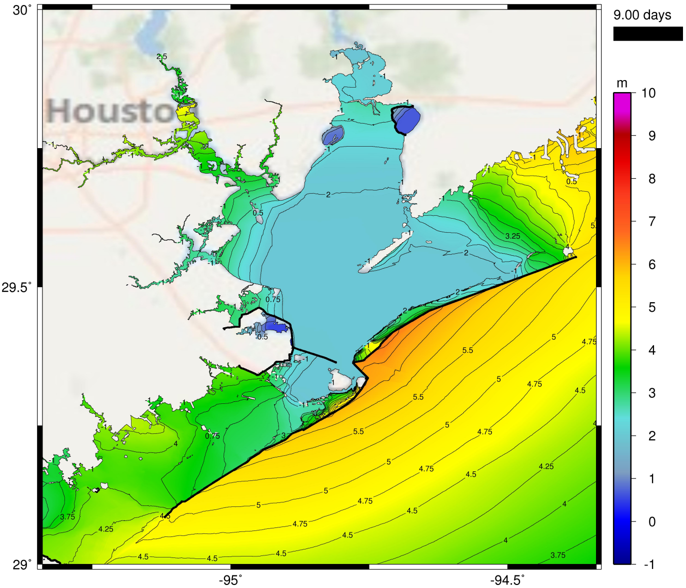


Ike Dike



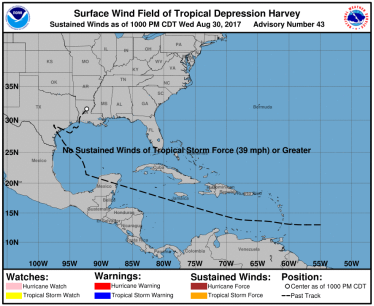
Galveston Bay
1
2
3
C
D
1 - Galveston Seawall
2 - Texas City Dike
3 - Texas City Levee
C - Raised FM-3005
D - Raised HWY-87
✚- Ike Dike Gate Sys.
Houston Ship Channel
Coastal Shoreline
Gulf of Mexico
Texas
N
0 4 8 16 24 32 40 Km

Ike Dike: Ike15PtA

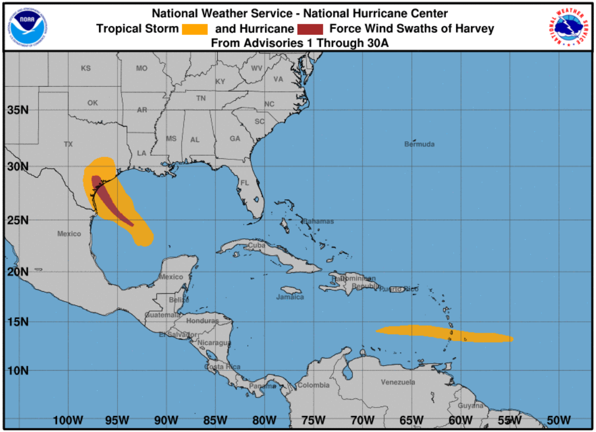


Response: Hurricane Harvey

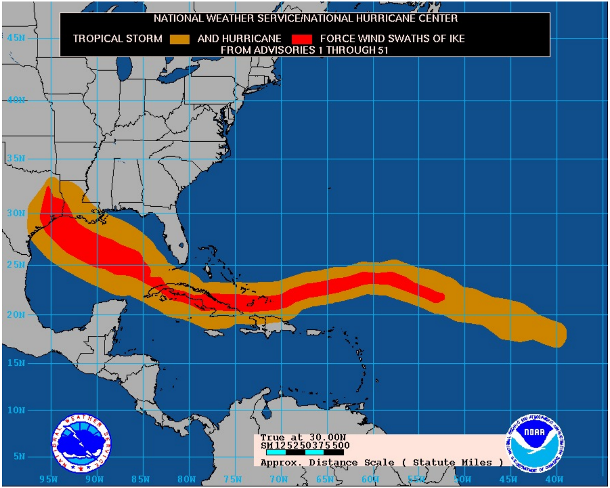
- During Hurricane Harvey, ADCIRC+SWAN was executed in real-time at TACC to provide information to the Texas State Operations Center. This information wasused in emergency planning, especially in transportation.
- Acknowledge: Jason Fleming, Seahorse Consulting and Carola Kaiser, LSU



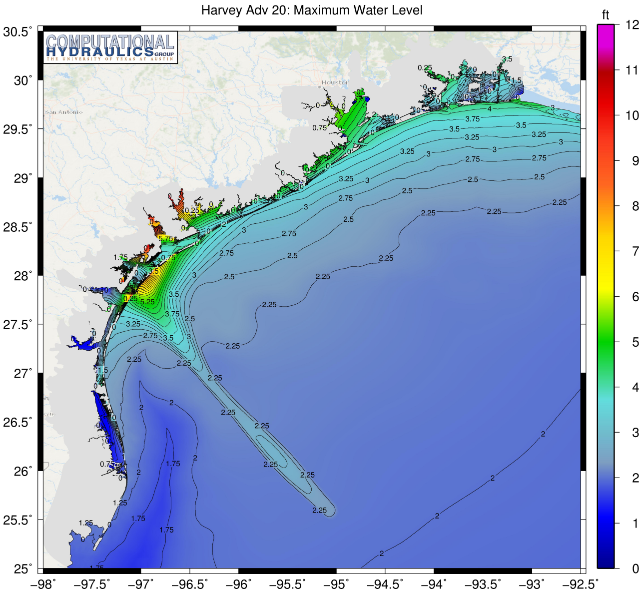
Hurricane Harvey Winds



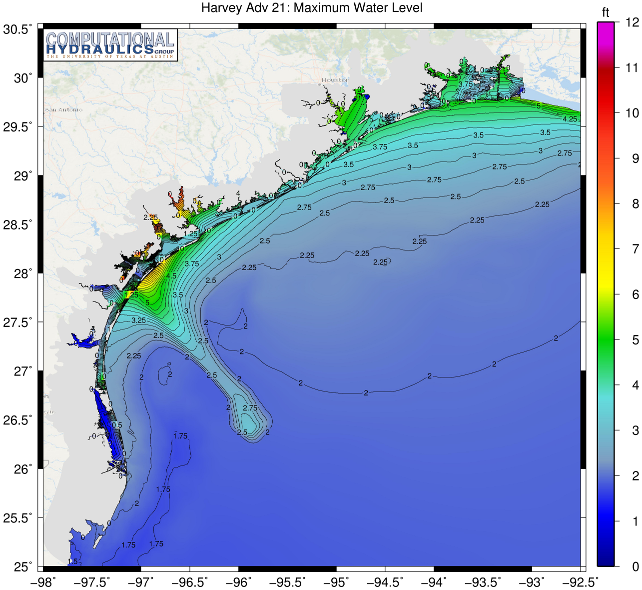
Hurricane Ike



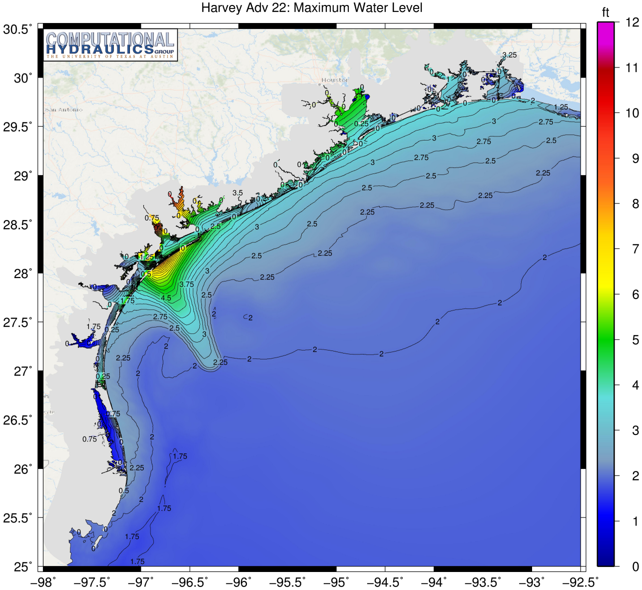
Hurricane Harvey Forecasts



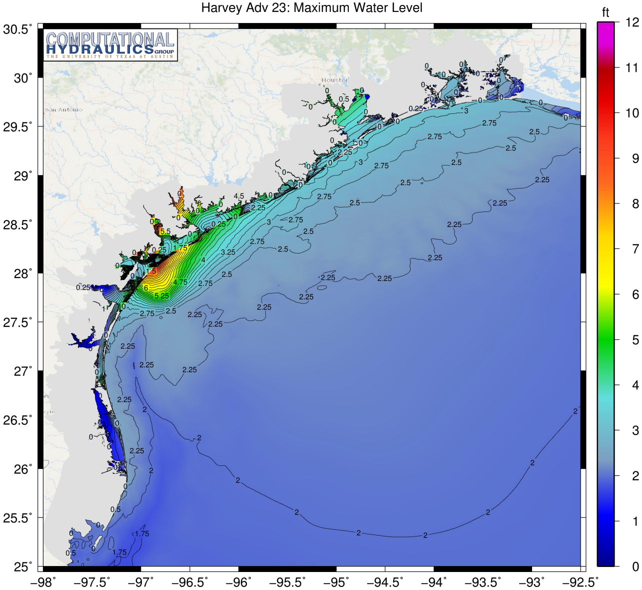
Hurricane Harvey Forecasts



Hurricane Harvey Forecasts



Hurricane Harvey Forecasts



Validation:Gauge data provided by John Goff (UT Austin)

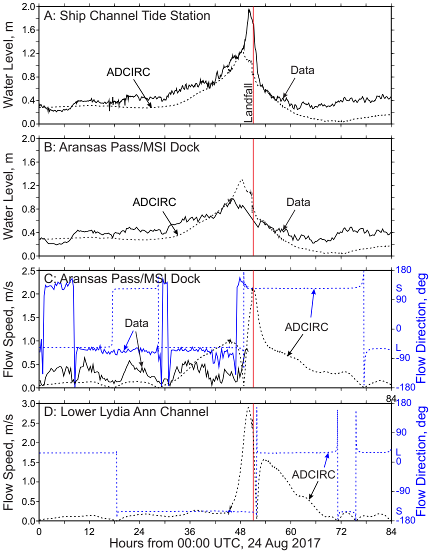


Figure 3

ADCIRC within DesignSafe

DesignSafe is a cybinfrastructure for the natural hazards engineering community:

- Provides a web-based portal for executing ADCIRC and ADCIRC+SWAN "in the cloud."
- Provides interfaces and links to other software for visualization and postprocessing.
- Provides data services for archiving and publishing data
- Provides a place to share code and data among groups of researchers
- Provides a forum for the natural hazards community to communicate information about natural hazards research

Current and Future Challenges

- Coupling storm surge with rainfall runoff during severe storms
- Sediment erosion and deposition during events
- Storm surges in the Arctic–impact of sea ice
- Fluid/structure and fluid/vegetation interaction
- High performance computing and new computing architectures
- Uncertainty quantification and data driven modeling–data analytics
- Sociological, environmental, economic impacts.