Improvements of Surge Response Function Methodology

Application for Extreme Hurricane Surge Estimation for Texas Coastal Bridges

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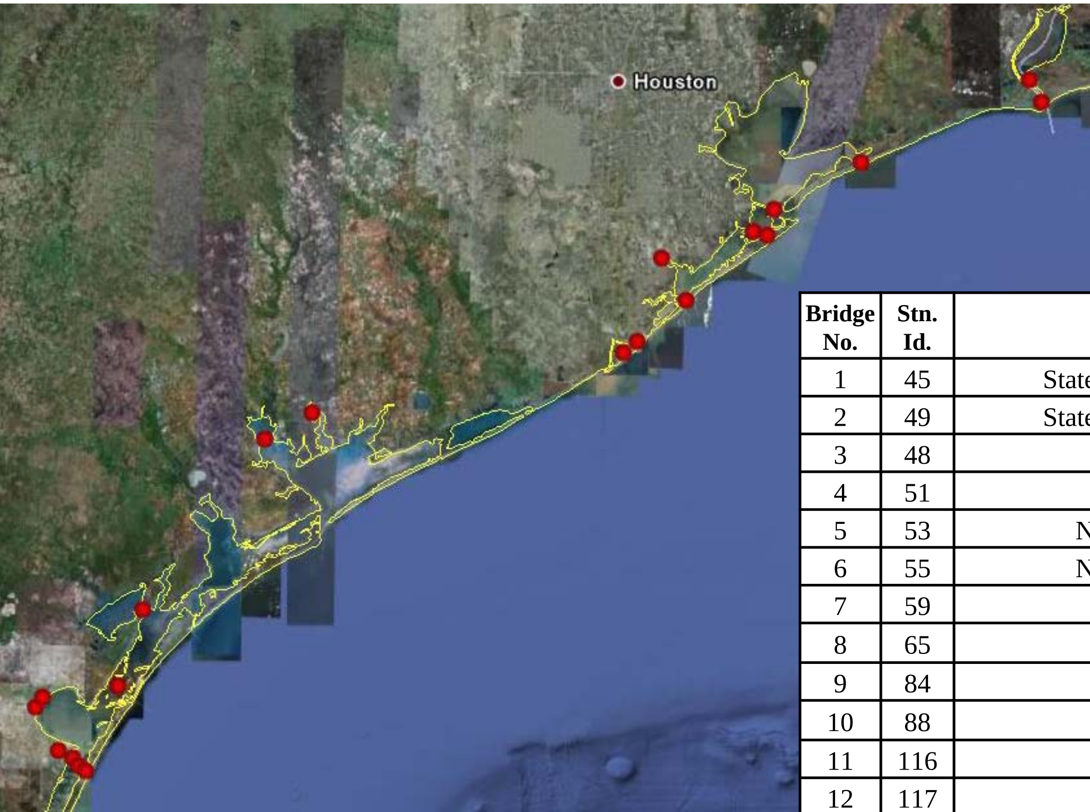
Road 523 to Surfside beach in the Gulf of Mexico, caused by Hurricane Ike
Texas, September 12, 2008
Image by REUTERS/Carlos Barria: http://www.boston.com/bigpicture/2008/09/the_short_but_eventful_life_of.html

Motivation

Twenty Coastal Bridges in the Texas Coast



Twenty Target Bridges along the Texas Coast

Bridge No.	Stn. Id.	Description	Lon.	Lat	Location
1	45	State Hwy Park Road 22_No.1	-97.214	27.619	Corpus Christi
2	49	State Hwy Park Road 22_No.2	-97.240	27.635	
3	48	Kennedy Causeway	-97.261	27.658	
4	51	Padre Island Bridge	-97.312	27.680	
5	53	Nueces Bay Causeway 1	-97.395	27.813	
6	55	Nueces Bay Causeway 2	-97.370	27.844	
7	59	Cemetery Road	-97.104	27.884	
8	65	Johnson Causeway	-97.020	28.120	
9	84	Port Lavaca	-96.598	28.650	Matagorda
10	88	Weedhaven	-96.432	28.732	
11	116	FM1495 Road	-95.341	28.922	Galveston
12	117	Hwy 332	-95.293	28.956	
13	127	San Luis Pass	-95.122	29.082	
14	130	FM 2004 Road	-95.207	29.213	
15	141	Galveston Causeway	-94.885	29.295	
16	142	Pelican Island Bridge	-94.824	29.311	
17	147	Texas City Dike Road	-94.810	29.363	
18	157	Rollover Pass	-94.500	29.508	
19	181	Martin Luther King Jr. Drive (Hwy 82)	-93.895	29.766	
20	182	Jetty Road	-93.853	29.696	

Motivation

Physical Scaling Laws for Surge Response Function Method

(Irish et al., 2009)

$$x' = \frac{x - x_o}{R_p} - \lambda - F(1-R')H(1-R')$$

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

where

x' is the dimensionless alongshore dimension,

ζ' is the dimensionless storm surge,

x is the alongshore location of interest,

x_o is the distance alongshore to the landfalling eyelocations,

R_p is the hurricane pressure radius, a measure of hurricane size,

λ is the continental shelf slope determined by linear regression,

$F(1-R')H(1-R')$ is the correction factor accommodating a secondary effect^{+},

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

γ is specific weight of water,

m_x is the location-dependent constant determined by linear regression,

Δp is the pressure differential between the far-field barometric pressure (1013 mb)

Motivation

Surge Response Function Approach (SRF, Irish et al. 2009)*

$$\zeta(x,y) = \phi([x,y], \Delta p, R_p, [x_o, y_o])$$

where

$\zeta(x,y)$ is the peak surge at location $[x,y]$,

ϕ represents the surge response function,

$\Delta p = P_f - c_p$

where, c_p is the central pressure and P_f is a far – field pressure,

R_p is the storm pressure radius, and

$[x_o, y_o]$ is the location of eye at landfall.

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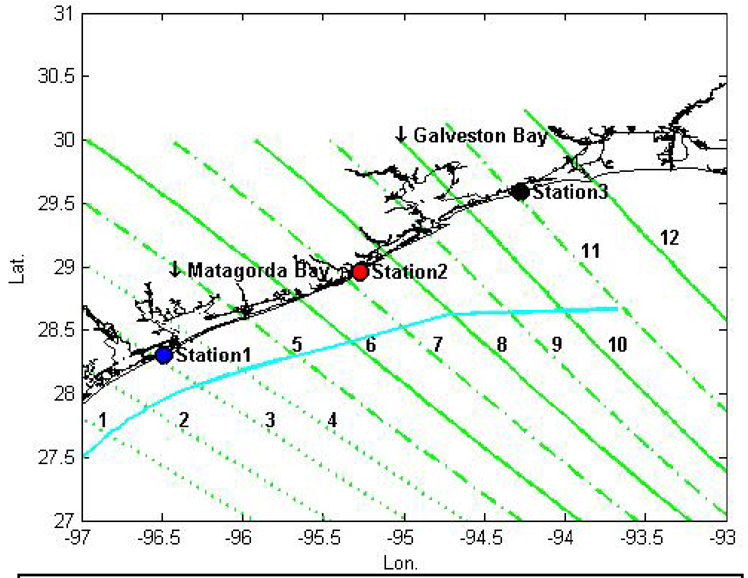
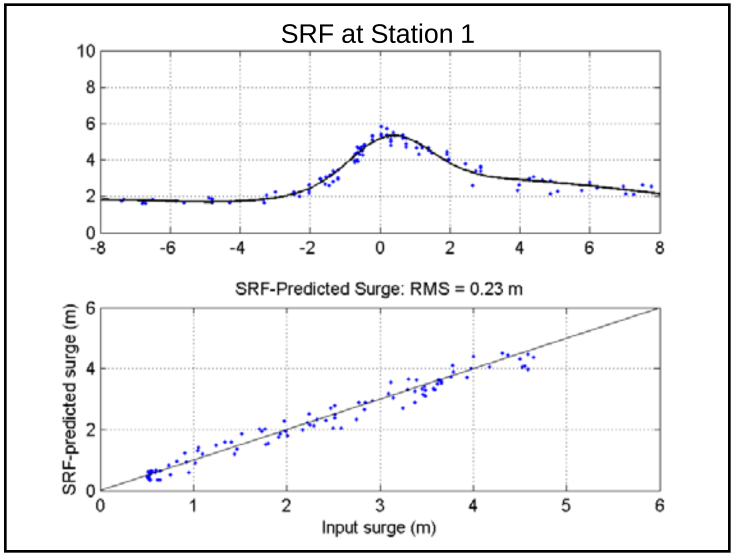
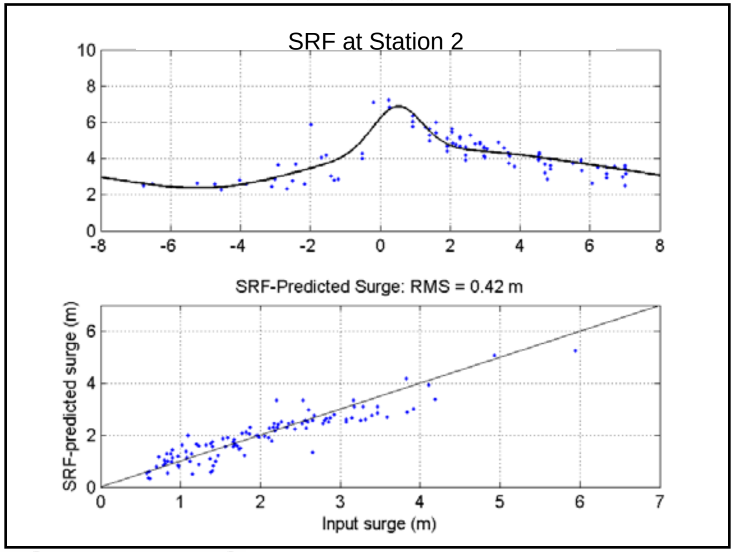
* J.L., Irish, D.T. Resio, M.A. Cialone, "A surge response function approach to coastal hazard assessment. Part 2: Quantification of spatial attributes of response functions," Nat. Hazards, doi:10.1007/s11069-009-0381-4

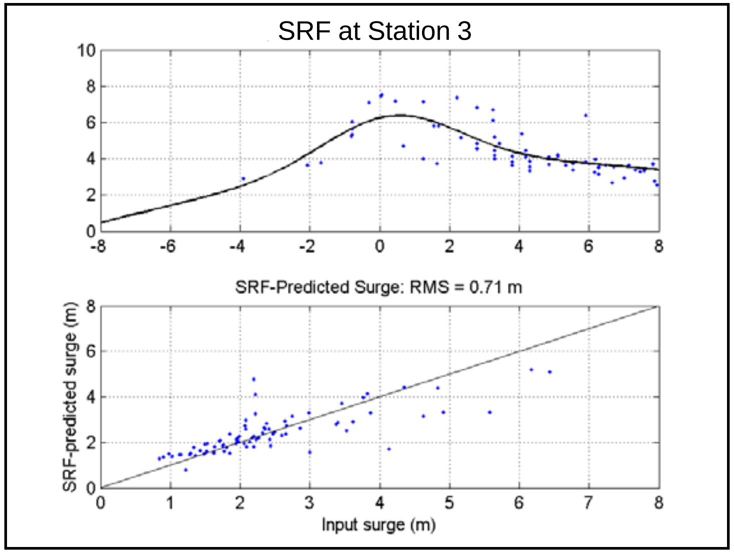
Motivation

Physical Scaling Laws for Surge Response Function Method





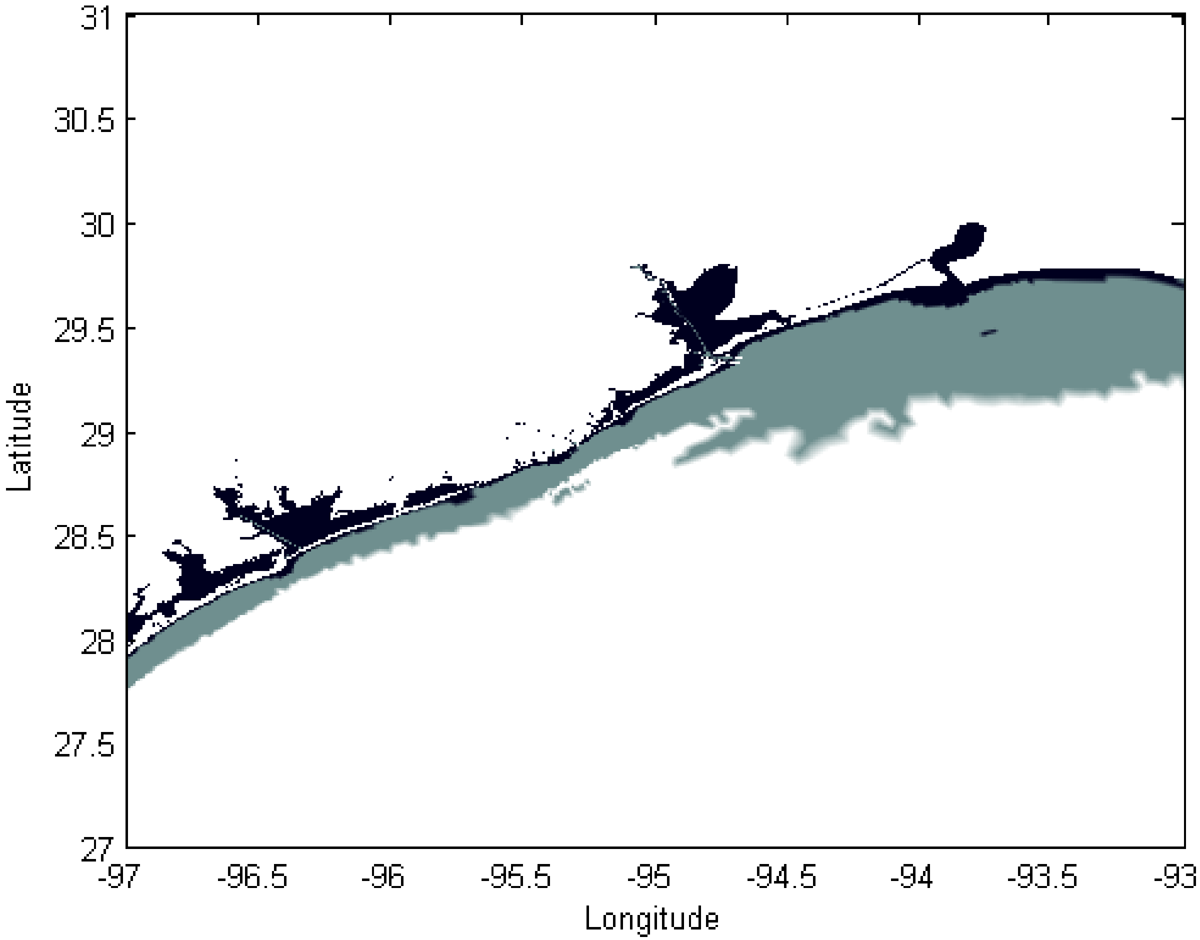




Approach

Variation in geographical features along the Texas coast.

•Rapidly varying bottom slope (or L_{30}) along the Texas coast, especially in the vicinity of Galveston.



Conclusion

•**Varying bottom slope of continental shelf along the Texas coast makes significant effects on the alongshore surge distribution (Especially,in the wide continental shelf region near Galveston)**

•**The effect can be measured in relation with storm size relative to local continental shelf width**

- $\lambda(x_o, R_p)$ --> $\lambda(x_o, R_p, L_{30})$

  :To locate the Max. peak depending on L_{30} near hurricane landfall

- $m_r(R_p/L_{30})$: To limit offshore-ward extent for surge generation

•**SRFs defining surge distributions on RHS and LHS, separately, more accurately realize surge distributions and capture the peak of SRF more efficiently.**

Outline

- Motivation
- Approach
- Conclusion
- **Numerical Simulations**
- **Improvements in Surge Response Function**
- **Development of Surge Response Function**
- **Application for Peak surge estimation**
- **Summary and Questions**

Numerical Simulations

Numerical Storm Surge Simulation Model

- **<u>ADCIRC</u>** (Westerink *et al., 1992 and 2004***)**:**
  - Hydrodynamic model:
  - Finite element in space (flexible nodal densities)
  - Solving Generalized Wave-Continuity Equation (GWCE)
  - **<u>Forced by the hurricane meteorology:</u>**

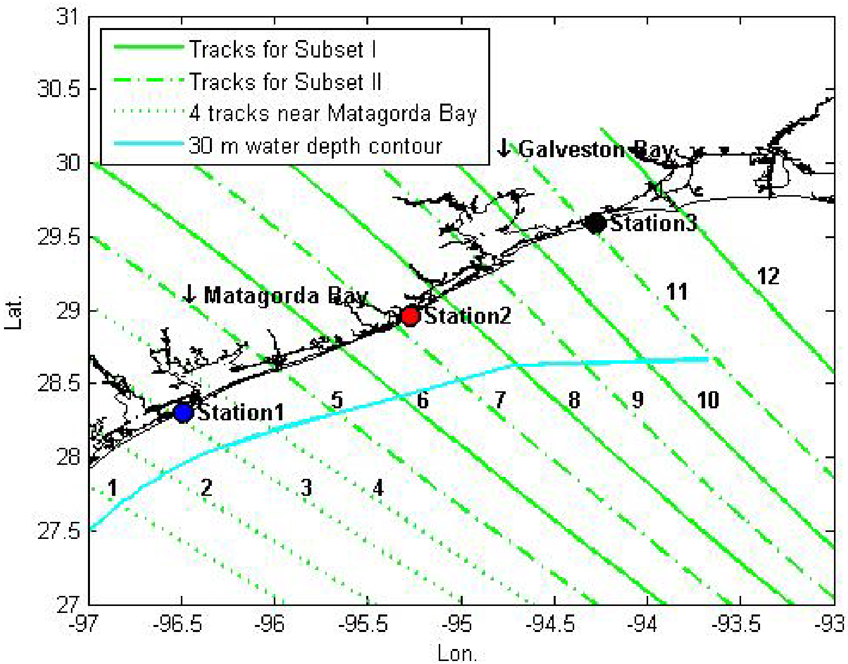
    Planetary Boundary Layer Model (PBL):
    - Thompson & Cardone 1996**
    - Model forcing:
      - Wind stress
      - Barometric pressure
    - Parameterization of the hurricane meteorology (c_p, R_p, $S(t)$, v_f, θ_f, …)

* http://www.adcirc.org/adcirc_theory_2004_12_08.pdf

**THOMPSON E. F. , CARDONE V. J. (1983). "Practical modeling of hurricane surface wind fields", Journal of waterway, port, coastal, and ocean engineering, vol. 122, no. 4, 195-205.

Numerical Simulation

Hurricane selection based on optimal sampling



Subset I				
x_{eye} [Lon.]	y_{eye} [Lat.]	v_f [km/s]	c_p [mb]	R_p [km]
-95.65	28.75	5.7	960	20.4
-95.65	28.75	5.7	960	38.9
-95.65	28.75	5.7	960	66.0
-95.65	28.75	5.7	930	14.8
-95.65	28.75	5.7	930	32.8
-95.65	28.75	5.7	930	47.8
-95.65	28.75	5.7	900	11.1
-95.65	28.75	5.7	900	27.6
-95.65	28.75	5.7	900	40.4

Subset II				
x_{eye} [Lon.]	y_{eye} [Lat.]	v_f [km/s]	c_p [mb]	R_p [km]
-95.35	28.90	5.7	960	32.8
-95.35	28.90	5.7	900	32.8

- Total more than 125 storms simulations on 12 + parallel tracks
- Synthetic hurricane meteorology
  - R_p: 11~66 km
  - c_p: 900~960 mb
  - θ_f <= 17 ° with $_{WRT}$ shoreline orientation
  - v_f = 5.7 m/s
  - 515 stations along the Texas coastline (mean interval between stations = 2.8 km)
- Beyond the scope:
  - wave setup, runup, astronomical tides
  - The sensitivity to v_f, θ_f, Holland B (storm peakedness)

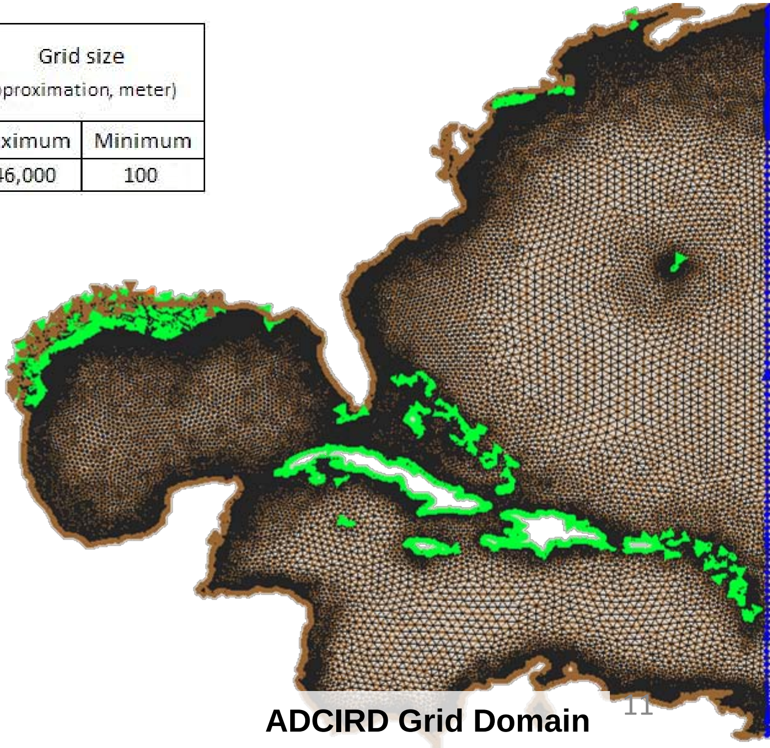
Numerical Simulation

A Large Grid Domain

- Entire Gulf of Mexico water body and North Atlantic basin
- Highly resolved nearshore and inland bay system along the Texas coast
- dt = 0.5sec., 1400 cpu-time requirement for completion of a single 5-day run

East coast domain triangular mesh information

Area [km^2]	Maximum Bathymetry [m]	Minimum Bathymetry [m]	Number of Nodes	Number of Elements	Grid size (Approximation, degree)		Grid size (Approximation, meter)	
					Maximum	Minimum	Maximum	Minimum
8.3522×10^6	7,858.09	(-)71.67	1,344,247.00	2,628,785.00	0.400	0.005	46,000	100



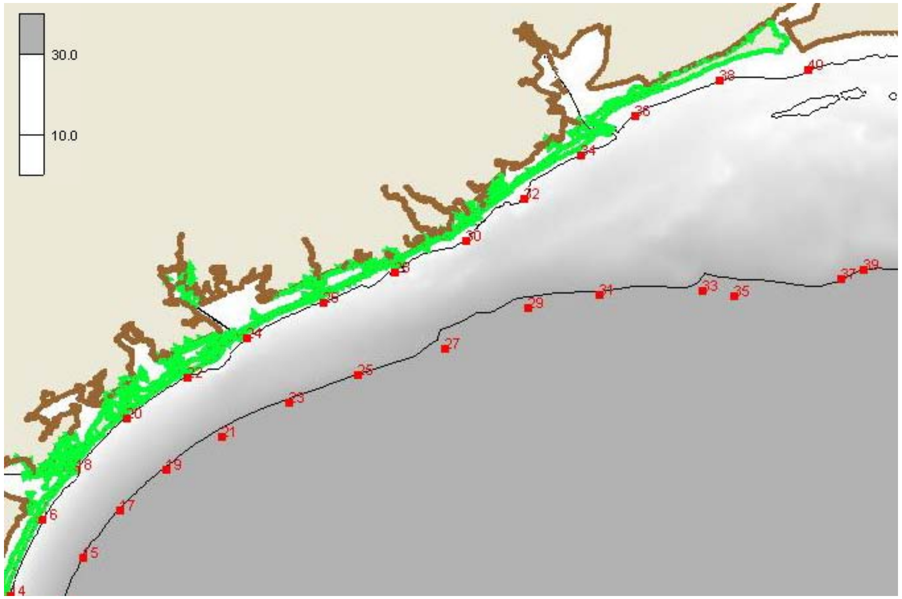
ADCIRD Grid Domain

Improvement of SRF

Definition of the characteristic continental shelf width, L_{30}

L_{30}: continental shelf expansion off the coast to the 30m water depth contour

- 75% of surge is generated in depth shallower than 30m
- L_{30} specified on virtual orthogonal lines with respect to shoreline orientation. (with 30 km space)

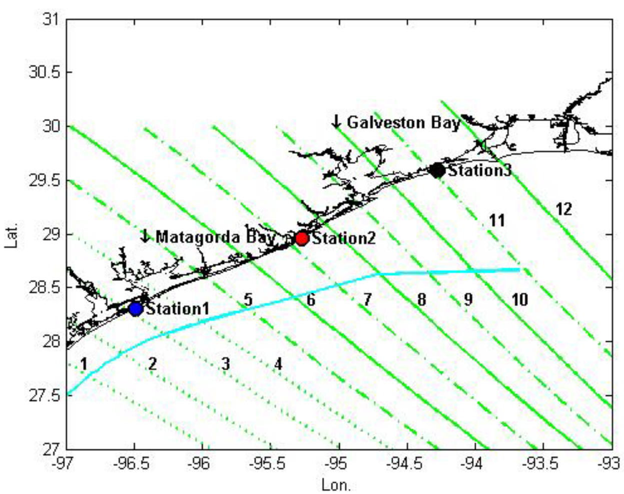


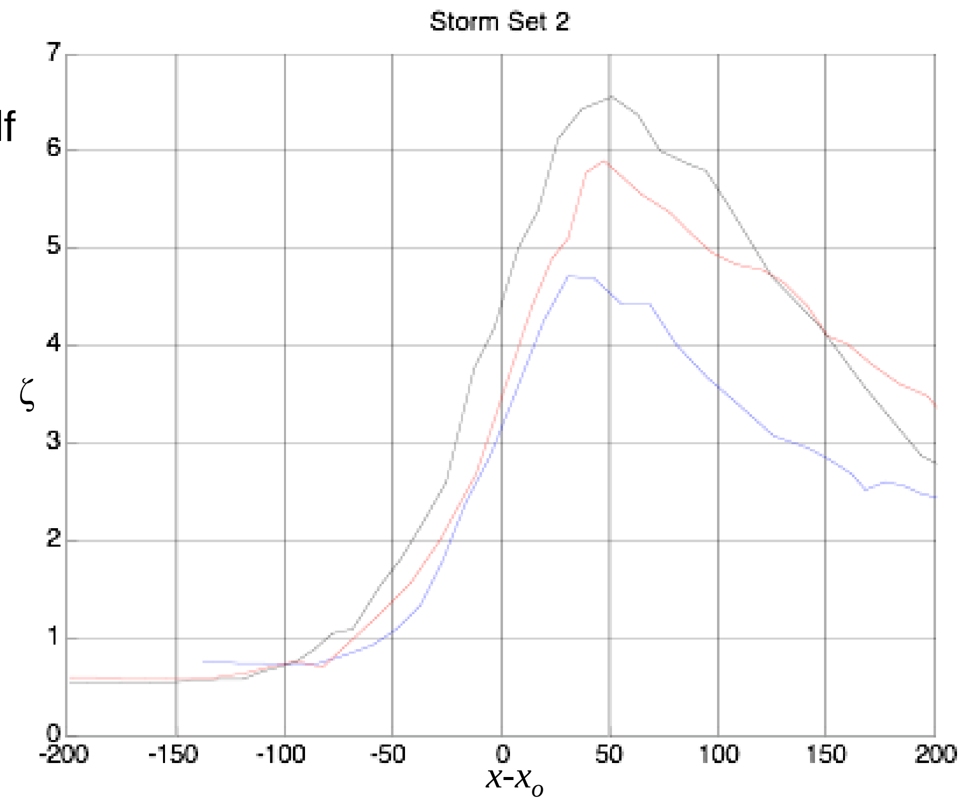
L_{30} varies between 25 km and 110 km along the Texas coast

Determination of the parameter λ

The slope of the linear regression is applied to determine the continental shelf parameter, λ

$$x_{peak} - x_o = \lambda R_p$$

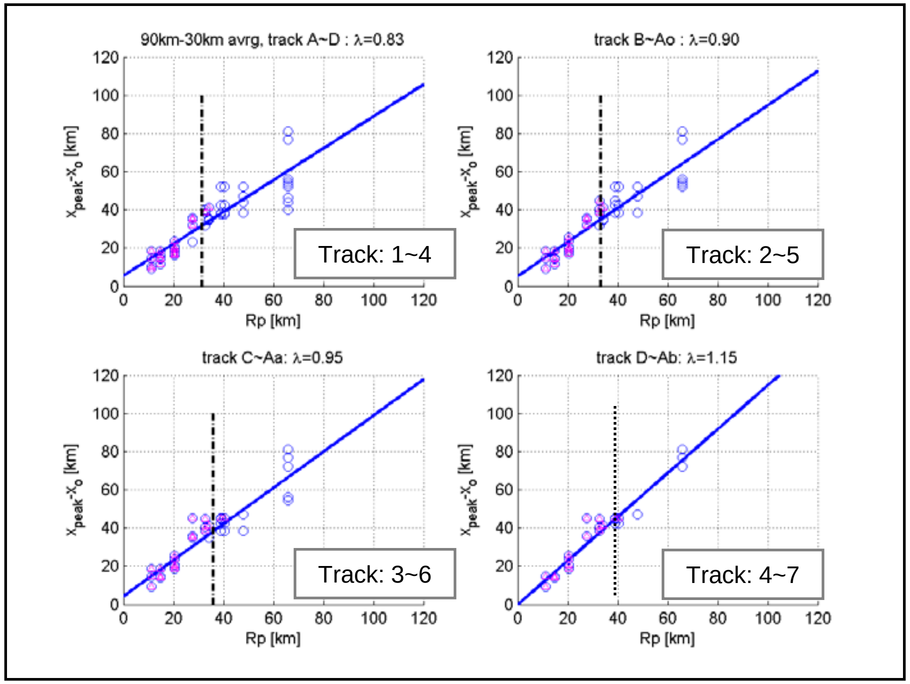


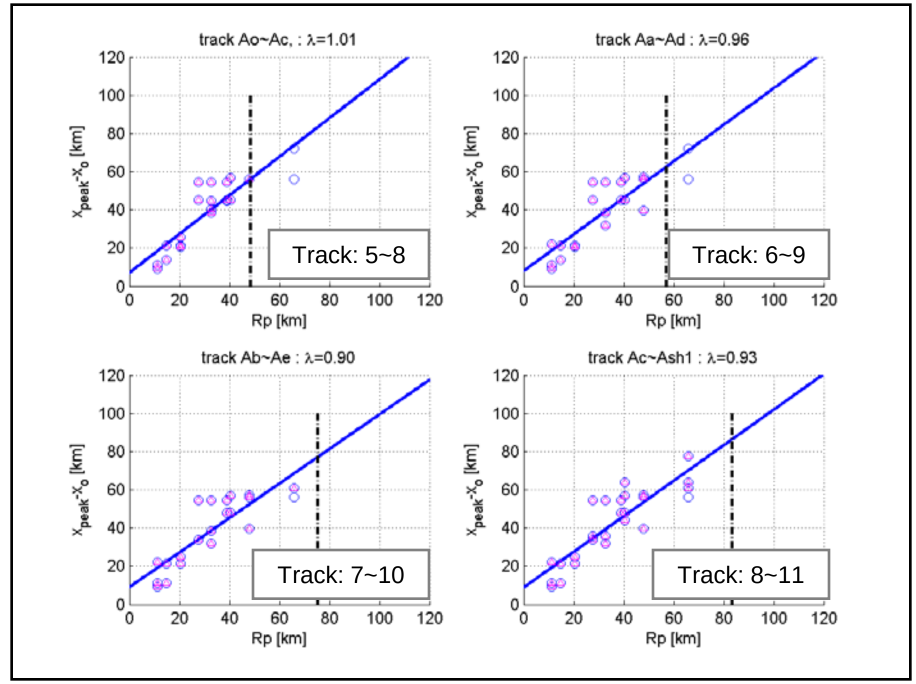


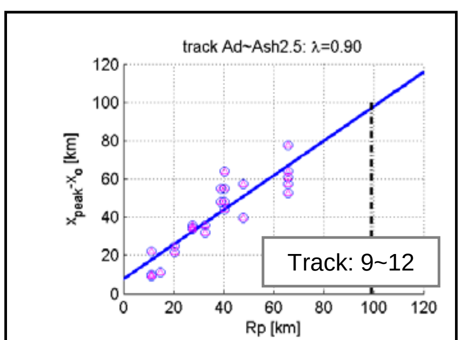
Storm set 2					
Track #	x_{eye} [Lon.]	y_{eye} [Lat.]	v_f [km/s]	c_p [mb]	R_p [km]
2	**27.080**	**-95.558**	**11**	**900**	**40.4**
6	**27.610**	**-94.530**	**11**	**900**	**40.4**
10	**28.210**	**-93.664**	**11**	**900**	**40.4**

Improvement of SRF

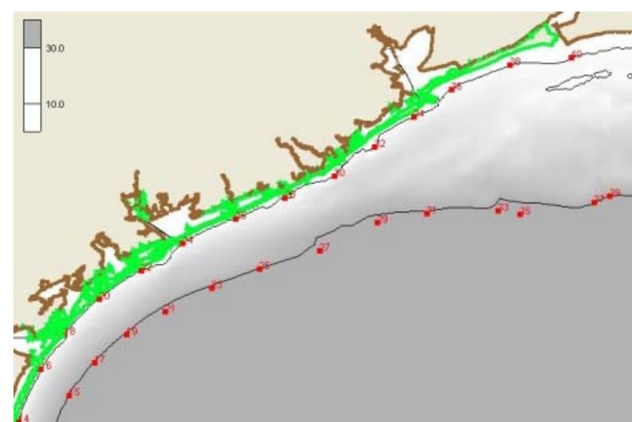
Determination of the parameter λ





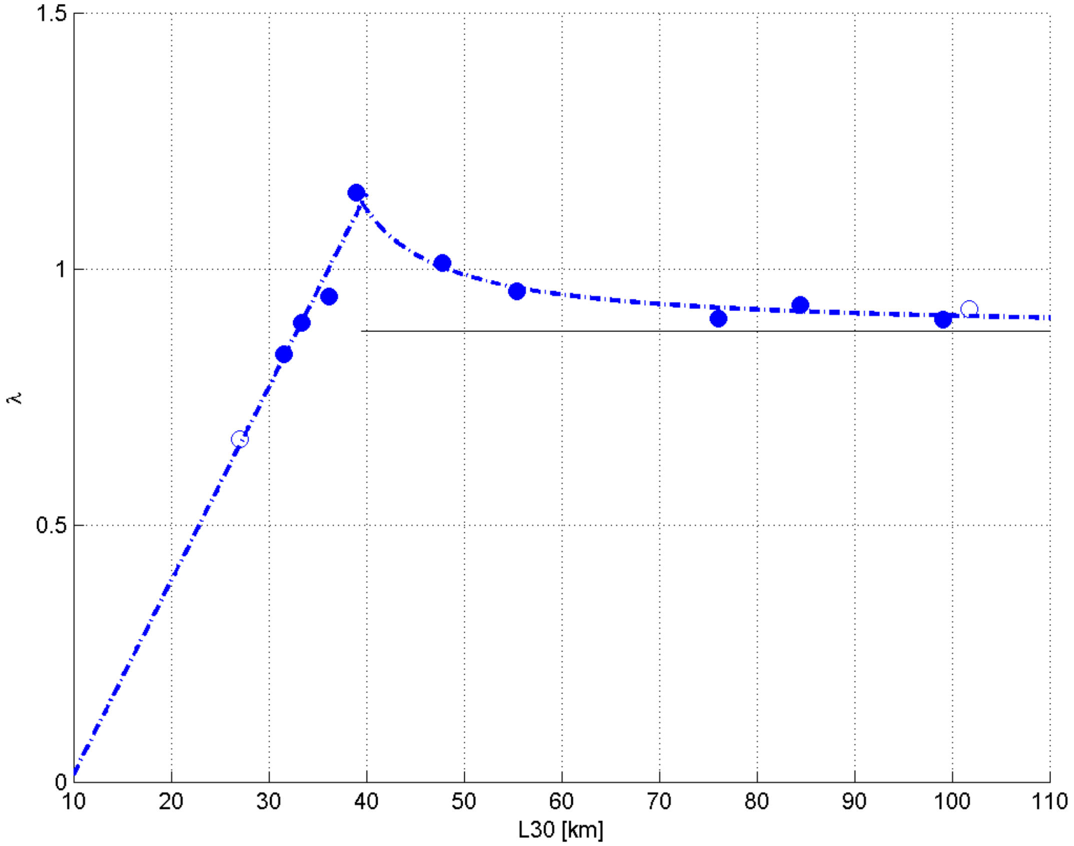


λ varies between
0.76 (Corpus Christi) to 1.15 (Galveston)
in the Texas coast (L_{30} > 25 km)



Improvement of SRF

Determination of the parameter λ



L_{30} vs. λ	
L_{30}	λ
27.8	0.76
31.6	0.83
33.4	0.90
36.2	0.95
38.9	1.15
47.8	1.01
55.4	0.96
76.0	0.90
84.4	0.93
99.1	0.90
101.8	0.92

$$\lambda = \begin{cases} 0.04L_{30}(x_o) - 0.36 & \left(25\ km \le L_{30} \le 40\ km\right) \\ \dfrac{2.03}{L_{30}(x_o) - 31.41} + 0.88 & \left(L_{30} > 40\ km\right) \end{cases}$$

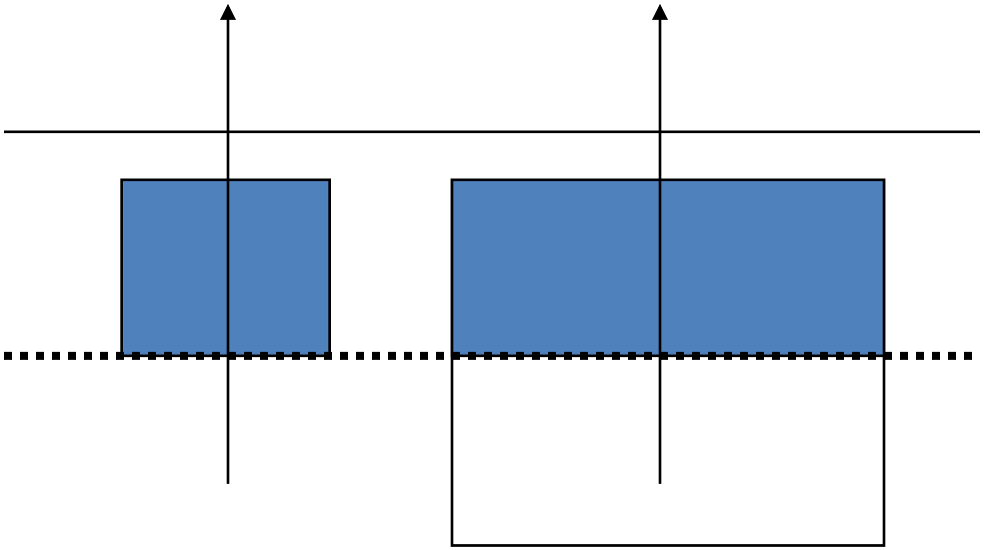
Improvement of SRF

Determination of the parameter m_r

Hydrodynamic based storm surge scale (Irish and Resio, 2009)

$$\zeta \cong \phi(\Delta p, L_{30}, R_p)$$

$$\psi_x = \begin{cases} \dfrac{R_p}{L_{30}} & \text{where } \dfrac{R_p}{L_{30}} \le 1 \\ 1 & \text{otherwise} \end{cases}$$



Improvement of SRF

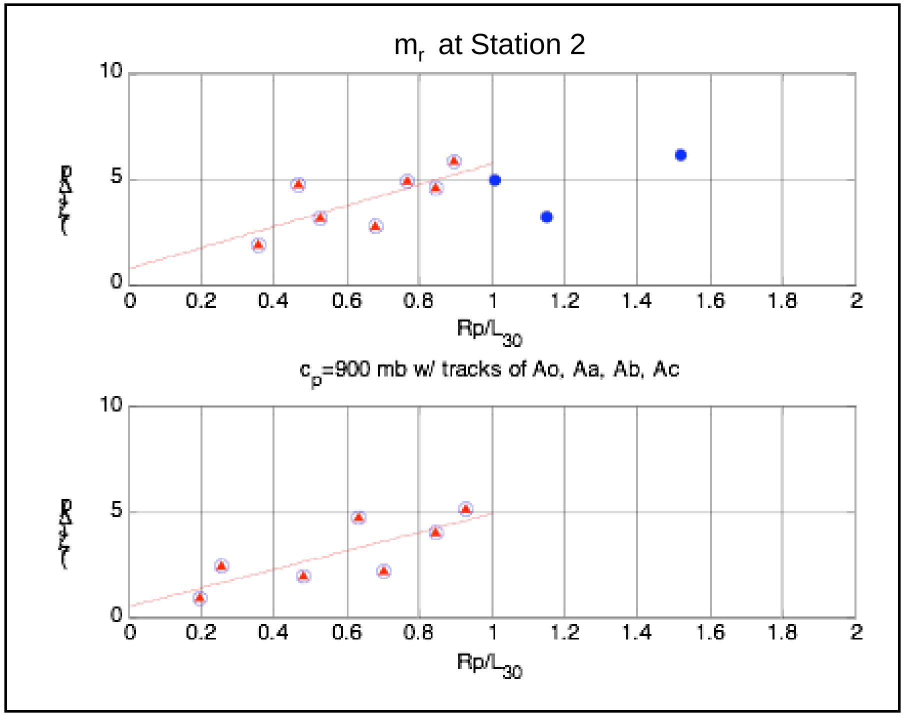
Determination of the parameter m_r

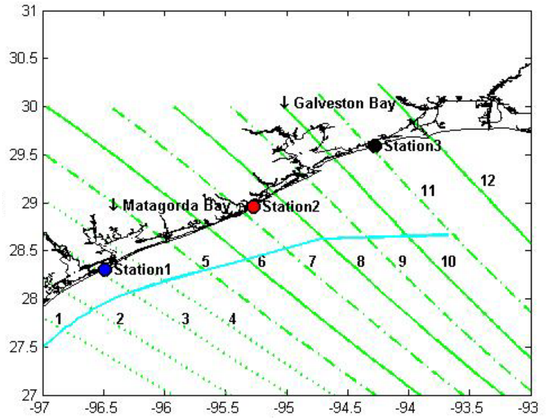
$$\zeta_2' = \zeta_1' - m_r \psi_x \times \chi(L_{30})$$

where,

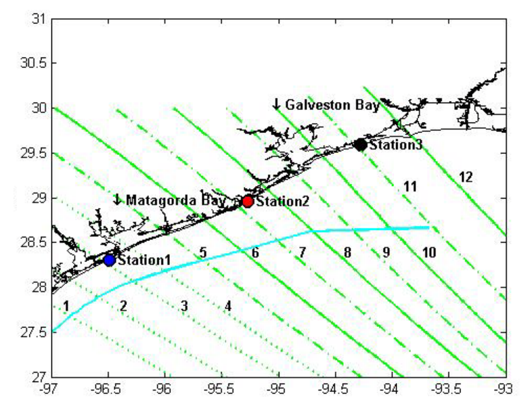
$$\psi_x = \begin{cases} \dfrac{R_p}{L_{30}} & \text{where } \dfrac{R_p}{L_{30}} \le 1 \\ 1 & \text{otherwise} \end{cases}$$

$$\chi(L_{30}) = (2.38E\text{-}2)L_{30}$$





Development of SRF

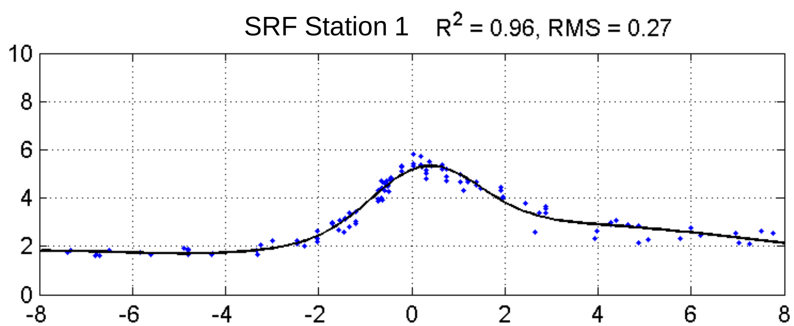


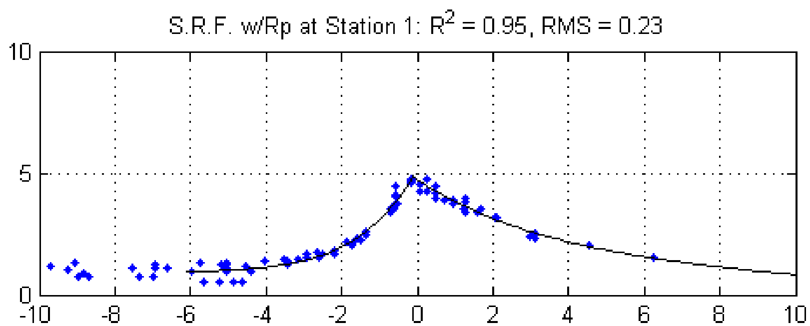
Development of SRFs:

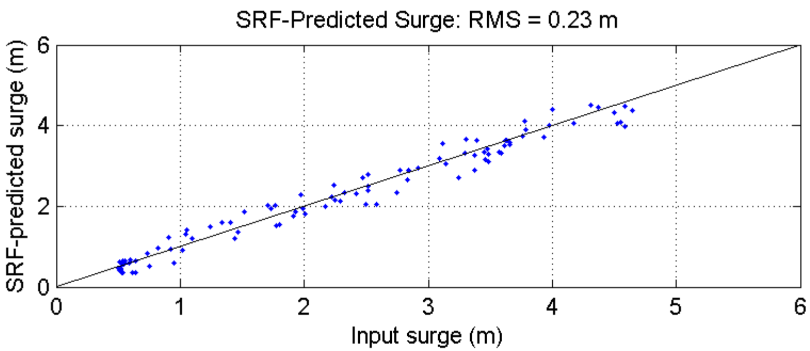
•SRFs for twenty bridges:

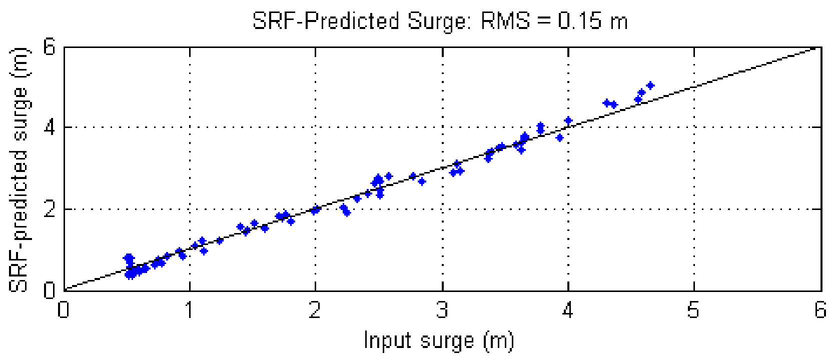
A pair of two, 3-term Gaussian Function

$$\Phi(x') = a_1 e^{-\left(\frac{x'-b_1}{c_1}\right)^2} + a_2 e^{-\left(\frac{x'-b_2}{c_2}\right)^2} + a_3 e^{-\left(\frac{x'-b_3}{c_3}\right)^2}$$









Development of SRF

Development of SRFs:

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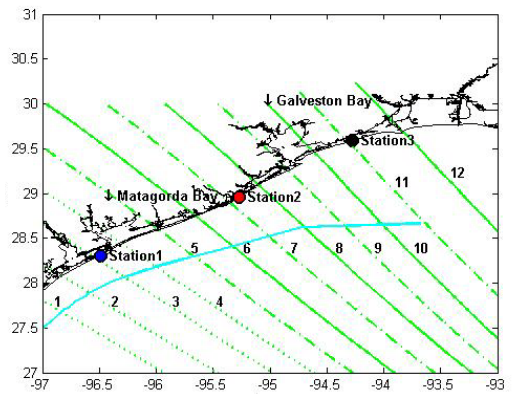

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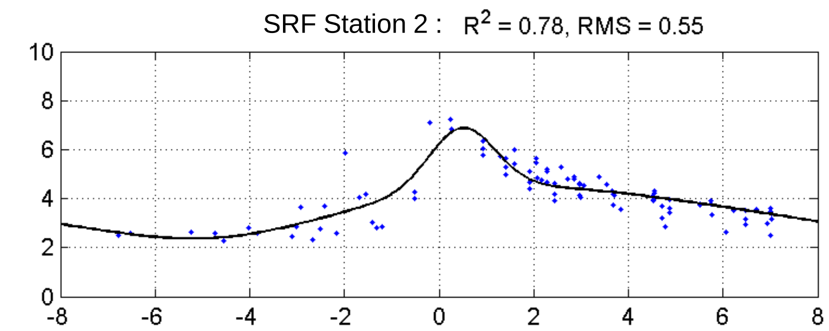

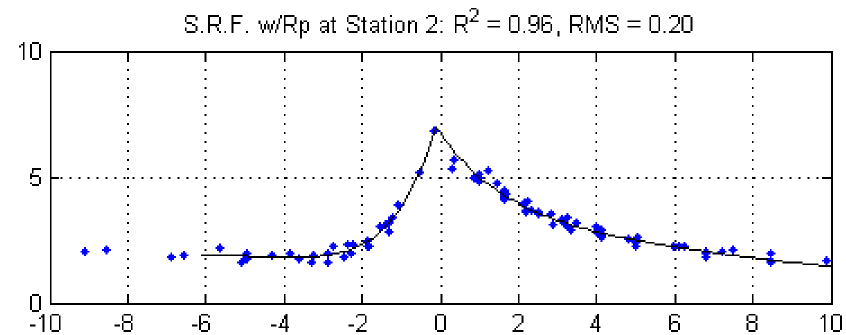

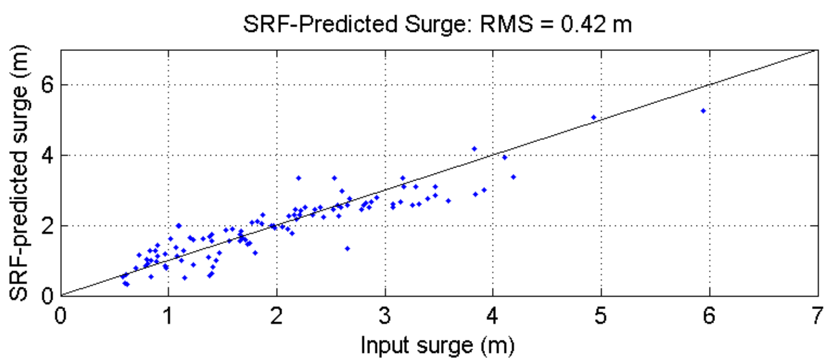

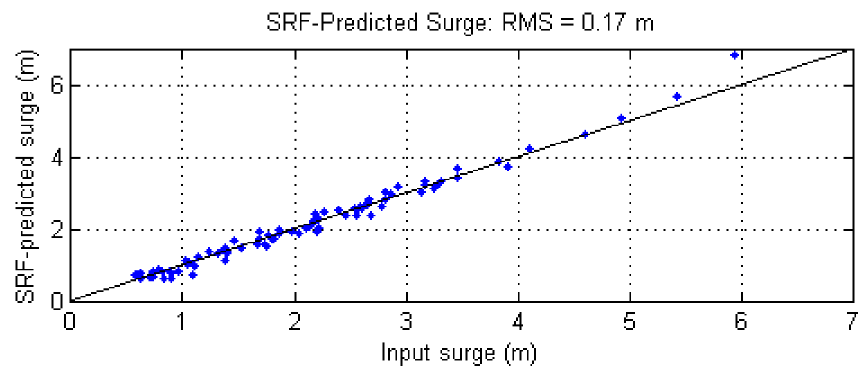

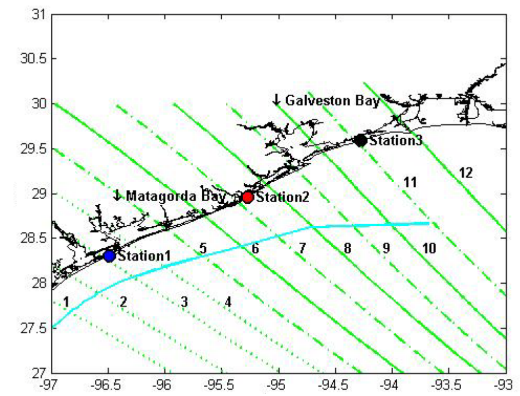

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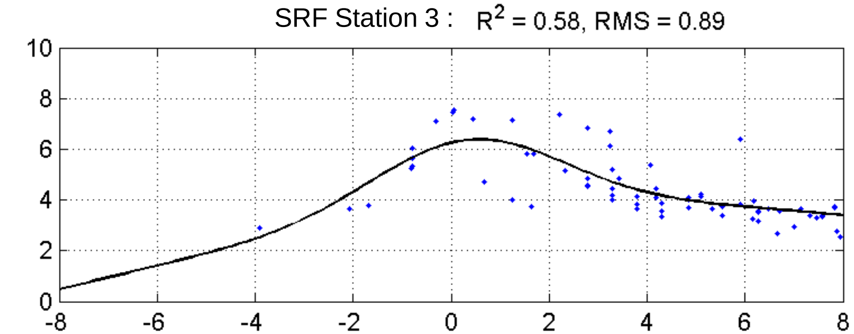
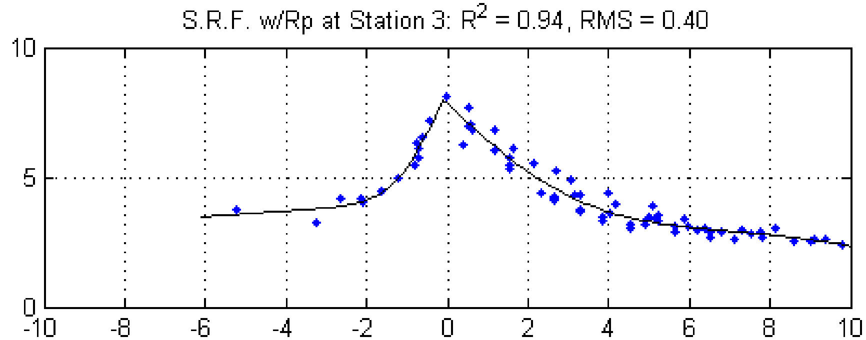
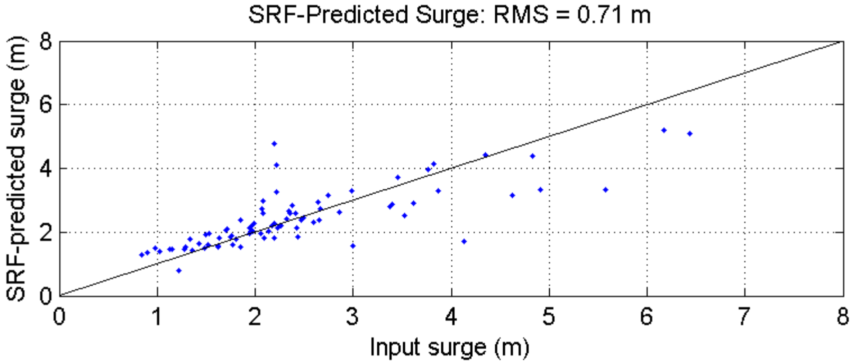
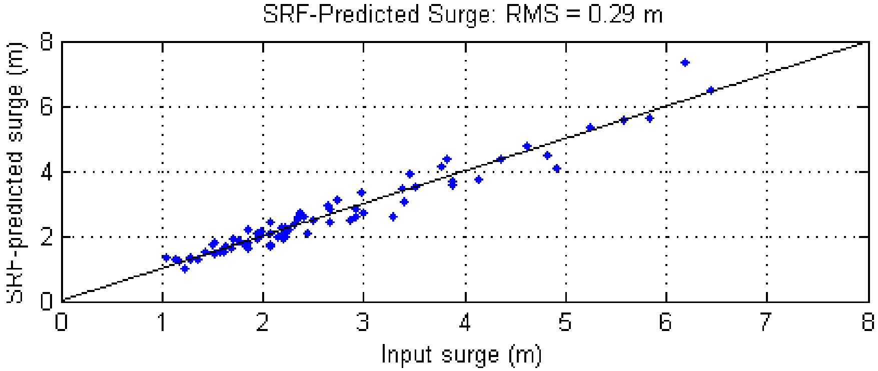








Summary & Discussion

The modified SRFs

- Explicitly account for the relationship between **the surges and storm size relative to L_{30} of storm**

- **Performance of SRFs improved to mean RMS of 20 cm (14~29 cm) compared to previously mean RMS of 37 cm (23~71 cm) over the expanded range of Texas open coast**

- The capability of the SRF in **capturing the spatial trends in storm surge responses** on a given hurricane conditions **was proved** through historical hurricane event s (Hurricane Carla (1961) and **Ike (2008)**)

Further study in process|| in the future

- Effects of waves, runup, astronomical tides, and the various random factors in the field.

- The effect of the different **storm forward speeds and approaching angles** on storm surge response.

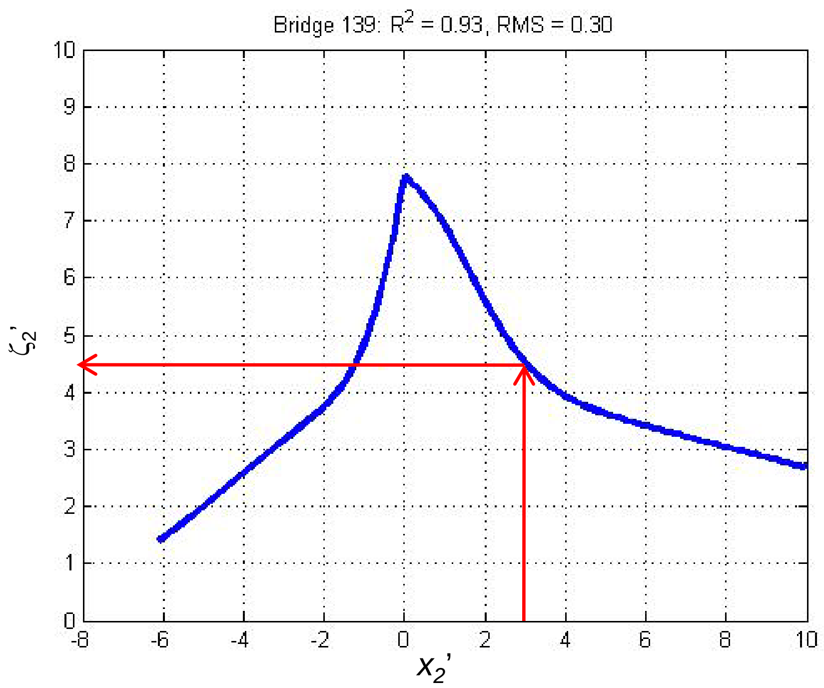
- The effects of surface wind interaction with the **complex geographical features inside the bay**

- **Timing issue** in regard to max. surges and reversed-surges

Application of SRF For Peak Surge Estimation

Application of SRF For Peak Surge Estimation

Peak surge calculation based on SRF



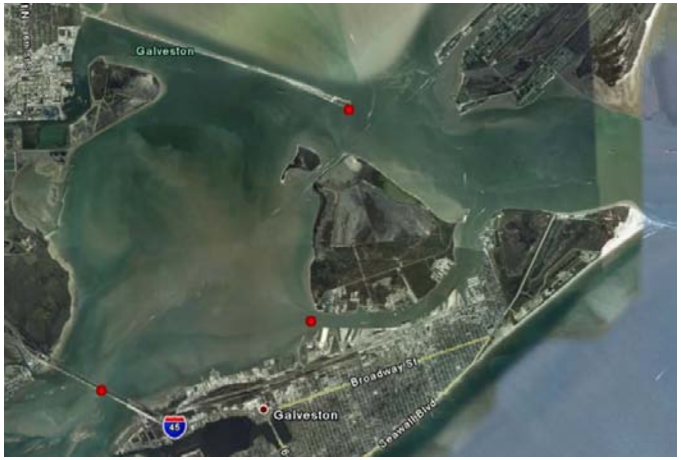
- $X = x - x_o \Rightarrow x_2' = f\{X, R_p, \lambda\}$
  - $x - x_o$ = -1000 ~ 1000 *km*
  - R_p = *8~120 km*
- $\zeta = g\{\zeta', C_p\}$
  - c_p = 870~960 mb
  - θ_f, v_f constant

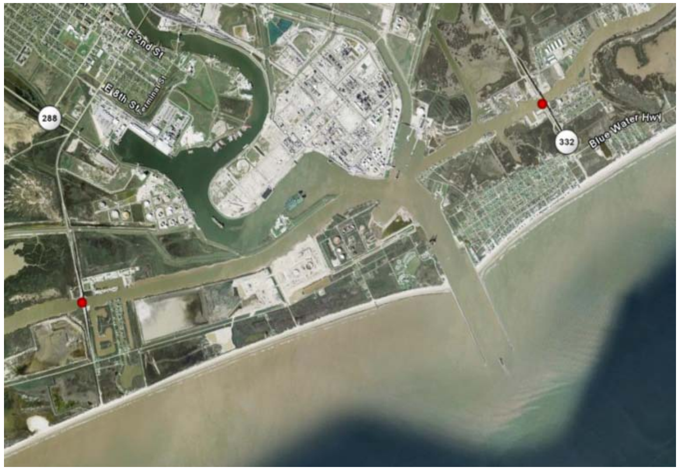
$$\Phi(x') = a_1 e^{-\left(\frac{x'-b_1}{c_1}\right)^2} + a_2 e^{-\left(\frac{x'-b_2}{c_2}\right)^2} + a_3 e^{-\left(\frac{x'-b_3}{c_3}\right)^2}$$

Motivation

Twenty Coastal Bridges in the Texas Coast

Ten Bridges in Galveston



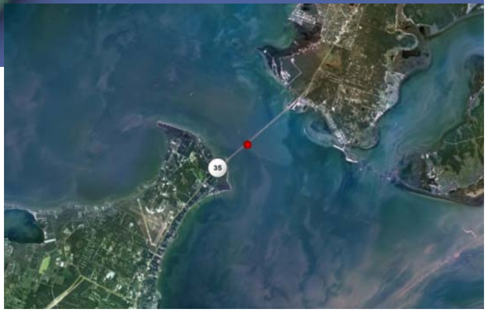


Motivation

Twenty Coastal Bridges in the Texas Coast

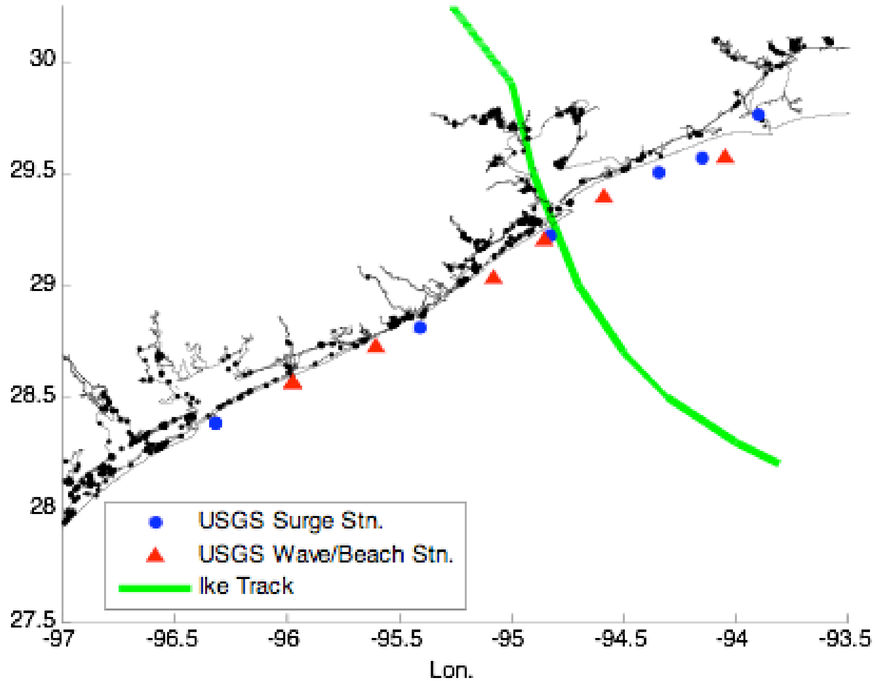
Two bridges in Matagorda bay

Eight Bridges in Corpus Christi



Application of SRF For Peak Surge Estimation

Hurricane Ike (2008) Description



Ike Storm Track* & Stations

Hurricane Meteorological Conditions

Storm Track :
Emerging into the Gulf of Mexico, Ike began tracking more northwestward in response to a weakness in the upper level ridge*

Landfall:
28.9N, 94.5W on SEP 13,08

Radius to the maximum wind speed : 37km

Lowest center pressure: 952 mb

Forward Speed: 4.5m/s

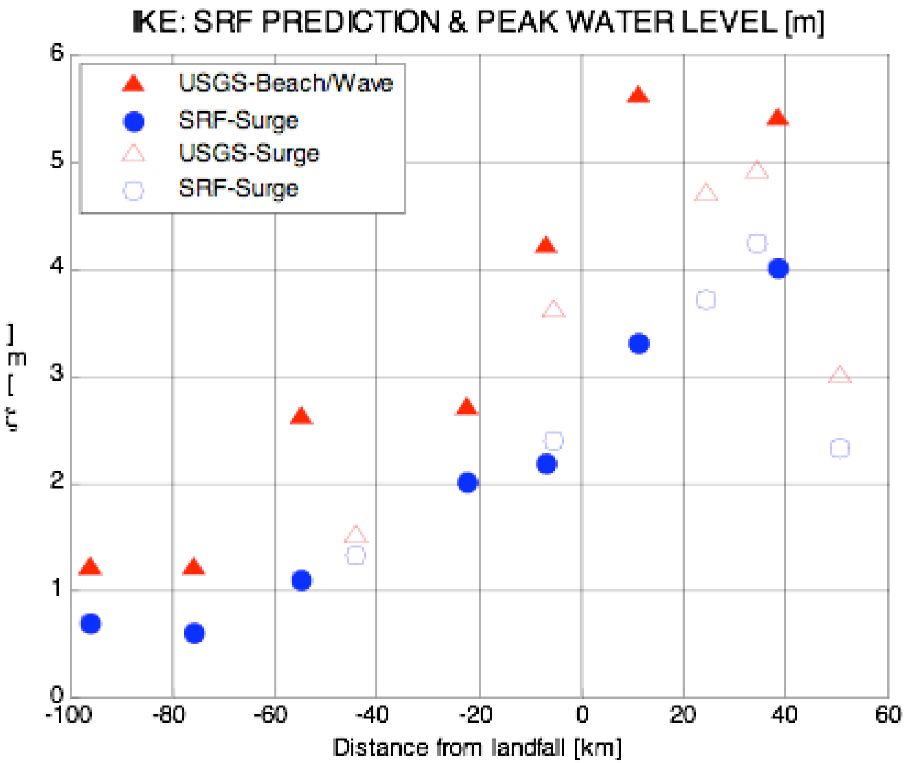
*Based on information from National Hurricane Center.

Application of SRF For Peak Surge Estimation

Comparison with Peak Water Level * Observations: Hurricane Ike

✓Peak Water Level (PWL): Peak surge water level observed through the pressure gauges in the site.

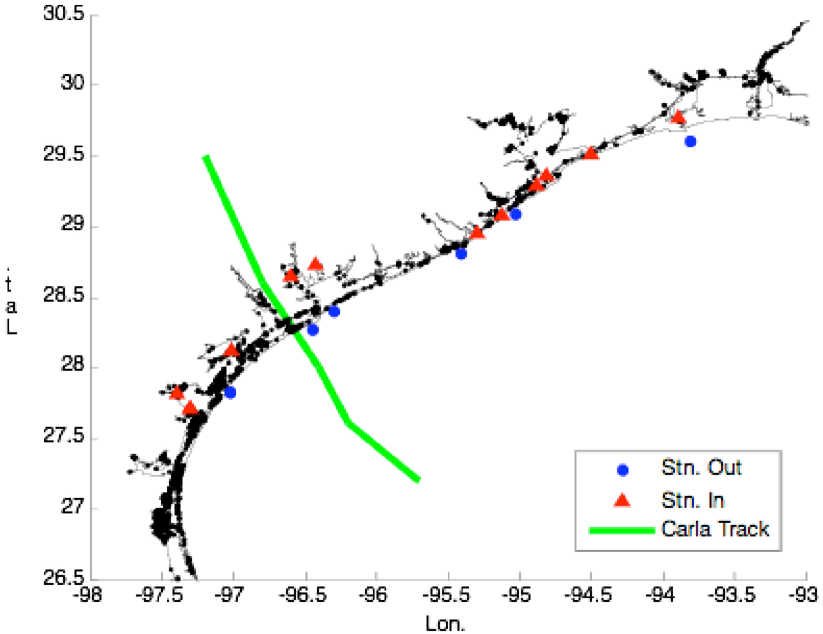
Hurricane Ike Surge Predictions			
Stnation No.	Distance from Landfall[km]	PWL above MSL [m]	SRF Prediction [m]
82	-96.2	1.2	0.6
94	-75.7	1.2	0.8
105	-54.8	2.6	1.2
110	-44.3	1.5	1.3
126	-22.6	2.7	2.0
138	-5.5	4.2	2.2
139	-7.1	3.6	2.4
151	11.0	5.6	3.3
161	11.0	4.7	3.5
167	24.5	4.9	4.0
170	38.5	5.4	3.7
182	55.8	3.0	2.3



*Provided by USGS

Application of SRF For Peak Surge Estimation

Hurricane Carla (1961) Description



Carla Storm Track* & Stations

Hurricane Meteorological Conditions

<u>Storm Track</u> :
Approaching the Texas coast in Gulf of Mexico, it steadily evolved to Category 5 tropical cyclone. When it made a landfall on September 11, 1961, between Prot O'Connor and Port Lavaca in Texas, Carla was a Category 4

<u>Landfall</u>:
28.0N, 96.4W on SEP 11,1961

<u>Radius to the maximum wind speed</u>: 56km

<u>Lowest center pressure</u>: 931 mb

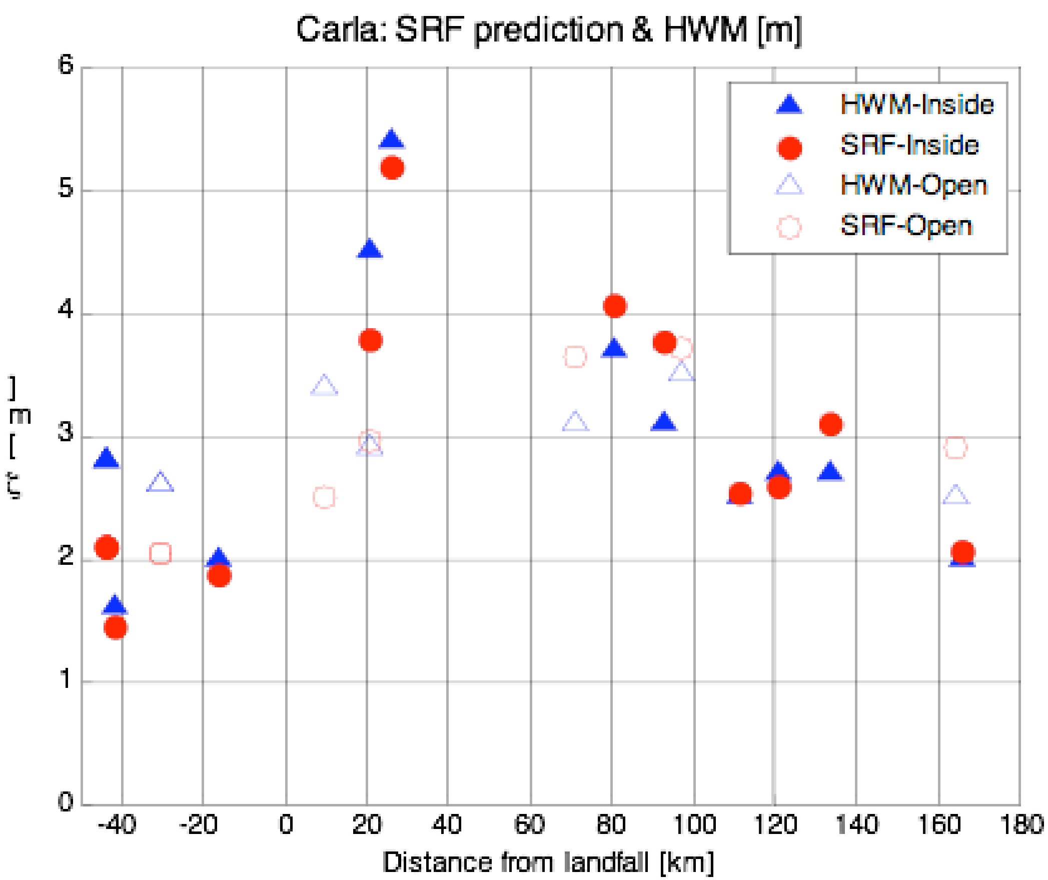
<u>Forward Speed</u>: 1.8 m/s

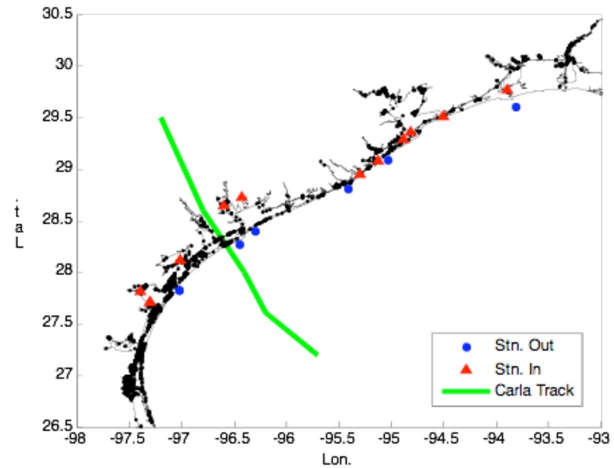
*Based on information from National Hurricane Center.

Application of SRF For Peak Surge Estimation

Comparison with High Water Mark* Observations: Hurricane Carla

✓High Water Mark (HWM): Determined from the high water level marks remained by debris or drift lines on the stations or buildings





*HWM reported by National Weather Service, NOAA (National Weather Service 1982)

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Questions

Thank you !!

Motivation

Bridge Damage Reports * (2008)

More than 96,560km of roadways are in the 100- year coastal flood plain in the United States (*Douglass et al., 2005*)

Hurricane Ivan (2004):

Damage of Escambia Bay Bridge in Florida, suspension of traffic and blockage of the supply route.

Hurricane Katrina (2005);

$803 million for I-10 Twin Span Bridge in Louisiana

$226.8 million for Bay St. Louis bridge on U.S. 90 in Mississippi

Total, $2.75 billion for the Federal Highway Administration's "Emergency Relief Program" *(Collins 2006)*.

Hurricane Ike (2008):

The state and interstate highways damages and debris on the road cost a $20 million effort for repair (*TxDOT, 2008*).

"Preliminary Damage Reports on Bridges", by Jerome O'Connor, MCEER and Paul McAnany, volunteer professional engineer
http://mceer.buffalo.edu/research/Reconnaissance/Katrina8-28-05/damage_reports_bridges.asp

Motivation

List of Damaged Coastal Bridges* (2008)

Alabama

•Cochrane-Africatown Bridge, Mobile, Alabama

•Railroad Bridge over Biloxi Bay, Mississippi

•US 90 to I-10 Interchange over Mobile Bay, Baldwin County, Alabama

Mississippi

•Aerial View of Biloxi Bay, Biloxi, Mississippi

•Interstate 10 (I-10) Eastbound, near Pascagoula, Mississippi

•Interstate 10 (I-10) Westbound, near Pascagoula, Mississippi

•Interstate 110 (I-110) Northbound over Back Bay of Biloxi, Mississippi

•Old Bridge Parallel to I-110 over Back Bay of Biloxi, Mississippi

•US 90, Mississippi

•US 90, Bay St. Louis, Mississippi

•US 90 Eastbound, Pass Christian to Bay St. Louis, Mississippi

•Pedestrian Bridge over US 90, Gulfport, Mississippi

•US 90 over Biloxi Bay, Mississippi

•Old Route over Biloxi Bay North of US 90, Mississippi

Louisiana

•Interstate 10 (I-10), New Orleans, Louisiana

•Interstate 10 (I-10) over Lake Pontchartrain, Orleans Parrish, Louisiana

•Route 11 Bridge over Lake Pontchartrain, Orleans Parrish, Louisiana

•Multi-Span Bridge over US 90, Near East Pearl River, Louisiana

•US 90 - Pavement Damage, near Slidell, Louisiana

•US 90 over Chef's Pass, Orleans Parrish, Louisiana

Bridge Hurricane Data Sheets

2004 Named Storms	Maximum Wind Speed (knots/hr)	Hurricane Category	Duration (Days)	Estimated Damage Costs (US $)
Alex	105	3	7	$5,000,000
Bonnie	55	TS	10	No reports
Charley	130	4	6	$14,000,000,000
Danielle	95	2	9	No reports
Earl	45	TS	3	No figure given
Frances	125	4	17	$9,000,000,000
Gaston	65	1	6	$130,000,000
Hermine	50	TS	5	No reports
Ivan	145	5	23	$18,050,000,000
Jeanne	105	3	16	$6,900,000,000
Karl	125	4	9	No reports
Lisa	65	1	15	No reports
AVERAGE				
TOTAL				

Provided by NMEA[4] (http://www.marine-ed.org/)
Data from the National Hurricane Center www.nhc.noaa.gov.
Hurricane category is based on the Saffir-Simpson scale. TS = tropical storm

"Preliminary Damage Reports on Bridges", by Jerome O'Connor, MCEER and Paul McAnany, volunteer professional engineer
http://mceer.buffalo.edu/research/Reconnaissance/Katrina8-28-05/damage_reports_bridges.asp

Motivation

Loss by the Hurricane Impact on the Coastal Bridges

“ With Hurricane Ivan in 2004 and Hurricane Katrina of August 2005, **low-lying coastal bridges suffered severe damage** due to hydrodynamic forces caused by storm surge.” *Ayman M. Okeil and C. S. Cai, 2008***

“The analysis of 44 damaged bridges reveals that, in general, regions with higher storm surge had more damage, although there were several instances where this was not the case**, primarily due to damage resulting from debris impact**.” by Jamie et al., 2008

Storm Debris Blocks Roads To Galveston: “Thousands of people living on the Texan coastline ignored evacuation orders to escape Hurricane Ike's destruction, and now most **roads are impassible, which has left many people stranded**.” (*NPR, 2008*)*

Debris is piled up on the southbound lane of the Gulf Freeway.

By Marisa Penaloza/NPR
http://www.npr.org/templates/story/story.php?storyId=94603508

Motivation

Main Causes for the Bridge Damages

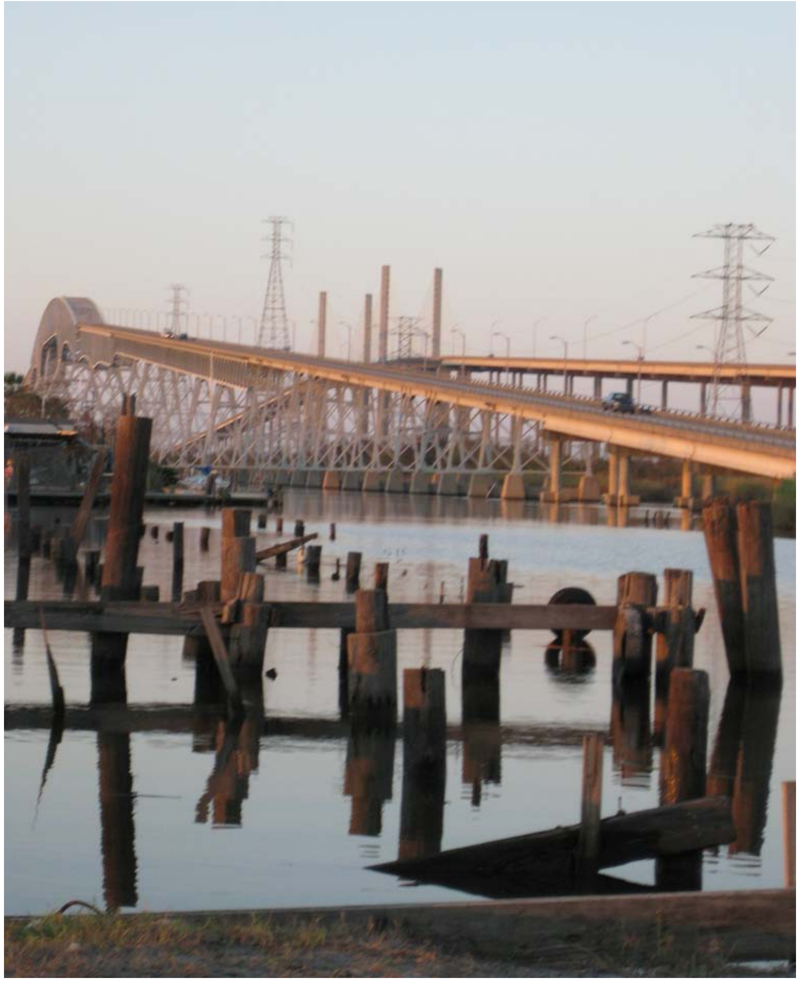
Due to **storm surges:**

increased <u>buoyancy forcing & Impact from debris</u>

lead to

- Longitudinal displacement (50cm or so) of the girder
  - → Falling down of adjacent girder
- Transverse directional excitation
  - → Two end link connects girders and piers break down

(Recent developments in bridge engineering, 2003, p155)



Rainbow Bridge between Port Arthur and Orange in Southeastern Texas. 9/26/08.
Photo by Carrie Housman
http://www.flickr.com/photos/15145271@N07/sets/72157607569509026/

Background

Background

Governing Equation for Storm Surge Generation*

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

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

Storm surges =response to Barometric response + Surface stress + geographical features

$$\zeta_B \approx \frac{\Delta p}{\gamma} \qquad \zeta_s \approx \left(\frac{\tau_s}{gh}\right)W$$

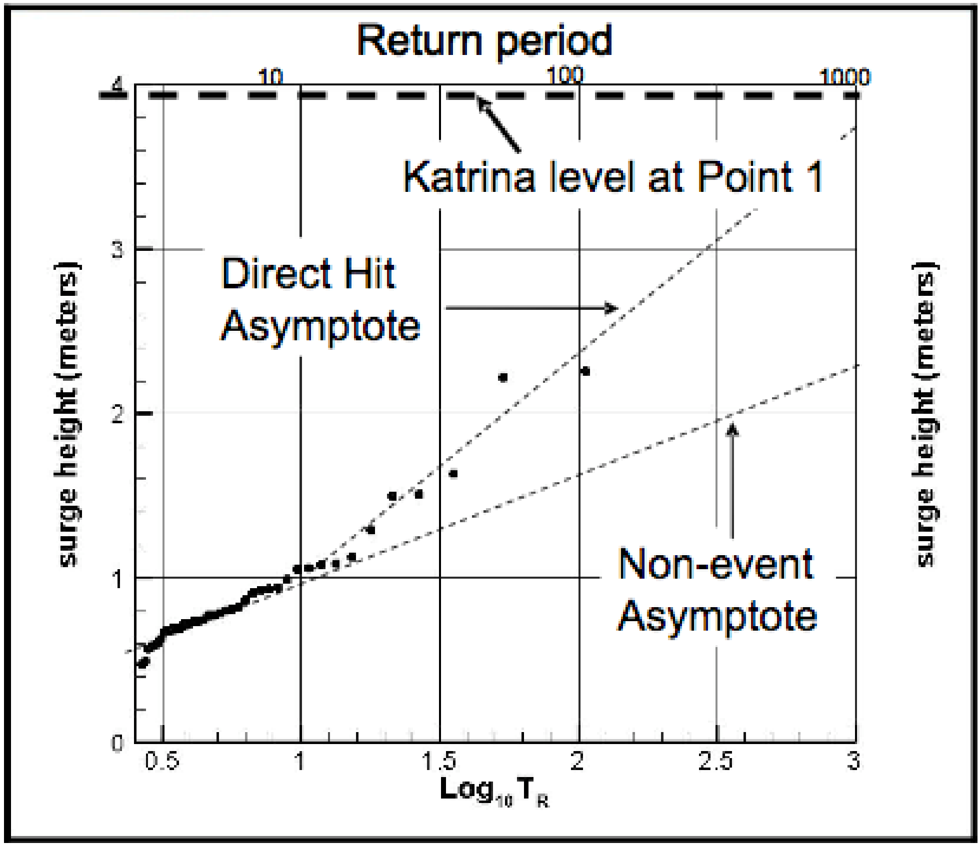
$$where,\ p = \rho_w g(\zeta - z), \tau_s = \rho c_f U^2$$

* http://www.adcirc.org/adcirc_theory_2004_12_08.pdf

Background

Historical Approach*

- Results extremely sensitive to record length
- Historical population cannot capture the changes in frequencies and intensities of storms on decadal scales
- Storms assumed to be from a homogeneous parent population
    - Climate variability typically excluded



* Based on “HopkinsSeminar.ppt”, by Dr. Jennifer Irish

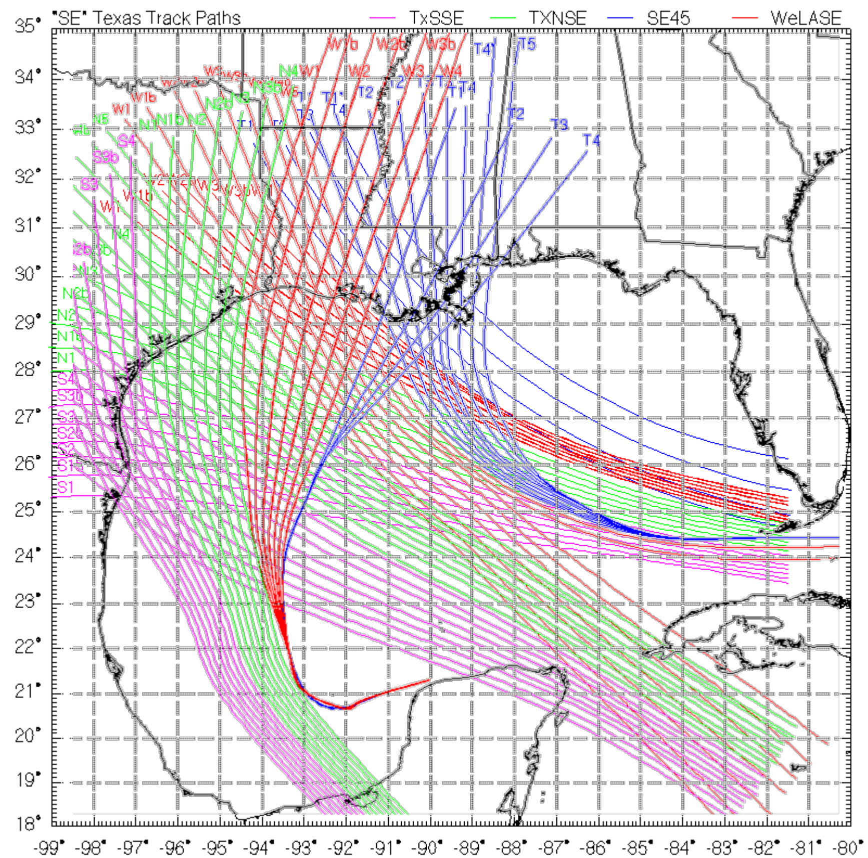
Background

Join Probability Method (*Ho and Myers,1975*)

- A statistical approach that utilizes the joint probability function to describe storm surge probability on certain condition

- Computational burden to accumulate sufficient data

- Not included a means account for uncertainties



TEXAS A&M ENGINEERING

* From "HopkinsSeminar.ppt", by Dr. Jennifer Irish

Methodology

Surge Response Function Approach*

Joint probability matrix:

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

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

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

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

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

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

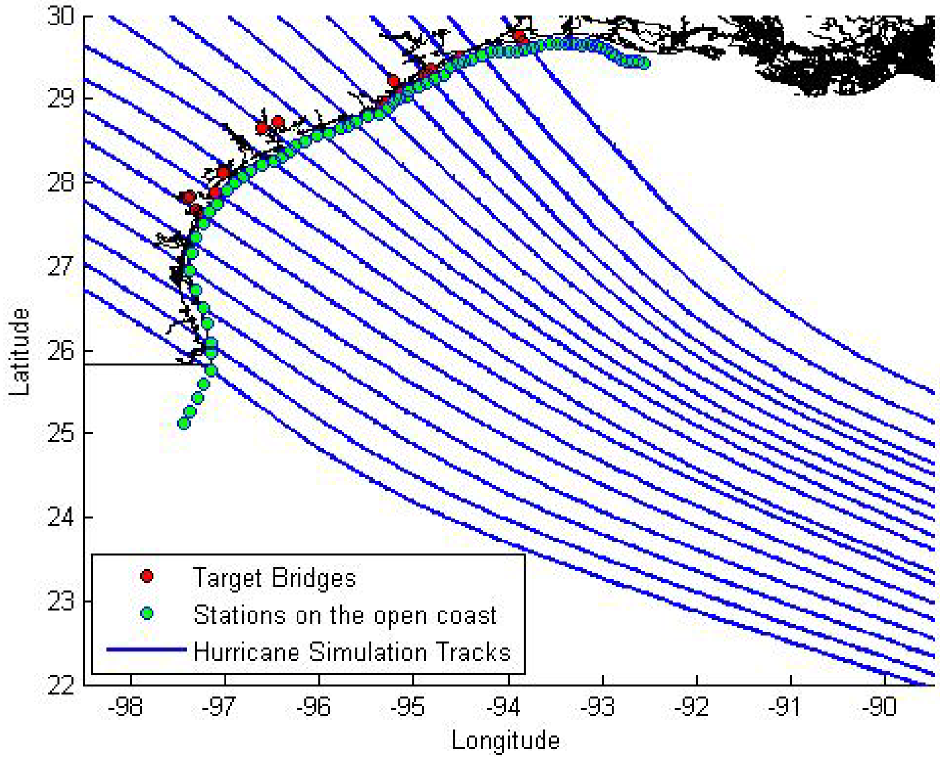
Uncertainty: $\sigma_{total}^2 = \sigma_{tide}^2 + \sigma_{\mathrm{model}}^2 + \sigma_B^2 + \sigma_{waves}^2 + \sigma_{winds}^2 + \sigma_{residual}^2$

* J.L. Irish, D.T. Resio, M.A. Cialone, “A surge response function approach to coastal hazard assessment. Part 1: Basic concepts," Nat. Hazards, in press.

Numerical Simulation

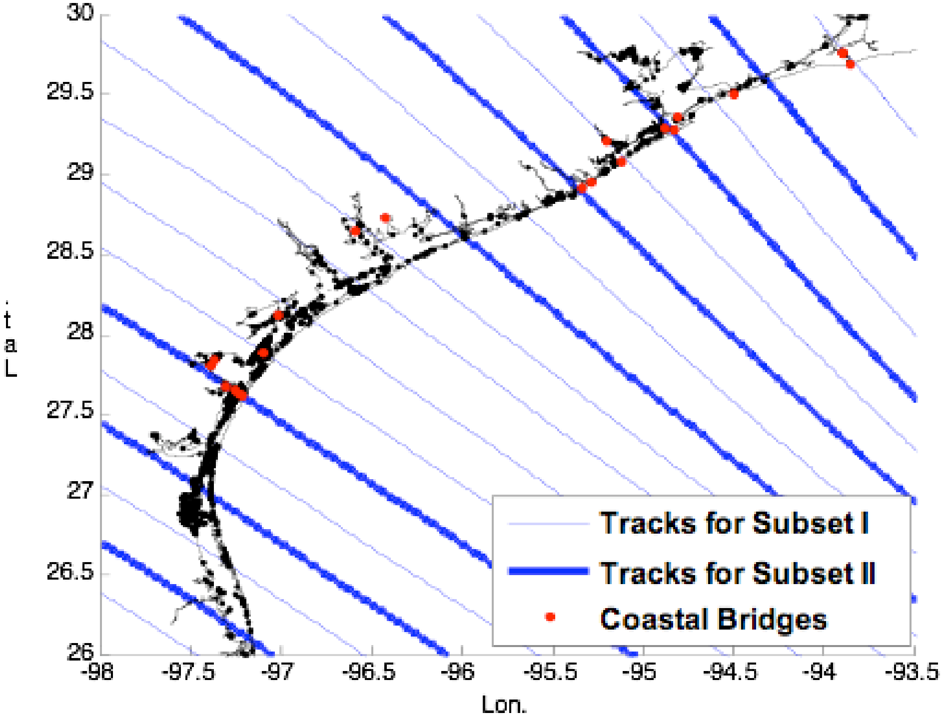
Hurricane selection based on optimal sampling

- Total 110 storms simulations on 18 parallel tracks
- Synthetic hurricane meteorology
  - Rp: 6~35.6 nmi (11~66 km)
  - C_p: 900~960 mb
  - ϑ <=17° with $_{WRT}$ shoreline orientation
  - V_f = 5.7m/s
  - 240 stations including 20 bridges
  (mean interval between stations = 2.8 km)
- Beyond the scope:
  - Tidal forcing & Ocean Wave Setup
  - The sensitivity to V_f, ϑ, Holland B (storm peakedness)



Numerical Simulation

Hurricane selection based on optimal sampling



Subset I				
x_{eye} [Lon.]	y_{eye} [Lat.]	v_f [km/s]	c_p [mb]	R_p [km]
-95.65	28.75	5.7	960	20.4
-95.65	28.75	5.7	960	38.9
-95.65	28.75	5.7	960	66.0
-95.65	28.75	5.7	930	14.8
-95.65	28.75	5.7	930	32.8
-95.65	28.75	5.7	930	47.8
-95.65	28.75	5.7	900	11.1
-95.65	28.75	5.7	900	27.6
-95.65	28.75	5.7	900	40.4

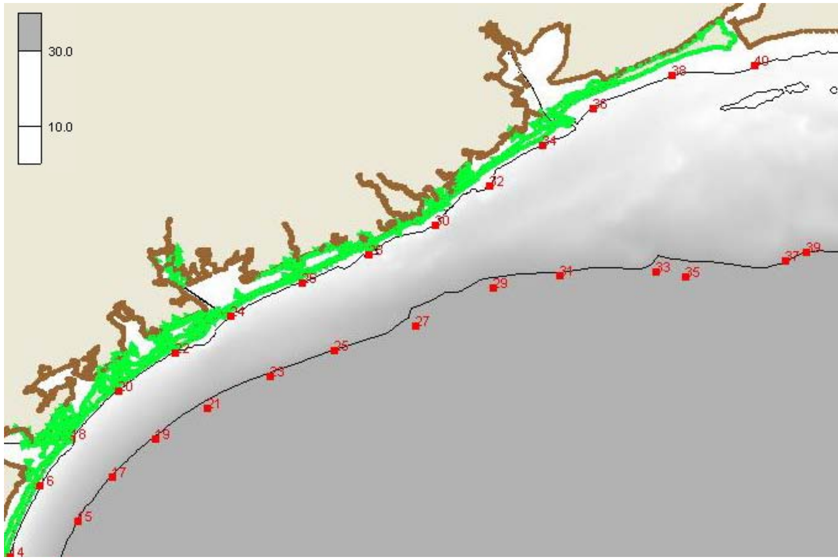
Subset II				
x_{eye} [Lon.]	y_{eye} [Lat.]	v_f [km/s]	c_p [mb]	R_p [km]
-95.35	28.90	5.7	960	32.8
-95.35	28.90	5.7	900	32.8

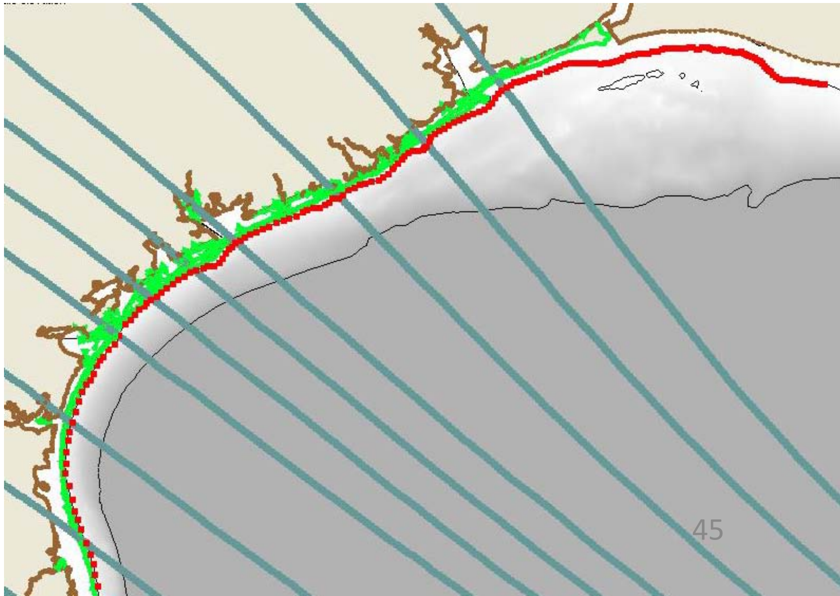
Improvement of SRF

Determination of the parameter λ

L_{30}: continental shelf expansion from the coast to the 30m water depth contour

- 10m and 30m water depth (every 60km spacing)
- specified on virtual orthogonal line with respect to shoreline orientation to measure L_{30}





Improvement of SRF

Determination of the parameter m_r

Hydrodynamic based storm surge scale (Irish et al. 2009)

$$\zeta \cong \frac{\lambda c_d}{\gamma_w} \Delta p \frac{L_{30}}{30\phi_*} \psi_x$$

$$\zeta_1' = \frac{\zeta_x \gamma_w}{\Delta p} - m_r \psi_x \times \chi(L_{30})$$

where,

$$\psi_x = \begin{cases} \dfrac{R_p}{L_{30}} & \text{where } \dfrac{R_p}{L_{30}} \le 1 \\ 1 & \text{otherwise} \end{cases}$$

$$\chi(L_{30}) = (2.38\text{E-}3) \times L_{30}$$

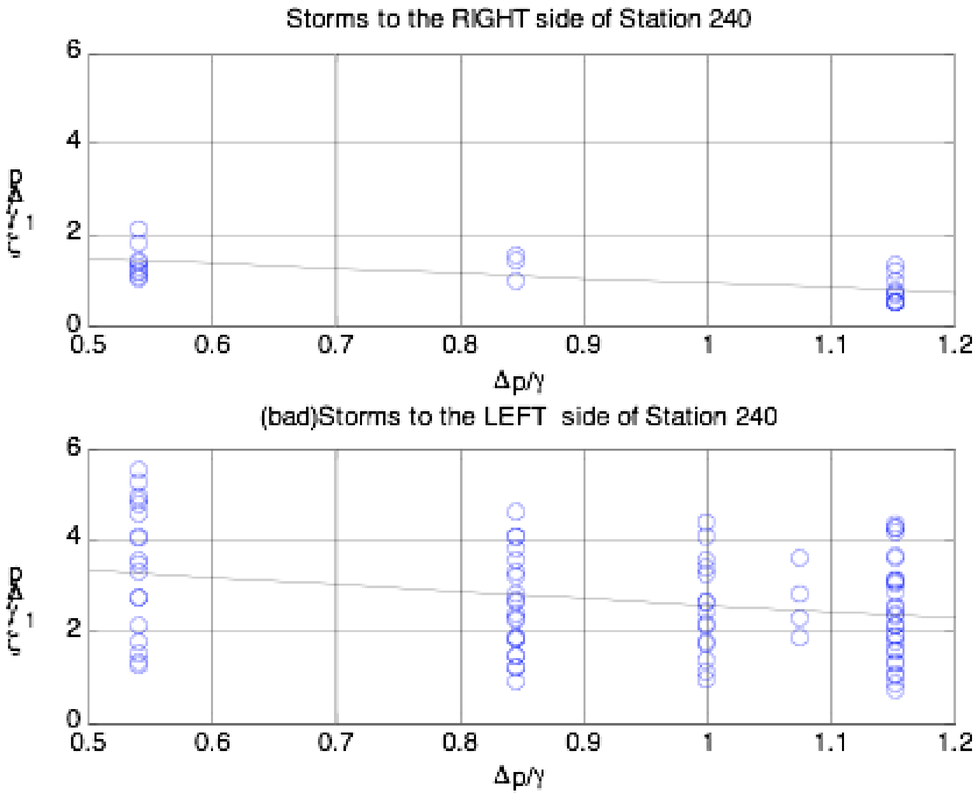
$$\phi_* \approx 1 \text{ where, } -50^\circ < \phi_* < 30^\circ$$

Advances in developing SRF

Determination of the parameter m_x

$$\zeta_1' = \frac{\zeta_x \gamma_w}{\Delta p} - m_x \left(\frac{\Delta p}{\gamma}\right) \times \alpha$$

$$\alpha = \begin{cases} 0.5 \ (x_2' >= 0) \\ 1 \ (x_2' < 0) \end{cases}$$



Application of SRF Method for Probability Estimation

Application of SRF Method for Probability Estimation

Flood probability analysis:

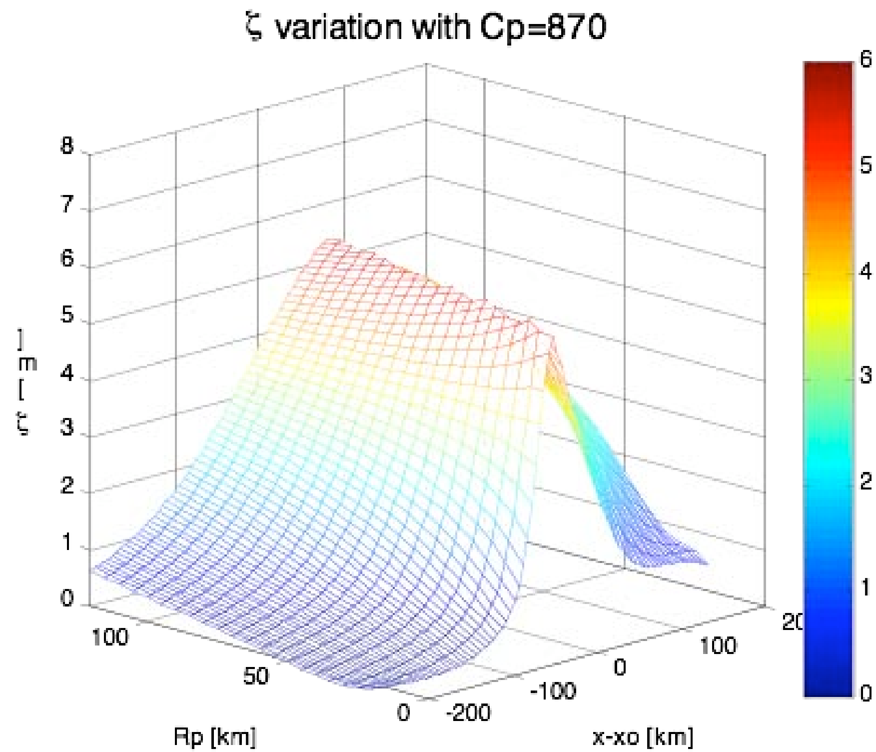
With a logical upper limit on the hurricane intensity, a Maximum Potential tropical cyclone Intensity (MPI, *Tonkin et al., 1999*), a maximum possible surge can be identified using the SRF.

Generation of the peak surge response surface:

The possible range of intensities and sizes in the Gulf of Mexico to be :

- c_p = 870mb (MPI)
- R_p = 8km to 120 km
- x-x_o<=200km

(storms making landfall within 200km of the location of interest)



Application of SRF Method for Probability Estimation

Flood probability analysis:

With a logical upper limit on the hurricane intensity, a Maximum Potential tropical cyclone Intensity (MPI, *Tonkin et al., 1999*), a maximum possible surge can be identified using the SRF.

The maximum possible surge levels:

A maximum elevation on the crest of the peak surge response surface

Bridges	ζ_{max} [m]	R_p [km]
San Luis Pass	6.7	116
Galveston Causeway	5.0	116
Rollover Pass	7.2	116