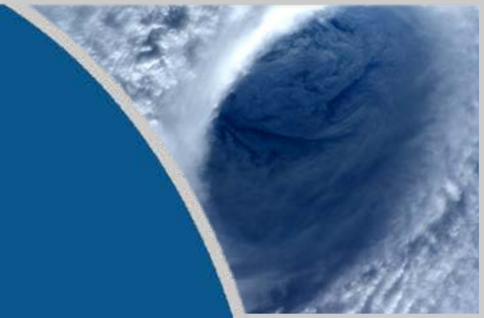
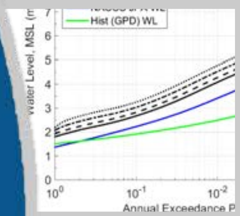
5th Annual Probabilistic Flood Hazard Assessment Research Workshop

Rockville, MD





Data, Models, Methods and Uncertainty Quantification in Probabilistic Storm Surge Models

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- PI: Norberto C. Nadal-Caraballo, PhD (USACE ERDC-CHL)
- Efrain Ramos-Santiago, Madison O. Campbell

- 20 February 2020

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US Army Corps of Engineers

ERDC ENGINEER RESEARCH & DEVELOPMENT CENTER

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Outline

- Introduction
- Probabilistic storm surge modeling
- Uncertainty
- Data Sources
- Methods and Models
    - SRR
    - Marginal Distributions
    - Generating synthetic storm set
    - Error and integration
- Epistemic uncertainty

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Introduction

- Project part of U.S. NRC's Probabilistic Flood Hazard Assessment (PFHA) research plan.
- Support risk-informed licensing and oversight activities.
- Develop hazard curves with uncertainty represented through confidence limit curves.
- Approach informed by USNRC guidance on probabilistic seismic hazard assessment (PSHA)
  - Evaluation of data, models, and methods used in probabilistic storm surge models.
  - Epistemic uncertainty is quantified and propagated through logic trees.
- Consider AEPs that go beyond traditional state-of-practice in non-nuclear facilities (e.g., 10^{-4} to 10^{-6}).

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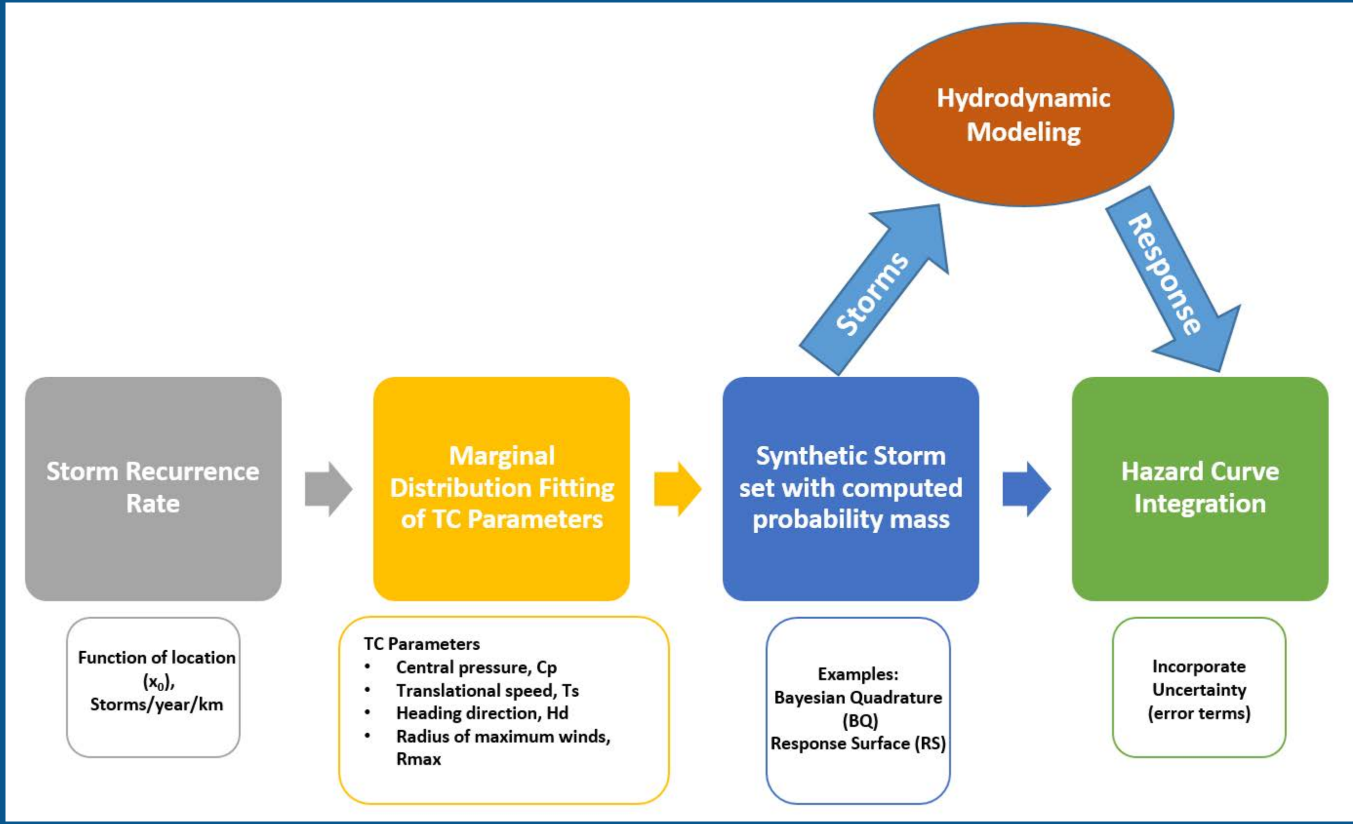
Probabilistic storm surge hazard modeling

- **Based on the joint probability analysis of tropical cyclone (TC) forcing and responses.**
- **Basic elements:**
  - **SRR: Frequency of occurrence at location.**
  - **Development of Synthetic TCs and their probabilities.**
  - **Hydrodynamic Modeling: wind and pressure fields, circulation modeling (water levels), wave modeling.**
  - **Integration of response and uncertainty.**



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Uncertainty

JPM Integral

$$\lambda_{r(\hat{x})>r} = \lambda \int P[r(\hat{x}) + \varepsilon > r|\hat{x}, \varepsilon]\, f_{\hat{x}}(\hat{x}) f_{\varepsilon}(\varepsilon) d\hat{x} d\varepsilon$$

$$\approx \sum_i^n \lambda_i\, P[r(\hat{x}) + \varepsilon > r|\hat{x}, \varepsilon]$$

where:

$\lambda_{r(\hat{x})>r}$ = AEP of TC response r due to forcing vector $\hat{x}$

$\hat{x} = f(x_o, \theta, \Delta p, R_{max}, V_t)$

λ = SRR (storms/yr/km)

$\hat{\lambda}_i$ = probability mass (storms/yr) or $\lambda\, p_i$, with p_i=product of discrete probability and TC track spacing (km)

$P[r(\hat{x}) + \varepsilon > r|\hat{x}, \varepsilon]$ conditional probability that storm i with parameters $\hat{x}_i$ generates a response larger than r

ε = unbiased error or aleatory uncertainty of r

- **Uncertainty:**
  - **Aleatory – natural randomness of a process, not reducible.**
  - **Epistemic – lack of knowledge about validity of models and data for the representation of real system.**
- **PSHA based approach:**
  - **Epistemic uncertainty based on the selection and application of alternative data, methods, and models.**
  - **Capture the center, body, and range of technically densible interpretations.**

Data Sources

- NOAA HURDAT2
- Extended Best Track Dataset - EBTRK (Demuth et al. 2006)
- GCM downscaling data
- Stochastic Track models
- Statistical models: e.g. R_{max} and Holland B
- Advance Tropical Cyclone Forecasting (ATCF) Data
- CHS Data (historical data reconstruction using metamodeling techniques)

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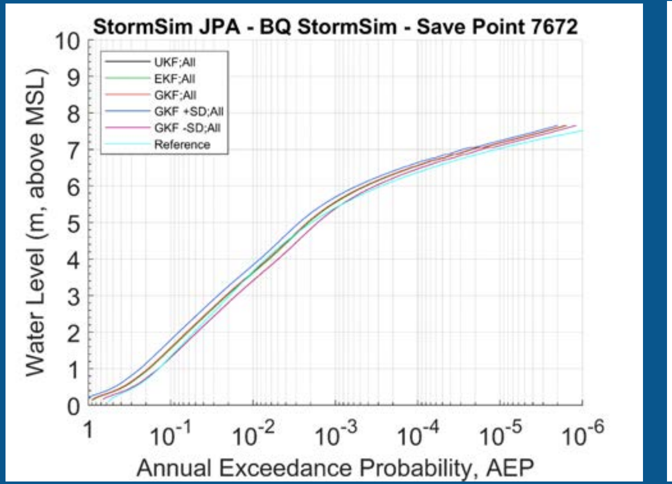
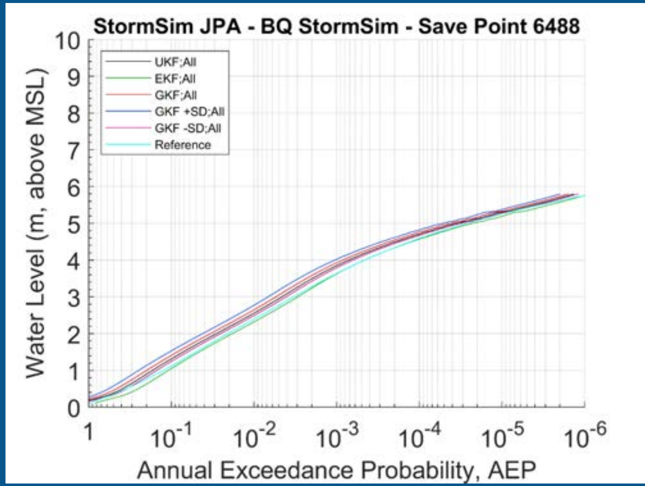
Epistemic Uncertainty in SRR Models

- **Models for Calculating SRR.**
  - **Uniform kernel function (UKF) or capture zone.**
  - **Gaussian kernel function (GKF).**
  - **Epanechnikov kernel function (EKF).**
- **SRR uncertainty contribution (Δp ≥ 28 hPa):**
  - **Sampling uncertainty – 65%**
  - **Selected period of record – 19%**
  - **Gaussian kernel size – 15%**
  - **Observational data – 1%**



The Battery, NY



Virginia Beach, VA

$$\lambda = \frac{1}{T}\sum_{i}^{n} w(d_i)$$

$$w(d_i) = \frac{1}{h_d}\begin{cases} 0.5, & if \left|\frac{d_i}{h_d}\right| < 1 \\ 0, & otherwise \end{cases}$$

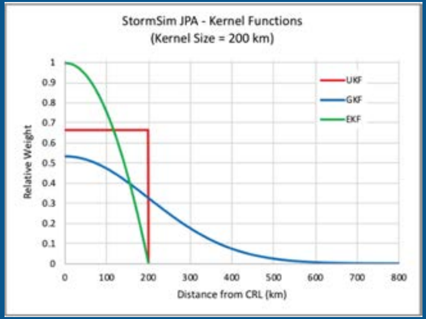
UKF

$$w(d_i) = \frac{1}{\sqrt{2\pi}h_d} exp\left[-\frac{1}{2}\left(\frac{d_i}{h_d}\right)^2\right]$$

GKF

$$w(d_i) = \frac{1}{h_d}\begin{cases} \frac{3}{4}\left[1 - \left(\frac{d_i}{h_d}\right)^2\right], & if \left|\frac{d_i}{h_d}\right| < 1 \\ 0, & otherwise \end{cases}$$

EKF



Differences less than 0.61 m

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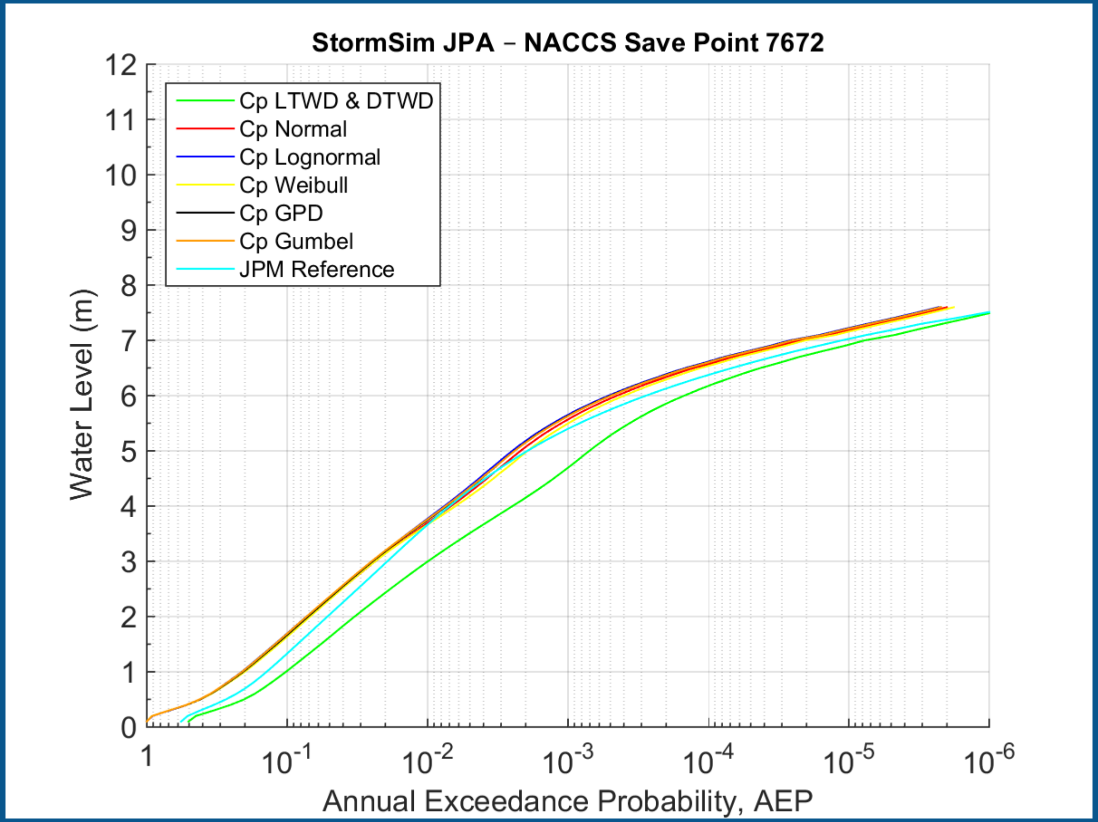
Defining Joint Probability of Storm Parameters

- **Effect of selection of *Δp* distribution on hazard curve.**



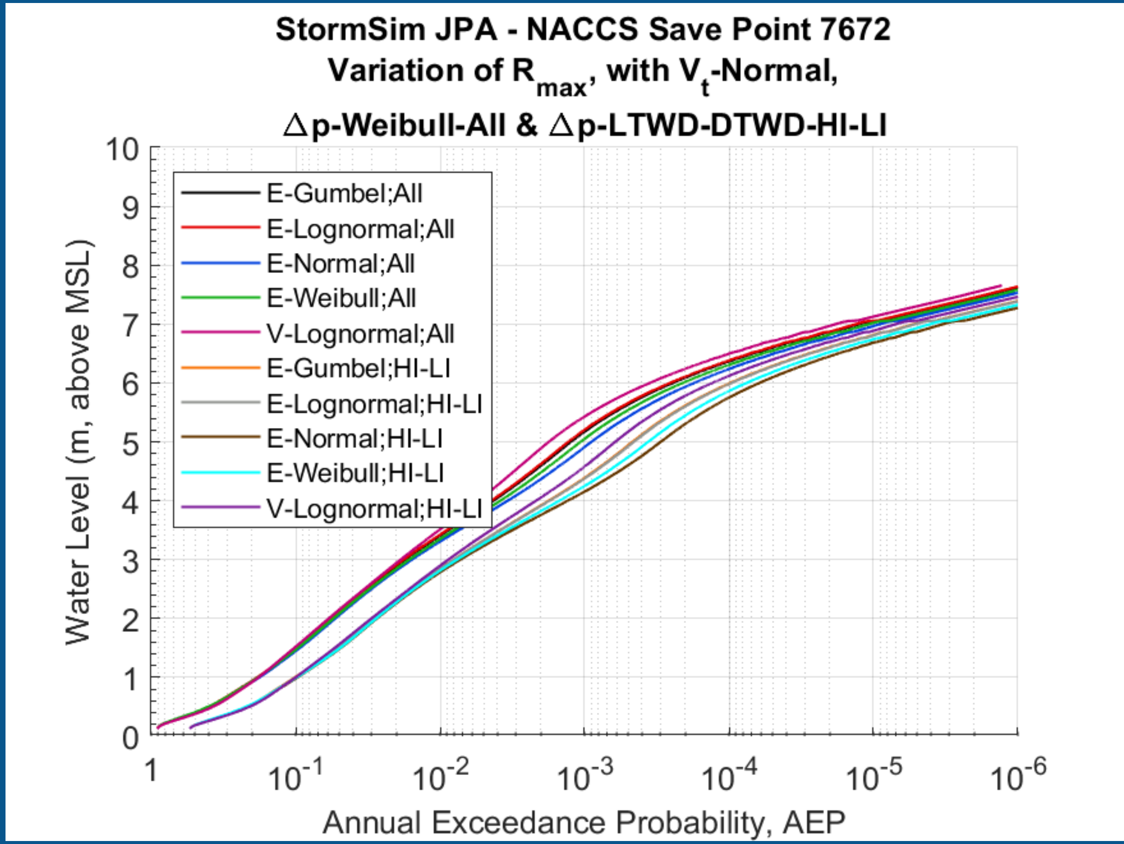
LTWD & DTWD curve considers the discretization of TCs into high and low intensity.

The effect is to lower the hazard curve.

Choice of Δp distribution showed limited impact

Defining Joint Probability of Storm Parameters

- **Effect of selection of R_{max} distribution on hazard curve**



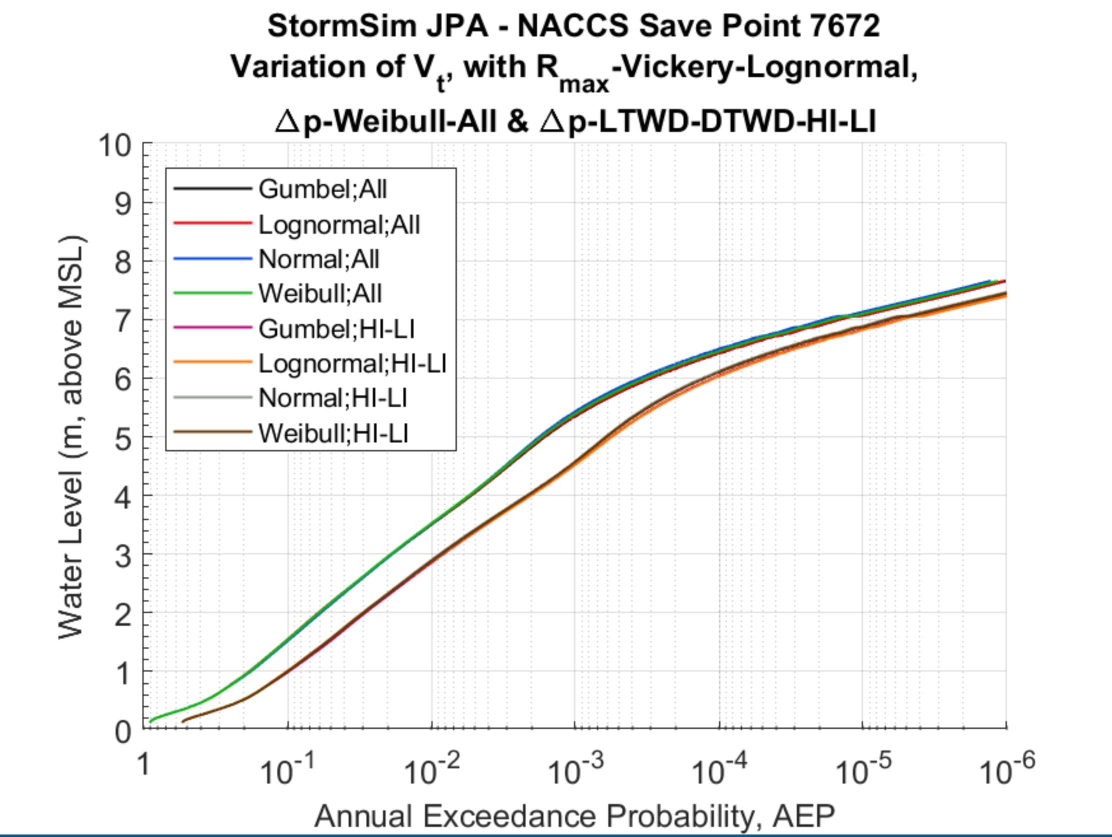
Data sources and distributions:

- EBTRK:
  - Gumbel
  - Lognormal
  - Normal
  - Weibull
- Vickery and Wadhera (2008) statistical model:
  - Lognormal

More spread in the family of curves than for central pressure.

Defining Joint Probability of Storm Parameters

- **Effect of selection of V_t distribution on hazard curve**



Data sources and distributions:
- HURDAT2 derived
  - Gumbel
  - Lognormal
  - Normal
  - Weibull

Smallest spread in the family of curves.
Grouping reflects the difference between considering all distributions and separating by intensity.

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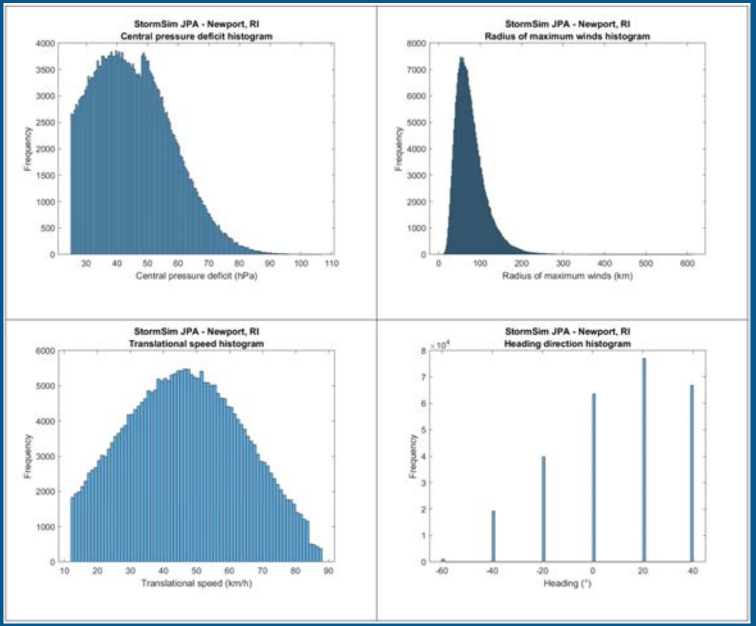
Generation of Synthetic Storm Sets

Three methods for computing synthetic storm probability masses:

- Hybrid optimal sampling approach (applied to JPM-Reference):
  - Discretization technique:
    - Bayesian Quadrature: R_{max} *and* V_f
    - Uniform Discretization: Δp and heading (θ)
  - Assignment of probability weights: Bayesian quadrature
- Monte Carlo Sampling
  - 1,000,000 yrs
  - Empirical distribution, implicit probability weights in sampling
- Meta Gaussian Distribution
  - TC parameter dependencies -> Gaussian Copula
  - Relative probability weights of each synthetic TC:
  - estimated dividing its multivariate probability by the sum of the multivariate probabilities of all the synthetic storms

Coastal Reference Location	Number of TCs Sampled
Virginia Beach, VA	364,228
The Battery, NY	211,997
Newport, RI	267,505
Boston, MA	205,668



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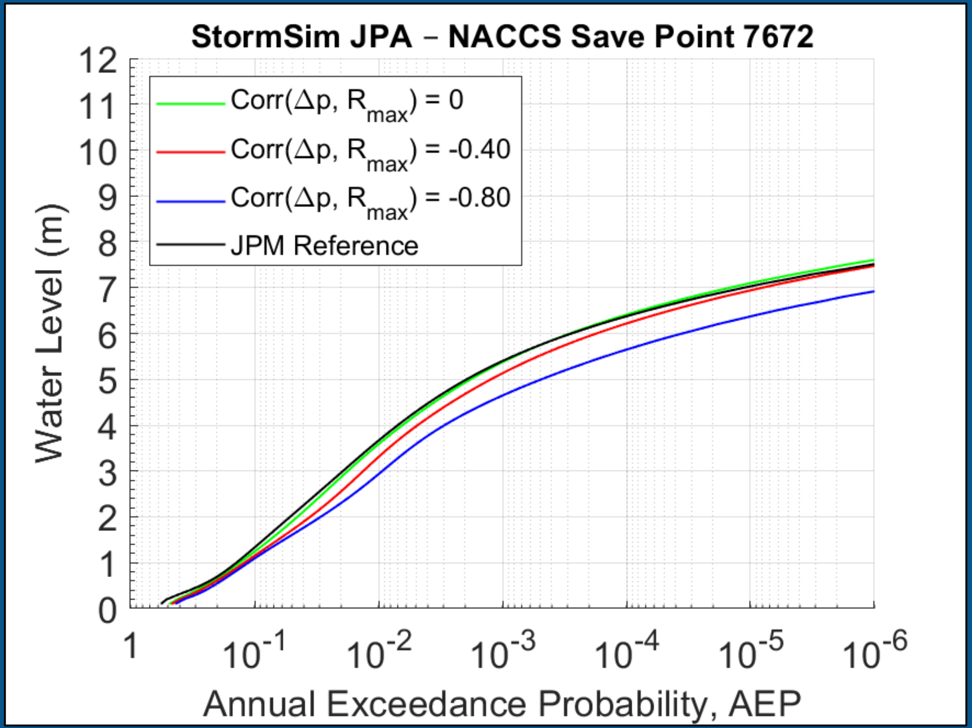
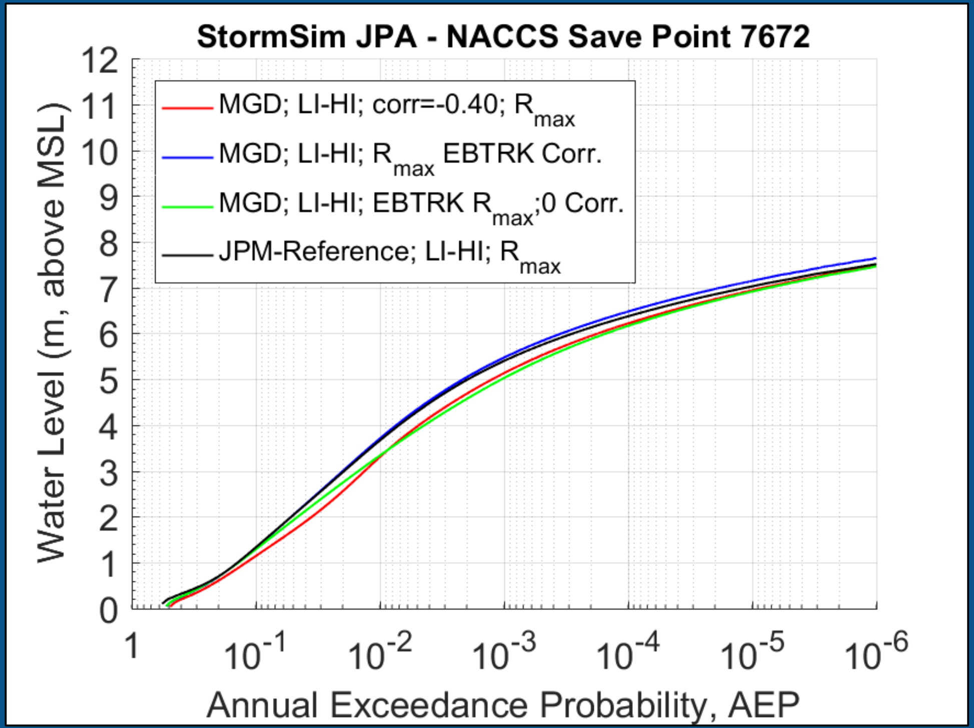
MGD Parameter

- **MGD allows explicit consideration of parameter correlations.**

Sensitivity analysis for Δp and R_{max} correlation



Comparison generalized correlation estimate vs correlation from data.



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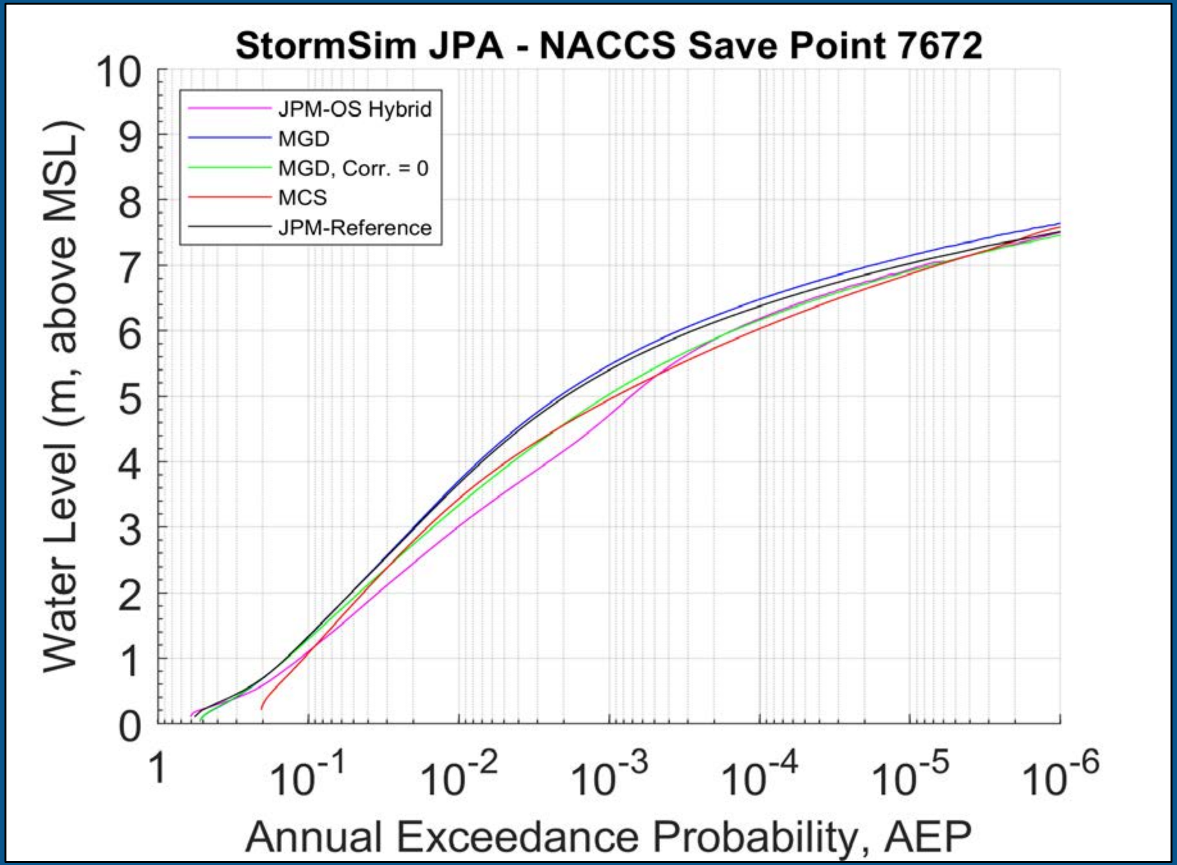
Generation of Synthetic Storm Sets



The Battery, NY					
Synthetic Storm Generation Method	Percent Change (%) JPM-reference				
	$1X10^{-2}$	$0.2X10^{-3}$	$1X10^{-3}$	$1X10^{-4}$	$1X10^{-6}$
JPM-OS Hybrid	-18.0	-16.7	-13.0	-3.1	-0.3
MCS	-6.3	-8.4	-8.3	-5.3	1.1
MGD	1.4	1.2	1.3	1.7	1.7
MGD, Corr.=0	-8.7	-8.2	-6.9	-3.3	-0.7
JPM-Reference	-	-	-	-	-

MGD was based on the same storms used for JPM-Reference. The method for both are consistent, being the only difference the assignment of probability weights. Small difference between the two results.

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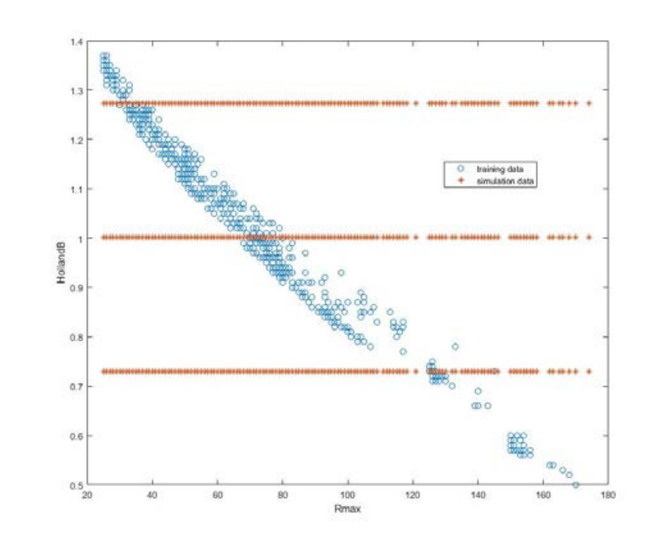
Sources of Error

- Hydrodynamic modeling
- Meteorological modeling errors
- Track error
- Holland B
- Tide (Gulf coast)

$$\sigma_\varepsilon = \sqrt{\sigma_{\varepsilon 1}^2 + \sigma_{\varepsilon 2}^2 + \cdots + \sigma_{\varepsilon i}^2}$$

Uncertainty	North Atlantic Coast Comp. Study (2015)	Sabine Pass to Galveston Bay Wave and Water Level Modeling Study (2015)	South Atlantic Coast Study: Puerto Rico and the U.S. Virgin Islands (ongoing)*	Flood Insurance Study: Coastal Counties, Texas (2011)	FEMA Region II Storm Surge Project (2014)	Mississippi Coastal Analysis Project (2008)
Hydrodynamic Modeling	0.48 m	0.91 m (combined with meteorological modeling)	0.20 m (constant) 0.30 (proportional)	0.56 to 0.76	0.39	0.23 m
Meteorological Modeling	0.38 m	-	0.14 (proportional) 0.09 (constant)	0.07 to 0.30	0.54	0.36 m
Strom Track Variation	0.25 m	0.09 m	N/A	0.20 x wave setup	N/A	N/A
Holland B	0.15 x storm surge elevation	0.17 x surge elevation	N/A	0.15 x surge elevation	N/A	0,15 x surge elevation
Astronomical Tide	variable	0.20 m	0.11 m	N/A	N/A	0.20 m

Holland B. Estimated, highly correlated to other parameters, specially R_{max}

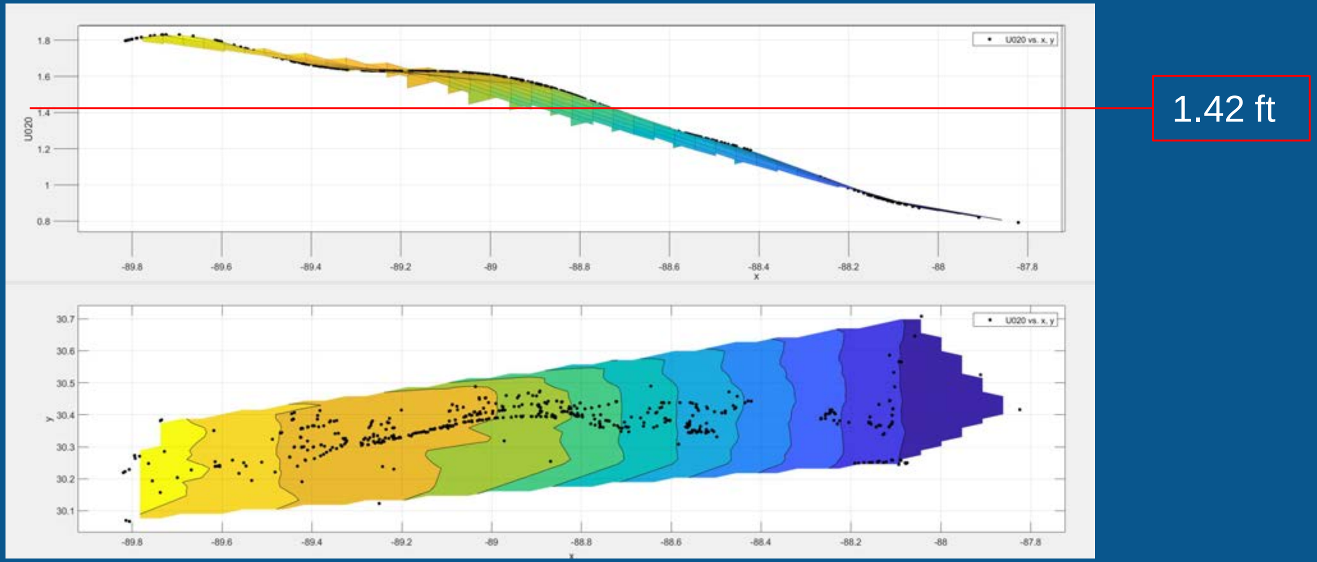


*Average values over 15,000 virtual gages

Spatially-varying modeling error

Modeling error: has a direct effect on hazard curve shape and confidence limits.

- Global uncertainty: 1.42 ft.
- Spatially varying uncertainty:



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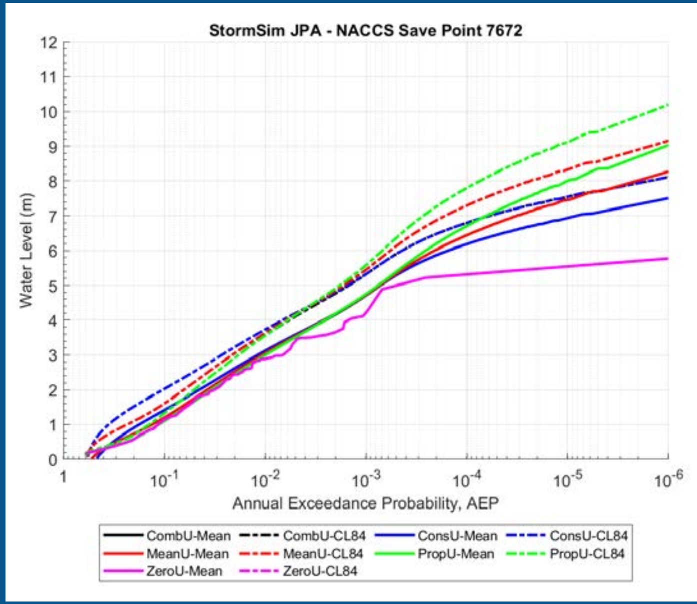
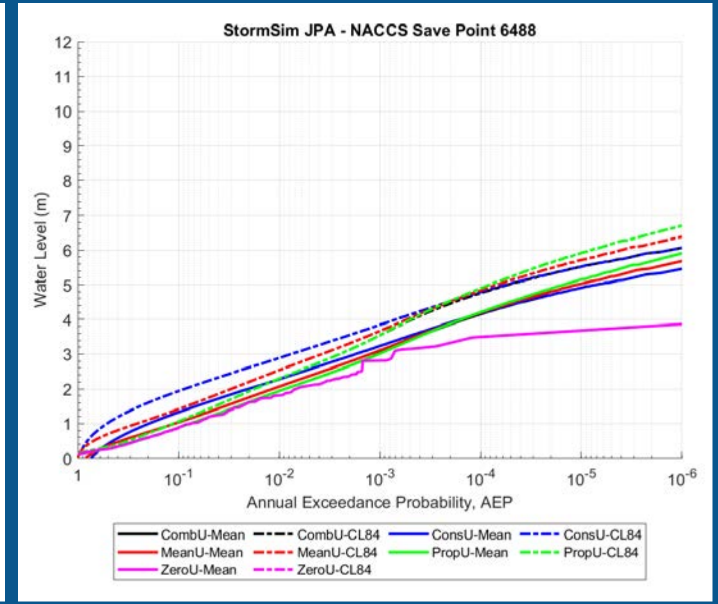
Characterization of Uncertainty in JPM integral

- **Methods:**
  - **Zero uncertainty, $\sigma = 0$**
  - **Constant uncertainty, $\sigma = 0.61$ m**
  - **Proportional uncertainty, $\sigma = 0.2*WL$**
  - **Constrained uncertainty, σ=min(σ_constant, σ_proportional)**
  - **Mean of constant and proportional, σ=mean (σ_constant, σ_proportional)**

$$WL_n = \mu + \sigma(Z^*)$$





CRL	JPM-OS Uncertain	Storm surge (m) AEP 1E-02	1E-03	1E-04	1E-05	1E-06	Percentage difference AEP 1E-02	1E-03	1E-04	1E-05	1E-06
6488	Combined	1.9	3.0	4.2	4.9	5.5	-	-	-	-	-
	Constant	2.3	3.2	4.2	4.9	5.5	17	7	1	0	0
	Mean	2.1	3.1	4.2	5.0	5.7	7	3	1	2	4
	Proportion	1.9	3.0	4.2	5.2	5.9	0	0	1	5	8
	Zero	1.8	2.8	3.5	3.7	3.9	-6	-7	-16	-25	-29
7672	Combined	3.0	4.7	6.2	6.9	7.5	-	-	-	-	-
	Constant	3.1	4.7	6.2	6.9	7.5	4	0	0	0	0
	Mean	3.1	4.7	6.4	7.5	8.3	1	0	4	7	10
	Proportion	3.0	4.7	6.7	8.0	9.0	0	1	8	15	20
	Zero	2.9	4.2	5.3	5.5	5.8	-4	-11	-14	-20	-23

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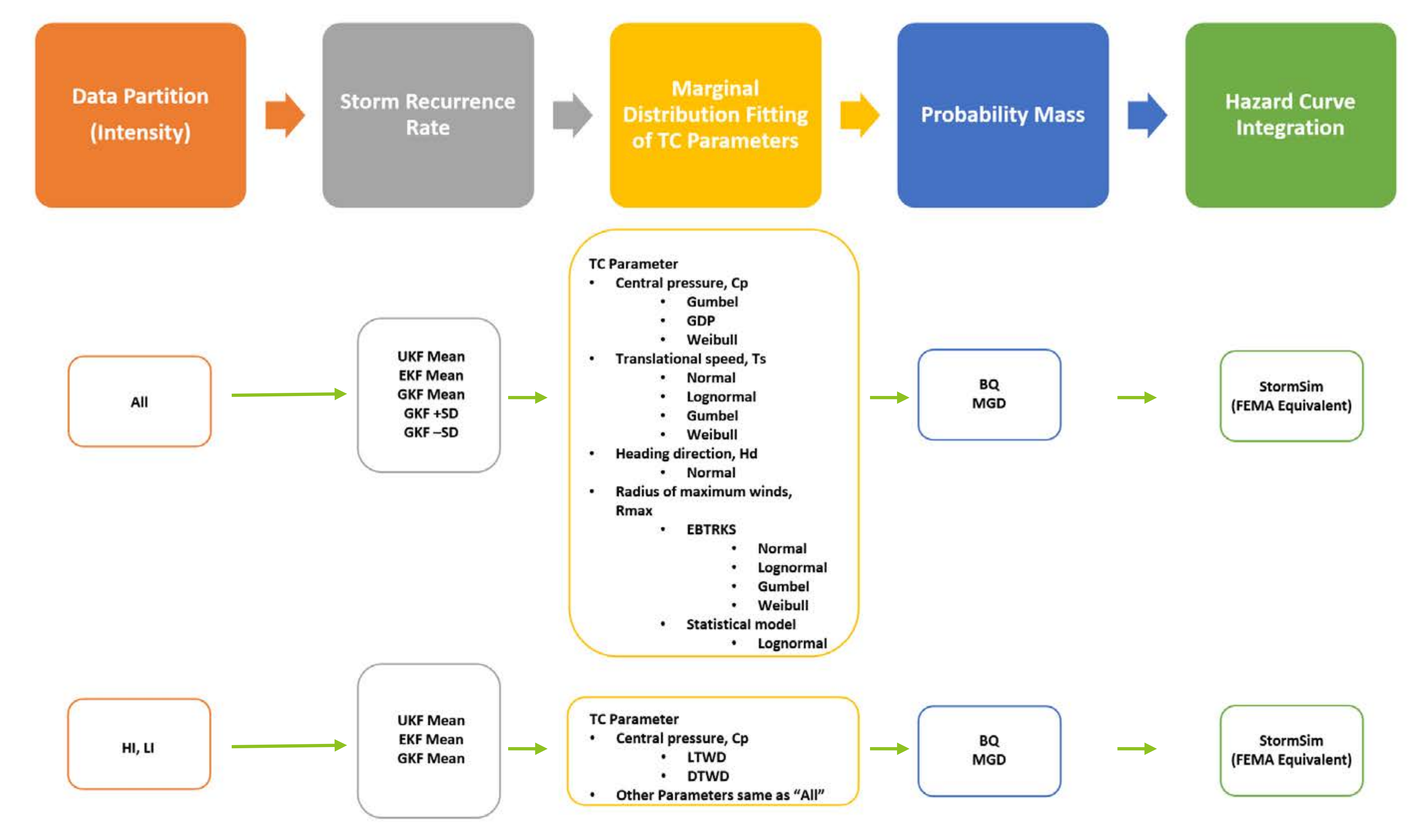
Epistemic Uncertainty – Simplified Logic Tree Example

The variations in data, model, and methods closely align with previous study approaches.



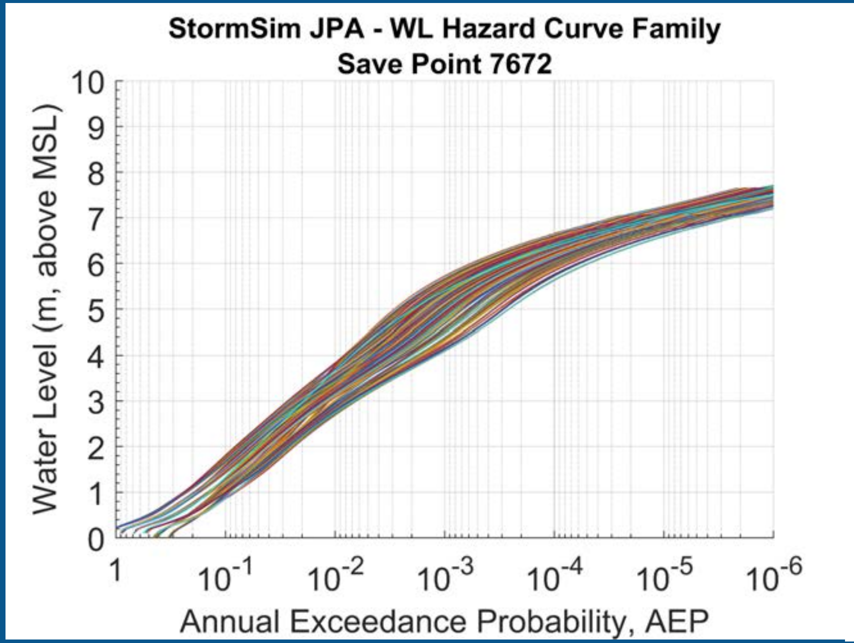
Family of Hazard Curves – The Battery, NY

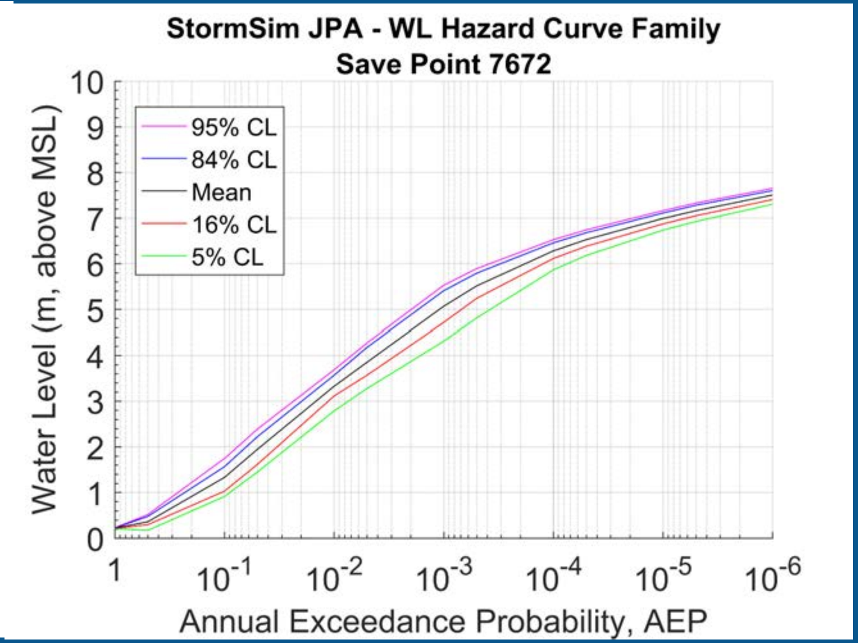
Family of hazard curves representing alternate data, model and methods.

Number of curves: 1,261.

About 1.2 m spread at 100 years and 1.5 at 1,000 years.

Uncertainty (84% CL-Mean) less than 0.40 m for the graphed AEPs.





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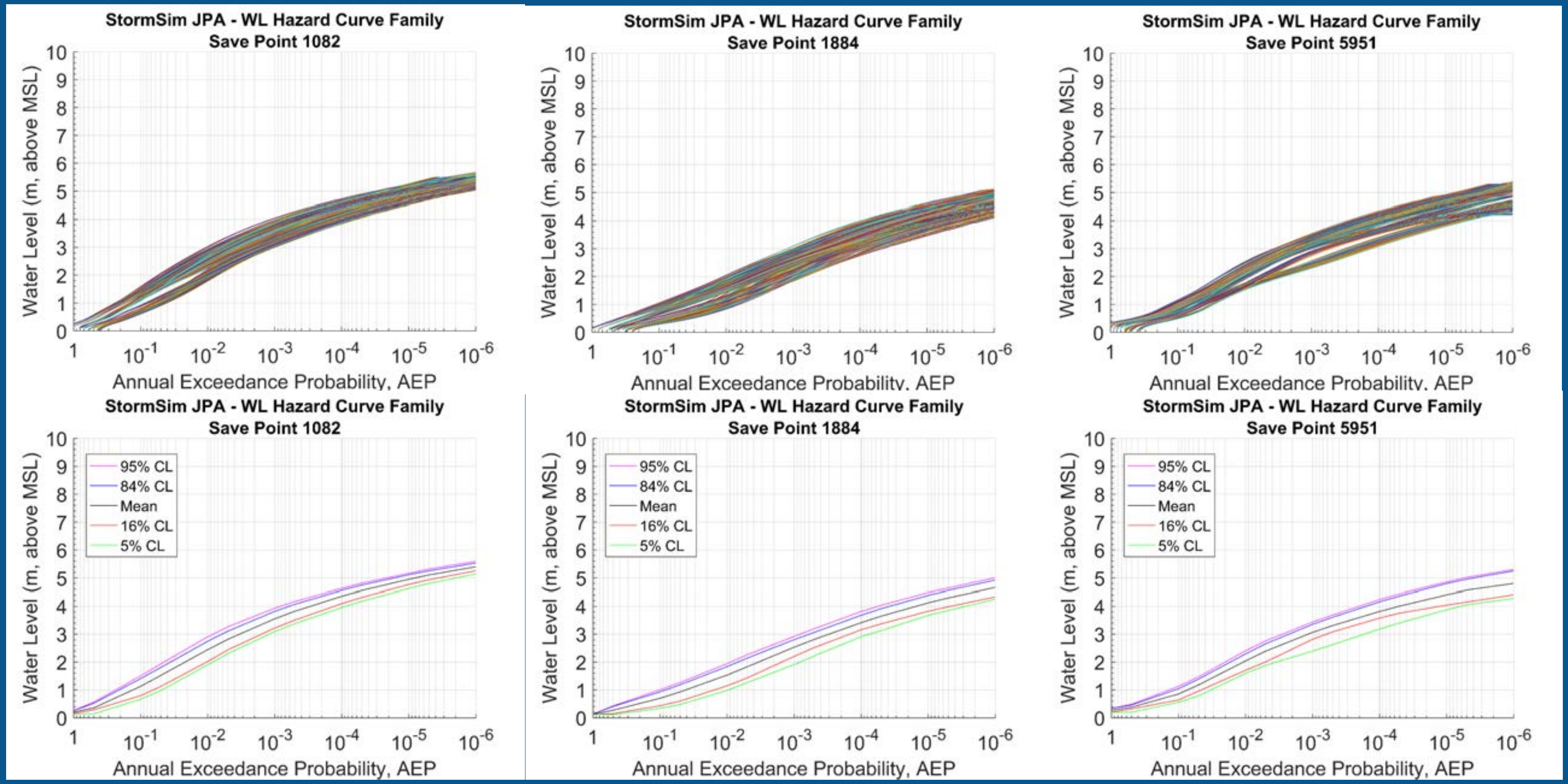
Family of Hazard Curves – Additional Locations

- **The uncertainty computed as the difference between the 84% confidence limit and the mean for the curves tops out at about 0.45 m for Chesapeake Bay.**
- **Curves cluster based on intensity grouping.**
- **Branches added based on method to characterize uncertainty would increase uncertainty.**



Newport, RI

Boston, MA

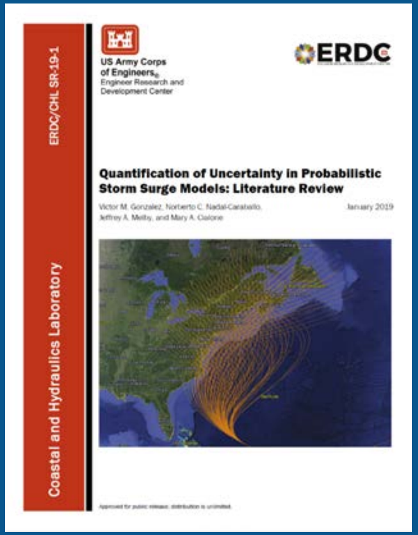
Chesapeake Bay, MD

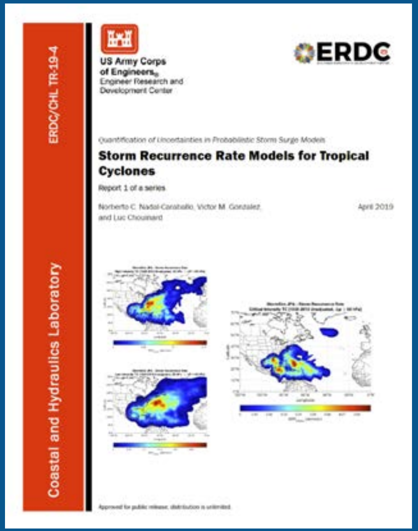
Reports

- **Gonzalez V.M., N.C. Nadal-Caraballo, J.A. Melby, and M.A. Cialone. 2019. *Quantification of Uncertainty in Probabilistic Storm Surge Models: Literature Review*. ERDC/CHL SR-19-1.**

- **Nadal-Caraballo, N.C., V.M. Gonzalez, and L. Chouinard. 2019. *Quantification of Uncertainties in Probabilistic Storm Surge Models: Storm Recurrence Rate Models for Tropical Cyclones*, ERDC-CHL TR-19-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center.**

- **Nadal-Caraballo, N.C., V.M. Gonzalez, E. Ramos-Santiago, and M.O. Campbell. *Data, Models, and Methods for Defining Joint Probability of Storm Parameters and Generating Synthetic Storm Simulation Sets*. ERDC/CHL TR-20-X (In Review)**





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