Coastal Inundation Risk Assessment

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Coastal Inundation Risk Assessment
Why is Coastal Flooding Unique?

- Coasts are highly dynamic, landscape constantly changing
- Storm surge depends on meteorology + generation capacity
- Physics extremely important for accurate surge estimation
- A single event spans a wide range of return periods
- More difficult to mitigate because of the short timeframe
- Almost always have multiple hazards at same time
- ~50% of weather-related damages due to coastal storms (since 1980)

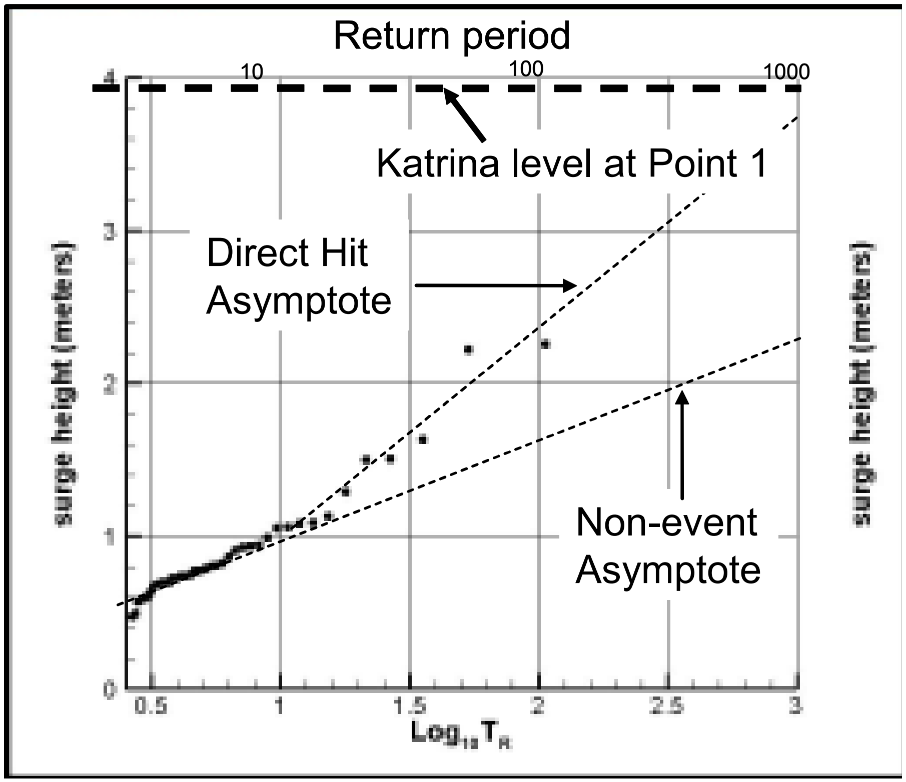
Coastal Inundation Risk Assessment
Outline

- Motivation for PFHA
- Surge response functions (SRF)
    - Theoretical Basis
    - Parameterization
    - Validation
- Extreme-value analysis: JPM-OS
- Uncertainty
- Examples
- Shortcomings/lack of knowledge

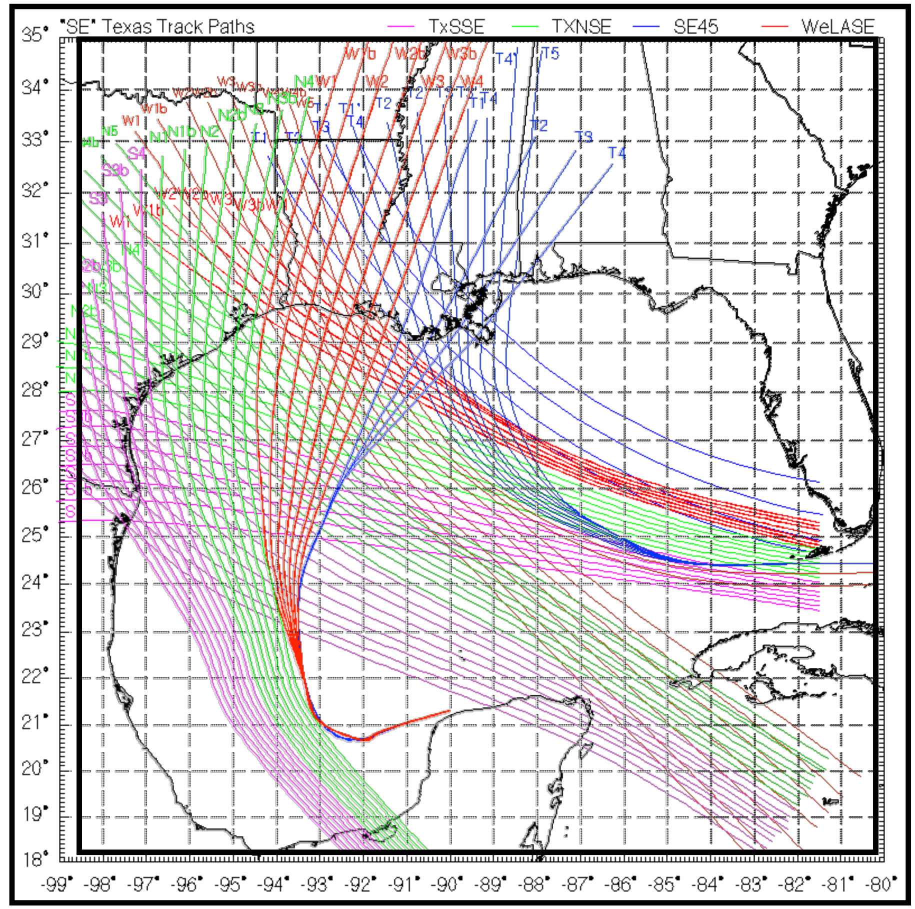
Coastal Inundation Risk Assessment
Motivation for PFHA

A robust and accurate method for determining hurricane surge extreme value probabilities is required.

Historical surge population approach



Joint probability method



Coastal Inundation Risk Assessment
Surge Response Functions

General form for maximum surge response:

$$\zeta_{\max}\left(x\right) = \phi(x, p_o, R_p, v_f, \theta, x_o) + \varepsilon_z$$

$$\varepsilon_z^2 = \varepsilon_{tide}^2 + \varepsilon_{surge\ simulation}^2 + \varepsilon_{waves}^2 + \varepsilon_{winds}^2 + \ldots$$

where:

ϕ is a continuous flood response function,

x is location of interest,

p_o is central pressure,

x_o is landfall location,

R_p is hurricane pressure radius near landfall (Thompson and Cardone 1996),

θ is hurricane track angle with respect to the shoreline,

v_f is hurricane forward speed near landfall, and

ε_z is epistemic uncertainty in the flood response (Resio et al. 2012)

From Resio, Irish, and Cialone, 2009, *Nat. Hazards*

Coastal Inundation Risk Assessment
Surge Response Functions

- Shallow-water momentum balance:

$$\frac{\partial u}{\partial t} + g\frac{\partial \zeta}{\partial x} = \frac{\tau_a}{\rho_w h(x)}$$

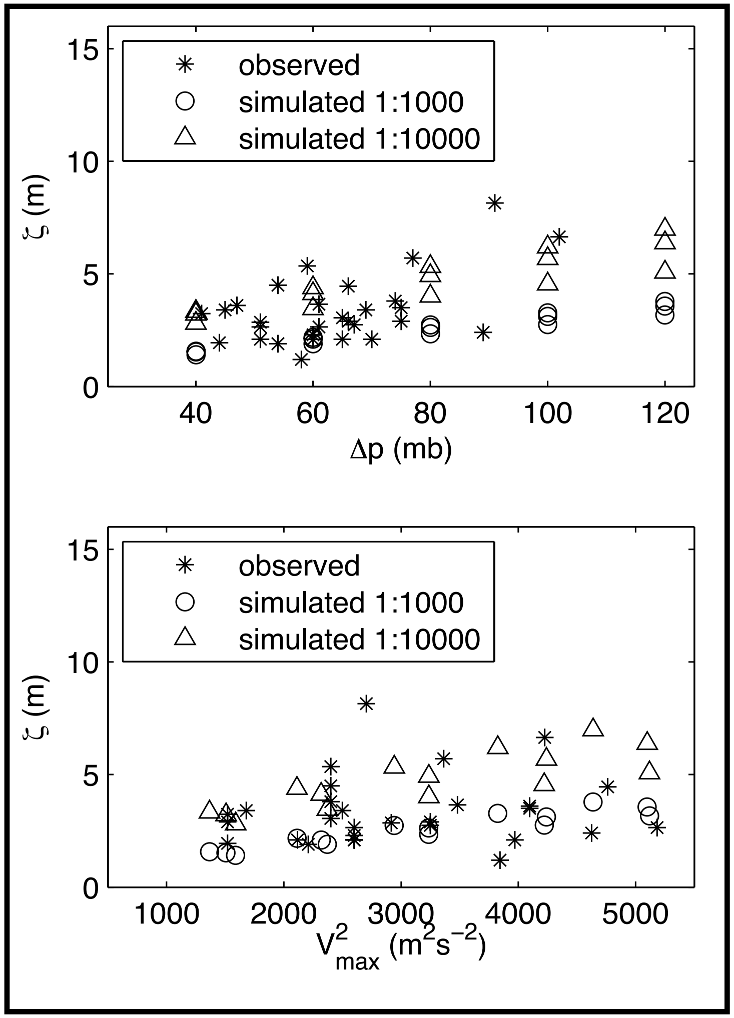
- Assume:
  - Steady winds over long period
  - Wind stress in quadratic form

$$\frac{d\zeta}{dx} = \left(\frac{\rho_a}{\rho_w}\right)\frac{c_d V^2}{g h(x)}$$

- Assume continental shelf of constant depth with width, L:

$$\zeta = \left(\frac{\rho_a}{\rho_w}\right)\frac{c_d V^2}{g\langle h\rangle}L \quad \Rightarrow \quad V^2 \ \alpha \ \Delta p \quad \Rightarrow \quad \zeta = \chi_1 \Delta p \frac{L}{\langle h\rangle}$$

where $\Delta p = P_{far} - p_o$



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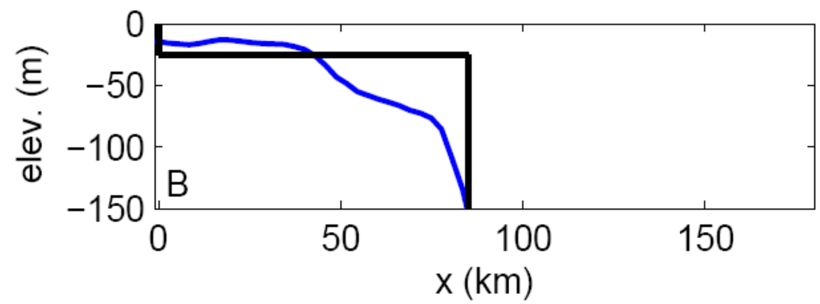
From Irish and Resio, 2010, *Ocean Eng.*

Coastal Inundation Risk Assessment
Surge Response Functions

- Influence of depth profile:

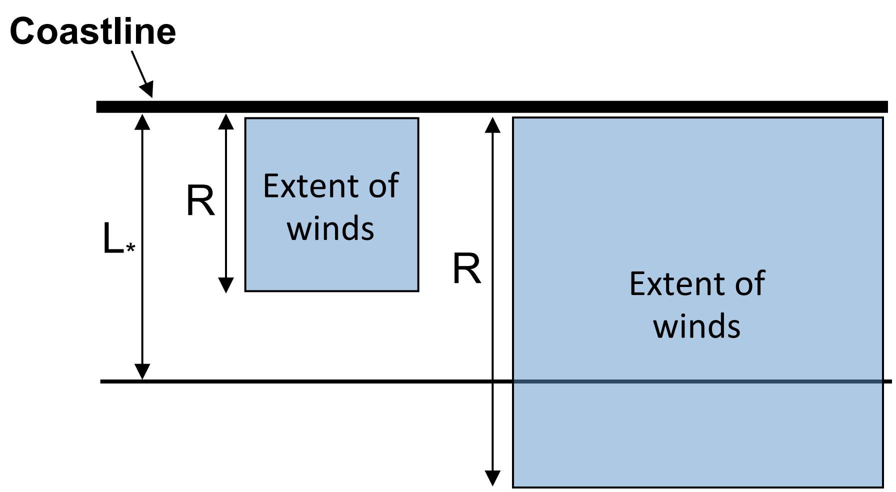
$$\zeta = \chi_1 \Delta p \frac{L_*}{h_* \phi_*}$$

ϕ_* = dimensionless depth function



- Influence of hurricane size:

$$\zeta = \chi_1 \Delta p \frac{L_*}{h_* \phi_*} \Psi_x \left(\frac{R}{L_*} \right)$$

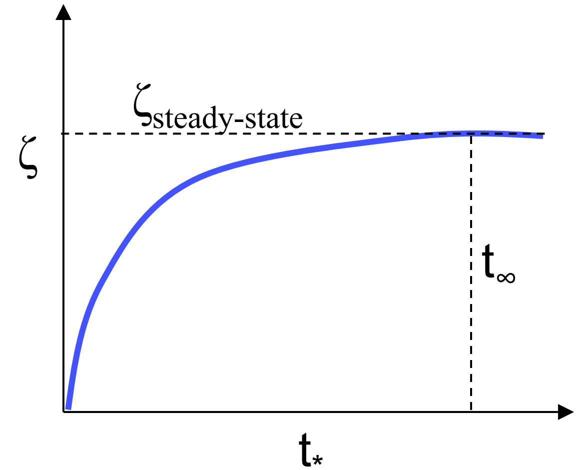


From Irish and Resio, 2010, *Ocean Eng.*

Coastal Inundation Risk Assessment
Surge Response Functions

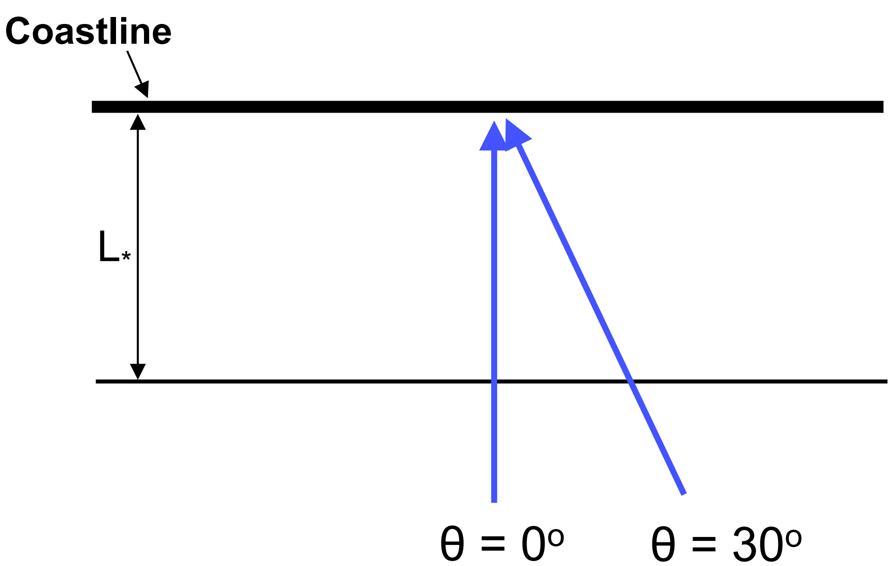
- Influence of forward speed:

$$\zeta = \chi_1 \Delta p \frac{L_*}{h_* \phi_*} \psi_x \left(\frac{R}{L_*} \right) \psi_t \left(\frac{t_*}{t_\infty} \right)$$



- Influence of approach angle:

$$\zeta = \chi_1 \Delta p \frac{L_*}{h_* \phi_*} \psi_x \left(\frac{R}{L_*} \right) \psi_t \left(\frac{t_*}{t_\infty} \right) \psi_\theta (\theta)$$



From Irish and Resio, 2010, *Ocean Eng.*

Coastal Inundation Risk Assessment
Surge Response Functions

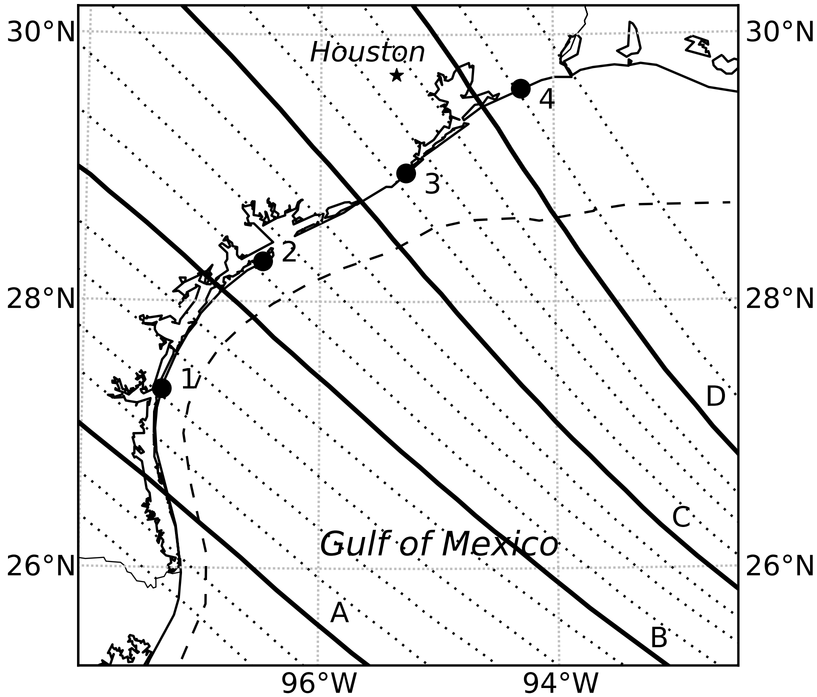
Storm surge and tides – ADCIRC (Luettich *et al.* 1992)

- Hydrodynamic model:

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

$$\frac{\partial \vec{U}}{\partial t} + \left(\vec{U}\cdot\nabla_H\right)\vec{U} = -g\nabla_H\left(\zeta_2 + \frac{p\,(x,y)}{g\rho_w} - \alpha\eta\right) + f\,\vec{k}\times\vec{U} + \frac{\vec{\tau_s}}{H\rho_w} - \frac{\vec{\tau_b}}{H\rho_w}$$

- Finite element, variable resolution
- Model forcing:
  - Wind stress & Barometric pressure (Thompson & Cardone 1996):
    - V_f, θ, c_p, R_p, track position, …
- Simulation time: 1000+ hours (on 1 CPU)



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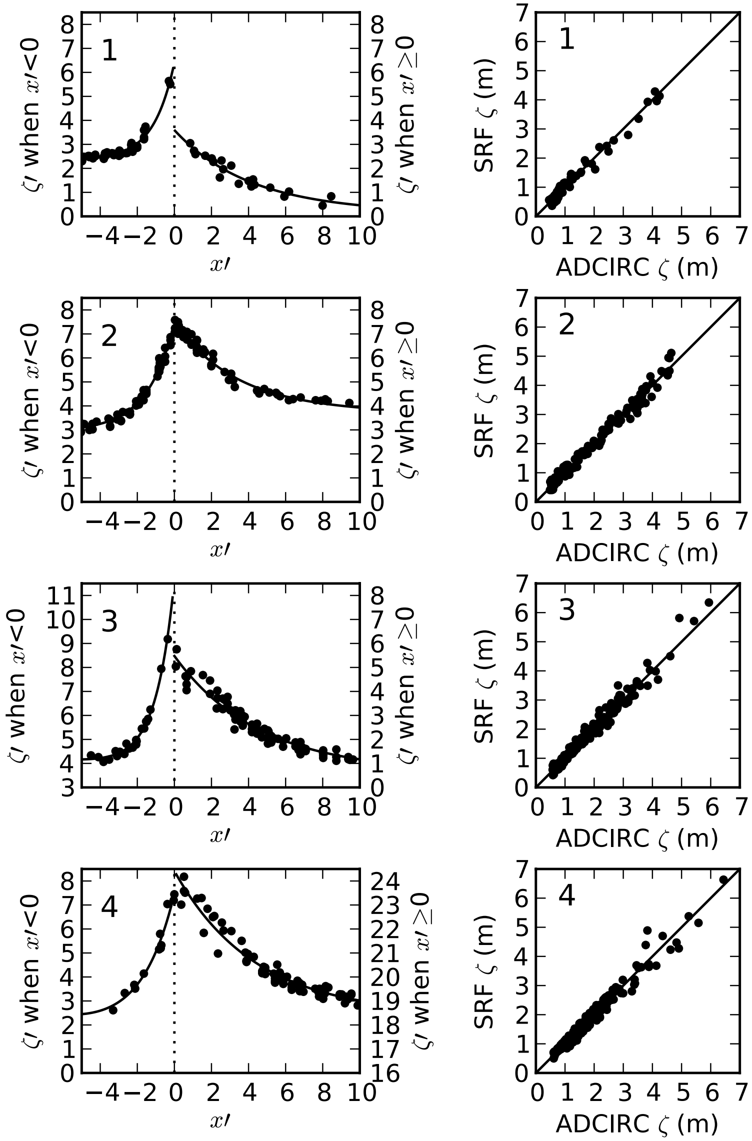
Coastal Inundation Risk Assessment
Surge Response Functions

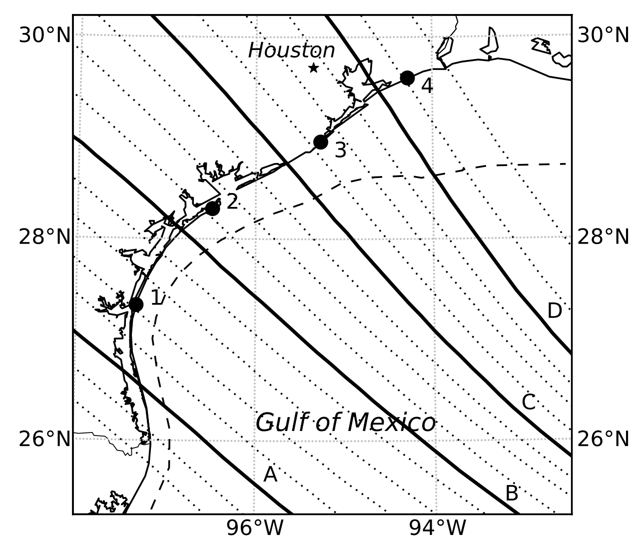


$$\zeta' = \frac{\gamma\zeta}{\Delta p} + m_2(x,x')\left(\frac{P_{far} - c_p}{P_{far} - c_{p-\max}}\right)^{\alpha(x,x')}\left(\frac{R_p / L_{30}(x_o)}{\left[R_p / L_{30}\right]_{ref}}\right)^{\beta(x,x')}$$

$$x' = \frac{(x - x_o)}{R_p} - \lambda(x_o) + cH\left(\frac{(x - x_o)}{R_p} - \lambda(x_o) - 1\right)\left(\frac{R_p}{L_{30}}\right) - F\left(1 - \frac{R_p}{R_{thres}}\right)H\left(1 - \frac{R_p}{R_{thres}}\right)$$

mean error = -3 to +1 cm ← NO BIAS!

RMS error = 11 to 22 cm



From Song et al., 2012 *Nat. Hazards*

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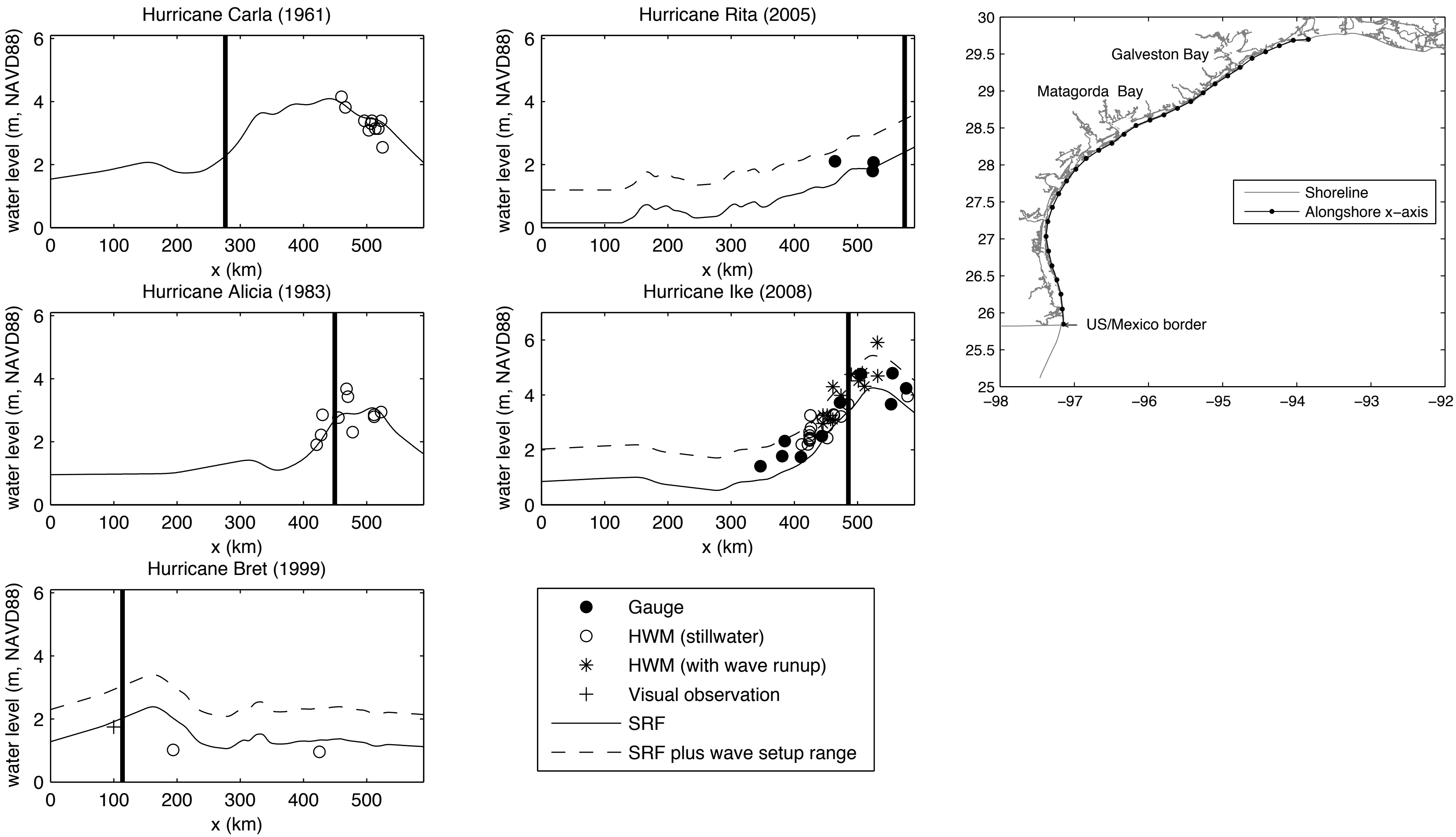
Coastal Inundation Risk Assessment
Surge Response Functions



From Irish et al., 2011, *Geophys. Res. Lett.*

Coastal Inundation Risk Assessment
Joint Probability Method with Optimal Sampling (JPM-OS)

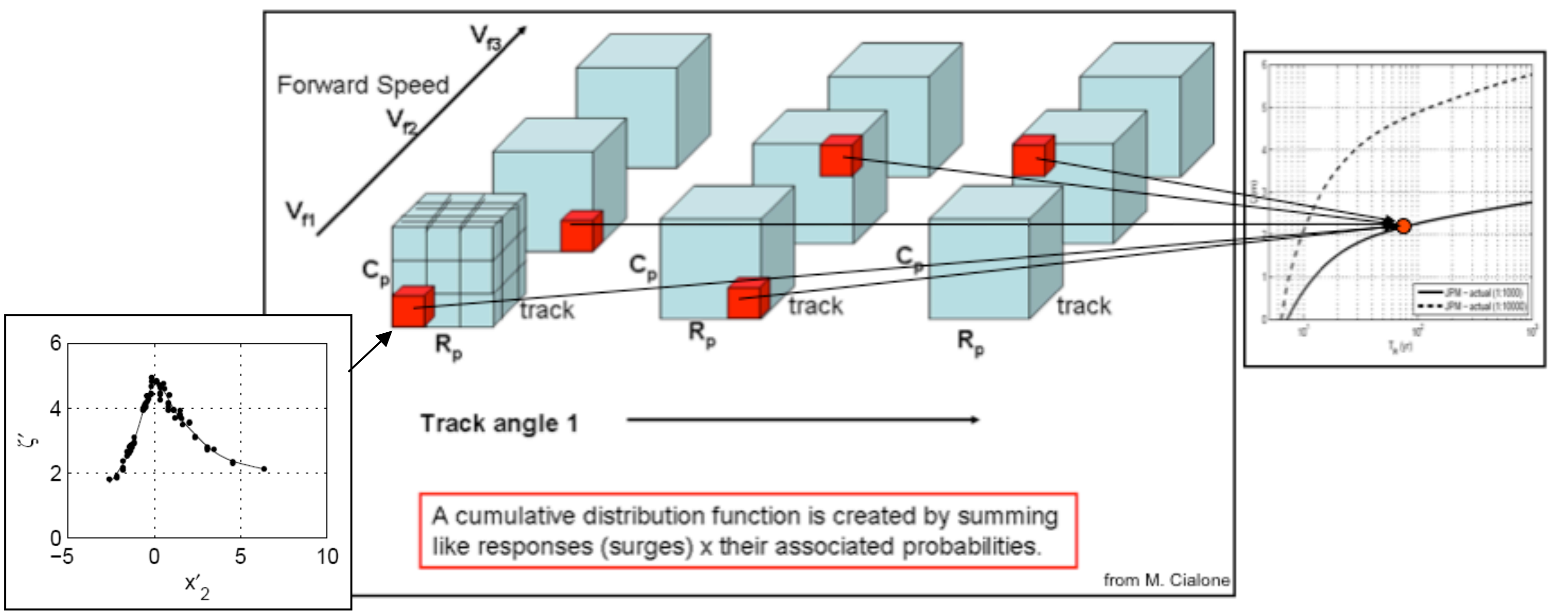
$$T_R\left(z_{\max}\right)=\left\{1-\int\limits_{p_o}\int\limits_{R_p}\int\limits_{v_f}\int\limits_{\theta}\int\limits_{x_o} f(p_o,R_p,v_f,\theta,x_o)\left[H\left(z_{\max}-\left[\phi(x,p_o,R_p,v_f,\theta,x_o,MSL)+\varepsilon_z\right]\right)\right]dx_o\,d\theta\,dv_f\,dR_p\,dp_o\right\}^{-1}$$

$$f(p_o,R_p,v_f,\theta,x_o)=\Lambda_1\Lambda_2\Lambda_3\Lambda_4\Lambda_5$$

$$\Lambda_1=f(p_o\,|\,x_o)=\frac{1}{a_1(x_o)}\exp\left[-\frac{\Delta p-a_o(x_o)}{a_1(x_o)}\right]\exp\left\{-\exp\left[-\frac{\Delta p-a_o(x_o)}{a_1(x_o)}\right]\right\}\;(Gumbel\ Distribution)$$

← Extreme-value distribution

$$\Lambda_5=g\left(\lambda,x_o\right)$$



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From Resio et al., 2009 Natural Hazards

Coastal Inundation Risk Assessment
Joint Probability Method with Optimal Sampling (JPM-OS)

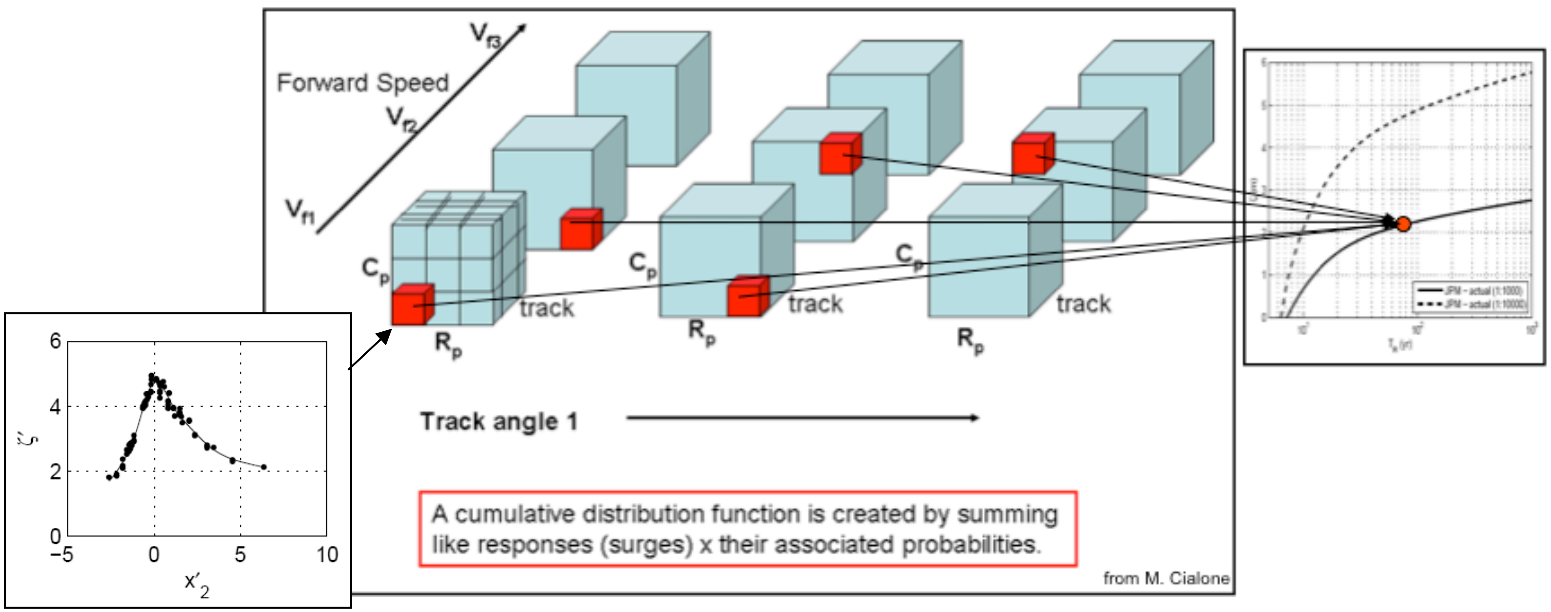
$$T_R\left(z_{\max}\right)=\left\{1-\int_{SST}\int_{p_o}\int_{R_p}\int_{v_f}\int_{\theta}\int_{x_o} f(p_o,R_p,v_f,\theta,x_o)\left[H\left(z_{\max}-\left[\phi(x,p_o,R_p,v_f,\theta,x_o,MSL)+\varepsilon_z\right]\right)\right]dx_o\,d\theta\,dv_f\,dR_p\,dp_o\,dSST\right\}^{-1}$$

$$f(SST,p_o,R_p,v_f,\theta,x_o)=\Lambda_{SST}\Lambda_1\Lambda_2\Lambda_3\Lambda_4\Lambda_5$$

$$\Lambda_1=f(p_o\,|\,x_o)=\frac{1}{a_1(x_o,t)}\exp\left[-\frac{\Delta p-a_o(x_o,t)}{a_1(x_o,t)}\right]\exp\left\{-\exp\left[-\frac{\Delta p-a_o(x_o,t)}{a_1(x_o,t)}\right]\right\}\ (Gumbel\ Distribution)$$

$$\Lambda_5=g\left(\lambda(t),x_o\right)$$

$$\Lambda_{SST}=\ ?$$



From Irish and Resio, 2013 ASCE Waterw.

Coastal Inundation Risk Assessment
Uncertainty

Uncertainty = Aleatory + Epistemic

Aleatory = 0.23 m, T_R = 50 yr
0.55 m, T_R = 500 yr

Epistemic = 0.70 m

$$\underbrace{\varepsilon^2_{tide} + \varepsilon^2_{surge\ simulation} + \varepsilon^2_{waves} + \varepsilon^2_{winds} + \ldots}$$

$$\underbrace{\varepsilon^2_{\Delta SST} + \varepsilon^2_{SLR} + \varepsilon^2_{p} + \varepsilon^2_{\lambda} + \ldots}$$

Aleatory + **Epistemic** = 0.74 m, T_R = 50 yr
0.89 m, T_R = 500 yr

From Irish and Resio 2013 ASCE Waterw.

Coastal Inundation Risk Assessment
Uncertainty - Aleatory

For estimating surges in large coastal applications to date, the standard has been to include epistemic uncertainty but to neglect aleatory uncertainty, assuming it was small for the range of annual exceedance probabilities required in those studies.

However, aleatory uncertainty can be shown to have a form such that

$$\left[\frac{F(z')}{F(z)}\right] = \Psi\left[\frac{T(z)}{N}, \frac{\sigma_1}{\sigma_2}\right]$$

where

$F(z), F(z')$ are the CDFs of the results with and without aleatory uncertainty included

Ψ is highly nonlinear function of its 2 arguments

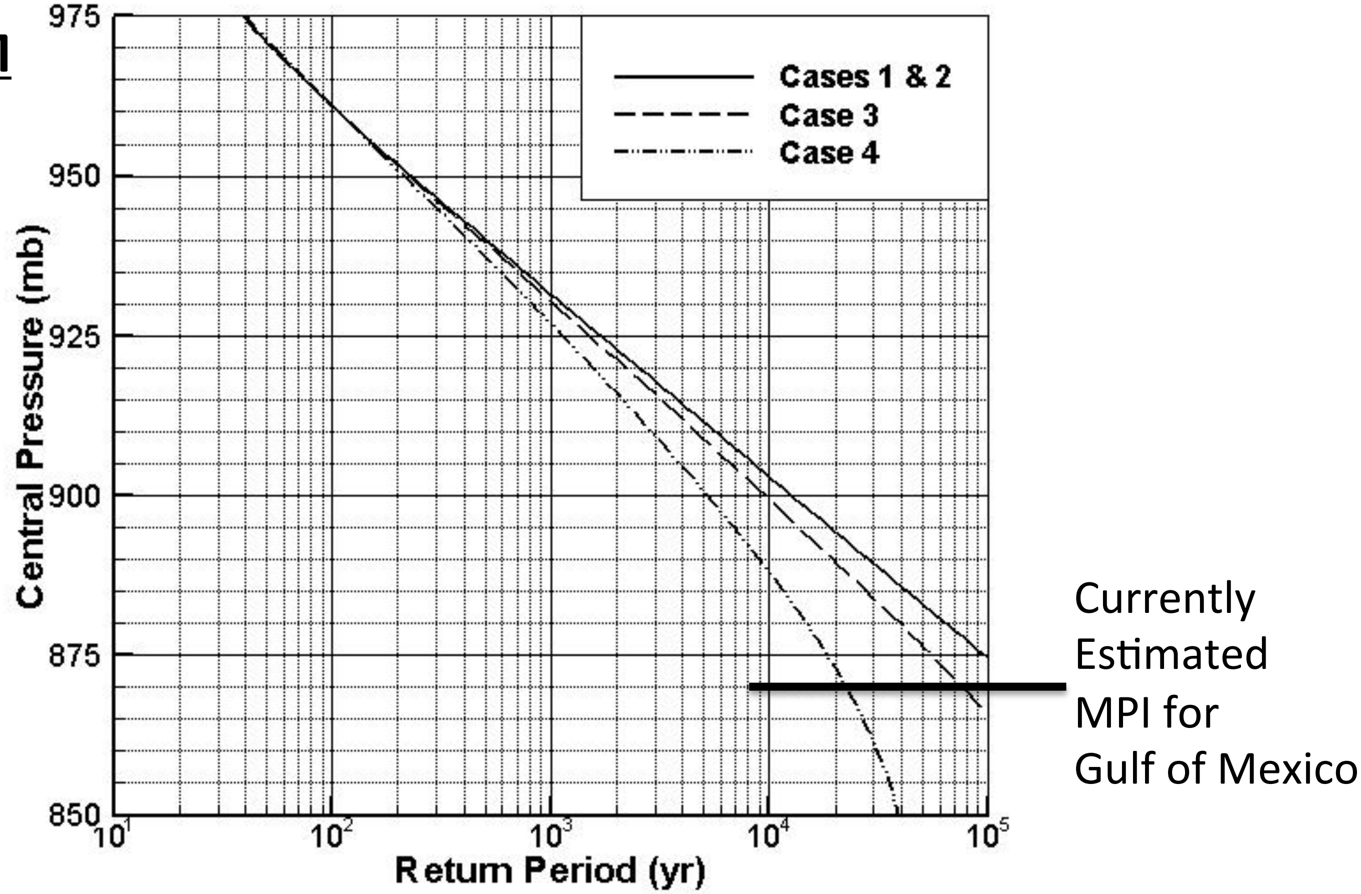
$T(z)$ is the return period associated with surge level z

N is the number of years in the sample

σ_1, σ_2 are the measures of dispersion for the extremal distribution and the uncertainty distribution (which varies with $T(z)$)

Coastal Inundation Risk Assessment
Uncertainty - Aleatory

Florida Example, JPM

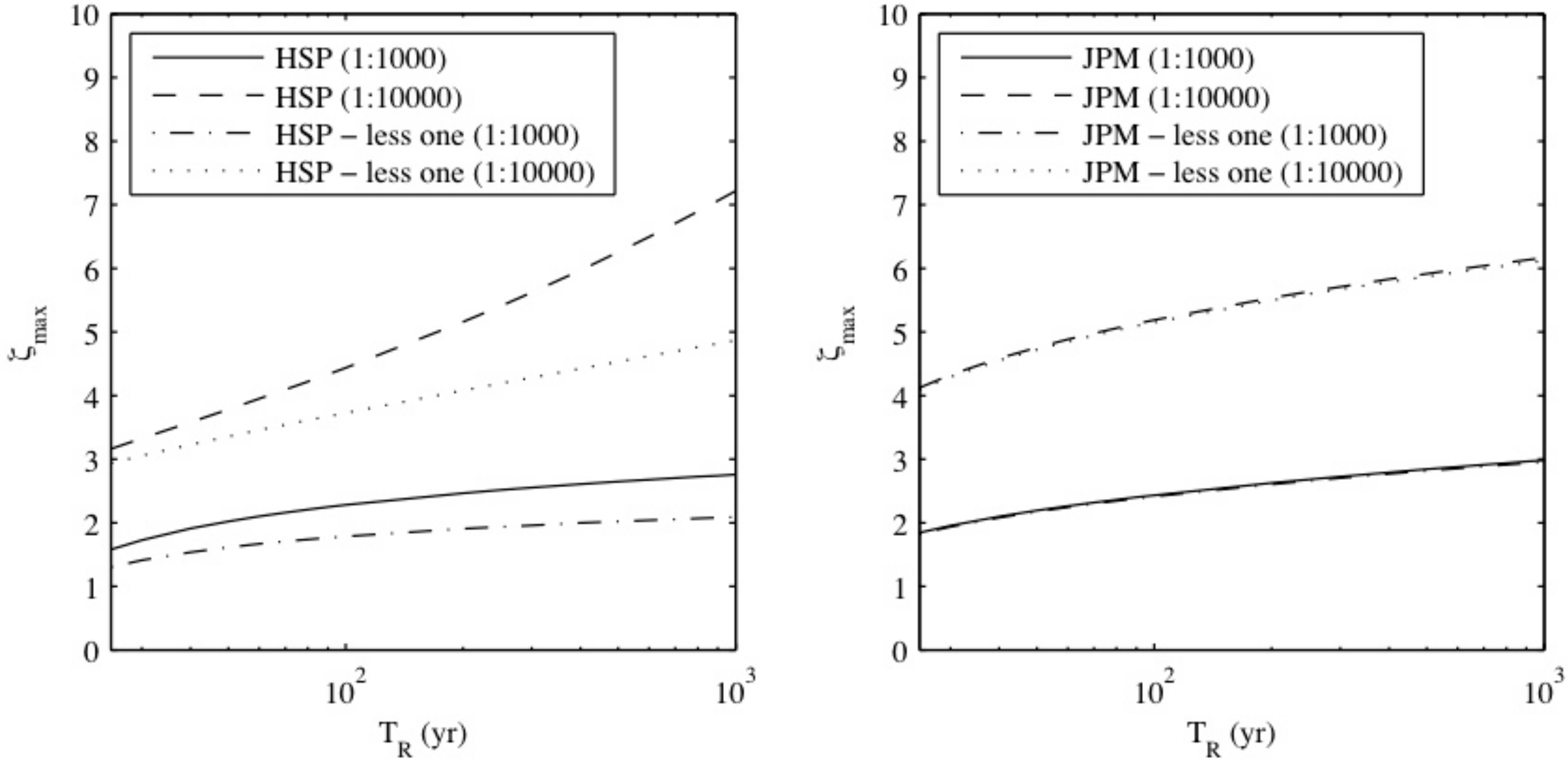


Estimated return periods with and without uncertainty:

- Case 1&2: deterministic and delta function approximation
- Case 3: using estimated standard deviations divided by 2
- Case 4: using actual estimated standard deviations

From Resio et al, 2013 Natural Hazards

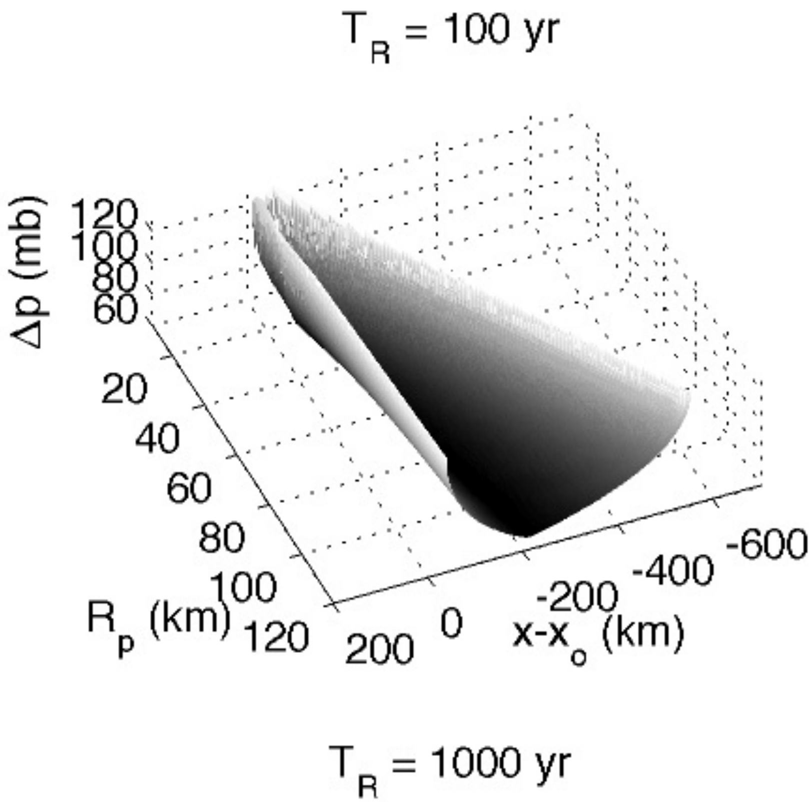
Coastal Inundation Risk Assessment
Examples – Strength of JPM-OS

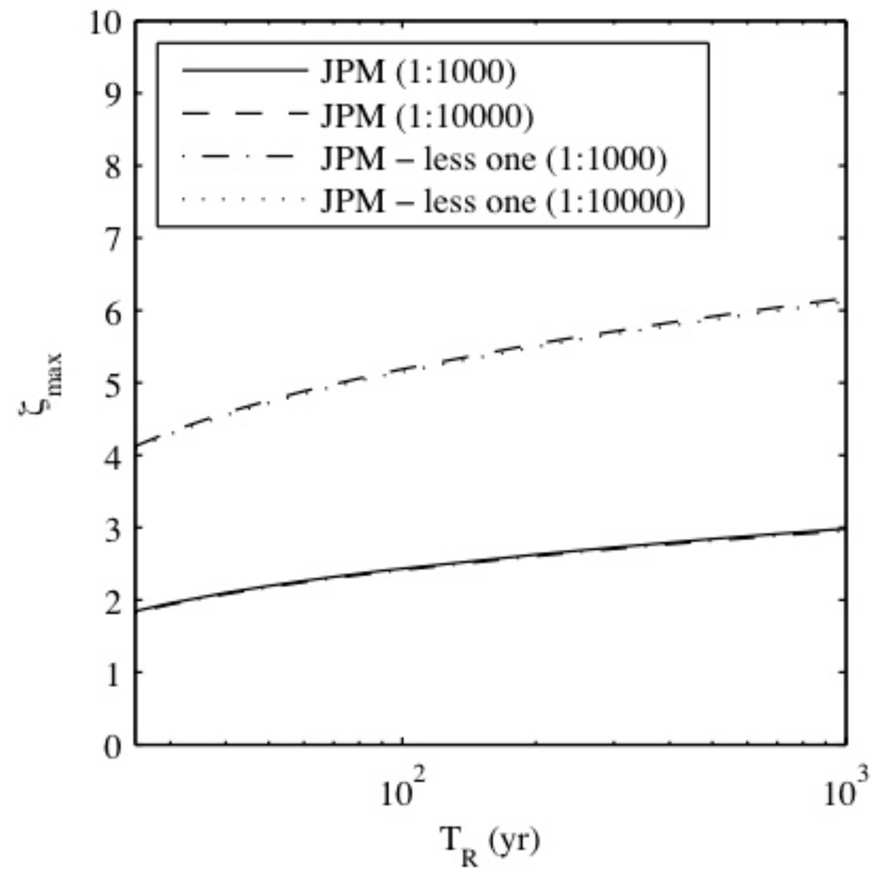


- Optimal sampling reduces computational requirements by 75%
- Means to bound upper tail of distribution using Maximum Possible Intensity
- Stable with respect to small changes in sample
- Considers all storms in parameter space contributing to surge level

From Irish et al., 2011, *J. Geophys. Res.*

Coastal Inundation Risk Assessment
Examples – Strength of JPM-OS





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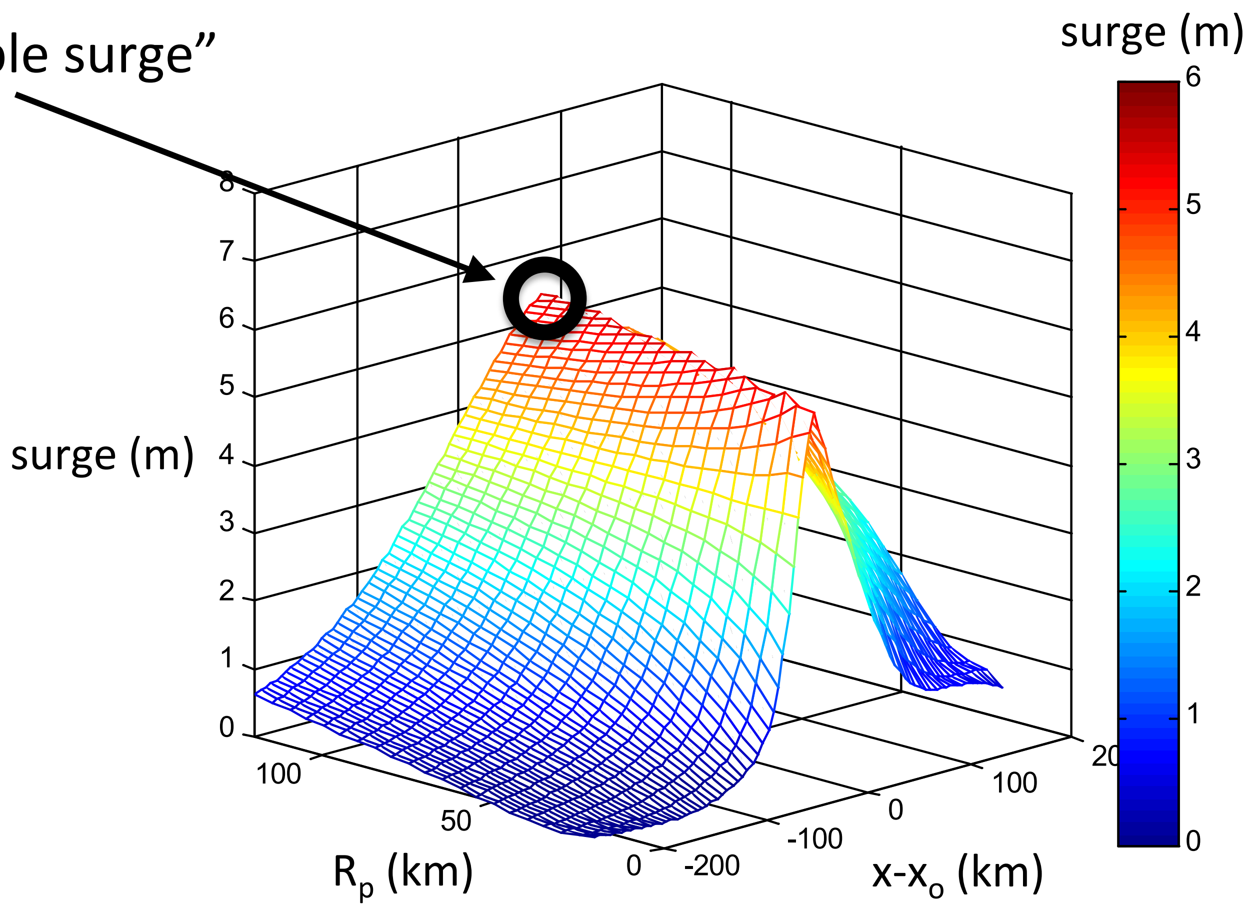
From Irish et al., 2011, *J. Geophys. Res.*

Coastal Inundation Risk Assessment
Examples – Upper Limits

<u>"Maximum possible intensity":</u>

p_o = 870 m (Tonkin 2000)

"Maximum possible surge"



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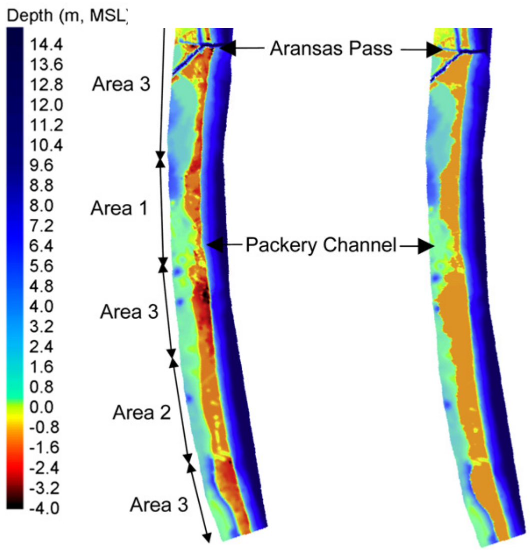
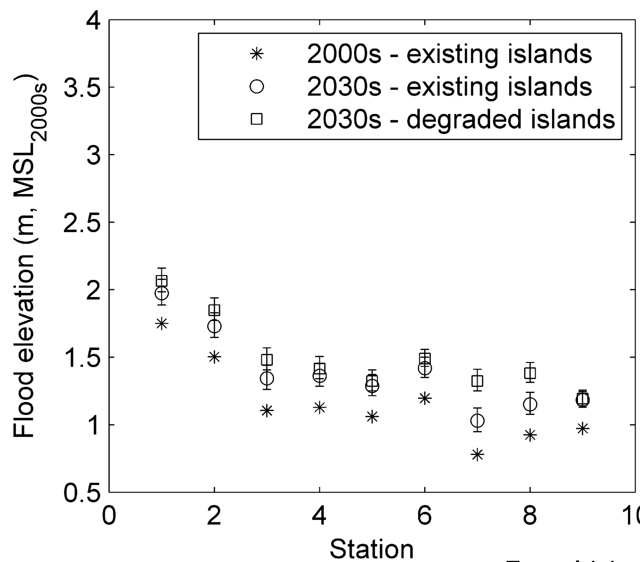
Coastal Inundation Risk Assessment
Shortcomings: Multi/Combined-Hazards

- Within singe events:
  - Surge + tides + waves + winds + precipitation
  - Tsunami + earthquake
- Consecutive events:
  - Storm then storm
  - Storm then tsunami, vice versa
- Concurrent events:
  - “Superstorm” Sandy = hurricane + Nor’easter
  - 2011 MS River flood = inland rainfall event + coastal storm
  - Tsunami + hurricane (??)

Coastal Inundation Risk Assessment
Shortcomings: Future Conditions (UNCERTAINTY!)

- Sea-level rise
- Climate variability/climate change
- Landform changes:





From Irish et al. 2011, Ocean *Coastal Mgt.*

- Human impacts:
  - Land use changes
  - Population growth/migration
  - Policy/Procedure
  - Maintenance
  - Adaptation

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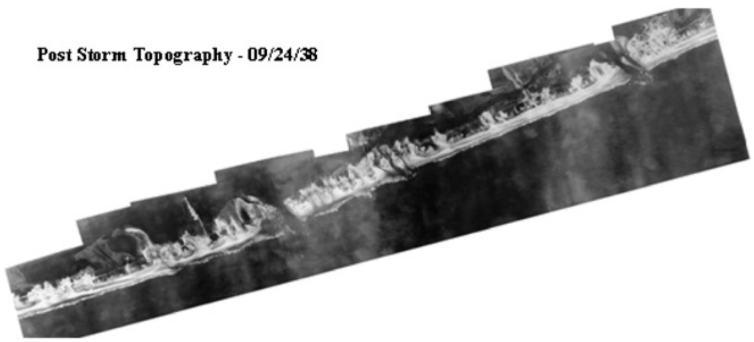
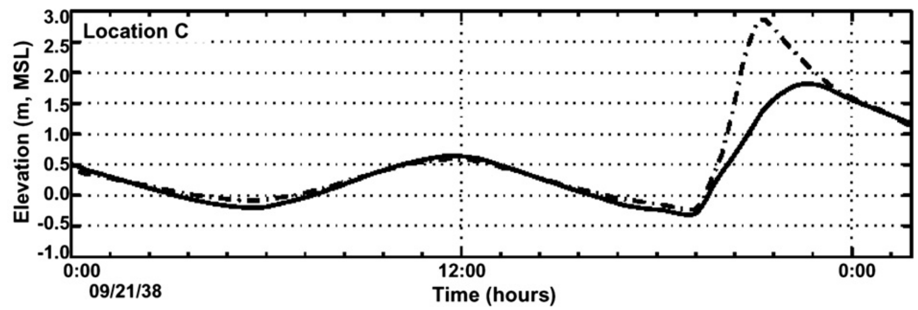
Coastal Inundation Risk Assessment
Shortcomings: Complex/Coupled Processes

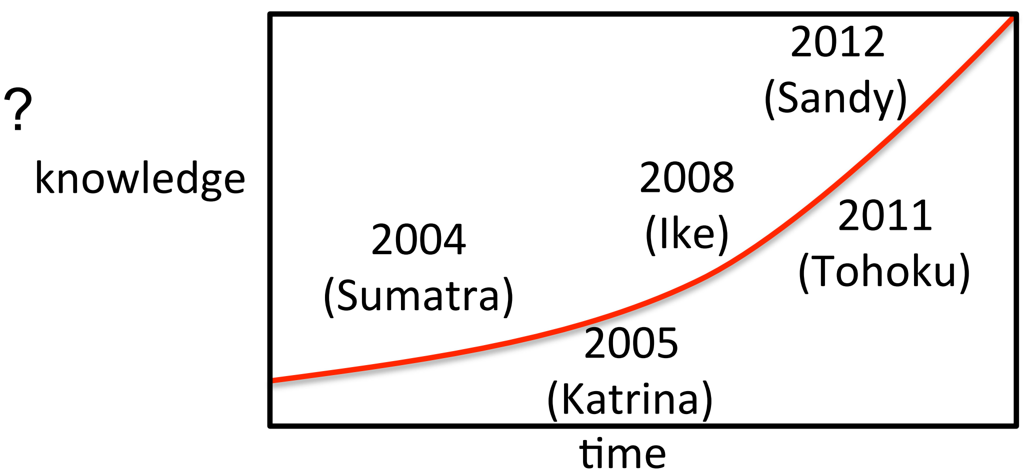
- Surge response coupled with sediment transport, vice versa
- Example: Barrier island overwash and breaching





From Cañizares and Irish 2008, *Coastal Eng.*

- Spatiotemporal variation in surges, waves, winds, etc.
- Natural limits
- Methods validation
- What else have we yet to learn?



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Coastal Inundation Risk Assessment
Shortcomings: Probability vs. Risk

Single flood probability = multitude of outcomes

Natural: Flood level +

- Velocity
- Forces
- Erosion

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Natural/Human

- Policy/Decisions
- Procedures
- Maintenance
- Adaptation