Hurricane Surge Response Functions

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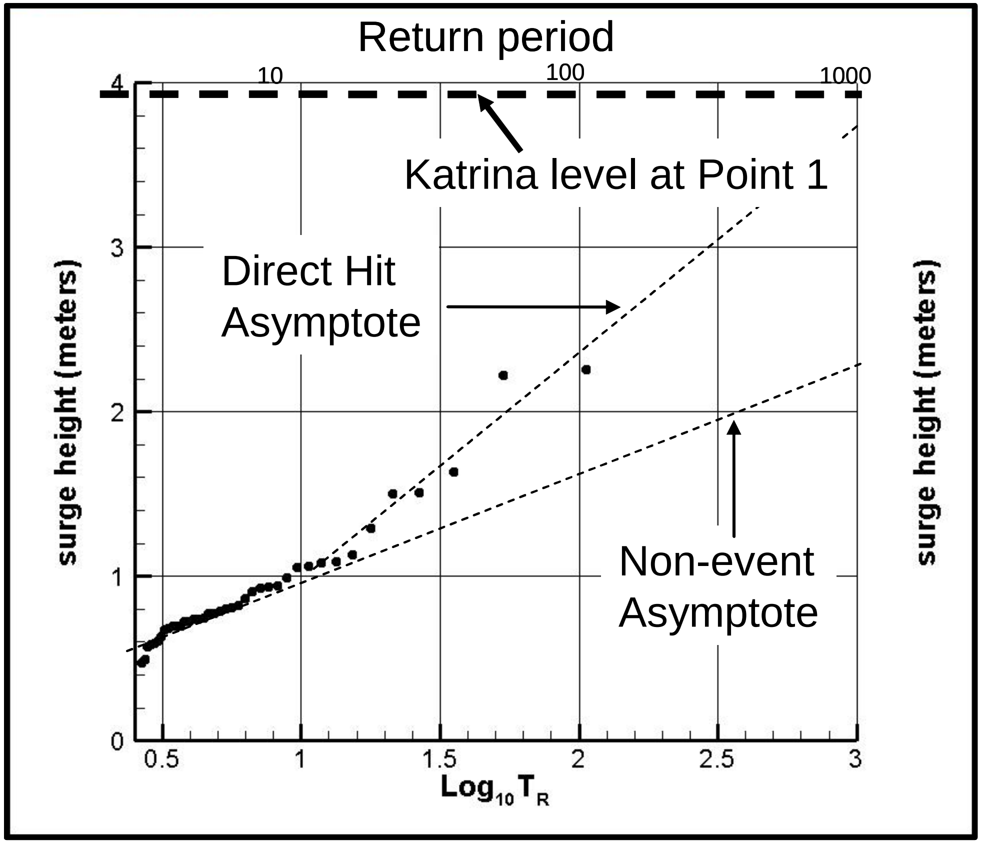
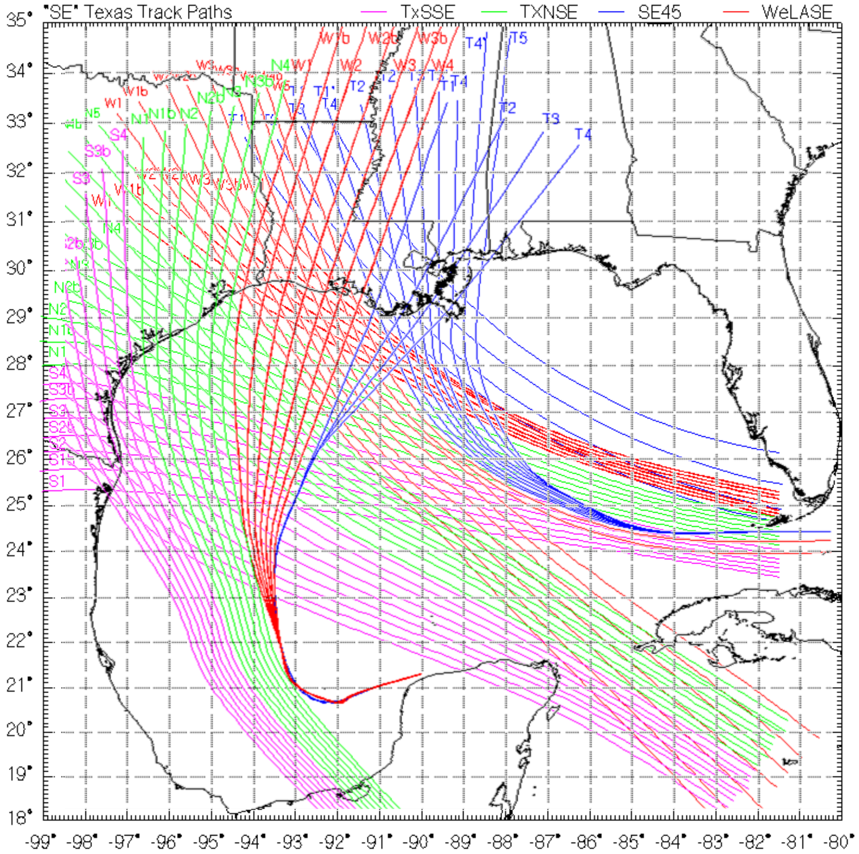
Surge Response Functions
Outline

- Motivation
- Background
- Methodology
- Surge Characteristics
- Parameterization
- Results
- Ongoing Research
- Hurricane Ike Verification
- Summary

Surge Response Functions
Motivation

1. An improved, efficient, and accurate risk-assessment method for coastal flooding is required.
2. Develop a continuous surge estimator for emergency response

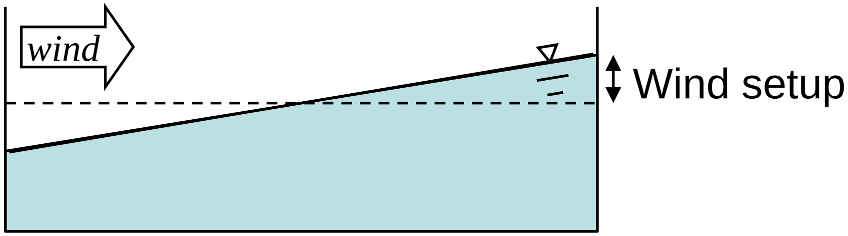




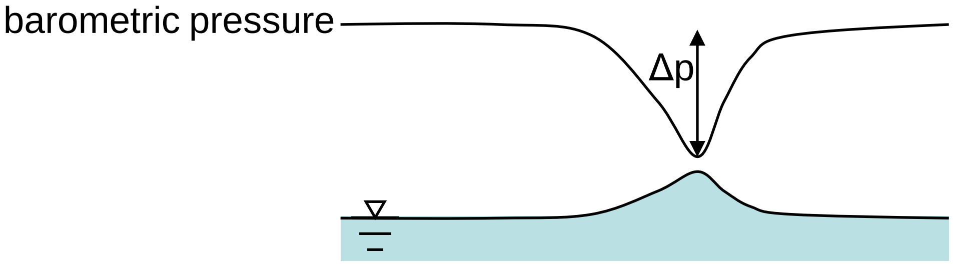
Surge Response Functions
Background – Surge Generation

Primary mechanisms:

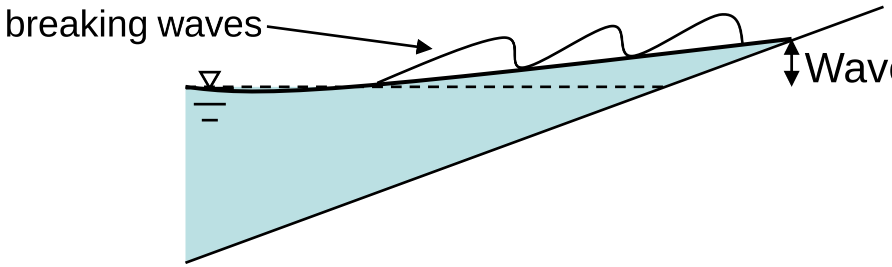
- Wind setup:



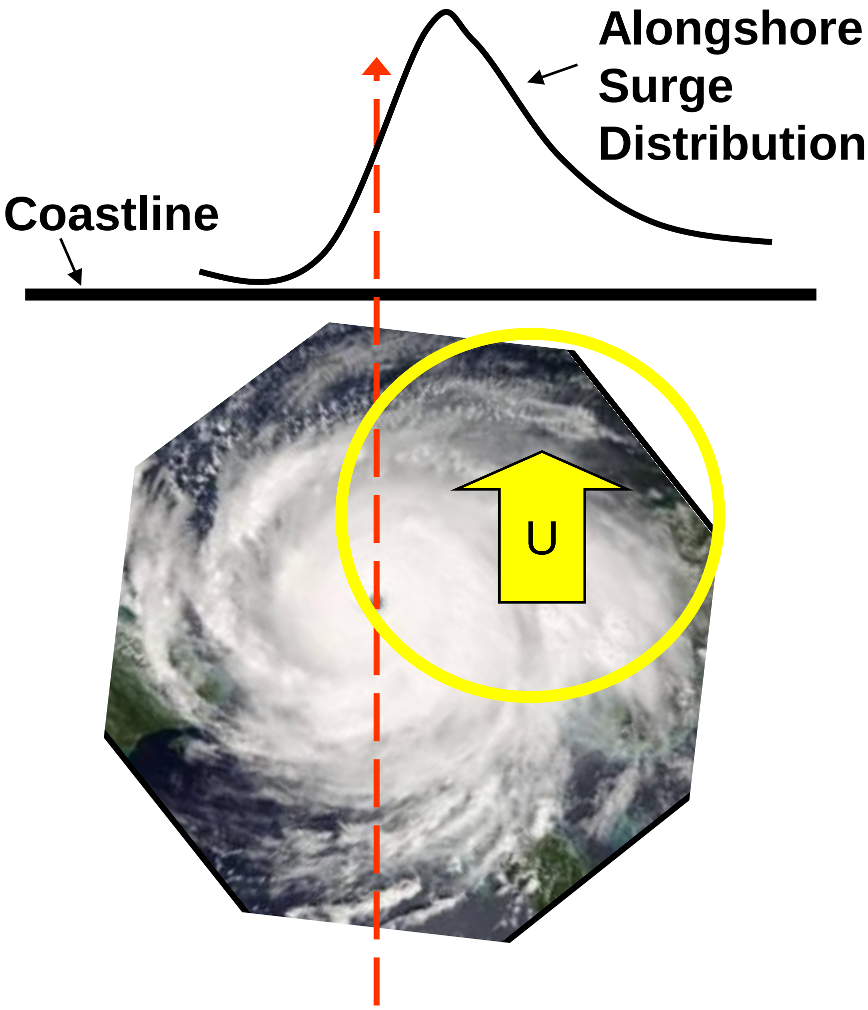
- Low pressure:

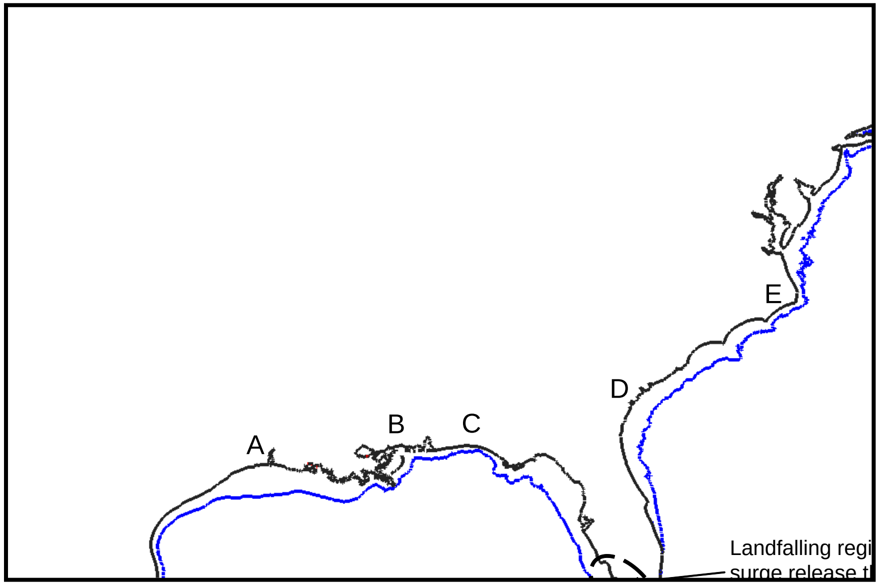


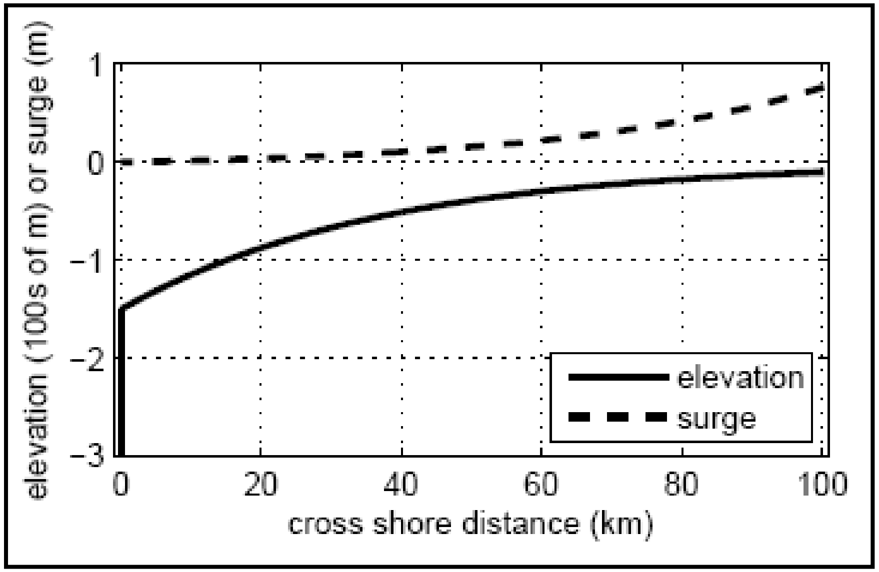
- Wave setup:



Surge Response Functions
Background – Surge Generation







Surge Response Functions
Background – Historical Approach

- Form data set of "largest" storms (measurements or hindcasts)
- Typical applications:
  - Points over Threshold (POT)
  - Annual series
- PARAMETRIC (GEV, Weibull, Log Normal or other assumed form):
  - Considers sampling size effects on "fitted" curve
  - Uses various fitting methods (MLM, MOM, etc.)
  - Allows parametric estimation of return periods larger than given by the historical record
- NON-PARAMETRIC (e.g., EST):
  - No assumptions on data's probability distribution in interior
  - Uses data to develop distribution in interior
  - Still extrapolates beyond data range using parametric "fit" to data
- Results extremely sensitive to record length
- Storms assumed to be from a homogeneous parent population
  - Climate variability typically excluded

Surge Response Functions
Methodology – Response Function Approach

General form for surge response at location x and time t:

$$\zeta(x,t) = \Phi(\underline{G}, \underline{W} \mid c_p, R_{\max}, v_f, \theta, S(t), t)$$

where

$\zeta(x,t)$ is the storm surge at location x and time t,

Φ is a numerical model used to generate surges over a grid,

$\underline{G}$ is a time invariant grid of bathymetry/topography,

$\underline{W}$ is a wind field over the grid at time t,

c_p is the central pressure,

$R_{\max}$ is the radius to maximum wind speed from the center of the storm,

v_f is the forward velocity of the storm,

θ is the geographic angle of the track, and

$S(t)$ is the position of the storm along the track at time t,

Surge Response Functions
Methodology – Response Function Approach

Joint probability matrix:

$$p(c_p, R_p, v_f, \theta_l, x) = \Lambda_1 \cdot \Lambda_2 \cdot \Lambda_3 \cdot \Lambda_4 \cdot \Lambda_5$$

$$\Lambda_1 = p(c_p \mid x) = \frac{\partial F[a_0(x), a_1(x)]}{\partial(\Delta p \mid c_p)} = \frac{\partial}{\partial x}\left\{ \exp\left\{ -\exp - \left[\frac{\Delta p - a_0(x)}{a_1(x)} \right] \right\} \right\} \text{ (Gumbel Distribution)}$$

$$\Lambda_2 = p(R_p \mid c_p) = \frac{1}{\sigma(\Delta P)\sqrt{2\pi}} e^{-\frac{(\bar{R}_p(\Delta P) - R_p)^2}{2\sigma^2(\Delta P)}}$$

$$\Lambda_3 = p(v_f \mid \theta_l) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\bar{v}_f(\theta_l) - v_f)^2}{2\sigma^2}}$$

$$\Lambda_4 = p(\theta_l \mid x) = \frac{1}{\sigma(x)\sqrt{2\pi}} e^{-\frac{(\bar{\theta}_l(x) - \theta_l)^2}{2\sigma^2(x)}}$$

$$\Lambda_5 = \Phi(x)$$

Uncertainty: $\sigma_{total}^2 = \sigma_{tide}^2 + \sigma_{\text{model}}^2 + \sigma_B^2 + \sigma_{waves}^2 + \sigma_{winds}^2 + \sigma_{residual}^2$

Surge Response Functions
Methodology – Numerical Simulation

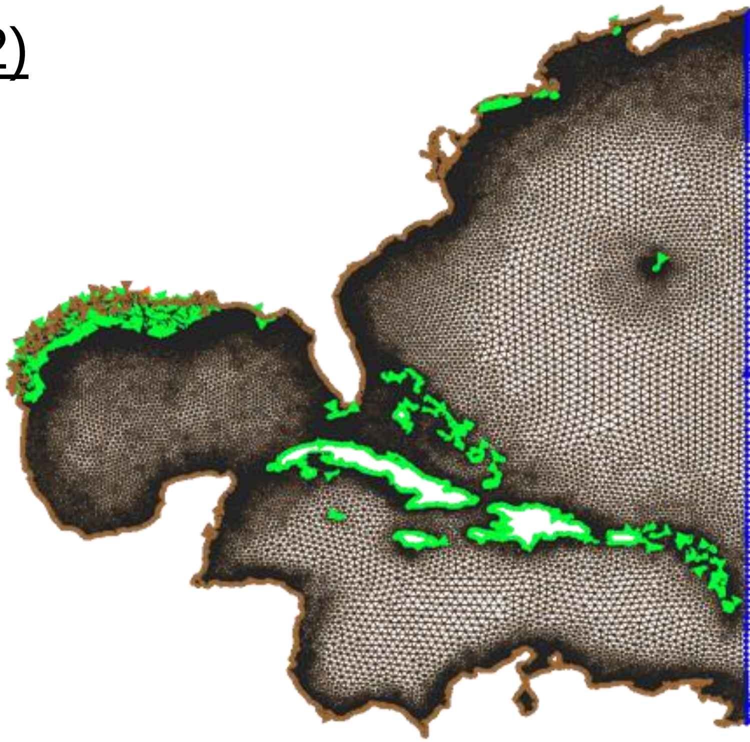
<u>Storm surge – ADCIRC (Luettich *et al.* 1992)</u>

- Hydrodynamic model:

$$\frac{\partial \vec{U}}{\partial t} + \left(\vec{U}\cdot\nabla_H\right)\vec{U} = -g\nabla_H\left(\varsigma + \frac{p}{g\rho_w} - \alpha\eta\right) + f\vec{k}\times\vec{U} + \frac{\vec{\tau_s}}{H\rho_w} - \frac{\vec{\tau_b}}{H\rho_w}$$

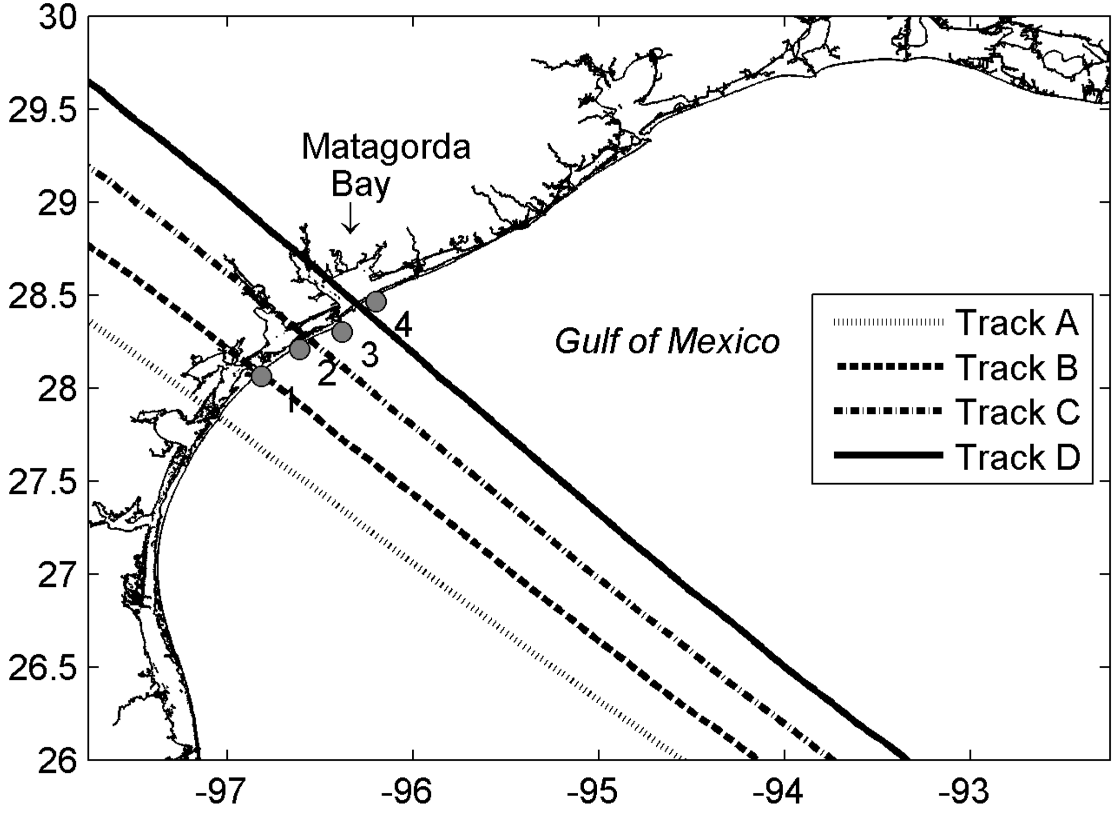
$$\frac{\partial H}{\partial t} + \nabla_H\left(\vec{U}H\right) = 0$$

- Finite element, variable resolution
- Model forcing:
    - Wind stress
    - Barometric pressure



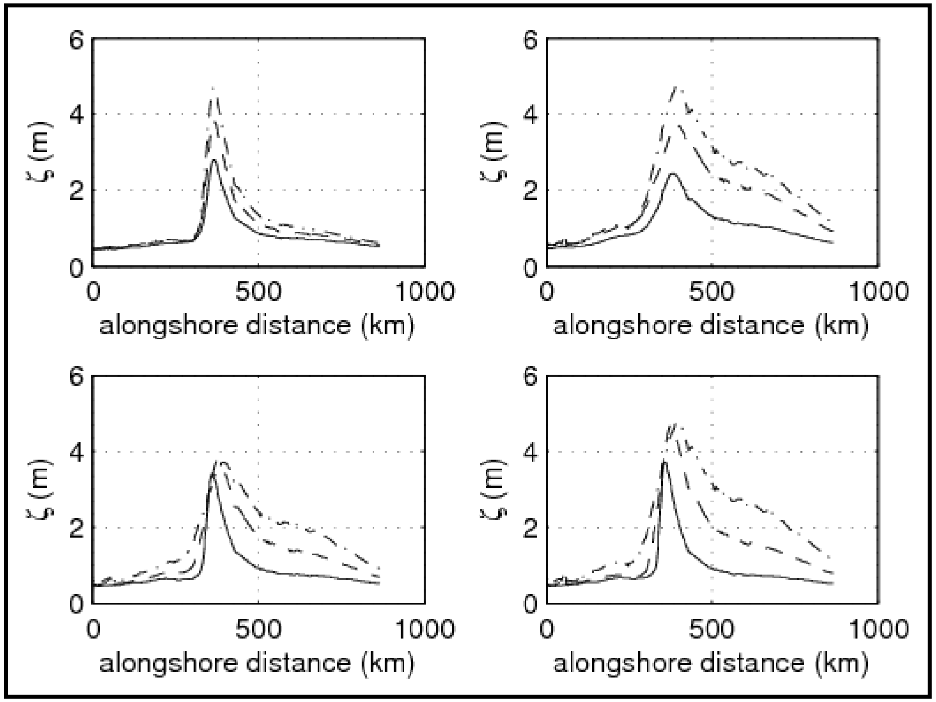
Surge Response Functions
Methodology – Numerical Simulation

- Planetary Boundary Layer Model (Thompson & Cardone 1996):
  - Input V_f, θ, c_p, R_p, track position, …
  - 75 storms on 4 tracks (V_f constant, θ ~ constant)

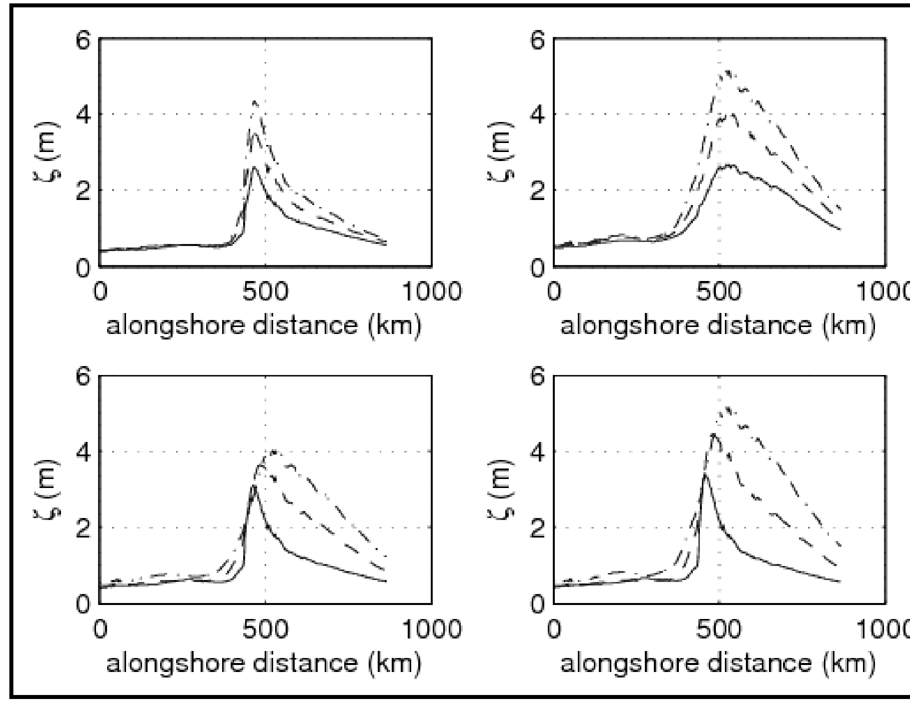


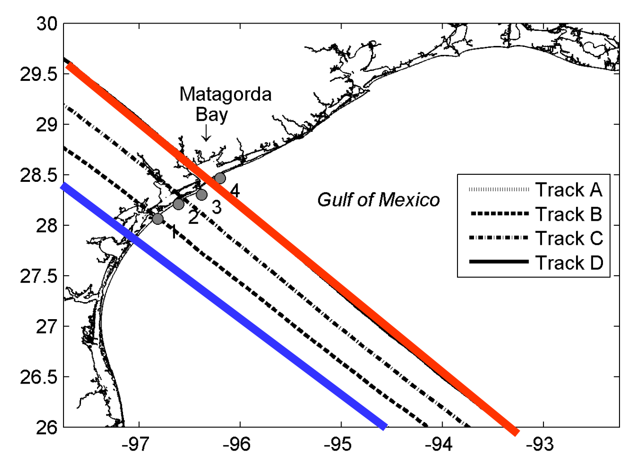
Surge Response Functions
Surge Characteristics – Alongshore Variation

Track A



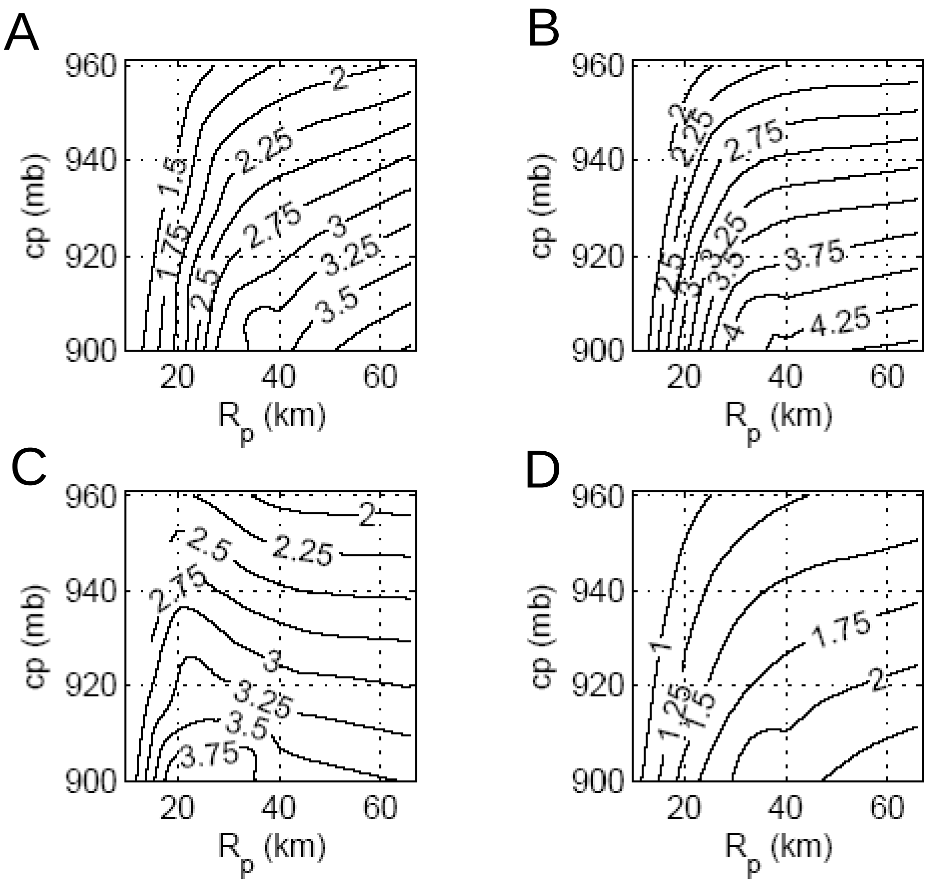
Track D

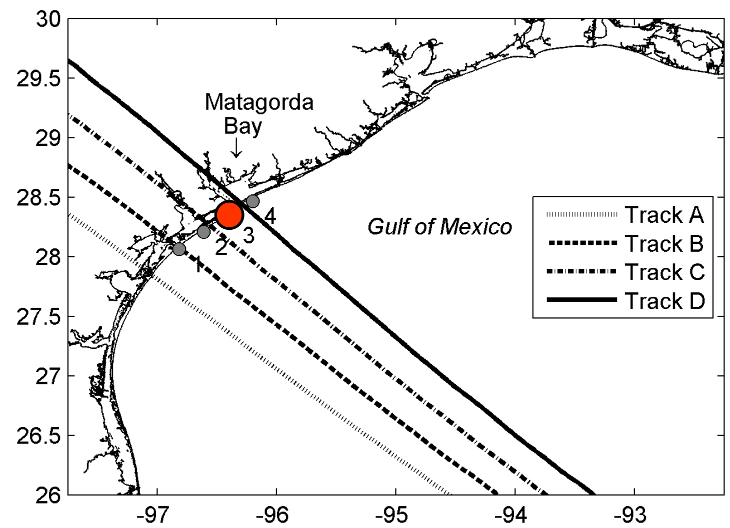




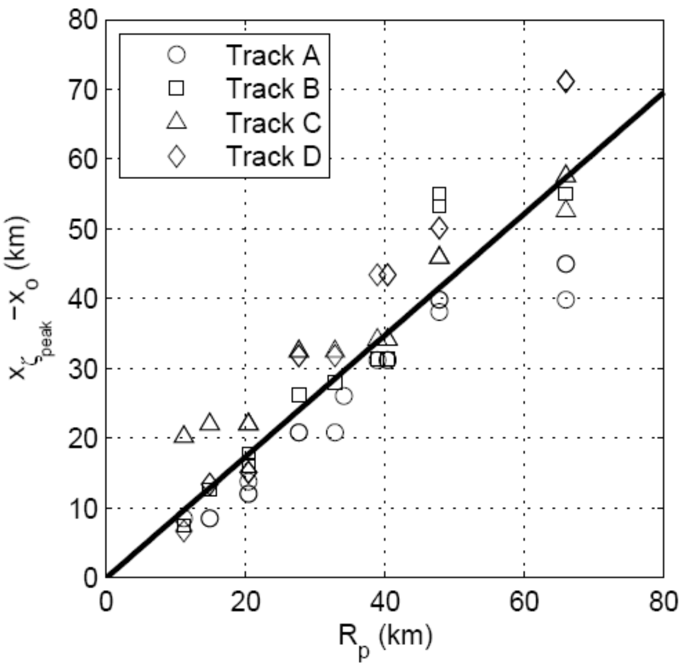
Surge Response Functions
Surge Characteristics – Response Surfaces

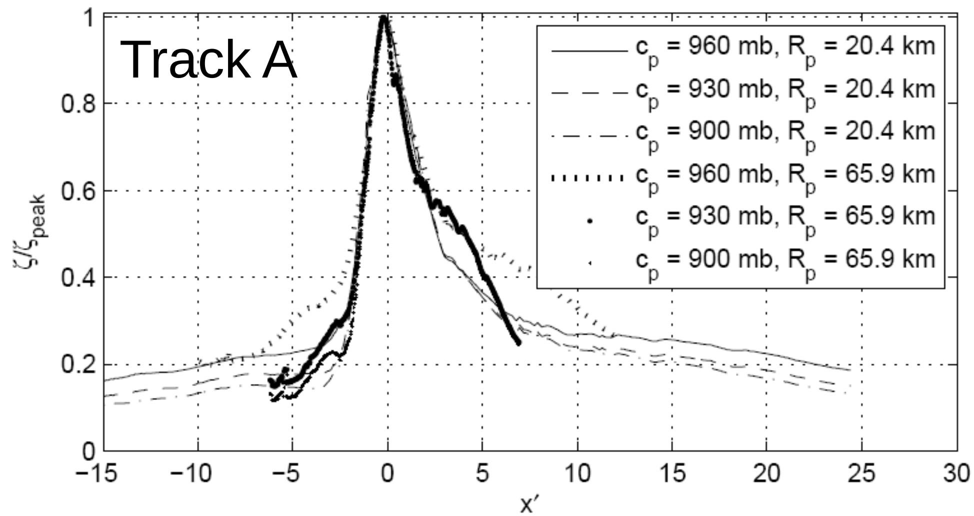
Location 3





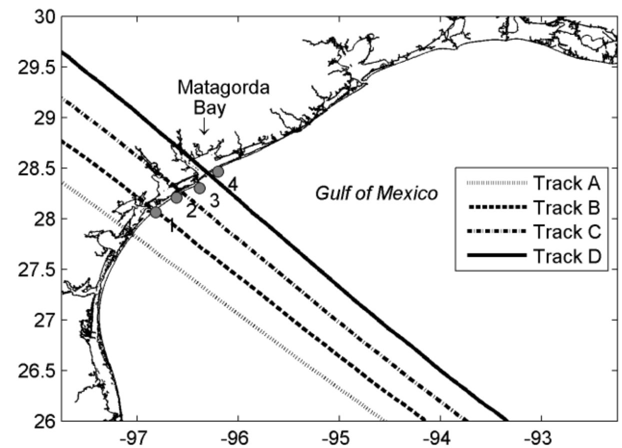
Surge Response Functions
Parameterization





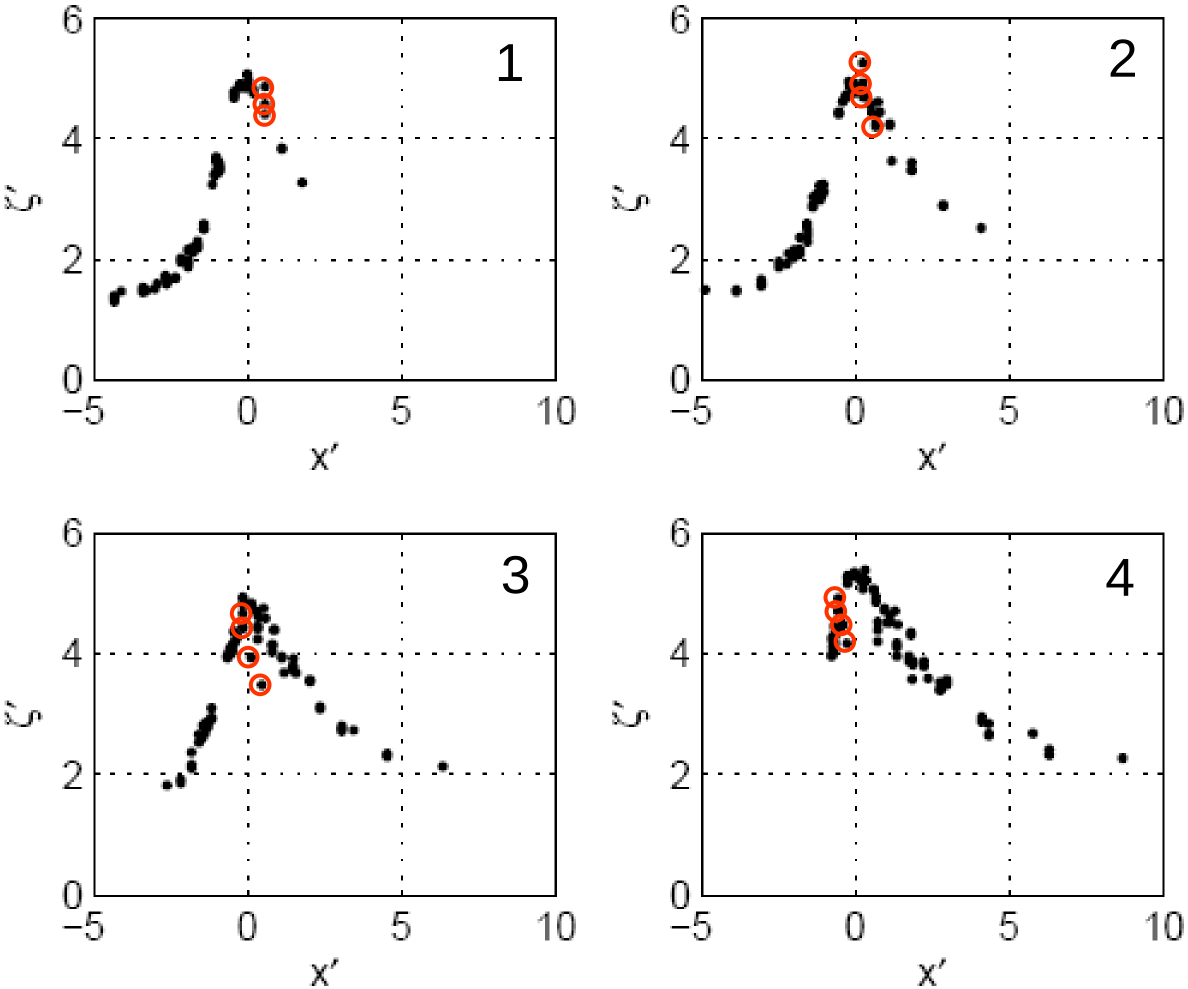
$$x' = \frac{(x - x_o)}{R_p} - \lambda$$

$$\zeta' = \frac{\gamma\zeta}{\Delta p} + m_x \Delta p$$



Surge Response Functions

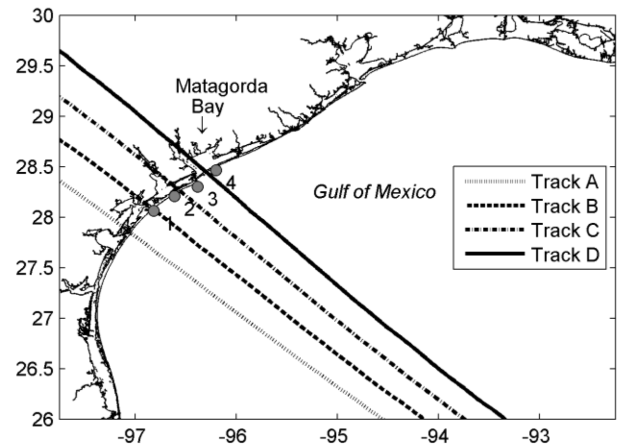
Parameterization – Response Function



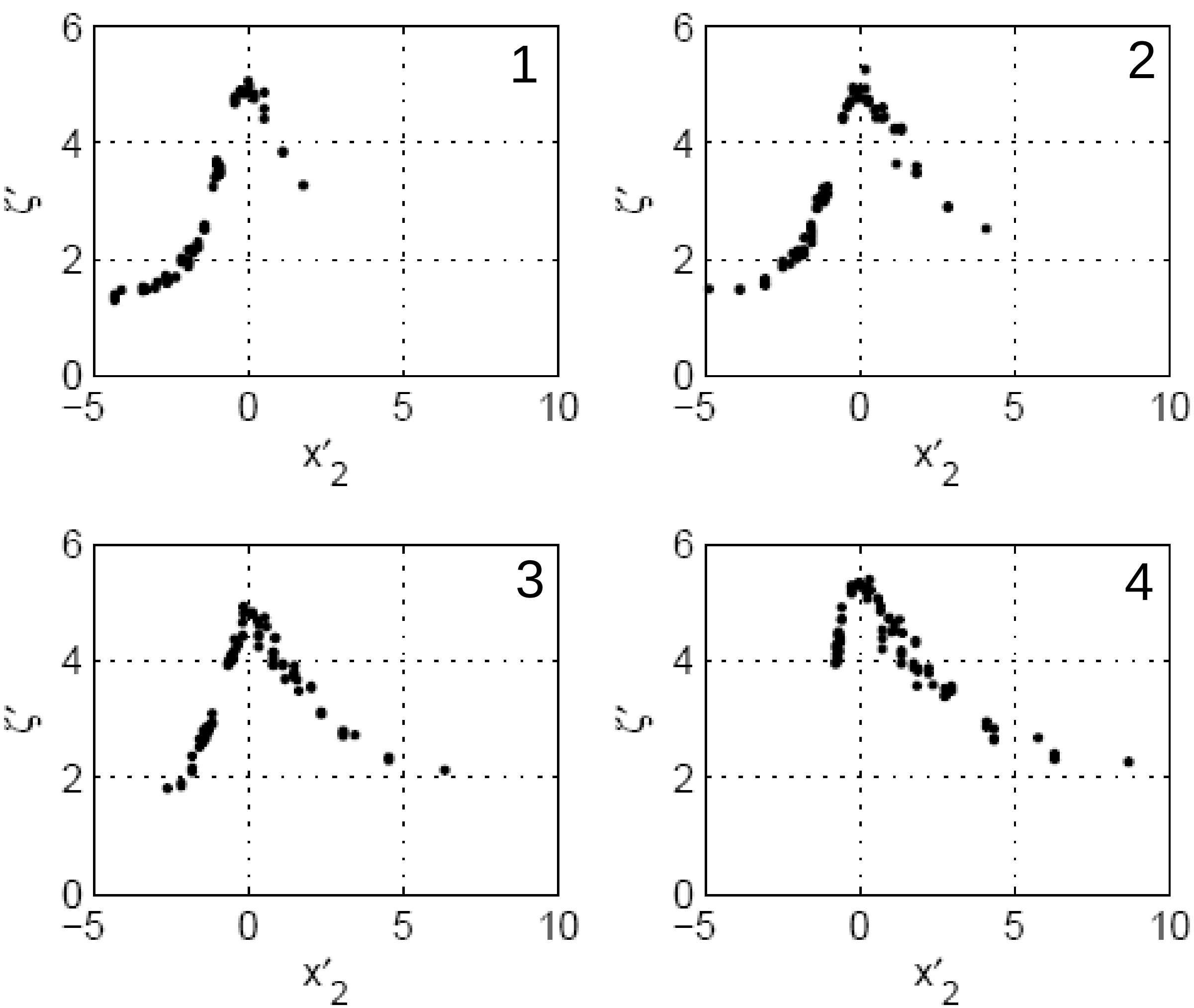
$$x_2' = x' - F(1-R')H(1-R')$$

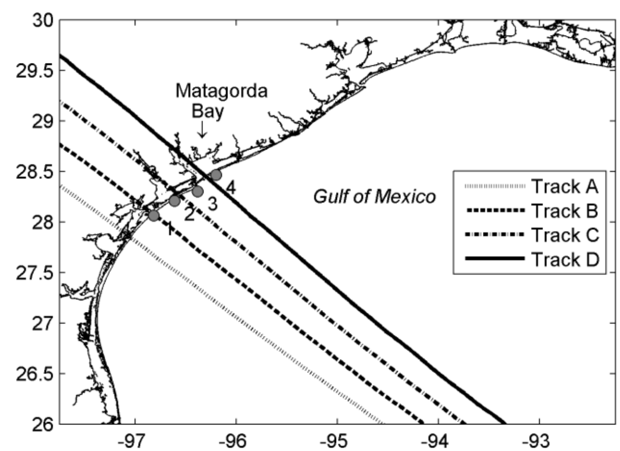
R' = *Rp*/*Rthres*

$$F(1-R') = \begin{cases} a_1(1-R') + b_1 & -\lambda \le x' \le 0 \\ a_2(1-R') + b_2 & 0 < x' \le \lambda \\ 0 & \lambda < |x'| \end{cases}$$



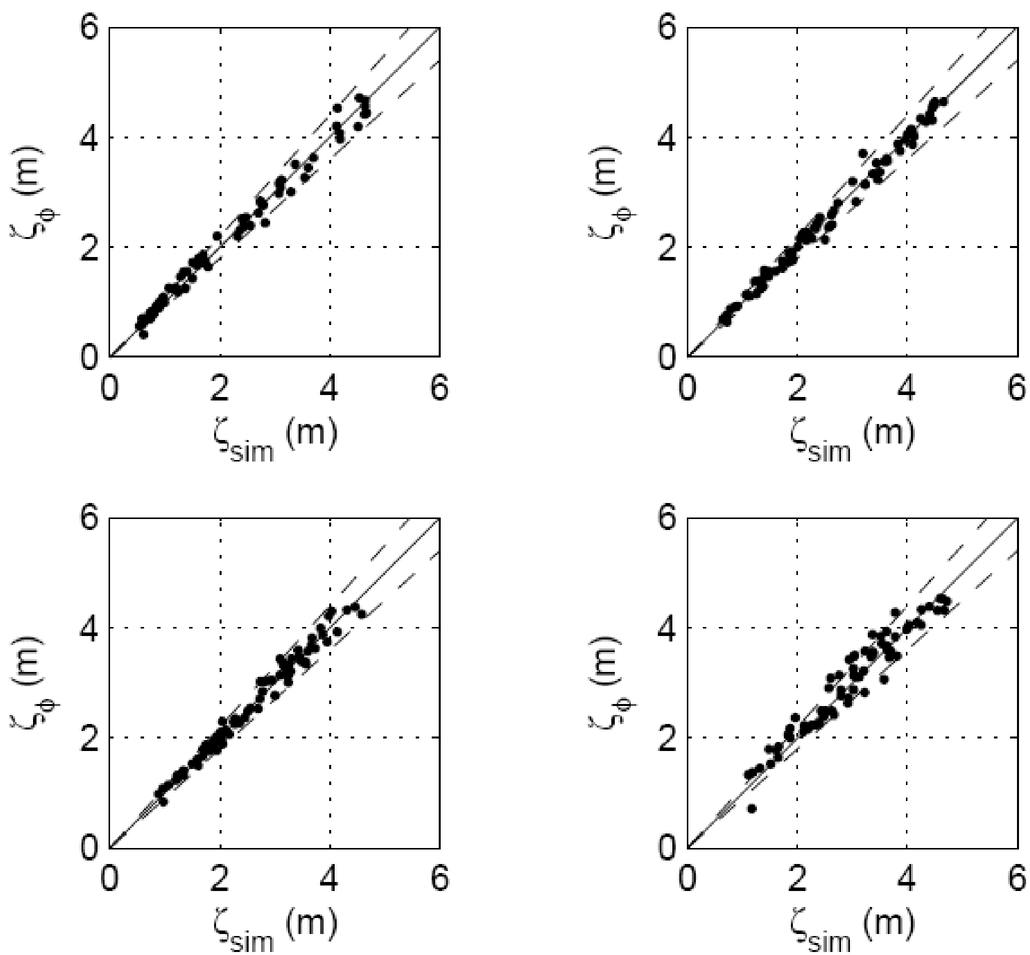
Surge Response Functions
Parameterization – Response Function

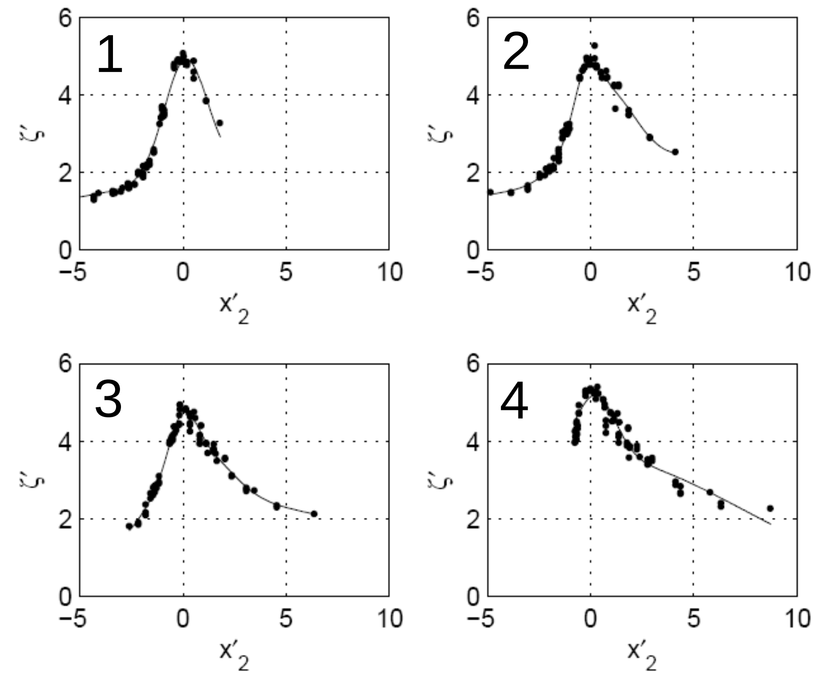


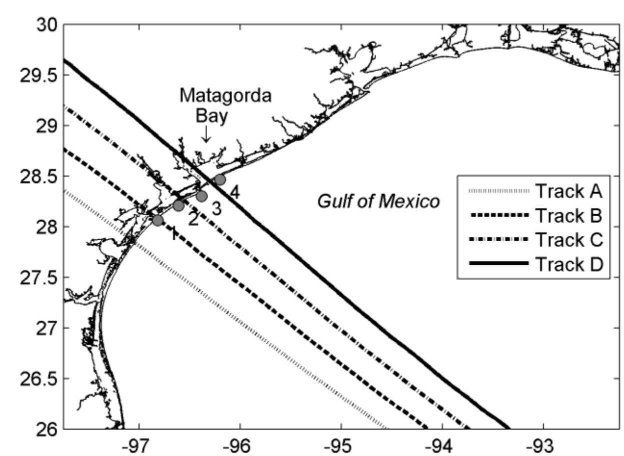


Surge Response Functions

Results – All Four Tracks at 30 km Spacing



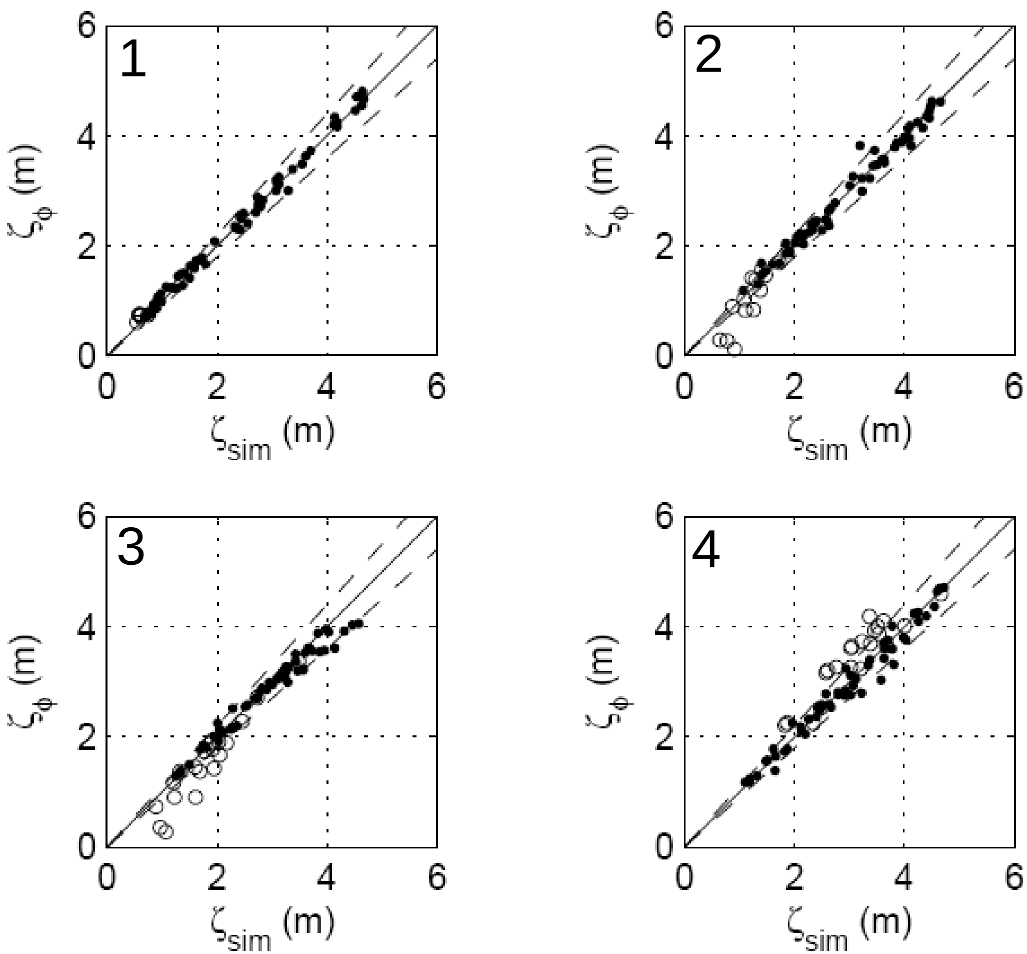


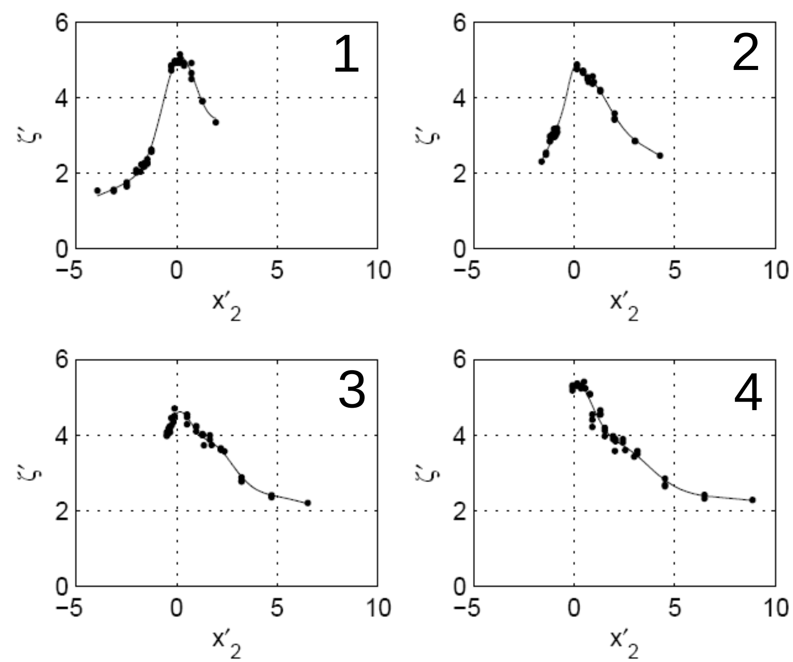


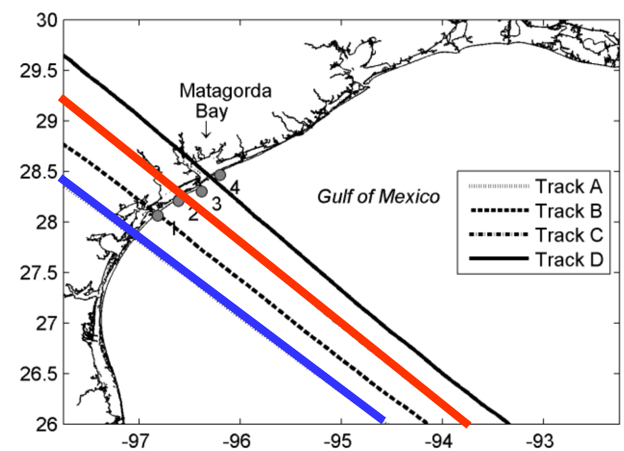
<u>75 simulations:</u>

mean error = 0 – +4 cm, RMS error = 12 – 24 cm

Surge Response Functions
Results – Two Tracks at 60 km Spacing

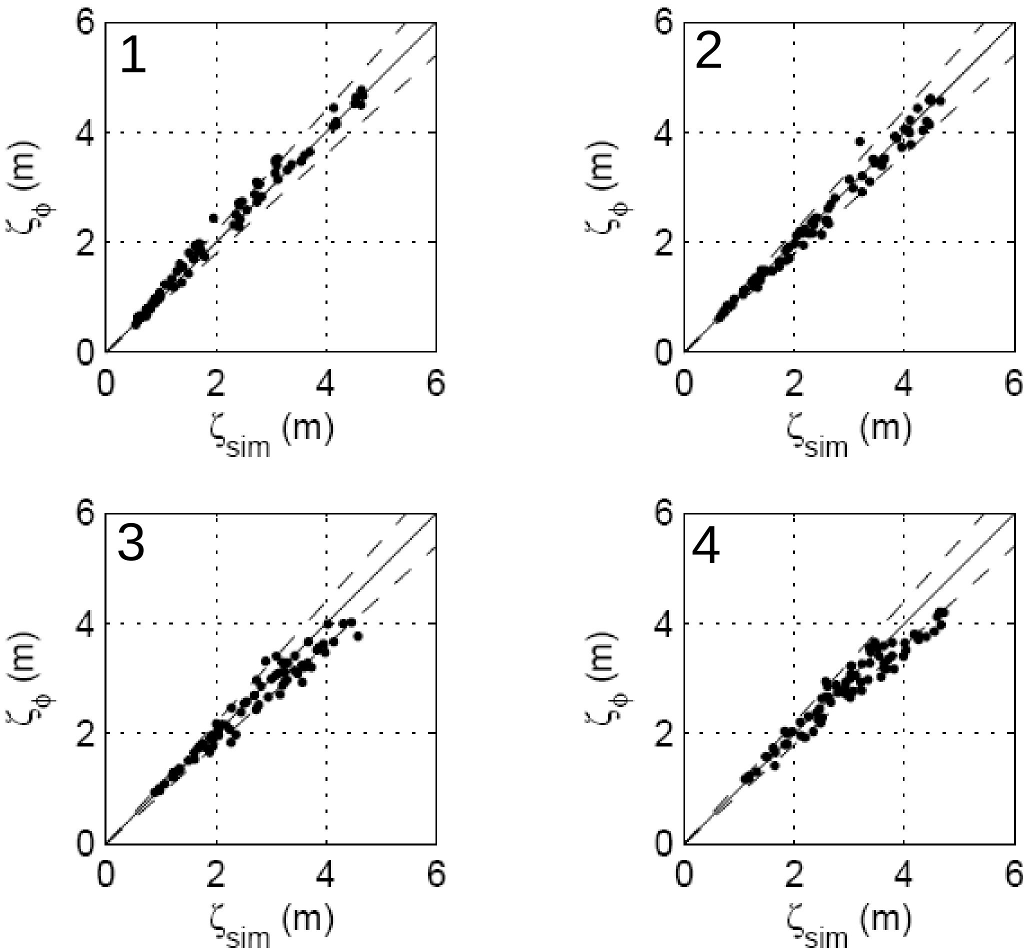


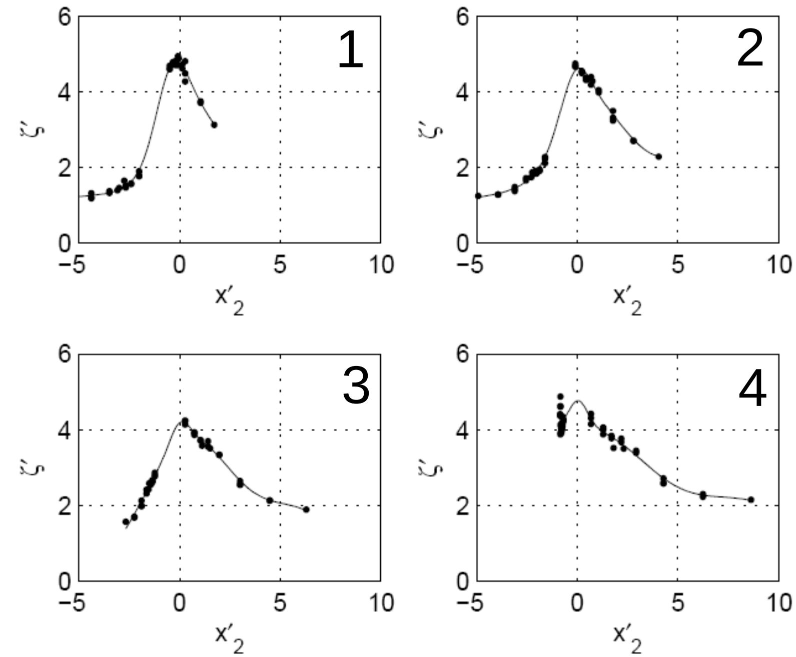


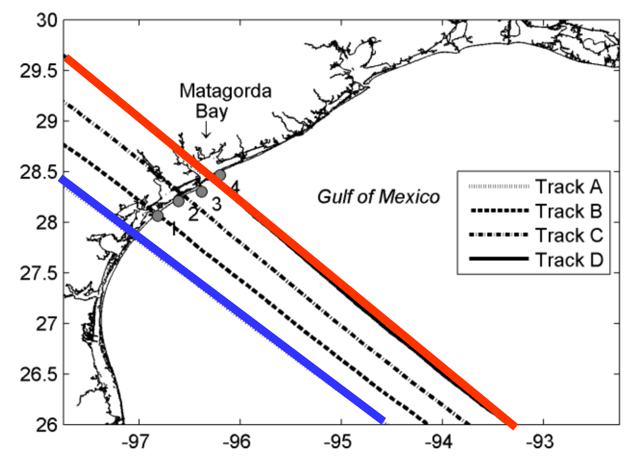


<u>37 simulations:</u>
mean error = -9 – +4 cm, RMS error = 10 – 19 cm

Surge Response Functions
Results – Two Tracks at 90 km Spacing



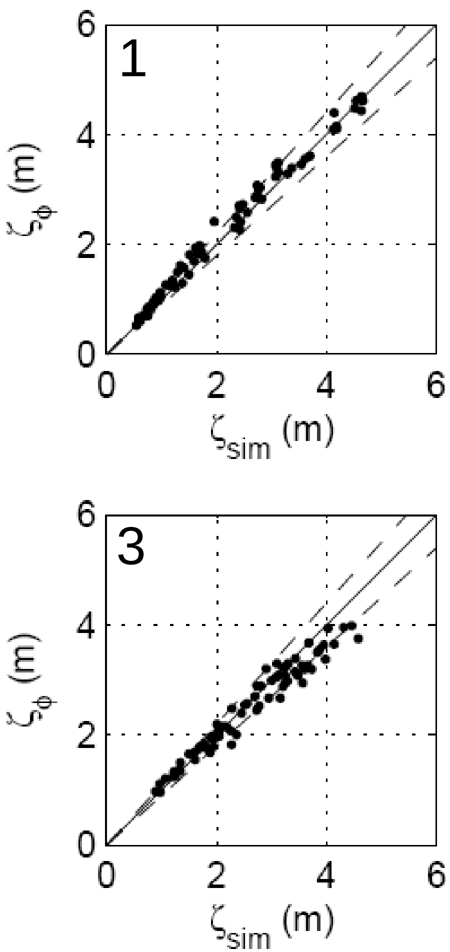


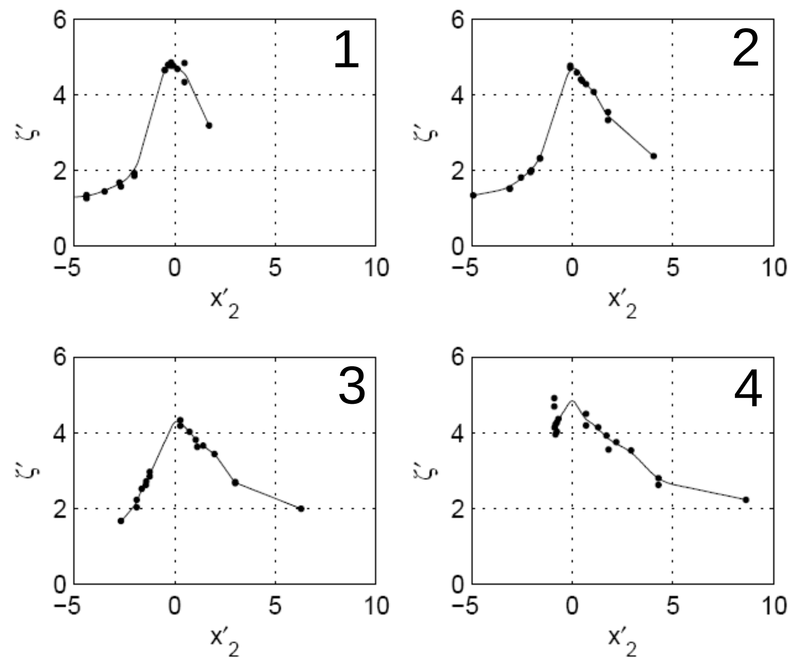


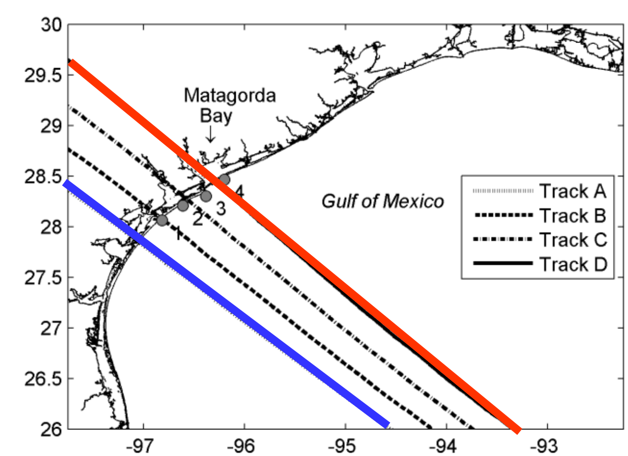
<u>38 simulations:</u>

mean error = -16 – +9 cm, RMS error = 15 – 30 cm

Surge Response Functions
Results – Two Tracks at 90 km Spacing, Limited Storms







<u>18 simulations:</u>
mean error = -17 – +10 cm, RMS error = 16 – 32 cm

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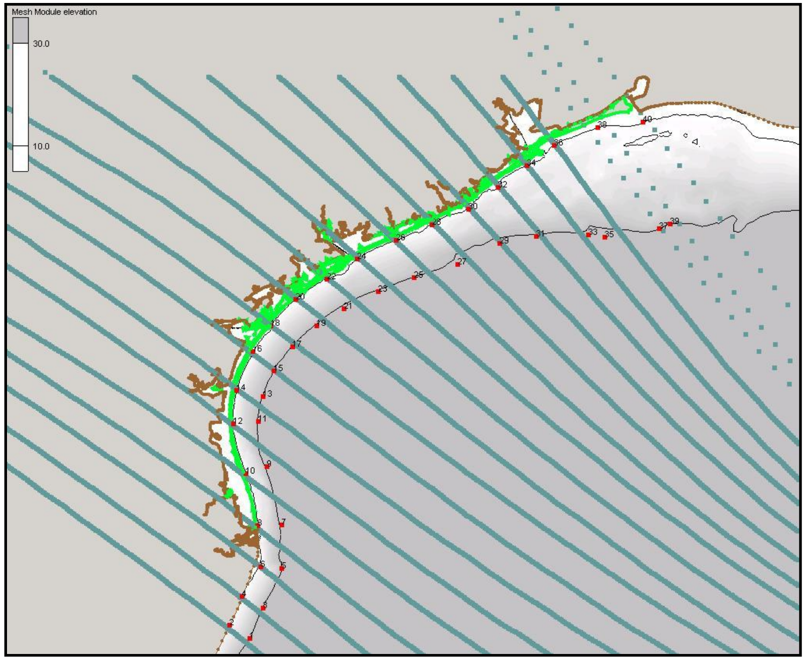
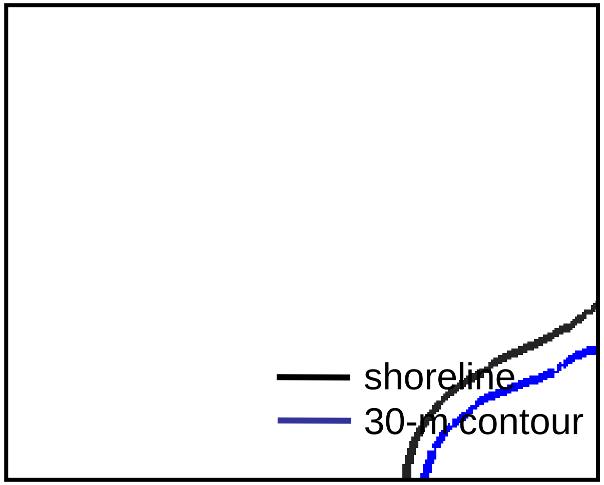
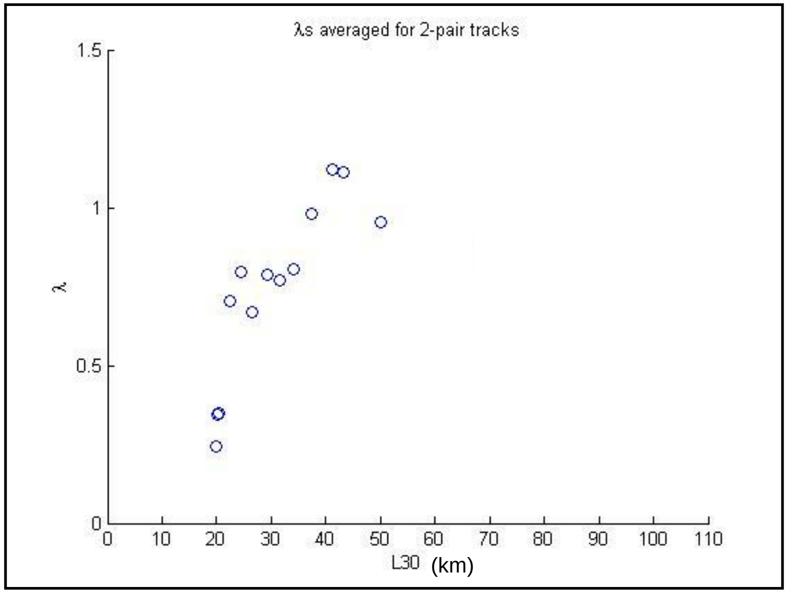
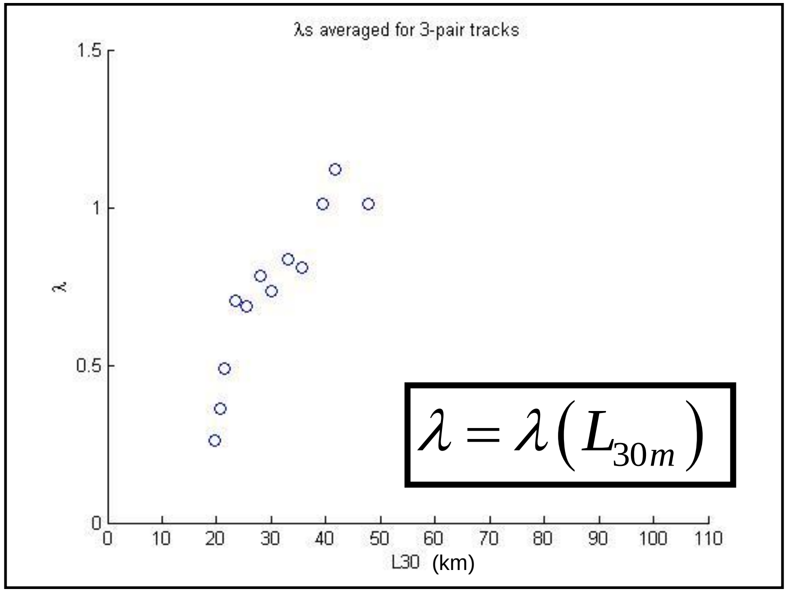
Surge Response Functions

Ongoing Research – Continental Shelf Width (Preliminary)

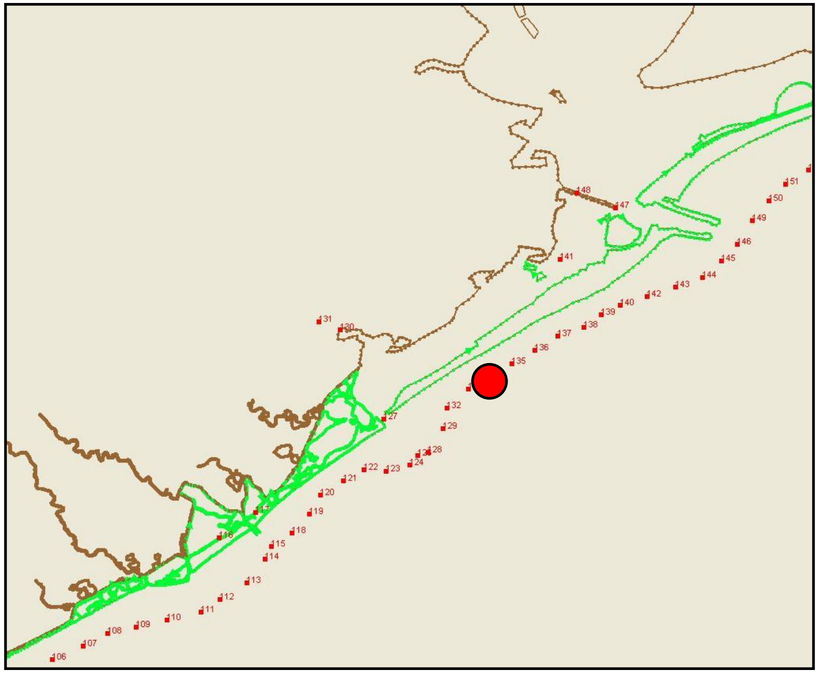




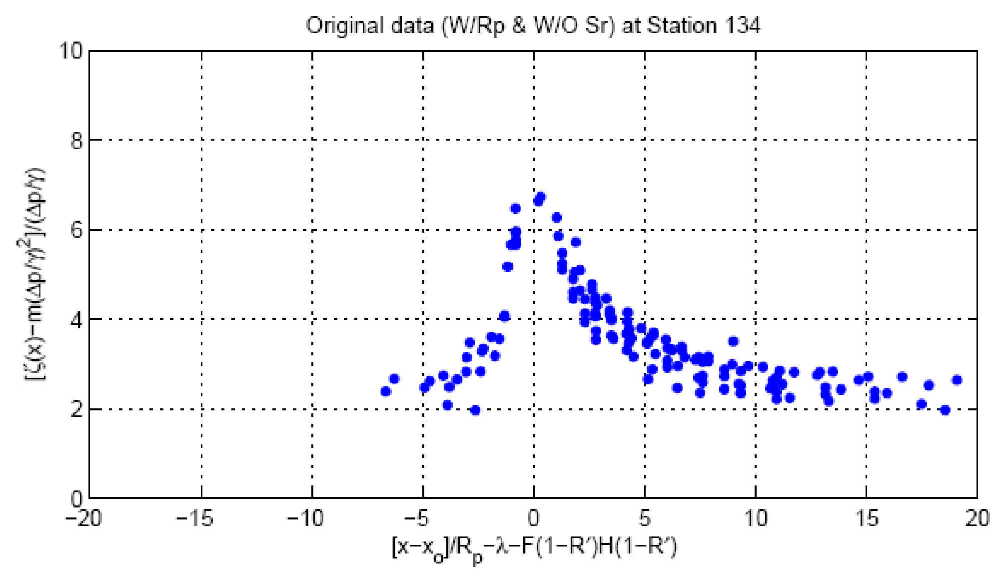


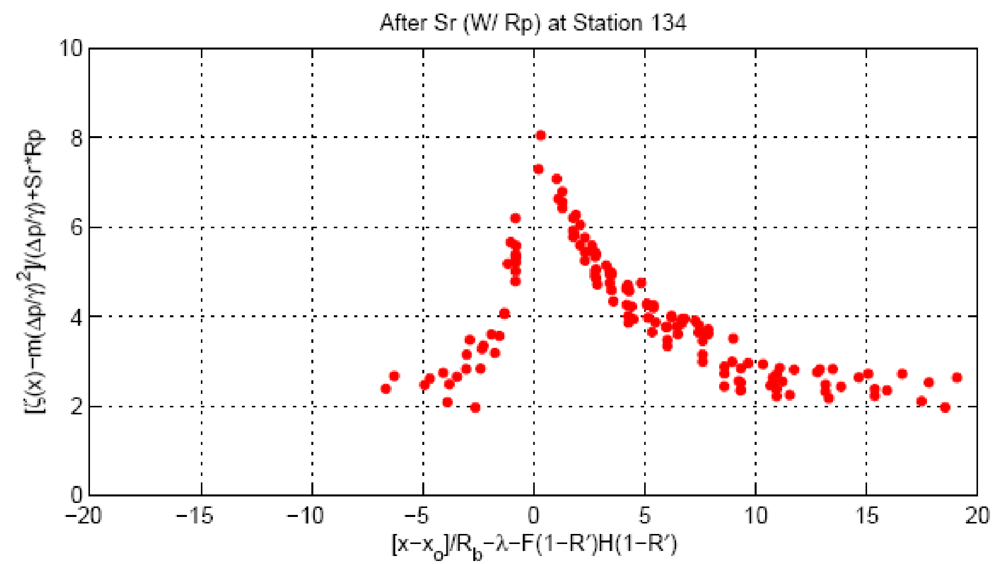


Surge Response Functions
Ongoing Research – Surge and Storm Size (Preliminary)



$$\zeta'_2 = \frac{\gamma\zeta}{\Delta p} + m_x \Delta p + S_R R_p$$

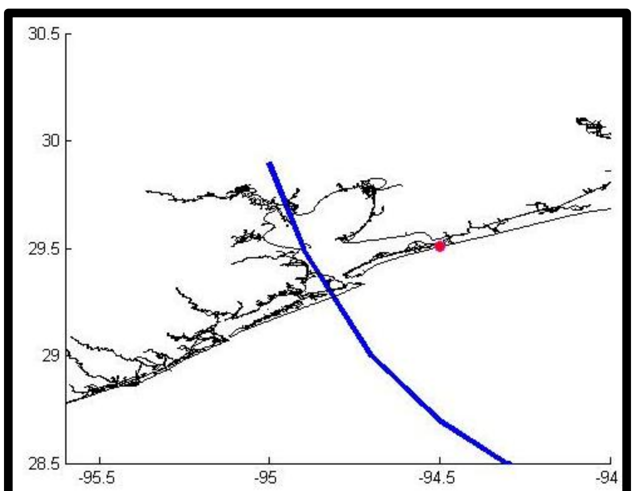




Surge Response Functions
Hurricane Ike – Preliminary Results

Maximum Surge Calculation near Rollover Pass

Rmax[km]	Peak [km]
10	10.78
14	12.48
18	13.32
22	13.88
26	14.29
30	13.76
34	13.30
38	12.94
42	12.65
46	12.41
50	12.21
54	12.04



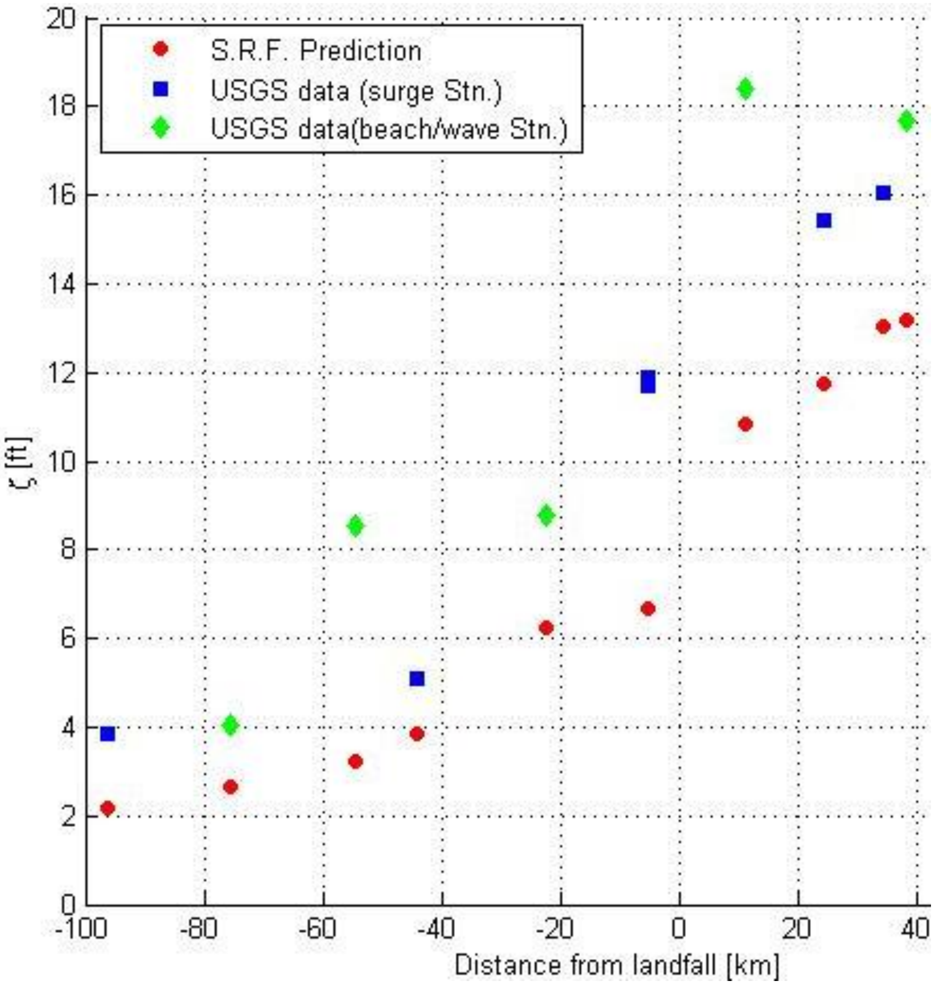
- Hurricane Ike characteristics: c_p=952 mb, R_{max} = 38 km
- Location 28 km to the right of the landfall

- *Water level elevation by tides and wave setup not included*
- *Impact of barrier island morphology not considered*

FEMA HWM = 14.70 ft, MSL (“wave runup”)

Surge Response Functions
Hurricane Ike – Preliminary Results

Comparison to USGS water level gauge data



- *Water level elevation by tides and wave setup not included*
- *Impact of barrier island morphology not considered*

ADCIRC Job Characterization on HYDRA

Each ADCIRC simulation ~ 1400 computational hours (32/64 processors)
Each coupled ADCIRC/wave simulation ~ 3500 computational hours (32/64 processors)

Advantages of using Hydra:

- Capable of running nine parallel simulations simultaneously
- Linkage to large data storage via K2 server

Hydra Usage Information for FY09:

- 296 jobs, 146267 cpu hours

Job Type	Total Jobs	Total Cpu Hours	Average Execution Time
1-cpu	153	65	25 minutes
32-cpu	82	76421	32 hours
64-cpu	60	68555	24 hours
128-cpu	1	1224	18 hours

Surge Response Functions
Summary

- Surge response approach presents solution to extreme-value statistics for coastal flooding
- Definable characteristics of response surfaces – given a single track:
  - Surge distribution scales with R_p and c_p
- Overall methodology must include a means to reflect uncertainty in predicted response surfaces
- Response surface prediction has potential to extend applicability of limited observation set (i.e. surges in stronger and weaker storms can be estimated)
- Response surface prediction reduces numerical simulation requirements by allowing functional interpolation between simulation results
- Application in coast bays viable