Numerical Simulation of Compound Flooding using Parametric Rainfall Models

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Motivation

- Compound flooding - a high-impact, simultaneous interaction between multiple sources
    - Storm surge from the ocean
    - River discharge
    - Rainfall
- Example: Hurricane Harvey (2017) - storm surge blocked drainage of rainfall runoff and amplified inundation
- Difficult to model due to the nonlinear nature of the interaction; no single model encompasses all flooding sources

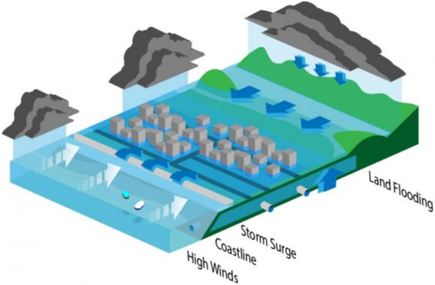


Image from http://sites.utexas.edu/climatesecurity/2020/03/25/flooding-from-all-directions-how-compound-flooding-threatens-urban-areas-in-oceania/

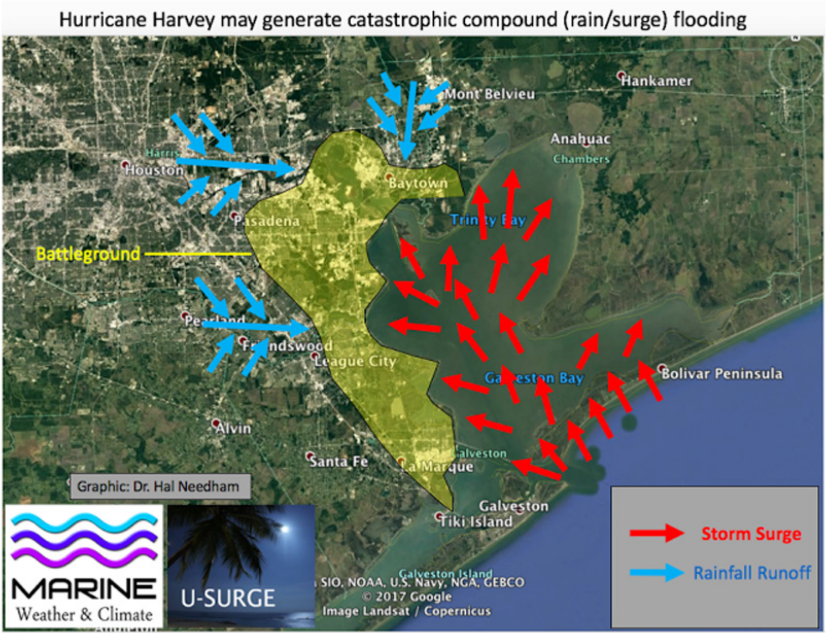
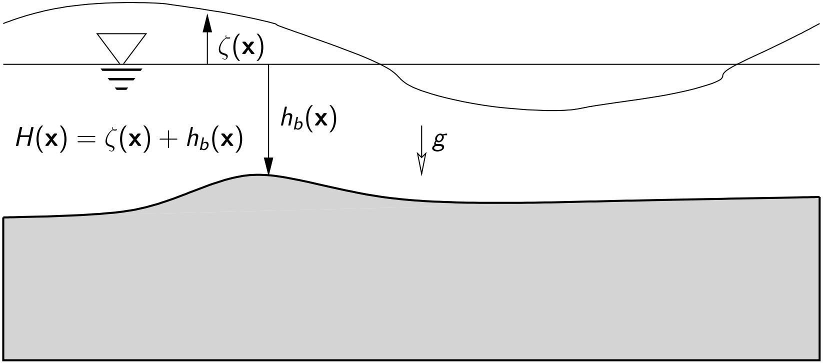


Image from U-Surge. https://wxshift.com/news/blog/harveys-rain-and-surge-flooding-could-be-catastrophic

Computational Difficulties

- Advanced Circulation model (ADCIRC) (Luettich and Westerink, 2004). A Fortran finite element program that simulates coastal storm surge given wind input
- Runoff effects can be added to ADCIRC via flux boundary conditions from gauge data
- Difficulty adding direct rainfall on ADCIRC due to the form of the equation and possibly the continuous Galerkin method
- This work: adding rainfall to the Discontinuous Galerkin Shallow Water Equation Model (DG-SWEM) (Kubatko, 2006) based on ADCIRC

Mathematical Model



ζ = surface elevation (positive above geoid)
h = bathymetric depth (positive below geoid)
H = total water depth (always greater than 0)

Mathematical Model

Assuming depth is small relative to horizontal scale, we can average over the z-direction to obtain

The Shallow Water Equations

$$
\begin{aligned}
\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} &= S(t,x,y) \\
\frac{\partial (Hu)}{\partial t} + \frac{\partial (Hu^2 + \frac{1}{2}g(H^2 - h^2))}{\partial x} + \frac{\partial (Huv)}{\partial y} &= g\zeta \frac{\partial h}{\partial x} + F_x \\
\frac{\partial (Hv)}{\partial t} + \frac{\partial (Huv)}{\partial x} + \frac{\partial (Hv^2 + \frac{1}{2}g(H^2 - h^2))}{\partial y} &= g\zeta \frac{\partial h}{\partial y} + F_y
\end{aligned}
$$

where
$\zeta =$ surface elevation
$H =$ total depth, $h =$ bathymetric depth
$u, v =$ depth-averaged horizontal velocities
$F_x, F_y =$ horizontal forces including friction
$S =$ source/sink term

Compact Form of the Equations

Rewriting terms into matrix/vector form gives

The Shallow Water Equations (conservation form)

$$\frac{\partial \mathbf{w}}{\partial t} + \nabla \cdot \mathbf{F}(\mathbf{w}) = \mathbf{r}(\mathbf{w})$$

where

$$\begin{aligned}
\mathbf{w} &= \begin{bmatrix} \zeta, & uH, & vH \end{bmatrix}^T \\
\mathbf{r} &= \begin{bmatrix} S, & gH\frac{\partial \zeta}{\partial x} + F_x, & gH\frac{\partial \zeta}{\partial y} + F_y \end{bmatrix}^T \\
\mathbf{F} &= \begin{bmatrix} uH & vH \\ Hu^2 + g(H^2 - h^2) & Huv \\ Huv & Hv^2 + g(H^2 - h^2) \end{bmatrix}
\end{aligned}$$

Discretization

- DG-SWEM uses the discontinuous Galerkin (DG) method to discretize in space and Runge-Kutta in time
- Combines advantages of FEM and FVM:
  - Finite element: high-order basis functions, works well on complex geometries
  - Finite volume: designed for conservation laws, guarantees local mass conservation, stability achieved from numerical flux

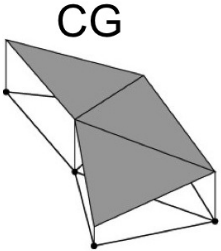
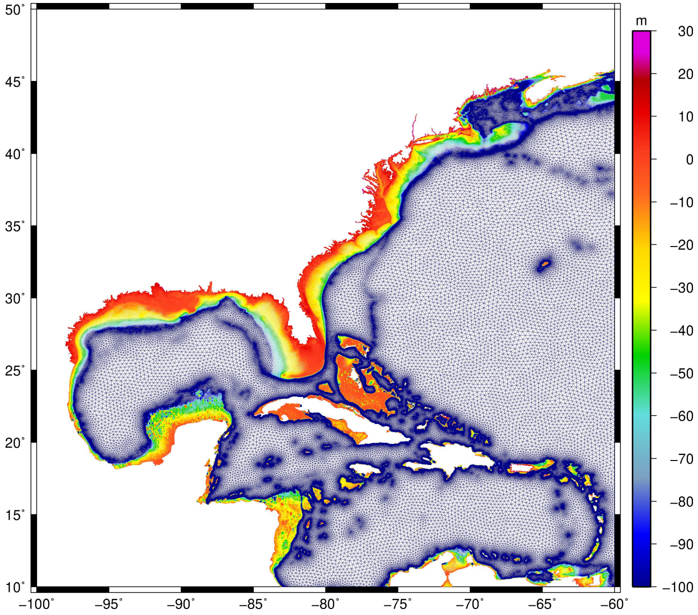


Image from `https://mathstats.uncg.edu/applied/dgfiniteelement/`

Computational Domain



Incorporating rainfall

- Directly specify rain intensity (m/s) at each node in the grid
  - Can be used in hindcasting, given observed rain data
  - Need to preprocess different types rain data
- Use parametric rainfall models
  - Rain intensity at each point can be estimated using storm data
  - If works, useful for forecasting
  - Comparison of existing parametric models in

    Brackins and Kalyanapu (2019). *Evaluation of Parametric Precipitation Models in Reproducing Tropical Cyclone Rainfall Patterns*. Journal of Hydrology.

R-CLIPER Rain Model

- Based on the work of Lonfat et al. (2004) and Marks and DeMaria (2003)
- Curve fitting using Tropical Rainfall Measurement Mission (TRMM) rainfall data from storm between 1998-2002:

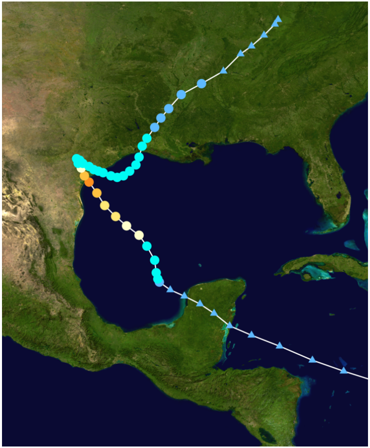
$$TRR(r, V) = \begin{cases} T_0 + (T_m - T_0)(r/r_m), & r < r_m \\ T_m e^{-((r-rm)/r_e)}, & r \geq r_m \end{cases} \tag{1}$$

where

$$\begin{aligned} TRR &= \text{rain rate (inch/day) at a given point} \\ r &= \text{radius from the point to the center of the storm} \\ V &= \text{maximum wind speed} \end{aligned}$$

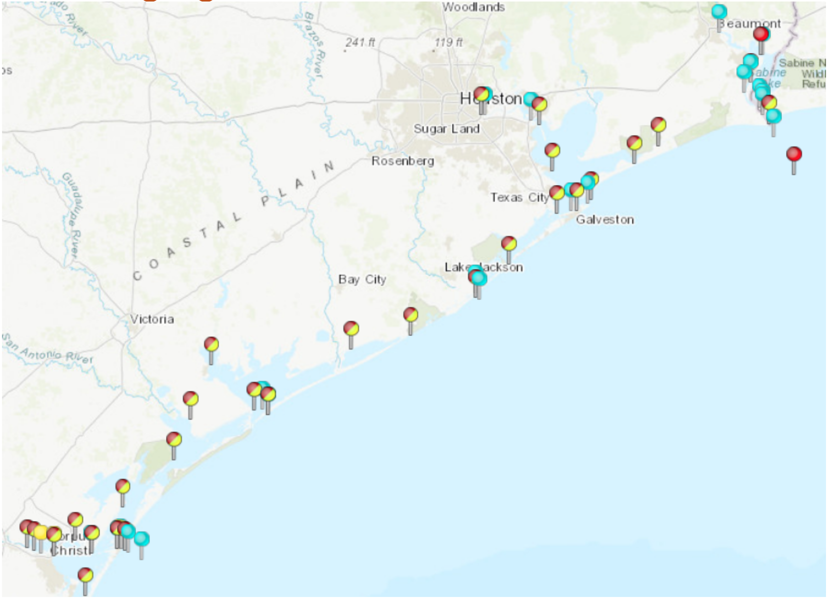
Test case: Hurricane Harvey (2017)

- Maximum total rain of 51 inches in the Houston city area
- Surge relatively low
- Simulation dates: August 23 - September 2, 2017
- Timestep = 0.5 seconds
- Used 3,200 processors, took about 13 hours on the Texas Advanced Computing Center (TACC)

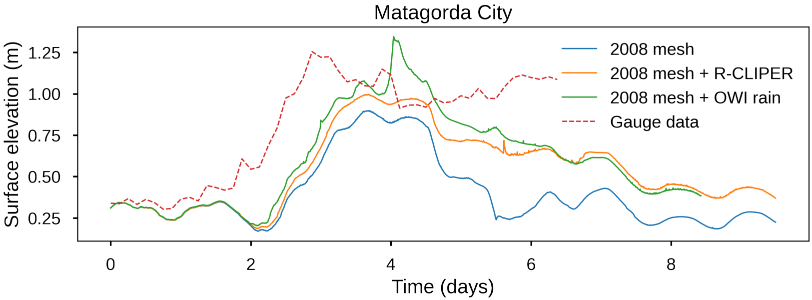


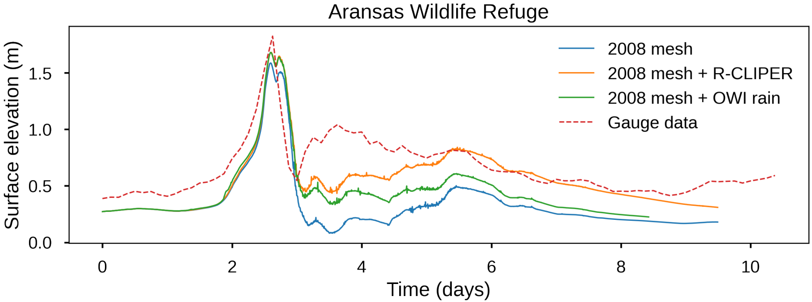
Track of Hurricane Harvey (2017)

Water level gauge locations



Results - Water Level Comparisons





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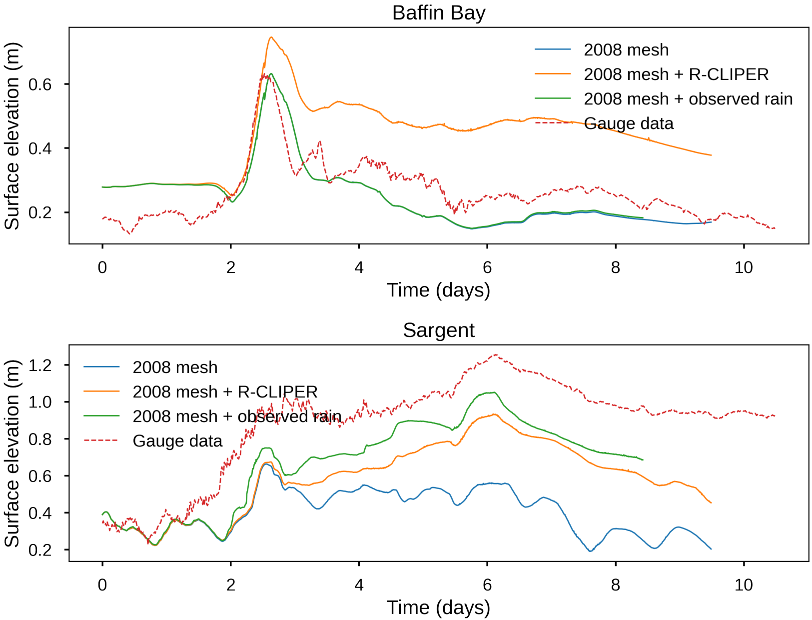

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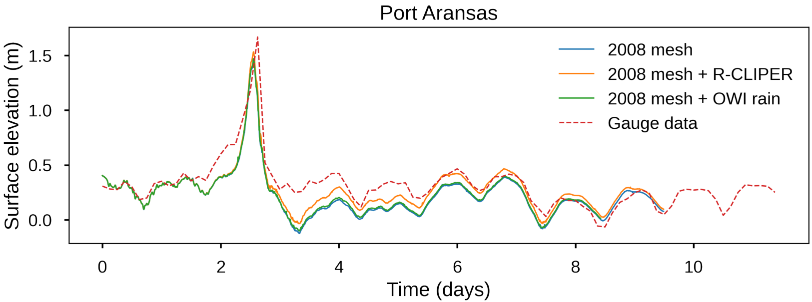
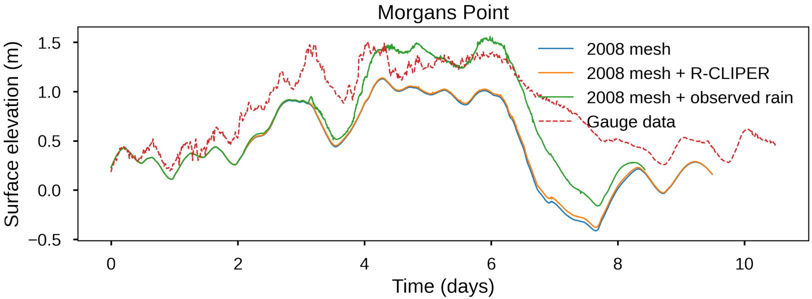
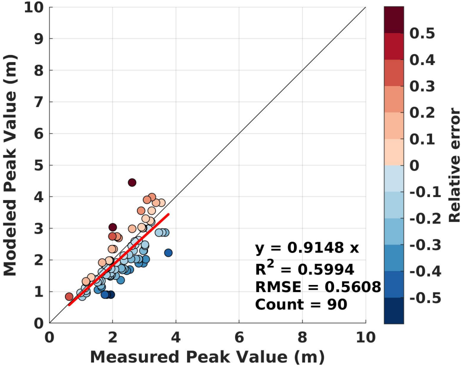


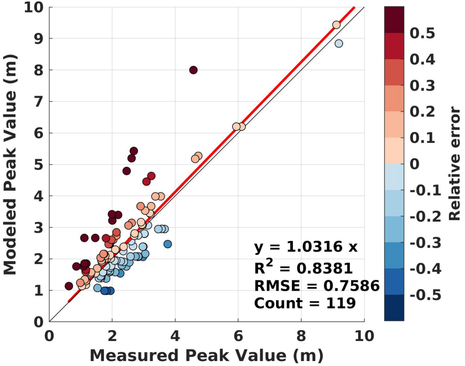


Results - High Water Marks Comparisons

DG-SWEM without rainfall

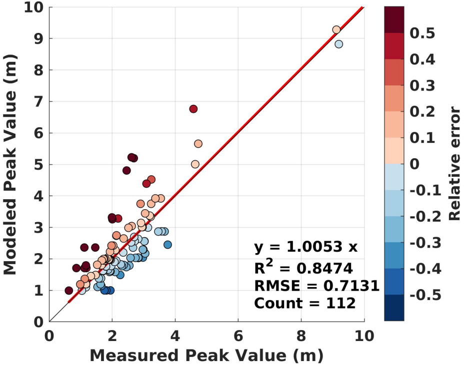


DG-SWEM with R-CLIPER

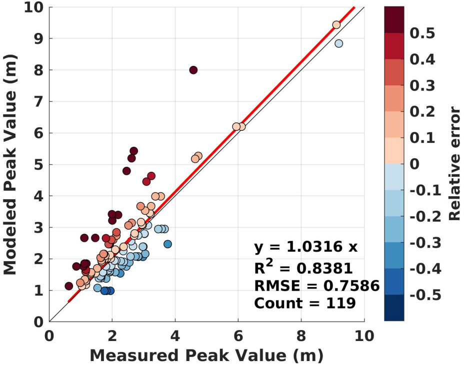


Results - High Water Marks Comparisons

DG-SWEM with observed rain



DG-SWEM with R-CLIPER



Conclusion and current work

- Incorportation of rainfall slightly raises overall surface elevation
- High water mark comparisons indicate a lot overprediction at certain points by both parametric and observed rain
- Underpredictions after peak for locations along the coast; no consistent trend of parametric vs. observed rain

Work in progress:

- Investigate the spatial distribution of high water marks
- Test other parametric rain models (IPET is being incorporated)
- Incorporate river discharge fluxes as boundary conditions
- Test other datasets

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