## RIC 2010
## External Flood and Extreme Precipitation Hazard Analysis for Nuclear Plant Safety

## Recent Advances in Storm Surge Modeling

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11 March 2010



## Outline

- Historical perspective.
- Getting a single storm right: The physics of single storm.
- Estimating the statistical likelihood of surges, including uncertainty.
- Estimating very-low-probability (annual frequency less than $10^{-6}$ annual probability) surge levels.

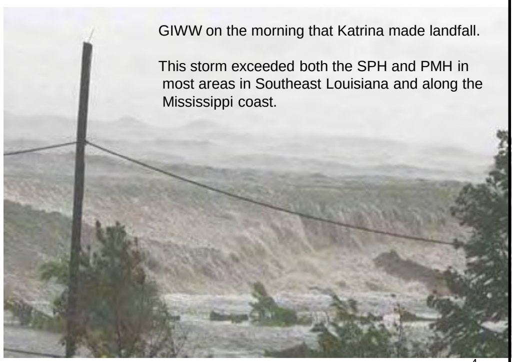


## Design Storm Concept

- Define a single storm that can be used to estimate design conditions. Advantage – only have to model a single storm. BUT, this should be an objective definition if this storm is to be rigorously defined.
- Need to determine a storm surrogate for surge. Early studies chose storm intensity (wind speed) for this purpose – Saffir-Simpson Scale analogue – Standard Project Hurricane (SPH) and Maximum Probable Hurricane (PMH) were defined.
- Definitions were quite subjective, incorporating words such as "reasonably characteristic" and "expected to occur."
- Data basis used in these early definitions and the models utilized in their execution were quite primitive.

GIWW on the morning that Katrina made landfall.

This storm exceeded both the SPH and PMH in most areas in Southeast Louisiana and along the Mississippi coast.



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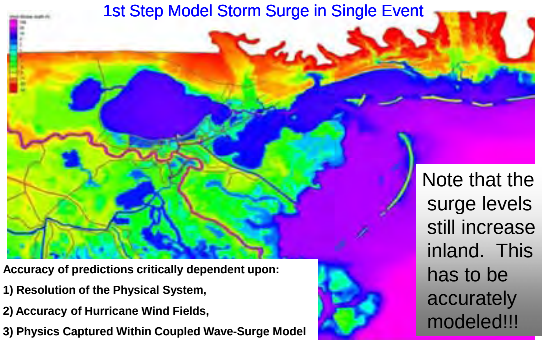
1st Step Model Storm Surge in Single Event



Note that the surge levels still increase inland. This has to be accurately modeled!!!

**Accuracy of predictions critically dependent upon:**

**1) Resolution of the Physical System,**

**2) Accuracy of Hurricane Wind Fields,**

**3) Physics Captured Within Coupled Wave-Surge Model**

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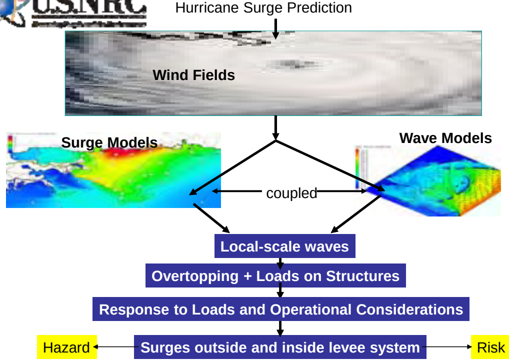
Hurricane Surge Prediction

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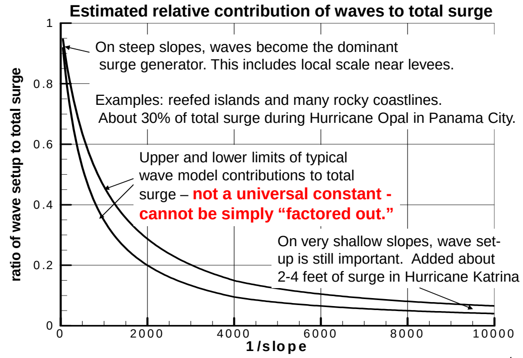


"Flooding can be a complex process – Flood protection must be addressed on a systems basis"

Large computational systems often trade off details for system compatibility

***"A model should be as simple as possible … but no simpler"***

***A. Einstein***

Extreme events often transcend the empirical calibration basis of operational models = need the right physics!

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Accuracy for a single event with IPET prediction system, including objective friction specification with "best" winds

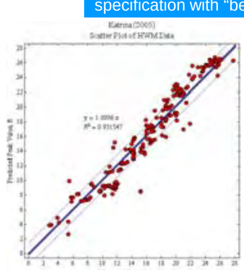

**Figure 5: Comparison of observed USACE High Water Marks (HWM) for Hurricane Katrina and the simulation using the H*WIND/IOKA wind fields. The red points are the values at the recorded USACE HWMs. Thin blue lines display a 1:1 correlation as well as 1.5 ft variance on each side.**

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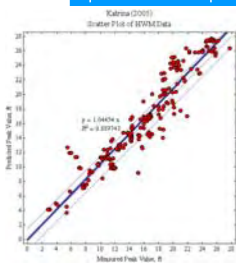
## Accuracy for a single event with IPET prediction system, including objective friction specification with parametric winds

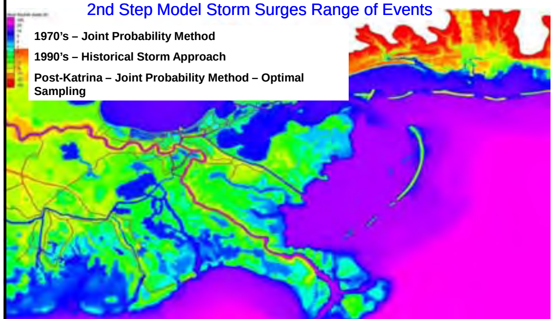


Comparison of observed USACE HWMs for Hurricane Katrina and the simulation using the PBL wind fields. at the recorded USACE HWMs. Thin blue lines display a 1:1 correlation as well as 1.5 ft variance on each side.



## 2nd Step Model Storm Surges Range of Events

- 1970's – Joint Probability Method
- 1990's – Historical Storm Approach
- Post-Katrina – Joint Probability Method – Optimal Sampling



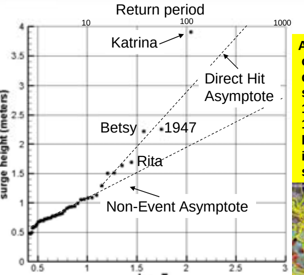


## Historical Statistical Approach

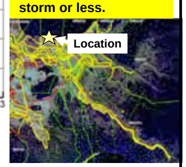
Several studies have now shown that the historical storm approach produces very unstable values for extrapolated return periods. A single storm can change the results markedly.

Culprits:

- Storm size
- Storm infrequency




**Addition of 1 storm creates a very large deviation in the 100-yr surge level. From over 1000 years to about 100 years and if we use less years in our record it could be the 65-year storm or less.**



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## Statistical Approach – JPM with Optimal Sampling (JPM-OS)

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

$\zeta(x,t) = \Phi(\underline{G}, \underline{W} \mid c_p, R_{max}, v_f, \theta, B, x_0, S(t), t)$

where

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

$\Phi$ 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,

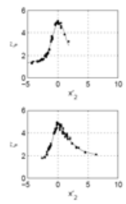
$v_f$ is the forward velocity of the storm,

$\theta$ is the geographic angle of the track,

$B$ is the Holland "B" parameter,

$x_0$ is the landfall location, and

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



***Bottom line: There are 6 important storm parameters plus storm track and the changes in near-coast storms that have to be considered in JPM.***

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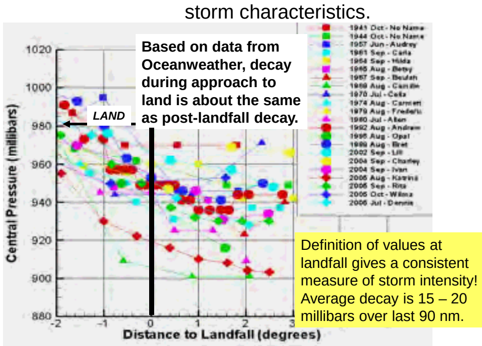
Part of getting the winds right is capturing the near-coast variation in storm characteristics.

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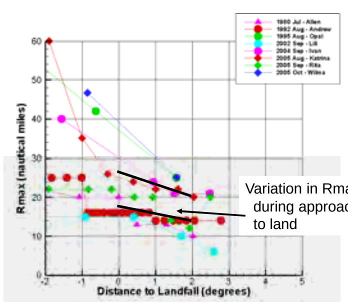
**Rmax increases by about 30% over last 90 nm**

**Also Holland B diminishes**




Variation in Rmax as a function of position relative to landfall.

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In any dimension we have for the pdf the ability to map from an n-dimensional space into a 1-dimensional space via a Dirac delta-function δ

$$p(\eta) = \iiint p(x_1, x_2, ..., x_n)\delta[\Psi(x_1, x_2, ..., x_n) - \eta]dx_1...dx_n$$

$x_i$ is a parameter affecting hurricane surge levels

$p(.)$ is the pdf

$\eta$ is the surge level

$\Psi$ is an analytical operator (modeling system) that coverts a specific set of values of $x_i$ to a surge

And the CDF which uses the Heaviside Function (an integral of the delta function)

$$F(\eta) = \int ... \int p(x_1, x_2, ..., x_n)H[\eta - \Psi(x_1, x_2, ..., x_n)]dx_1dx_2...dx_n$$

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Since we remain imperfect, we need to consider an error term also!!!!

$$F(\eta) = \int ... \int p(x_1, x_2, ..., x_n, \varepsilon)H[\eta - \Psi(x_1, x_2, ..., x_n) + \varepsilon]dx_1dx_2...dx_n d\varepsilon$$

$\varepsilon$ is the uncertainty in the surge level from the modeling

This means that we can leave some degree of randomness in our solutions – as long as we can estimate the statistical characterization of this term – which also includes tides, wind field errors, errors in physics, other omissions, etc.

The expected return period can be estimated from the CDF via the assumption that the storm occurrence is governed by a stationary Poisson process, with an average frequency of occurrence of λ.

$$T(\eta) = \frac{1}{\lambda[1 - F(\eta)]}$$

Unfortunately, nature often deviates from this simplistic assumptions – with years containing many storms not following the same distribution as years with few storms

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## The hurricane population in the Gulf of Mexico appear to be mixed.

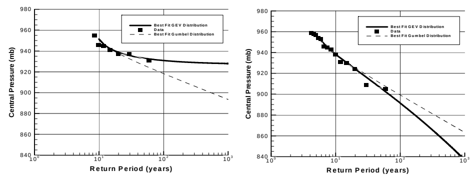


Figure 9c. Best-fit GEV and Gumbel distributions for GOM central pressures along with the data plotted with a simple plotting position, $T_r = \frac{n+1}{m}$ where n= number of years in the sample and m=rank, for all storms in years with 4 or less storms occurring in that year in left panel and all storms in years with more than 4 storms.

NOTE: Over a 30 mb difference (>5 ft surge for New Orleans area) at 100 year return period!

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## Statistical Approach – JPM with Optimal Sampling (JPM-OS)

**Joint probability matrix:**

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

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

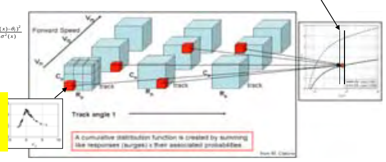
$$\Lambda_2 = p(R_p \mid c_p) = \frac{1}{\sigma(\Delta P)\sqrt{2\pi}} e^{-\frac{(\bar{R}_p(\Delta P) - R_p)^2}{2\sigma^2(\Delta P)}}$$

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

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

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

$$\sum p_{i,j,k,l,m}(|\eta - \eta_*| < \delta/2)$$




Different storms can produce results in the same bin.



## Summarizing:

Uncertainty arises in all estimates due to lack of knowledge:
- Sample size effects
- Lack of "science" effects

Sample Size Effects:
- Sample size effects can be estimated based on coefficients of variation in the sample itself.
- Samples with large coefficients of variations are indicative of more uncertainty in the estimated values for given return periods.
- Typical 90% values in surge level uncertainty at the 100-year return period are in the range 2 – 4 feet

Lack of Science Effects:
- Omissions of tides, deviations from parameterized wind fields, variations in near-coast rates of change, etc.
- Errors in numerical models

The sum of of this uncertainty is added statistically to each estimated surge value befor it is included in the JPM computation



## Probabilistic-Only Approach produces large uncertainties in very-low probability surges

**Uncertainty in an estimate is very difficult to estimate without some assumption regarding the parent distribution and the "effective" number of samples (which depends on the spatial autocorrelation attributes of the phenomenon). For extremes, these tend to vary as a function of return period and number of samples.**

$S_x \sim \phi\left(\frac{T}{\sqrt{N}}\right)$, where $S_x$ is the rms of the Gaussian uncertainty band

For a Gumbel Distribution, with a distributional rms of $S$

$S_x \sim S\sqrt{\frac{1.100y^2 + 1.1396y + 1}{N}}$, for large $T$ $y \approx \ln(T) - \frac{T}{2}$

**Note: Re-sampling does not include sample size dependence.**

For large T

$$T_n \approx \frac{T}{n}$$

The "return period" of an event should be defined in a manner which considers the design life.

**Unfortunately, this makes the estimation of very-low- probability events very uncertain – about the same magnitude as the surge level itself. Is there a good alternative??**

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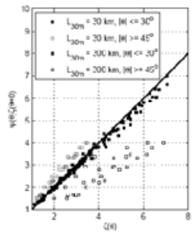
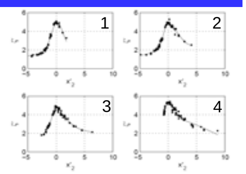
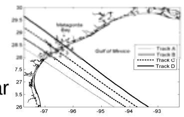
## Characteristics & Form of Surge Response Functions (SRF)





Along coast variation and effect of storm angle at coast all produce clear maximum values.

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Becomes Asymptotic

$$\zeta = \left(\frac{\rho_a}{\rho_w}\right)\frac{c_d V^2}{g}\int_0^L \frac{dx}{h(x)} = \left(\frac{\rho_a}{\rho_w}\right)\frac{c_d V^2}{g\langle h\rangle}L \qquad \zeta = \left(\frac{\rho_a}{\rho_w}\right)\frac{c_d}{\langle h\rangle}\frac{\lambda}{\rho_a g}L$$

*Storm Intensity* — NO

$$\zeta = \chi_1 \Delta p \frac{L_*}{h_* \phi_*}\psi_x\left(\frac{R}{L_*}\right) \qquad \psi_x\left(\frac{R}{L_*}\right) = \left(\frac{R}{L_*}\right) \; when \left(\frac{R}{L_*}\right) \le 1$$

*Storm Size* — YES

$$\zeta = \chi_1 \Delta p \frac{L_*}{h_* \phi_*}\psi_x\left(\frac{R}{L_*}\right)\psi_t\left(\frac{t_*}{t_\infty}\right) \qquad \psi_t\left(\frac{t_*}{t_\infty}\right) = \left(\frac{t_*}{t_\infty}\right) \; when \left(\frac{t_*}{t_\infty}\right) \le 1$$

*Storm Forward Speed* — YES

**Functional dependence of the surge on forcing parameters as they become large-valued.**

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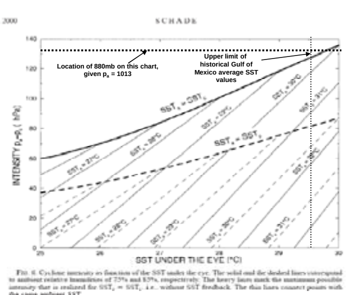
**Given that the uncertainty becomes very large for very-low probabilities, can we find some physical guidance for focusing on this range.**

Schade (2000) shows the behavior of the PMI under different assumptions and background fields. His work is in reasonable agreement with that of Tonkin *et al.* (2000).




Maximum Possible Intensity
880 mb ???

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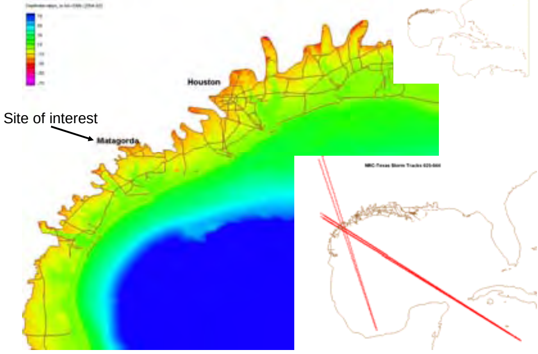
## Deterministic-probabilistic approach

NRC-Texas ADCIRC Grid

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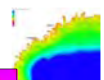
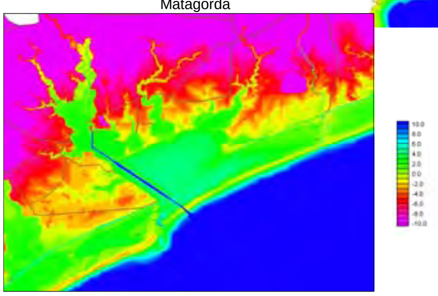
NRC-Texas ADCIRC Grid



Matagorda




In a complex coastal area like this, simple transect models are virtually worthless!!

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## Storm Suite

| RUN No. | Fields Available | | Evaluation Performed | | | | |
|---|---|---|---|---|---|---|---|
| | Wind | Pres | W-Indf | P-Indf | Rp (nm) | Holland B | Vf (kt) |
| RUN025 | 59.6 | 880 | 46.5 | 904 | 30-42 | 1.35-0.9 | 5.5 |
| RUN026 | 58 | 880 | 42.4 | 918.6 | 45-63 | 1.35-0.9 | 5.5 |
| RUN027 | 61.1 | 870 | 48.4 | 893.8 | 30-42 | 1.35-0.9 | 5.5 |
| RUN028 | 59.4 | 870 | 44.4 | 908.6 | 45-63 | 1.35-0.9 | 5.5 |
| RUN029 | 61.4 | 880 | 47.5 | 905.8 | 30-42 | 1.35-0.9 | 11 |
| RUN030 | 59.2 | 880 | 44.5 | 918.6 | 45-63 | 1.35-0.9 | 11 |
| RUN031 | 62.8 | 870 | 49.3 | 895.8 | 30-42 | 1.35-0.9 | 11 |
| RUN032 | 60.6 | 870 | 46.4 | 908.6 | 45-63 | 1.35-0.9 | 11 |
| RUN033 | 64.3 | 880 | 54.6 | 901.9 | 30-42 | 1.35-0.9 | 22 |
| RUN034 | 61.8 | 880 | 50.9 | 912.3 | 45-63 | 1.35-0.9 | 22 |
| RUN035 | 65.6 | 870 | 55.9 | 891.9 | 30-42 | 1.35-0.9 | 22 |
| RUN036 | 63 | 870 | 52.7 | 902.3 | 45-63 | 1.35-0.9 | 22 |
| RUN037 | 62.3 | 880 | 50 | 902.8 | 30-42 | 1.35-0.9 | 11 |
| RUN038 | 60 | 880 | 44.4 | 919.6 | 45-63 | 1.35-0.9 | 11 |
| RUN039 | 63.7 | 870 | 51.9 | 892.8 | 30-42 | 1.35-0.9 | 11 |
| RUN040 | 61.4 | 870 | 46.3 | 909.8 | 45-63 | 1.35-0.9 | 11 |
| RUN041 | 65.1 | 880 | 55.1 | 902.8 | 30-42 | 1.35-0.9 | 22 |
| RUN042 | 62.2 | 880 | 48.8 | 919.6 | 45-63 | 1.35-0.9 | 22 |
| RUN043 | 66.4 | 870 | 56.5 | 892.8 | 30-42 | 1.35-0.9 | 22 |
| RUN044 | 63.5 | 870 | 50.5 | 909.6 | 45-63 | 1.35-0.9 | 22 |

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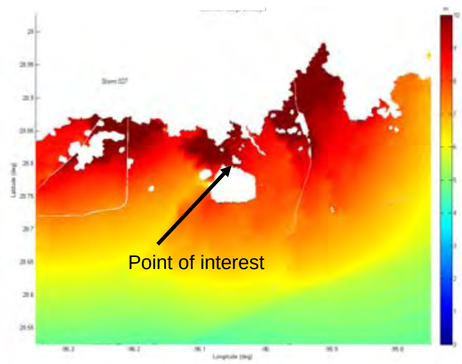
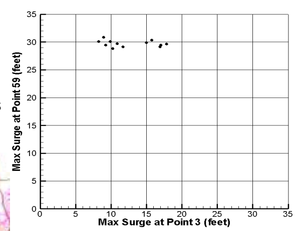
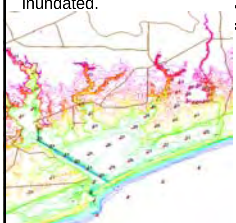



In this figure, we show the values of the surge at Point 59 (inland) plotted against the surge values at Point 3 (coast) for storms in which each Point was inundated.



Three key points:

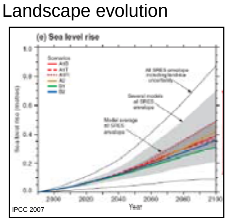
1) Elevation of Point 59 is around 28.5 ft
2) There seems to be a natural limiter for the total surge depth in these storms
3) A simple transect model cannot reproduce these results.

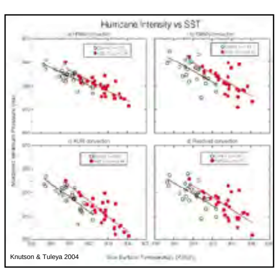


## The Future: Other Considerations

A method for determining hurricane flood level extreme value statistics which considers long-term and short-term environmental trends:

- Sea level rise
- Hurricane frequency
- Hurricane intensity
- Landscape evolution

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Questions????