U.S.ARMY

Overview of Probabilistic Coastal Flooding Hazard Assessment Methods

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Coastal SHAC-F Research Webinar
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US Army Corps of Engineers

FLOOD RISK MANAGEMENT RESEARCH & DEVELOPMENT
PREPARATION RESPONSE RECOVERY MITIGATION
Tools for Driving Down Risk

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

DISCOVER | DEVELOP | DELIVER

Outline

- Introduction
- Atmospheric forcing
- Probabilistic Coastal Flooding Hazard Assessment Methods
  - Extreme Value Analysis
  - Joint Probability Method / Probabilistic Coastal Hazard Analysis
    - TC parameterization
    - Data sources
    - Probability distributions
    - Synthetic TCs
    - Hazard Curves
- Summary
  - Logic-tree approach

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Background: Motivation

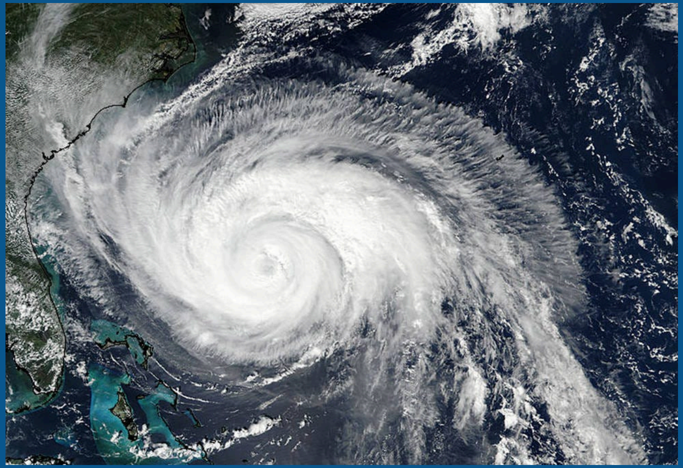
- **Between 1980 and 2019, 44 tropical-cyclone billion-dollar disasters (1.1 event/year) have have affected the U.S.**
- **TCs are the 2nd most frequent disaster event in the U.S., after severe storms (113).**
- **Have caused more damage ($945.9 billion, CPI-adjusted) than all other weather and climate disasters combined ($808.7 billion, CPI-adjusted).**
- **Per event losses is also dominated by tropical cyclones ($21.5 billion per event).**

Rank	Event	Year	CPI-Adjusted Cost (Billions)	Deaths
1	Hurricane Katrina	2005	$168.8	1,833
2	Hurricane Harvey	2017	$130.0	89
3	Hurricane Maria	2017	$93.6	2,981
4	Hurricane Sandy	2012	$73.5	159
5	Hurricane Irma	2017	$52.0	97

https://www.ncdc.noaa.gov/billions

Introduction: Quantification of Coastal Hazards

- Coastal hazards due to tropical cyclones, extratropical cyclones, and other extreme storms: storm surge, surge + tide, wave action, currents, wind, rainfall, and flooding.
- Federal agencies and stakeholders need up-to-date, accurate, easily accessible coastal hazards information on a national scale, including uncertainty.



- Probabilistic coastal flooding hazard assessment methods:
  - Coastal storm risk management
  - Reduce vulnerability to storm damage
  - Develop strategies to enhance resiliency
- Extreme coastal storms are rare in space and time, and are not well represented in historical observation records.

Probabilistic Coastal Flooding Hazard Assessment

- **Region-specific coastal hazards**

Type of Atmospheric Forcing	
South Atlantic Coast **Gulf of Mexico, Pacific Ocean** **Tropical Cyclones** Extratropical Cyclone	**Great Lakes** **Extratropical Cyclones**
North Atlantic Coast **Tropical and Extratropical Cyclones**	**Pacific Coast** **Extratropical Cyclones** Tropical Cyclones

Probabilistic Coastal Flooding Hazard Assessment

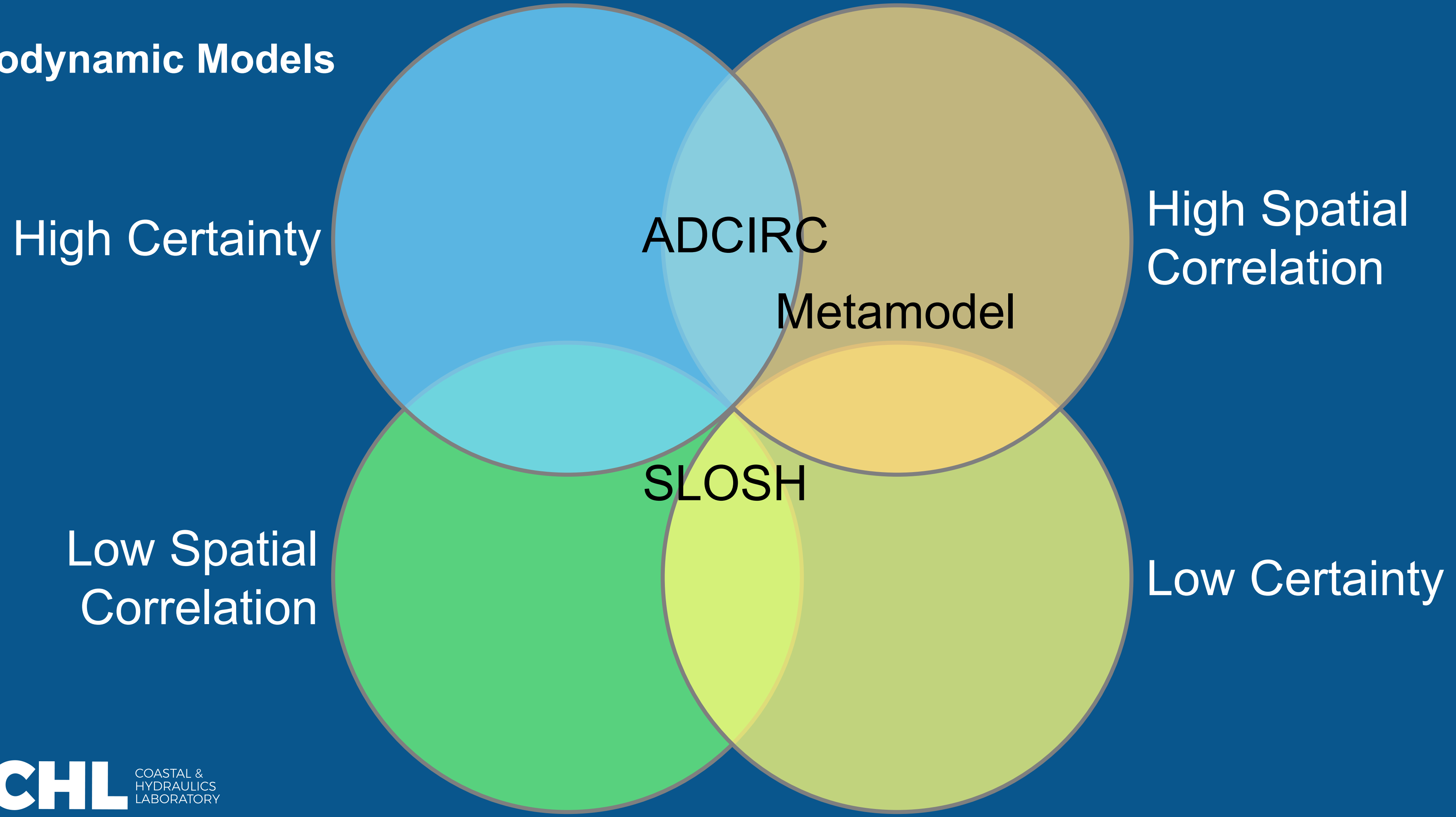
- **Standard of Practice**

Probabilistic Methods		
Tropical Cyclones	**Extratropical Cyclones**	**Convective Storms; Seiches**

• Synthetic events
• Numerical simulation
  • e.g., ADCIRC
• Probabilistic method
  • Multivariate
  • e.g., JPM, PCHA
	• Observations
	• "Pseudo-synthetics" Numerical simulation
	  • e.g., ADCIRC
	• Probabilistic method
	  • Univariate
	  • e.g., EVA (GPD)
		• Observations
		• Probabilistic method
		  • Univariate
		  • e.g., EVA (GPD)

Probabilistic Coastal Flooding Hazard Assessment

- **Hydrodynamic Models**



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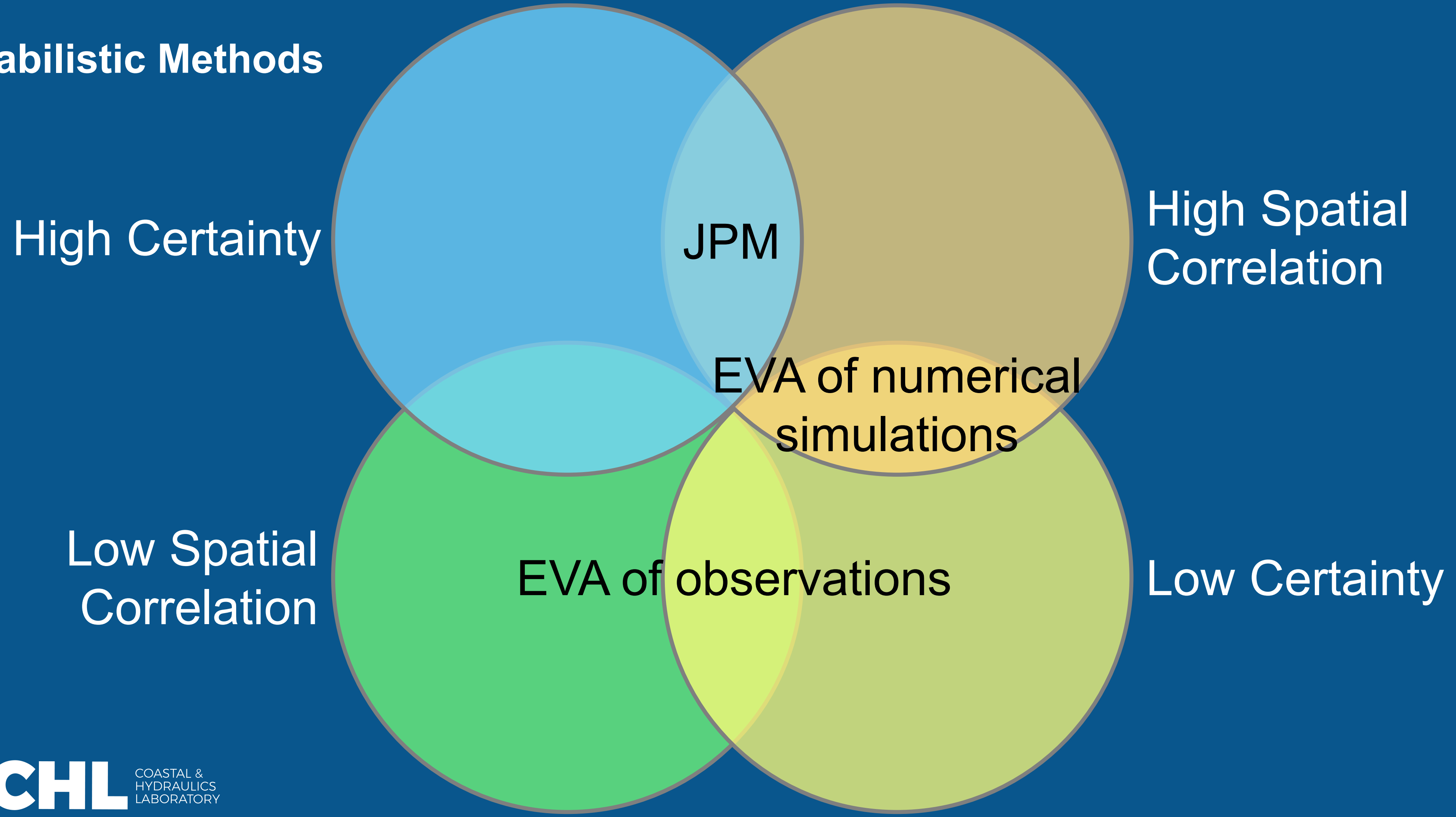
Probabilistic Coastal Flooding Hazard Assessment

- **Probabilistic Methods**



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Probabilistic Coastal Flooding Hazard Assessment

- **Standard of Practice: Probabilistic Methods**

Tier 1 – Low Fidelity
• **Univariate EVA of historical observations**   • Benchmarking, high-frequency events, convective storms, seiches
Tier 2 – Medium Fidelity

• **JPM with low-fidelity numerical simulations**
  • Benchmarking
• **EVA of high-fidelity numerical simulations**
  • Extratropical cyclones

Tier 3 – High Fidelity
• **JPM or PCHA with high-fidelity numerical simulations (including Focus Studies)**   • Tropical cyclones

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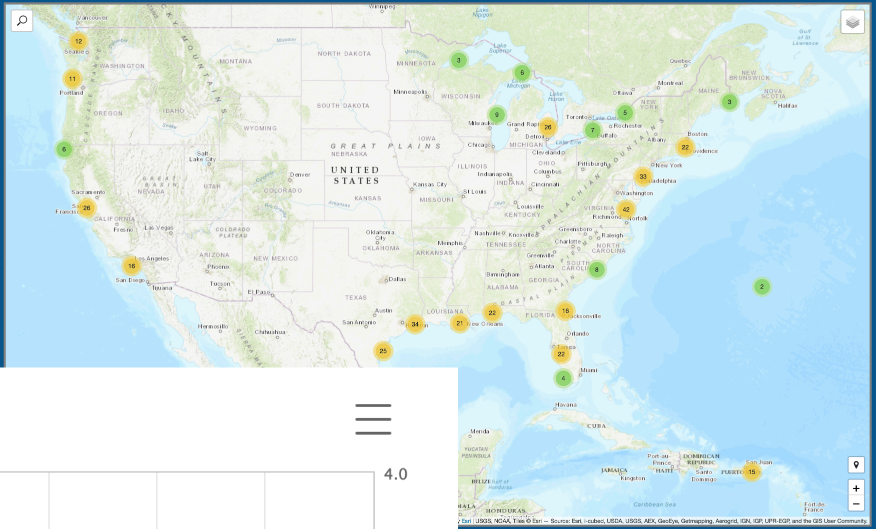
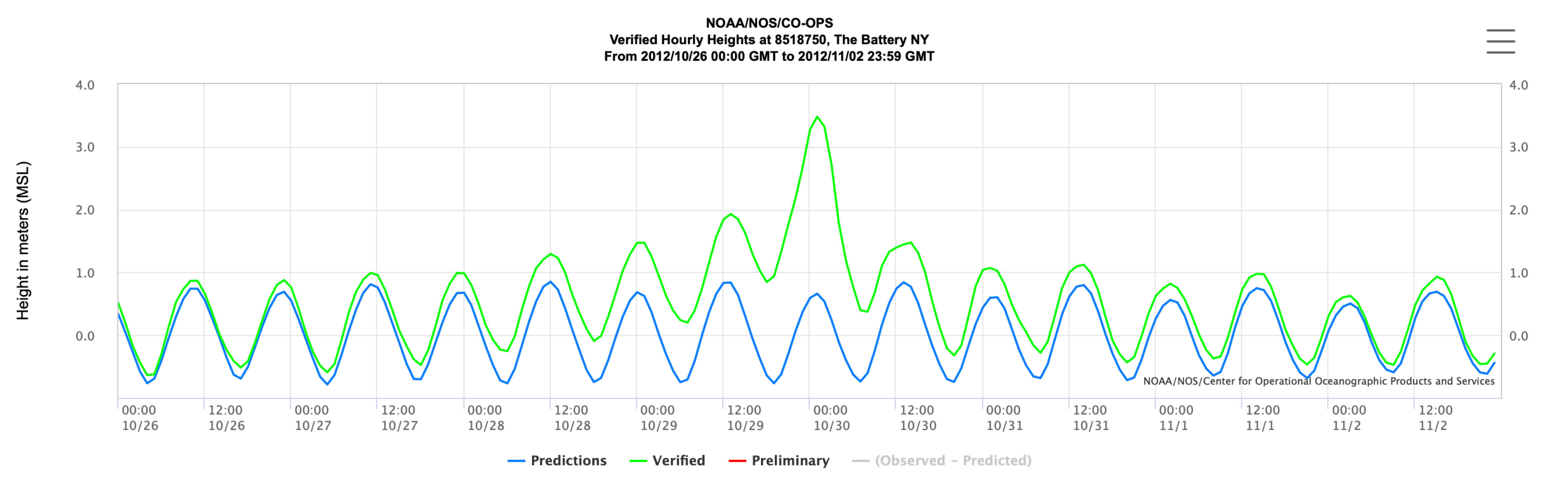
Extreme Value Analysis (EVA)

Data Sources: Water levels

- NOAA CO-OPS Tides & Currents
  - Predicted astronomical tides
  - Water level observations





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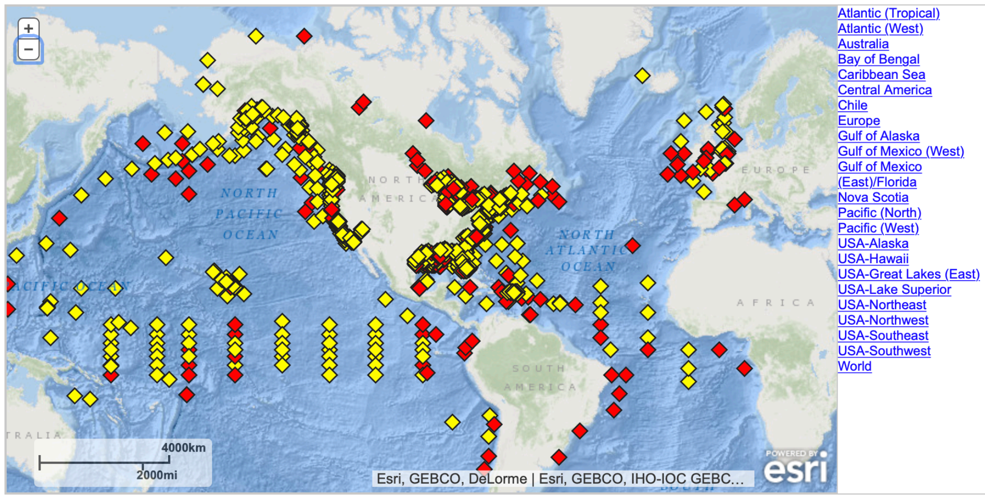
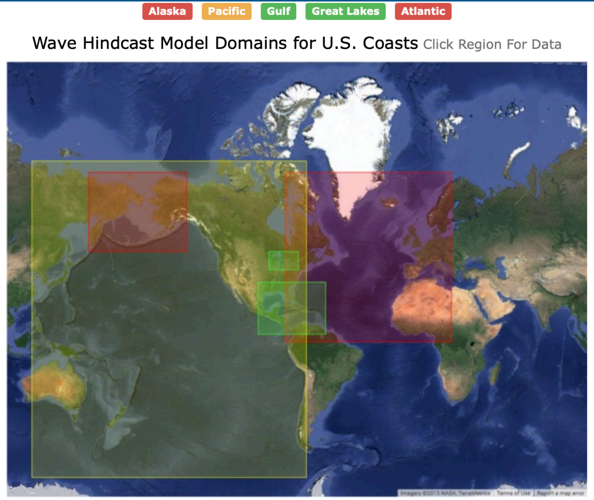
Extreme Value Analysis

Data Sources: Waves

- NOAA National Data Buoy Center
  - Wave height, peak period, direction
  - Wave spectra

- USACE-ERDC Wave Information Studies (WIS)
  - Long-term hindcast (20-30 years)
  - Continuous, hourly wave climatology
  - Resolution: every few miles along the coast





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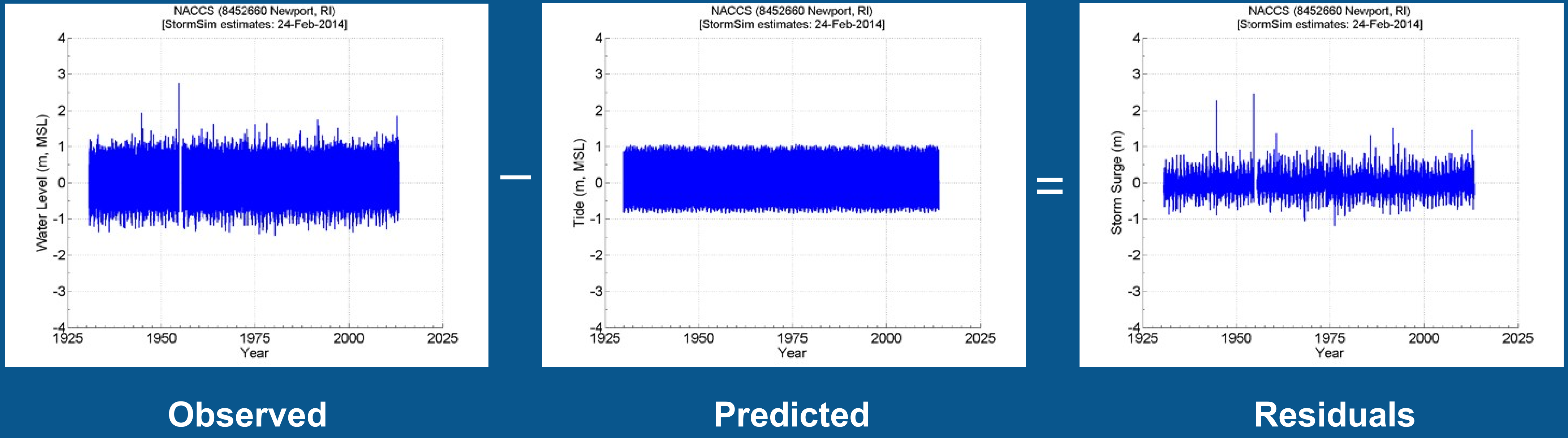
Extreme Value Analysis

Observed Water Level vs. Non-tidal Residuals (NTR)

- Non-Tidal Residuals = Observed WL[1] – Predicted WL[2]
  1. Detrended Time Series (zero-crossing at year 1992.5)
  2. Astronomical Tide Time Series (NTDE of 1983-2001)



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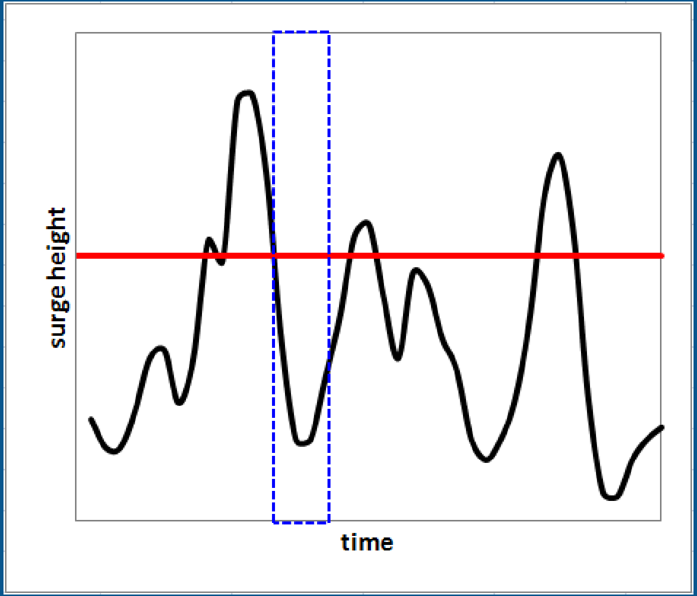
Extreme Value Analysis

Sampling Methods

- Block Maxima Series (BMS)
  - Annual Maxima
    - Sample each year's peak event, over the duration of the data
  - Monthly Maxima
    - Sample each month's peak event
  - Generalized Extreme Value (GEV) Distribution

- Partial Duration Series (PDS)
  - Peaks-Over-Threshold (POT)
    - Sample independent & identically-distributed (iid) peak events
    - Automated threshold selection methods (e.g., MRL)
  - Generalized Pareto Distribution (GPD)



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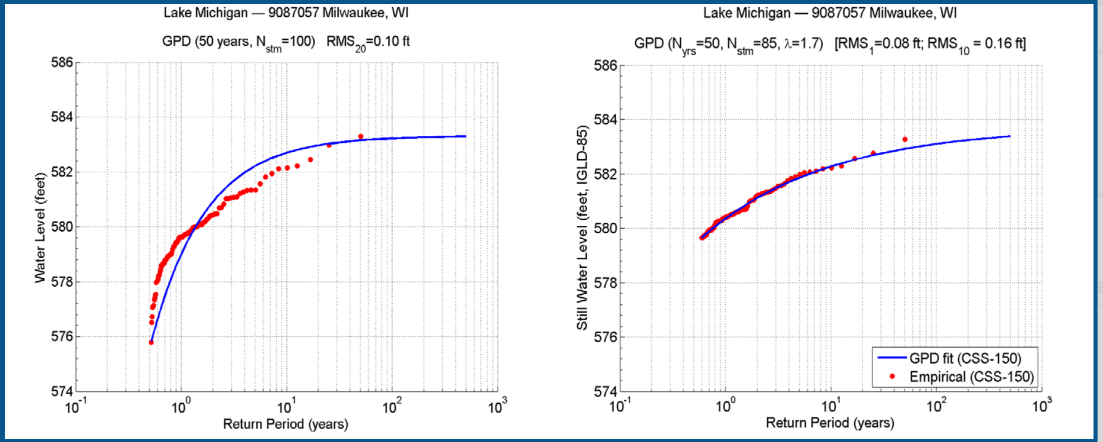
Extreme Value Analysis

Sampling Methods

- Block Maxima Series (BMS)
  - Significant extreme events can potentially be discarded
  - Can result in mixed populations of extreme and non-extreme events
  - Often results in over-conservative estimates
  - Sensitive to short record lengths

- Partial Duration Series (PDS)
  - Maximizes usage of available data
  - Can incorporate BMS
  - Flexible / complex – user defined threshold
  - Less sensitive to short record lengths
  - Less uncertainty in water level predictions



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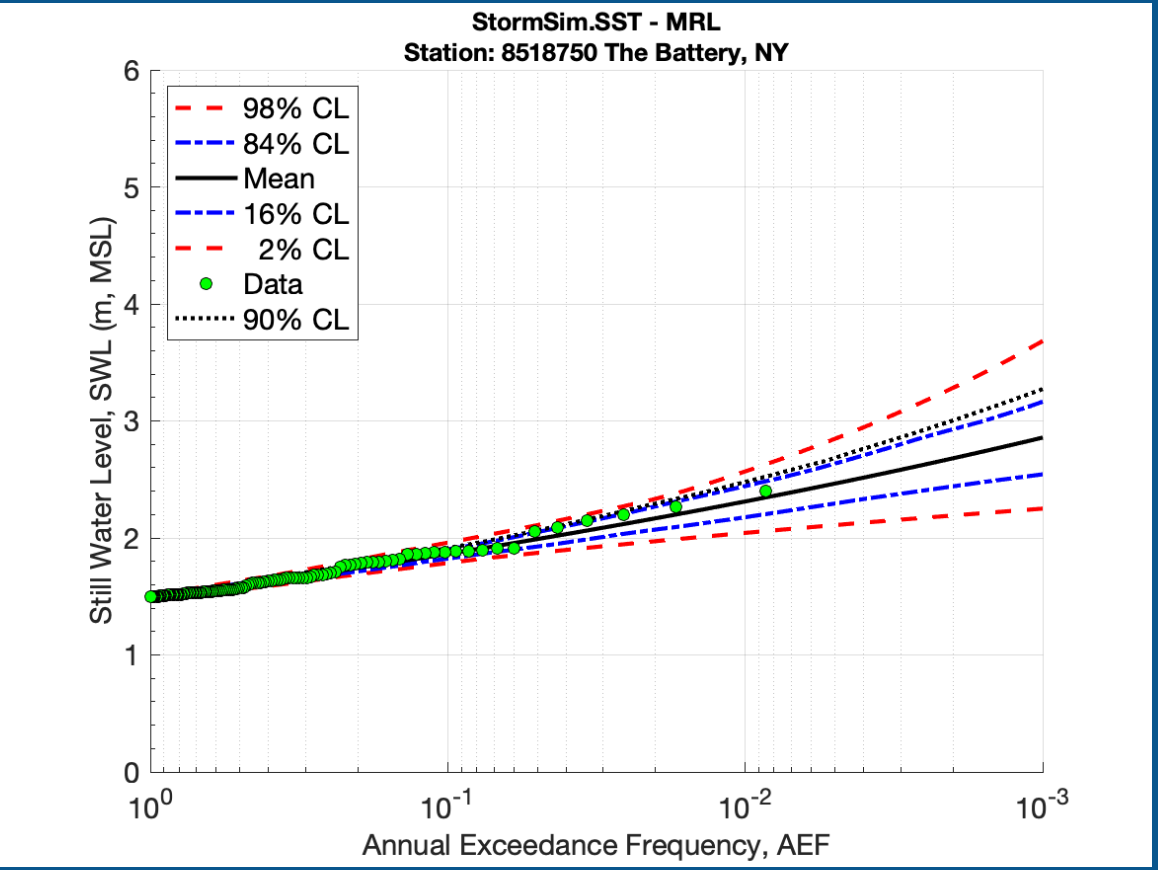
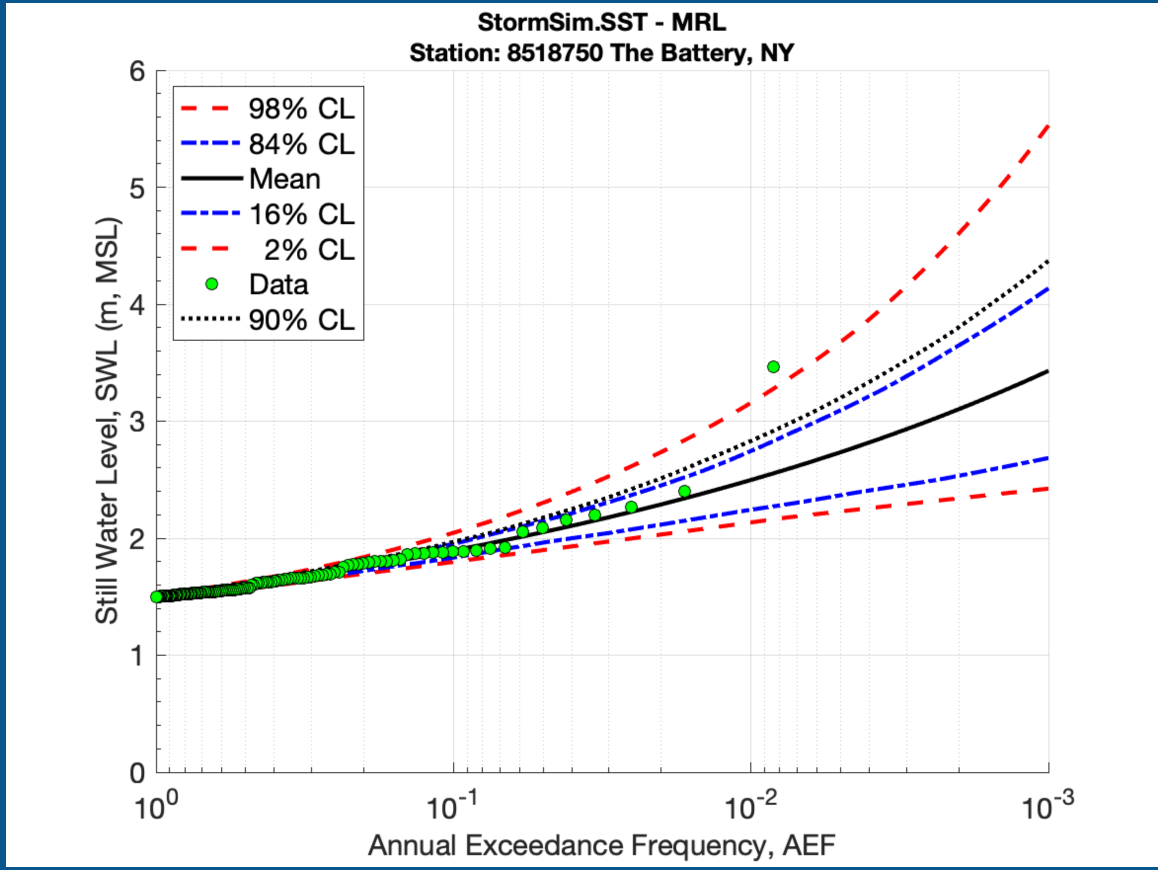
Extreme Value Analysis: Historical Water Levels





1% AEP @ 90% CL = 2.45 m
0.1% AEP @ 90% CL = 3.16 m

1% AEP @ 90% CL = 2.82 m
0.1% AEP @ 90% CL = 4.45 m

Joint Probability Method (JPM)

Background

- Characterization of individual TC parameters in the 1950's – Myers (1954)
  - Hydrometeorological report submitted to USACE
  - Track, location, pressure deficit, radius of maximum winds, etc.
- JPM - pioneered in the late 1960's – Russell (1968)
  - Dissertation on the probability distributions of hurricane effects
  - Full Monte Carlo Simulation
  - Wind, surge, and wave loads on offshore structures
- JPM – adopted for coastal storm surge studies in the 1970's (NOAA)

Joint Probability Method (JPM)

Background

- JPM with Optimal Sampling (JPM-OS) – aftermath of Hurricane Katrina (IPET 2009)
  - Response Surface (RS) – USACE/Resio (2007)
  - Bayesian Quadrature (BQ) – FEMA/Toro (2008)
  - Stochastic Track Model (STM) – Vickery (2008)
- Probabilistic Coastal Hazard Analysis (PCHA) Framework (USACE) – builds upon JPM-OS
  - Meta-Gaussian Copula (MGC)
  - Gaussian Process Metamodel (GPM)

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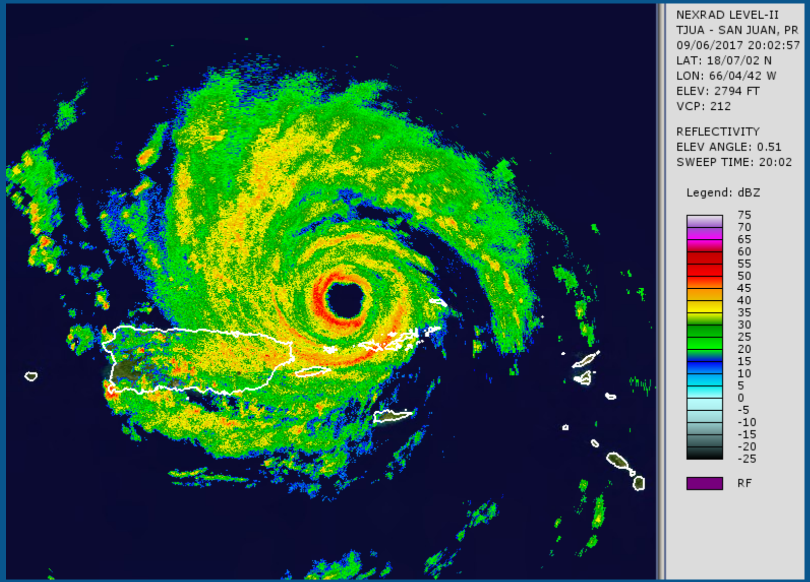
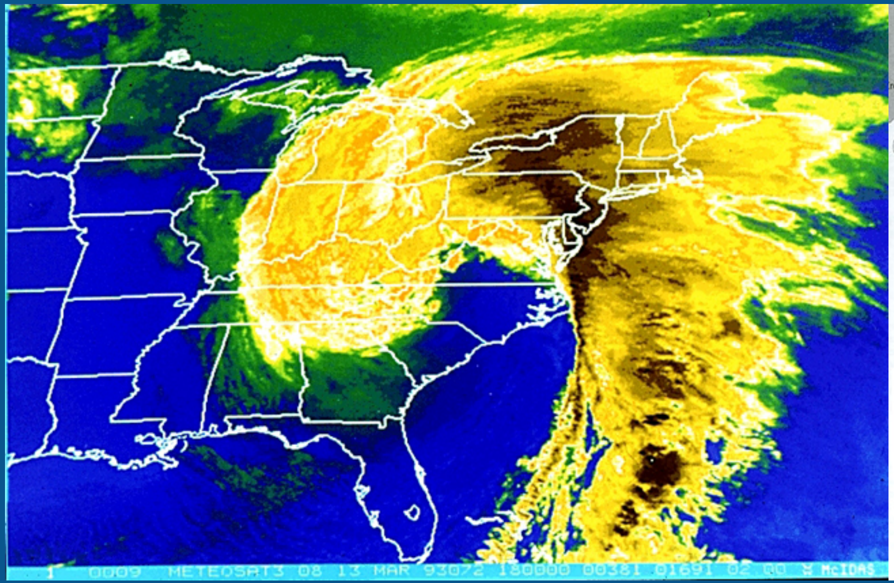
JPM – Atmospheric Forcing

Storm Climatology

- Tropical Cyclones (TC)
  - "Genesis" as tropical storms
    - Tropical storms / Hurricanes
    - Transitioning tropical cyclones
    - Post-tropical cyclones
      - Extratropical transition has occurred
- Extratropical Cyclones (XC)
  - "Pure" extratropical storms
    - e.g., Nor'easters
  - No tropical cyclogenesis



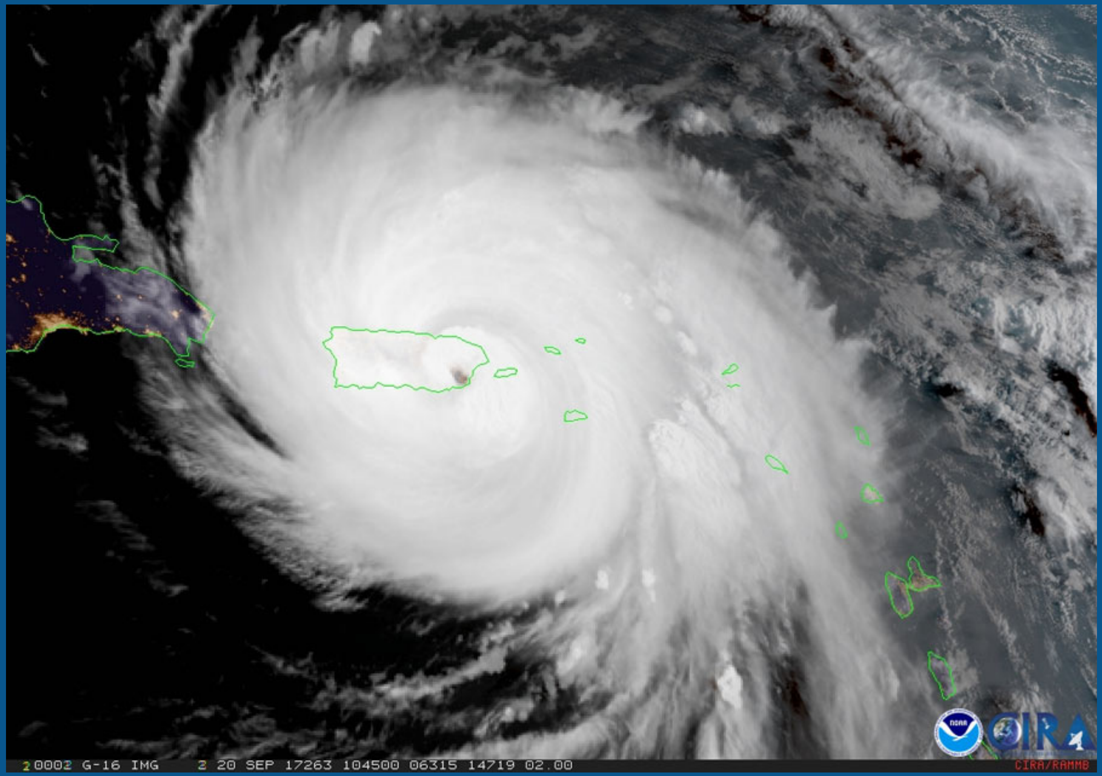


MARCH 1993 SUPERSTORM SURGE HEIGHTS
Source: NOAA National Disaster Survey Report

JPM – Representation of Tropical Cyclone Forcing

TC Parameterization: Response $= f(x_o, \Delta p, R_{max}, V_t, \theta)$

1. **Reference location (x_o)**
2. **Central pressure deficit (Δp)**
3. **Radius of maximum winds (R_{max})**
4. **Translational speed (V_t)**
5. **Heading direction (θ)**



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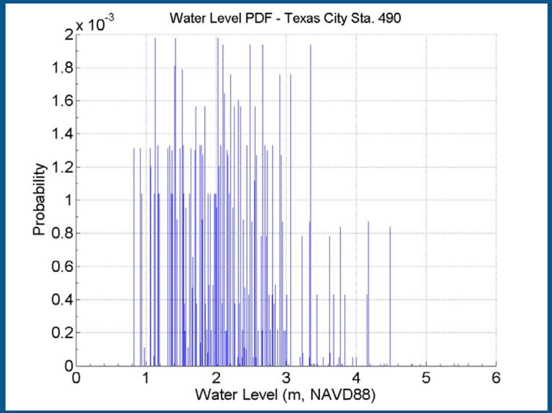
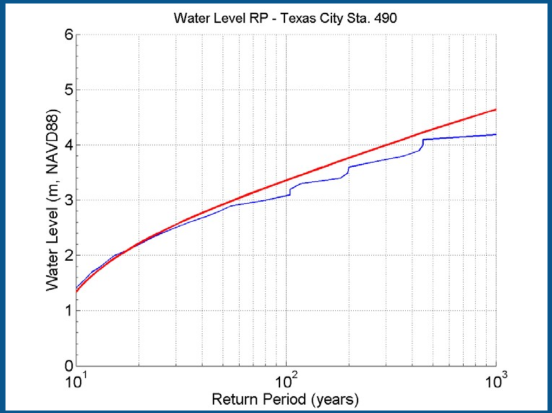
Joint Probability Method

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

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

λ = SRR (storms/yr/km)

$\hat{\lambda}_i$ = probability mass (storms/yr) or λp_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

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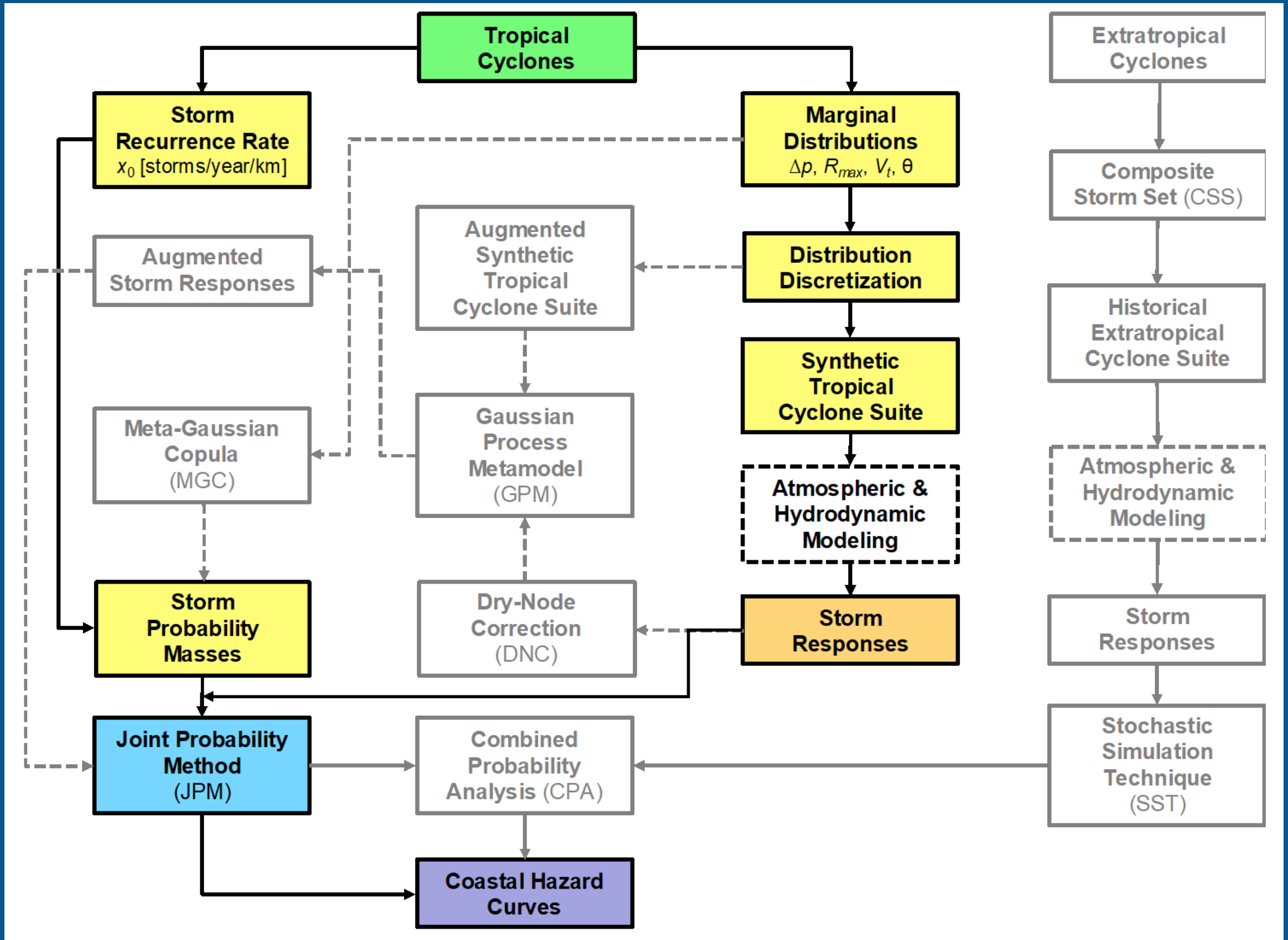
JPM – Joint Probability Analysis of TCs



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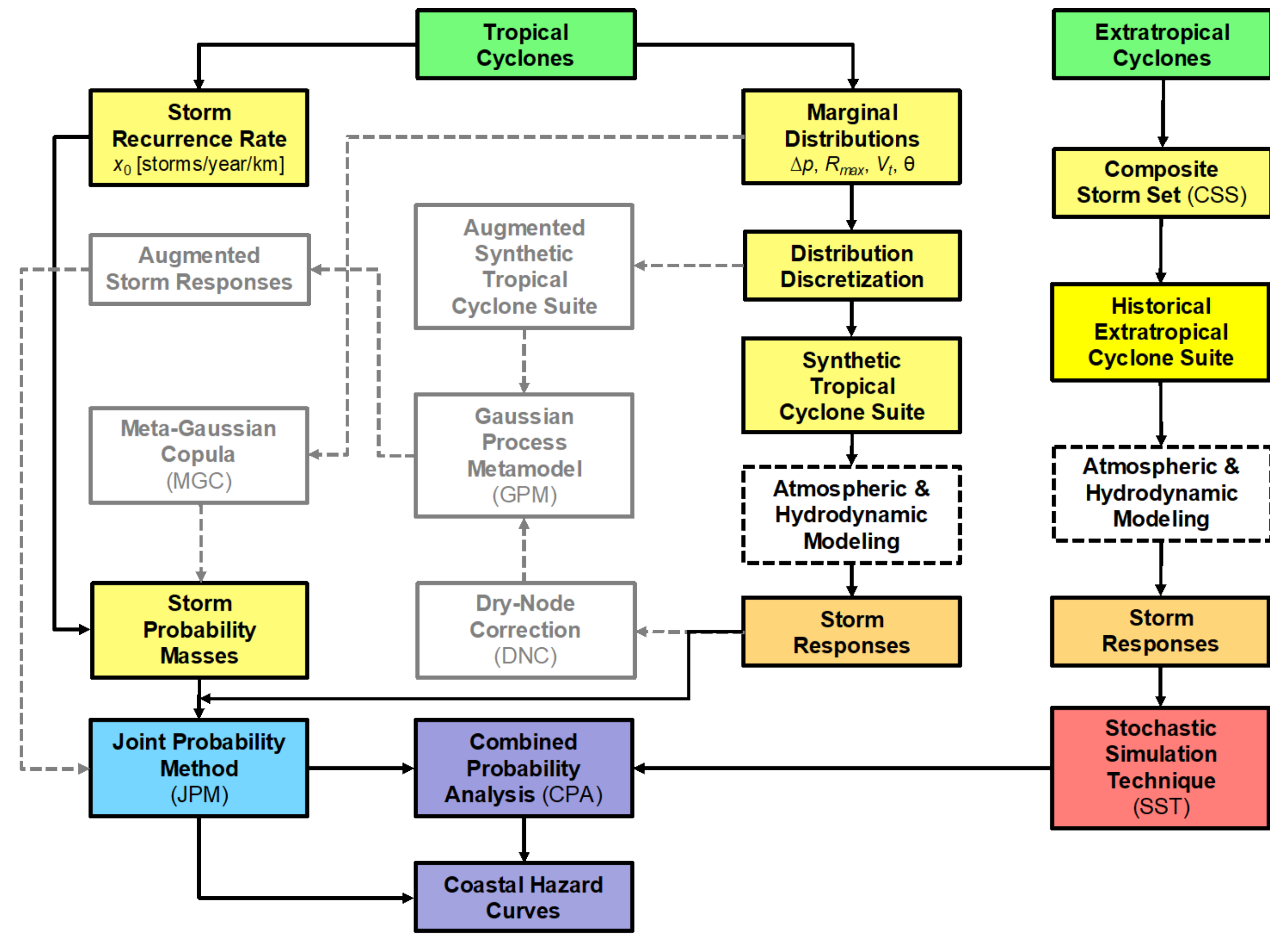
JPM – Joint Probability Analysis of TCs and XC



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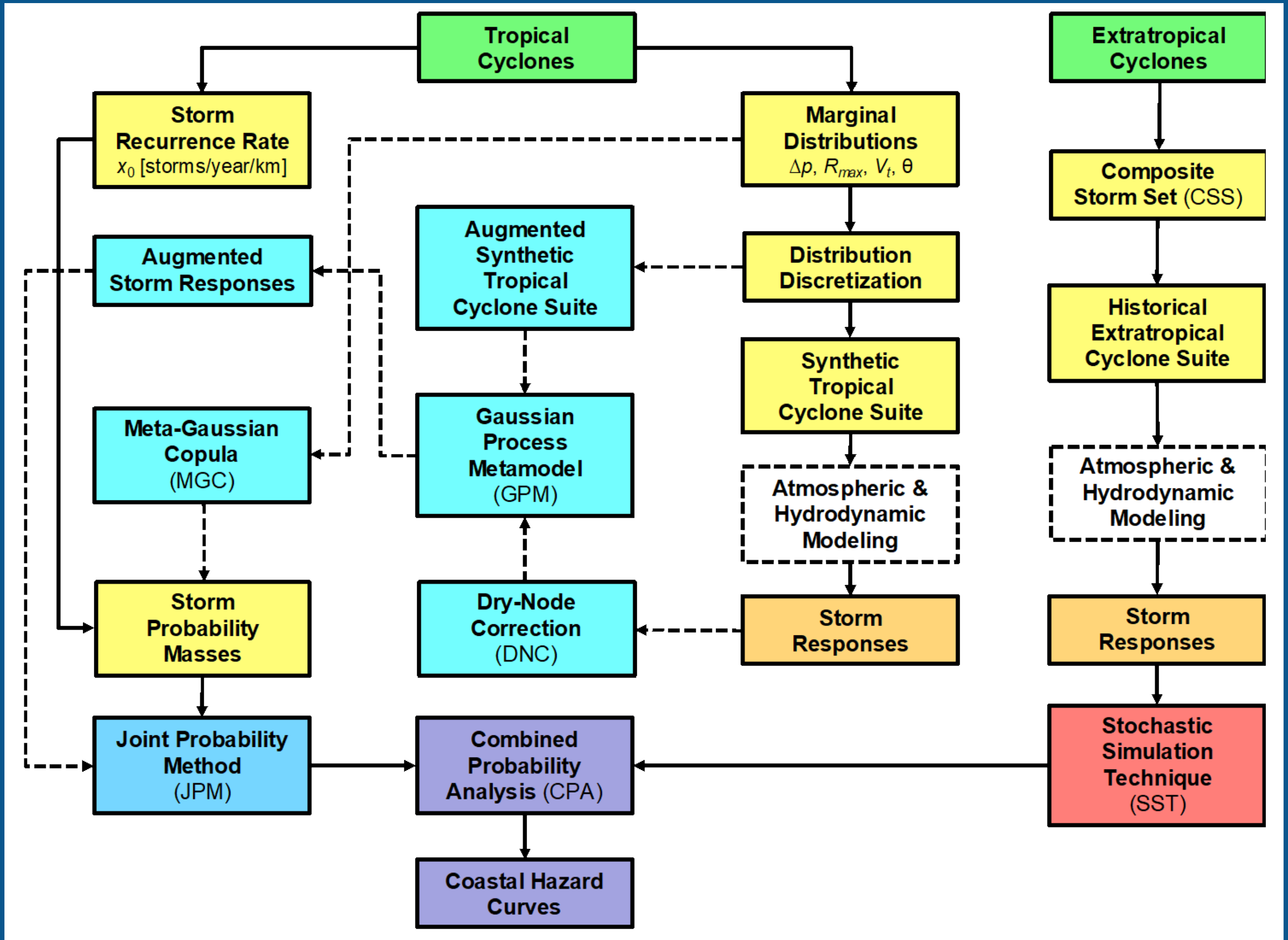
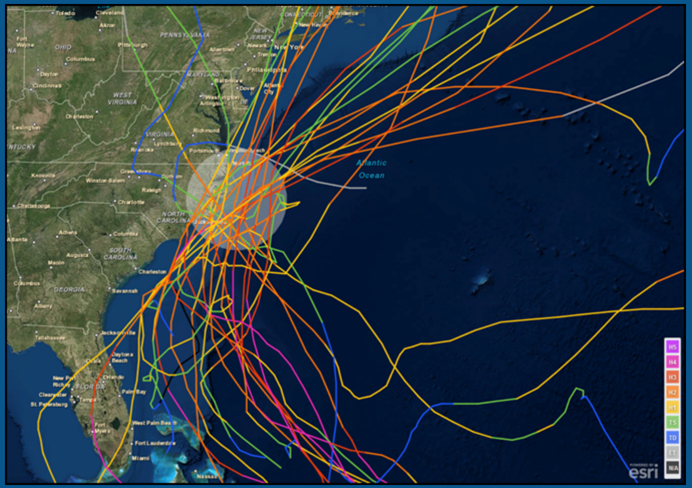
Probabilistic Coastal Hazard Analysis (PCHA)



JPM – Data Sources

TC Data Sources

- NHC HURricane DATa 2nd generation (HURDAT2)
  - TC parameters: max wind speed, central pressure, lat, lon
- Automated Tropical Cyclone Forecast (ATCF)
  - Best track data: 2019
- Colorado State (CSU) Extended Best Track (EBTRK)
  - R_{max} (1988 – 2018)
- Coastal Hazards System (CHS) Gaussian Process Metamodel Fills in gaps in central pressure and estimates R_{max}
  - Period: 1851 – 2019



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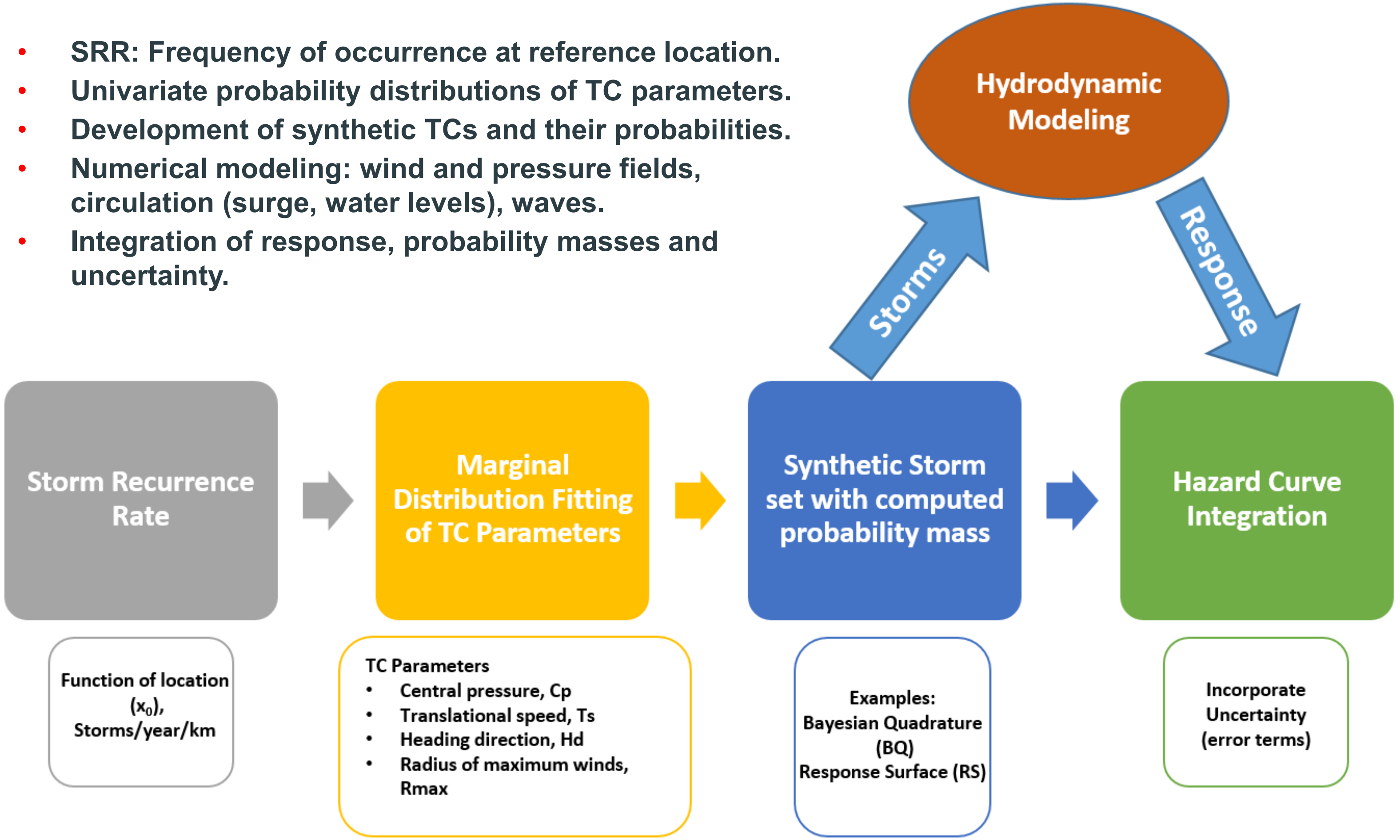
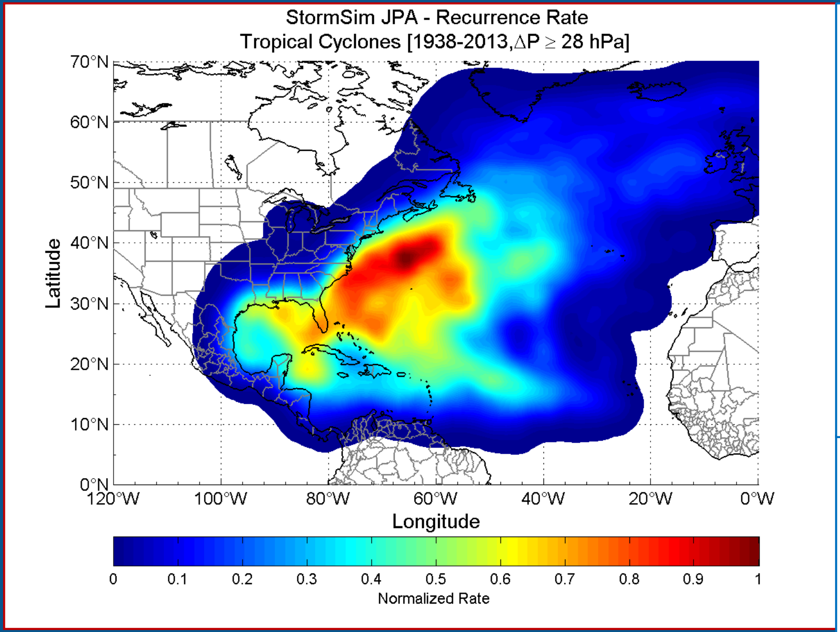
Joint Probability Method – Basic Components

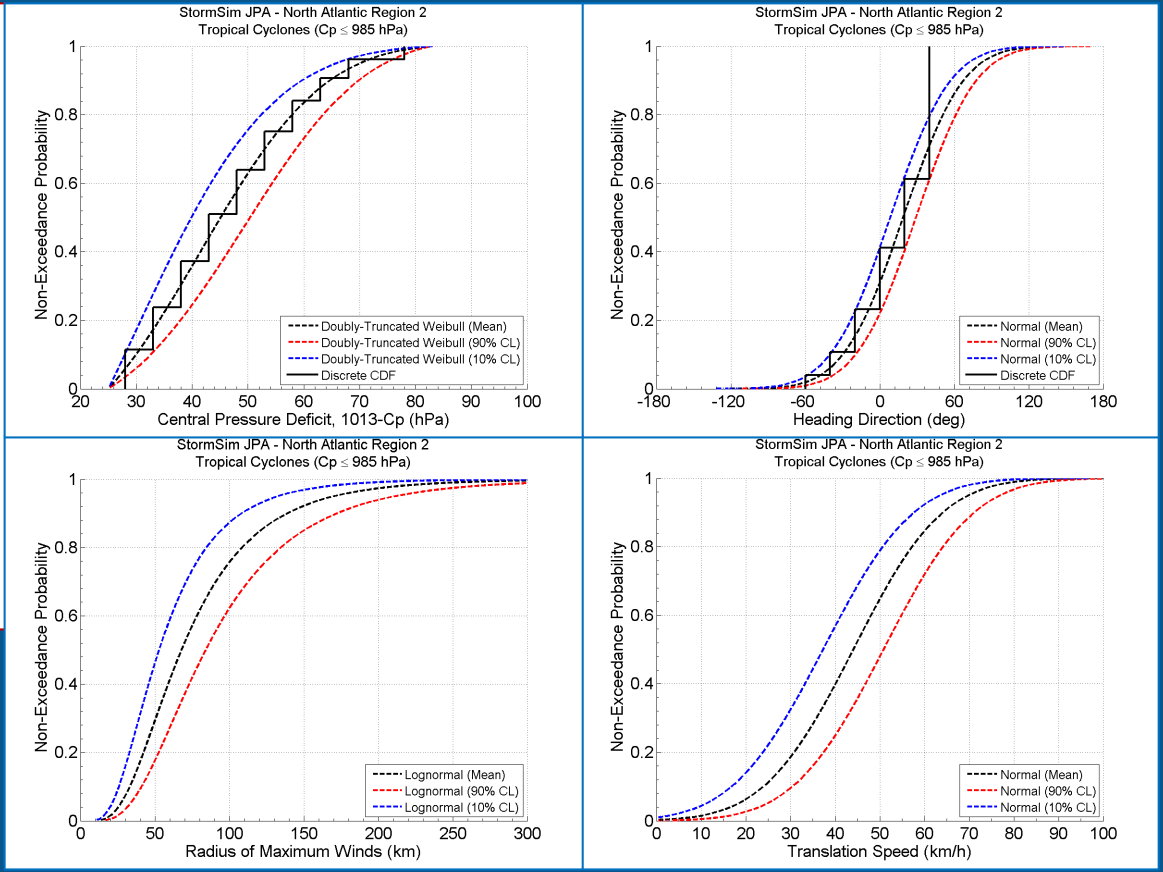
- SRR: Frequency of occurrence at reference location.
- Univariate probability distributions of TC parameters.
- Development of synthetic TCs and their probabilities.
- Numerical modeling: wind and pressure fields, circulation (surge, water levels), waves.
- Integration of response, probability masses and uncertainty.



JPM – TC Parameterization

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





Marginal Distribution Fitting of TC Parameters

Storm Recurrence Rate

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Joint Probability Method

Synthetic Storm set with computed probability mass

Storm Development / Discretization Approach

- Response Surface (RS)
  - Storm generation based on expert judgement
  - Storm surge response surface, interpolated in the $(\Delta p, R_{max})$ 2D space
- Bayesian Quadrature (BQ)
  - Coarse grid storm surge "benchmark"
  - Multiple storm sets generated by BQ; select the one closest to the "benchmark"
- Stochastic Track Model (STM)
  - Coarse grid storm surge "benchmark"
  - Discretization based on expert judgement, or generated by STM itself
- Probabilistic Coastal Hazard Analysis (PCHA)
  - Hybrid storm-generation approach: $\theta, \Delta p$ (regular spacing); R_{max}, V_t (BQ)
  - Discretization of the entire multi-parameter space $(\Delta p, R_{max}, V_t, \theta)$; Augmented TC Suite

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Joint Probability Method

Synthetic Storm set with computed probability mass

Storm Probabilities

- **Assumed Independence**

$$P(x_o, \Delta p, R_{max}, V_t, \theta) = P(x_o) \cdot P(\Delta p) \cdot P(R_{max}) \cdot P(V_t) \cdot P(\theta)$$

- **Correlation Tree (1:1 Dependence)**

$$P(x_o, \Delta p, R_{max}, V_t, \theta) =$$

$P(x_o)$ → $P(\Delta p | x_o)$ → $P(R_{max} | \Delta p)$

$P(x_o)$ → $P(\theta | x_o)$ → $P(V_t | \theta)$

- **MGC (Multivariate Dependence)**

$$P(x_o) \cdot \Phi_R\left(\Phi^{-1}(u_1), \dots, \Phi^{-1}(u_n)\right)$$

$$R = \begin{pmatrix} 1 & \rho_{1,2} & \cdots & \rho_{1,n} \\ \rho_{2,1} & 1 & \cdots & \rho_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{n,1} & \rho_{n,2} & \cdots & 1 \end{pmatrix}$$

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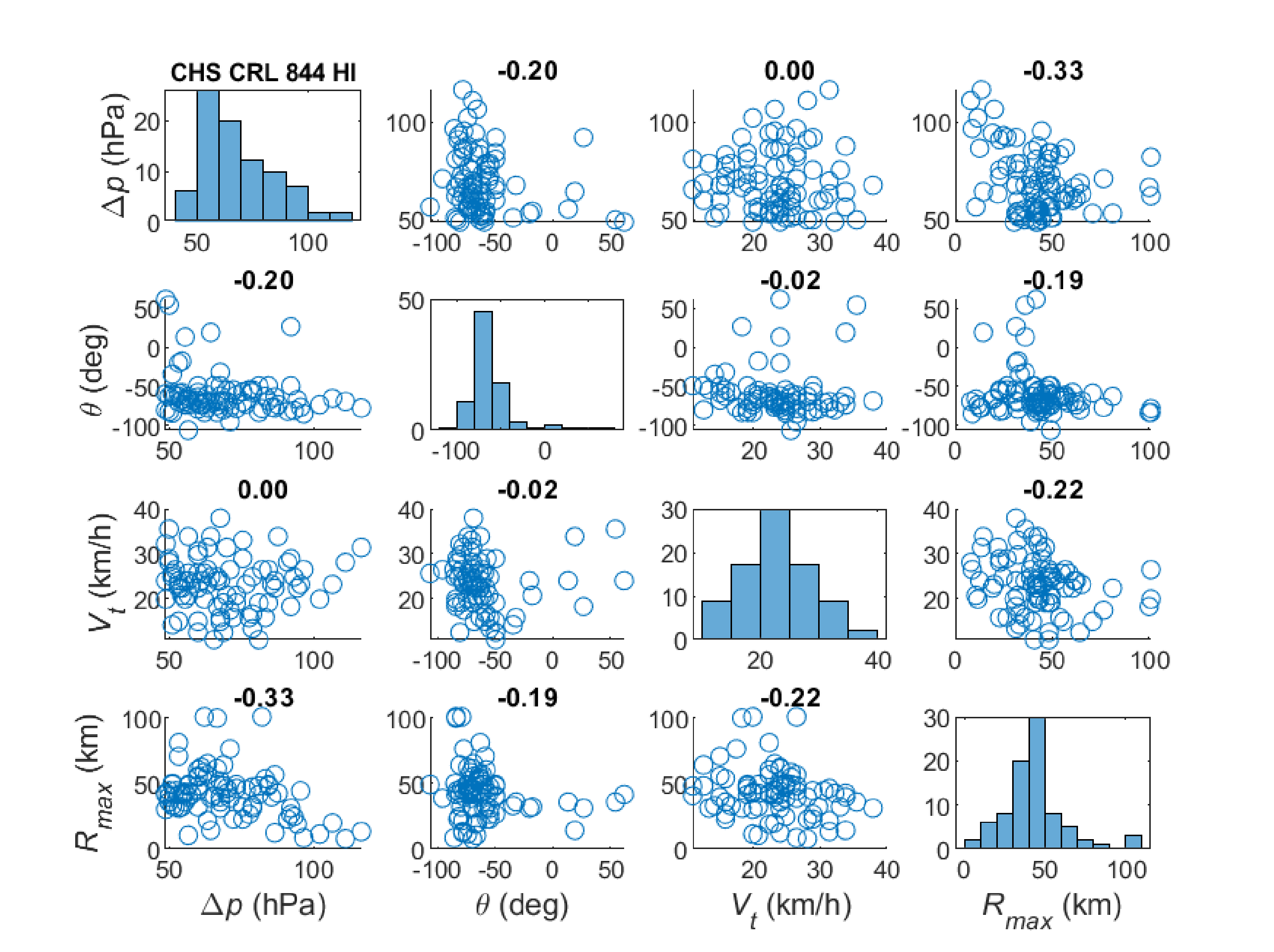
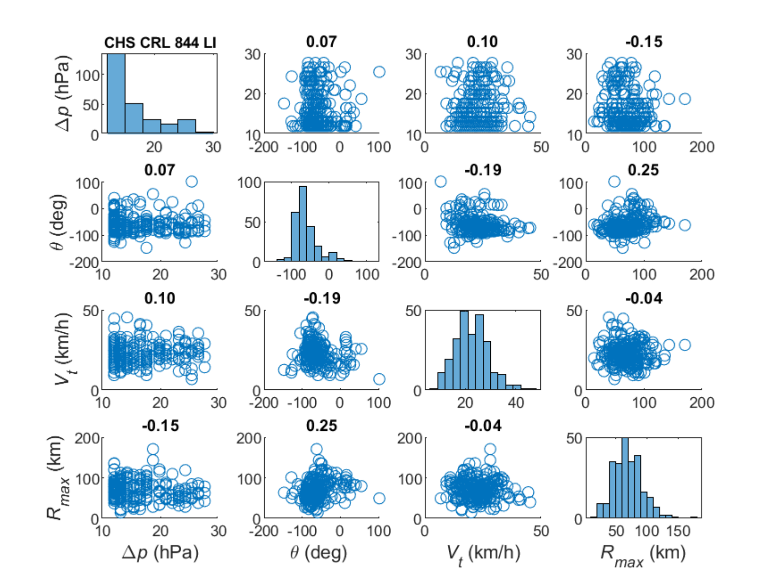
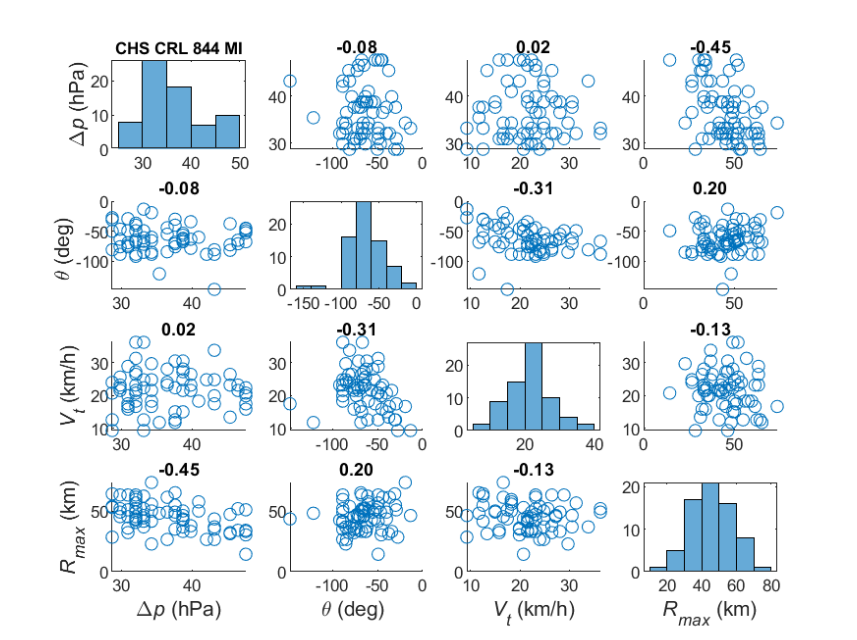
PCHA Example: SACS PR-USVI

Meta-Gaussian Copula: Correlation Matrix







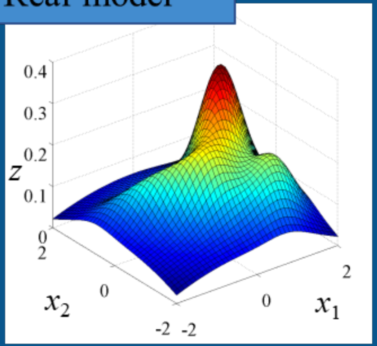
Synthetic Storm set with computed probability mass

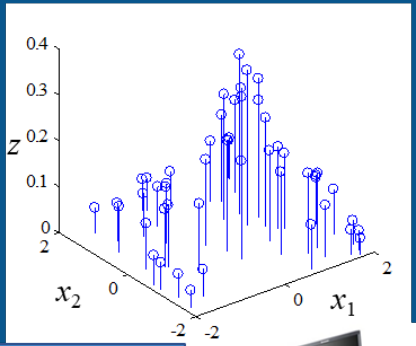
PCHA Example: SACS PR-USVI

Gaussian Process Metamodel (GPM)

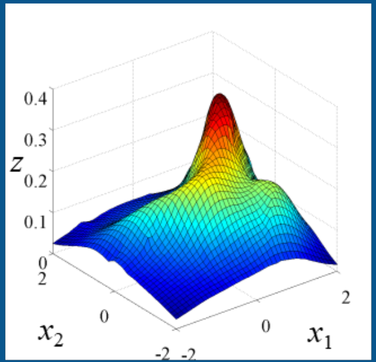
Synthetic Storm set with computed probability mass

Real model

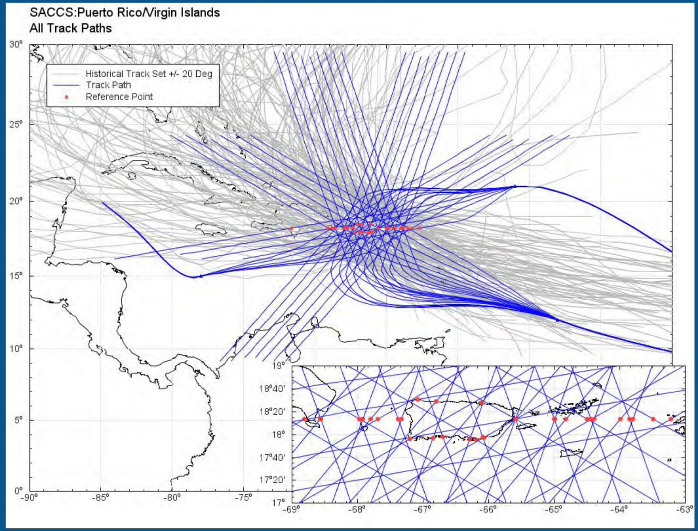




Support points



GPM approximation (global) + correction (local)

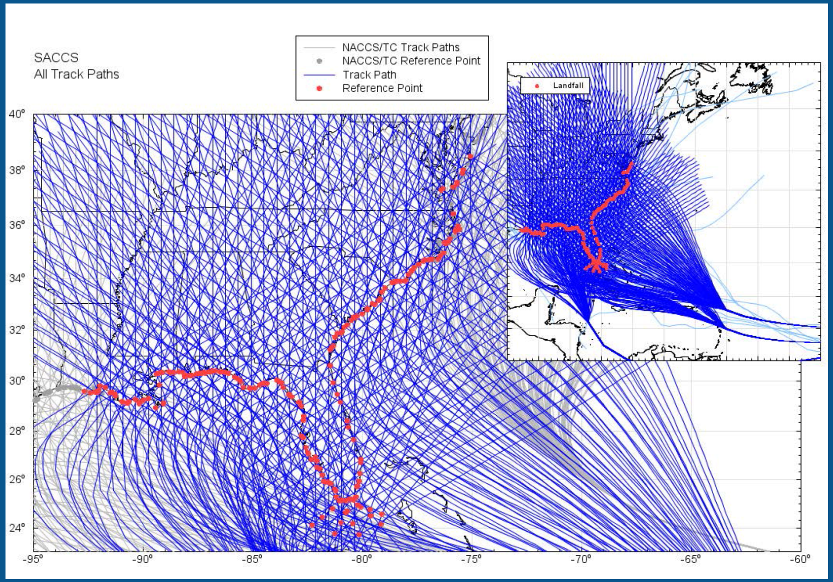


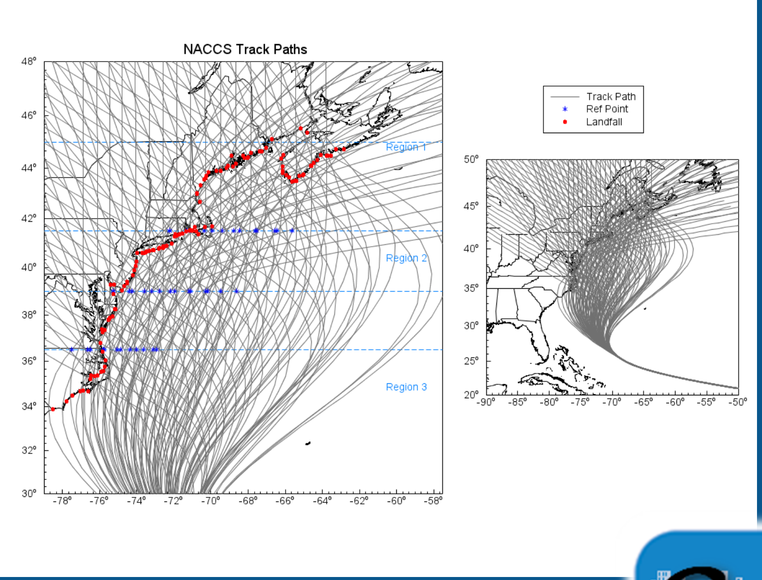
TC Parameter	Full Suite 300 TCs	Augmented Suite 348,000 TCs
θ (deg)	-60:20:60	-60:20:60
Δp (hPa)	8:10:148; 18:10:138	8:5:148
R_{max} (km)	8 to 143.6	10:5:155
V_f (km/h)	8 to 40	5:5:50

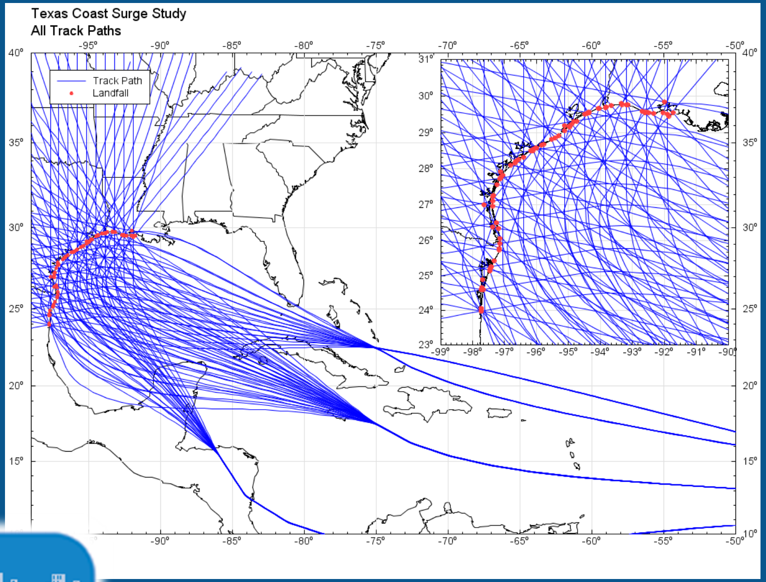
Joint Probability Method

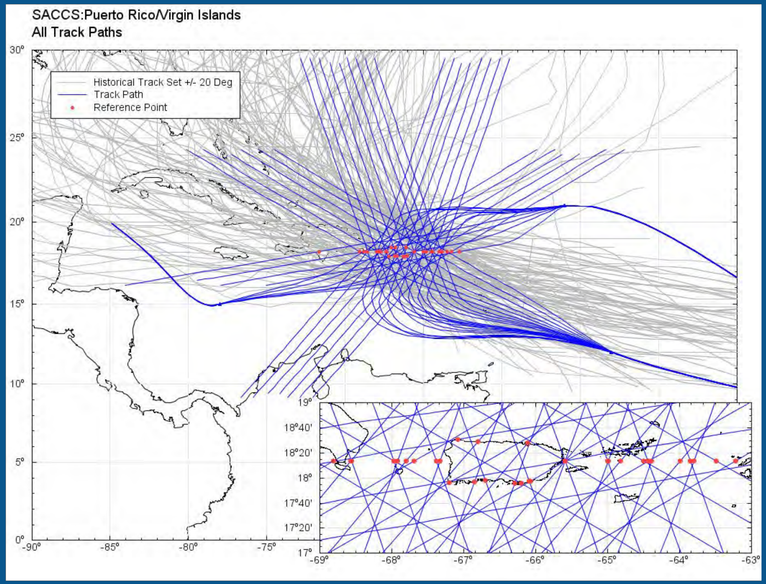
Synthetic TC Suites: Master Tracks

Synthetic Storm set with computed probability mass









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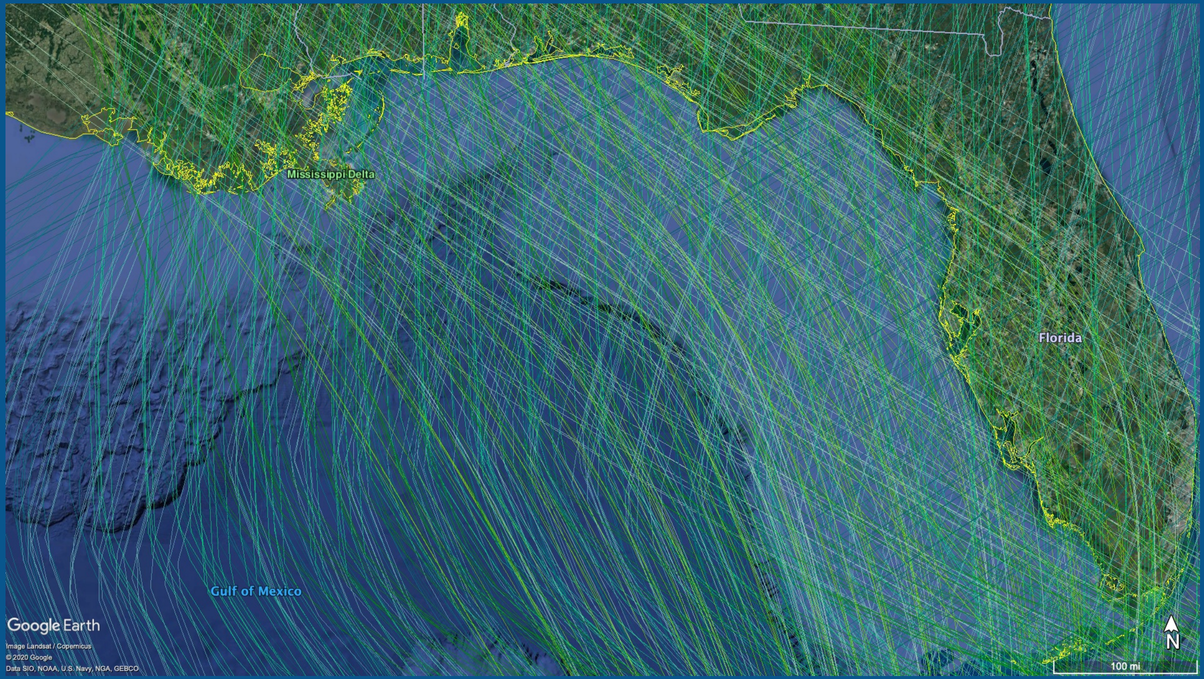
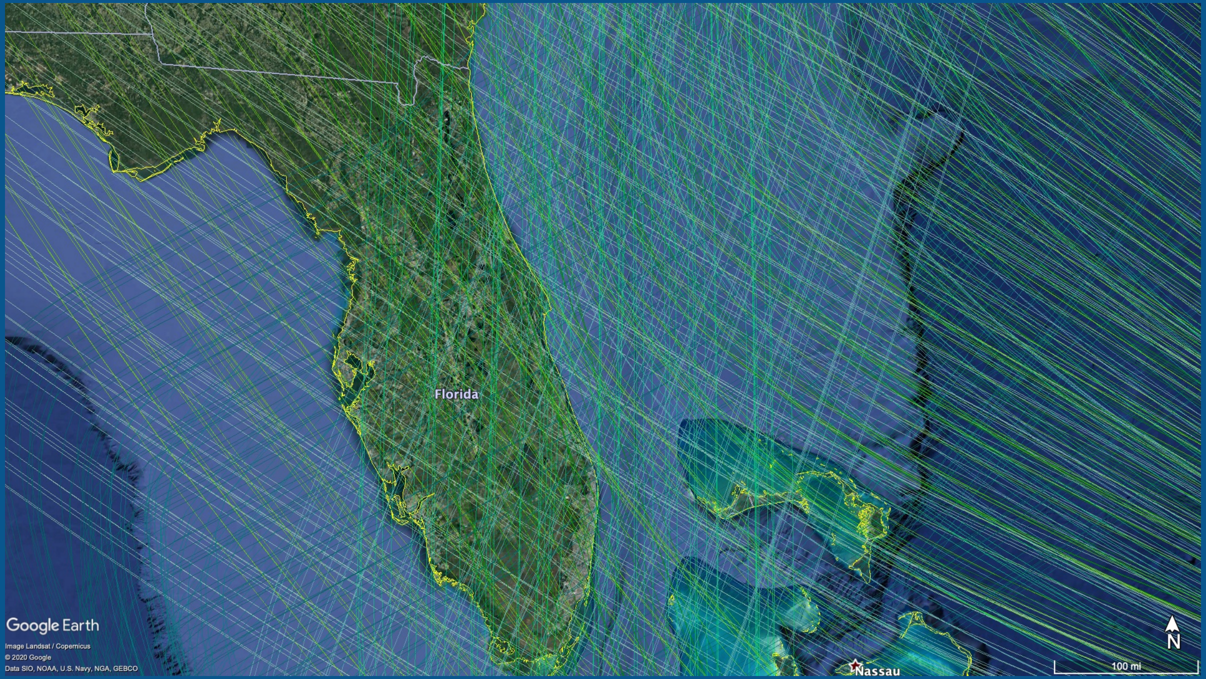
Joint Probability Method

Synthetic Storm set with computed probability mass

Synthetic TC Suites: R_{max} path



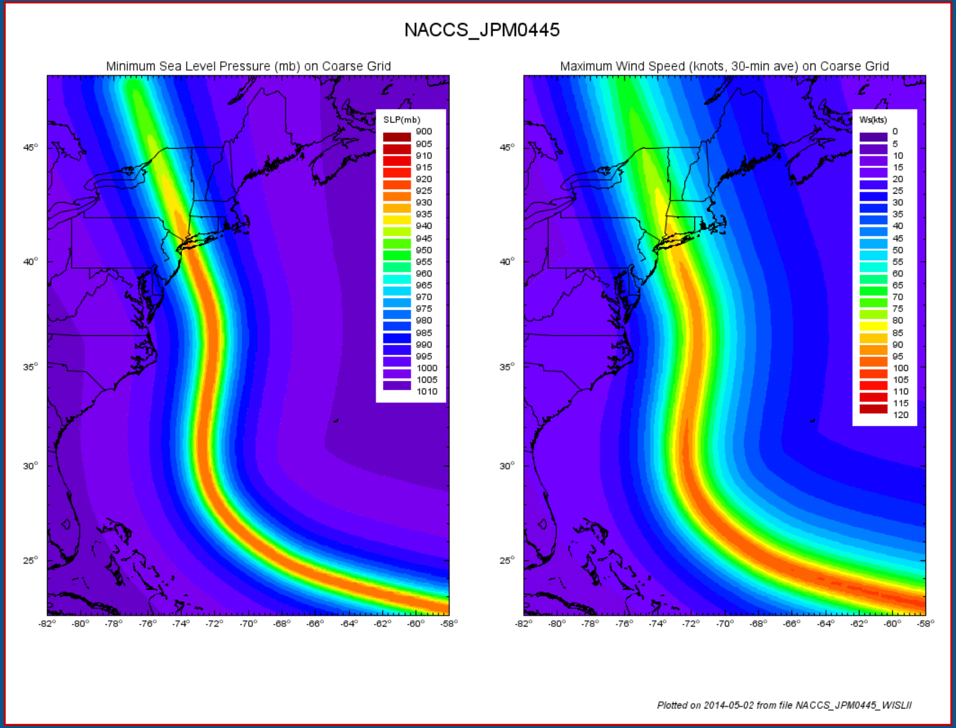


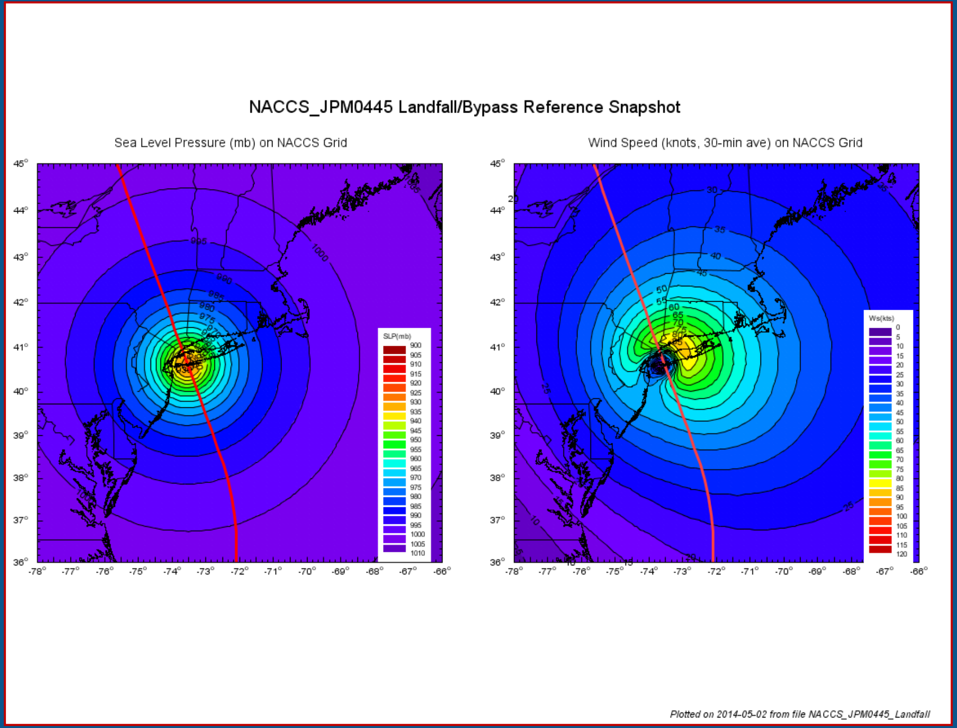
Joint Probability Method

Hydrodynamic Modeling

Atmospheric simulation of synthetic TCs

- Wind & Pressure Fields



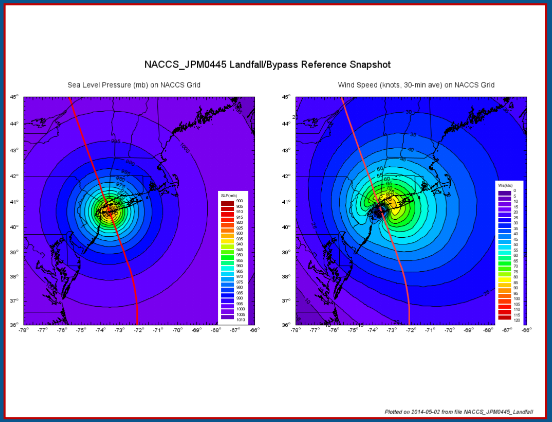


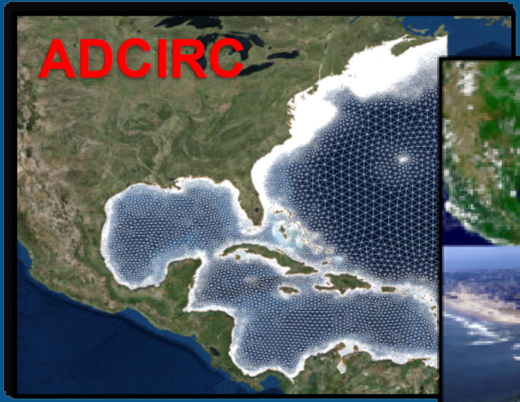
Joint Probability Method

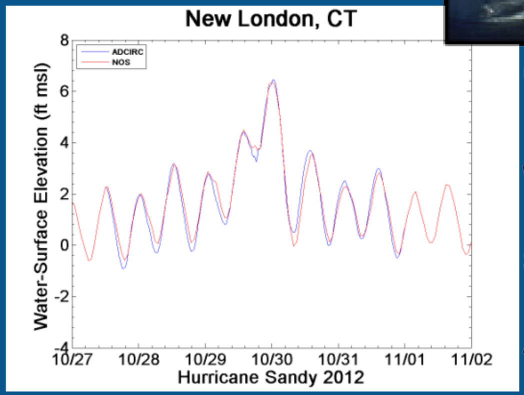
Hydrodynamic Modeling

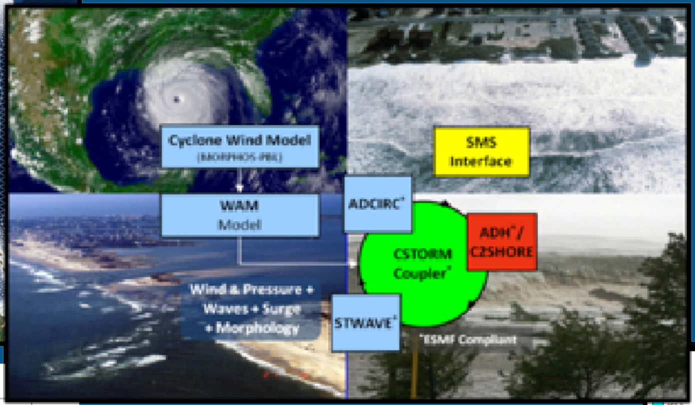
Hydrodynamic simulation of synthetic TCs

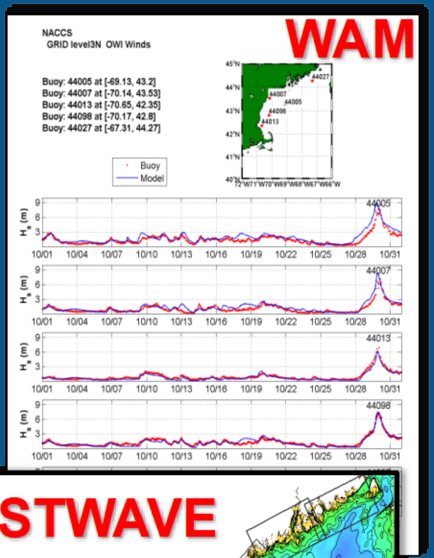
- Storm Surge/Water Level & Waves

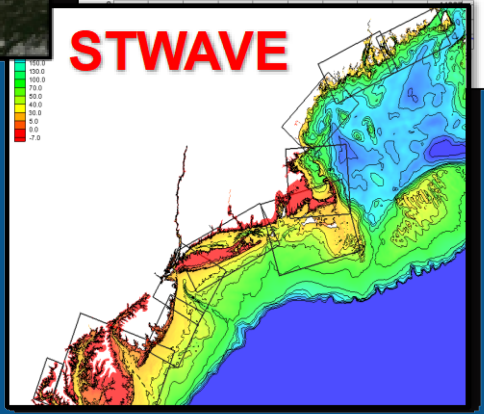












CSTORM-MS:
Coastal STORM Modeling System

WAM:
WAve Prediction Model

STWAVE:
STeady-State Spectral WAVE model

ADCIRC:
ADvance CIRCulation Model

3M nodes, min res ~20 m.

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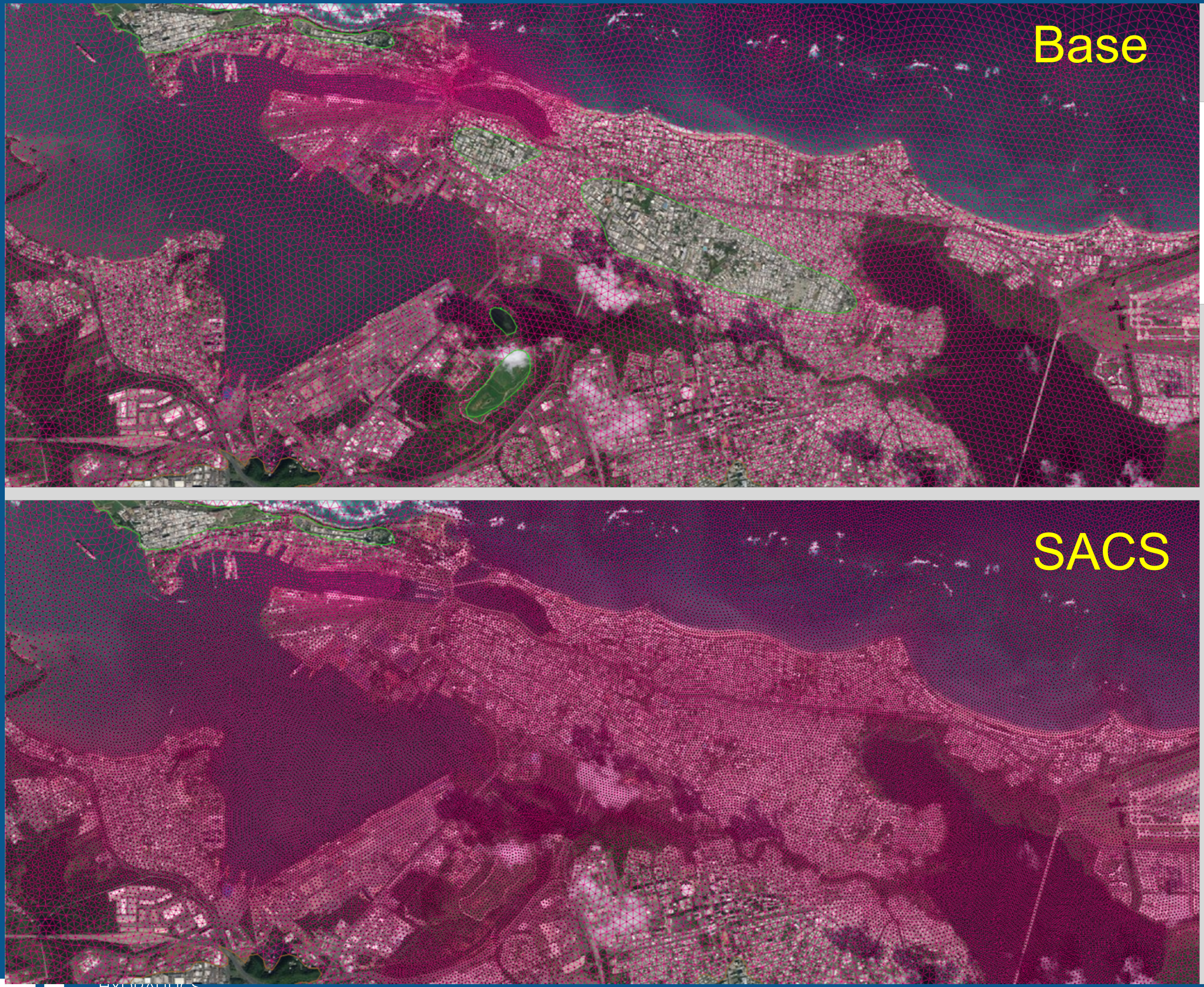
PCHA Example: SACS PR-USVI

CSTORM-MS COASTAL STORM MODELING SYSTEM

ADCIRC



San Juan

Resolution Before: 70-100 m

Resolution After: 30-85 m

Notes:

- The largest city in Puerto Rico, contains significant amount of critical infrastructure

Hydrodynamic Modeling

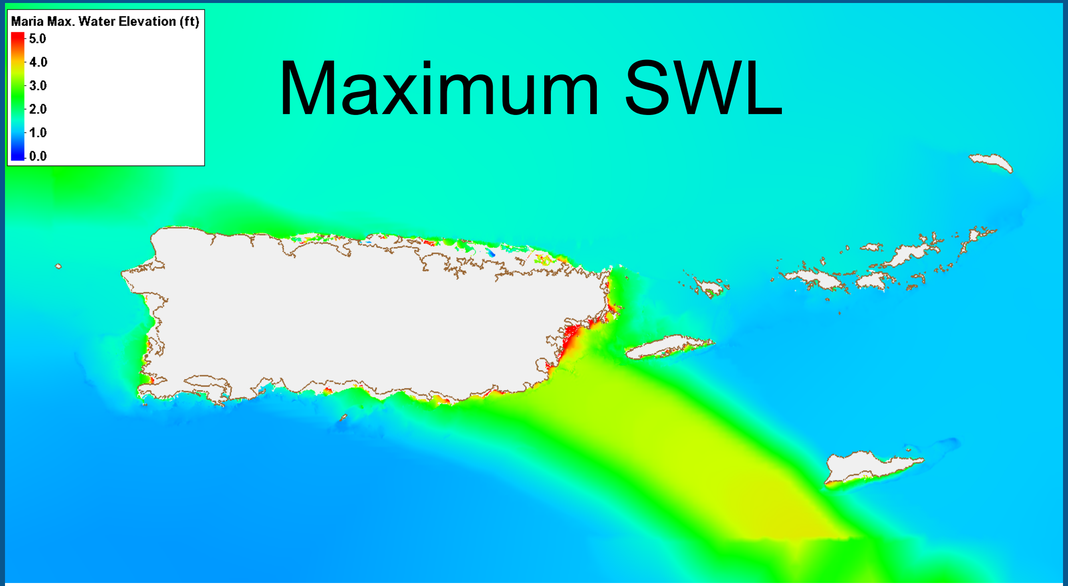
Base ADCIRC Mesh – Courtesy of Dr. Juan Gonzalez-Lopez

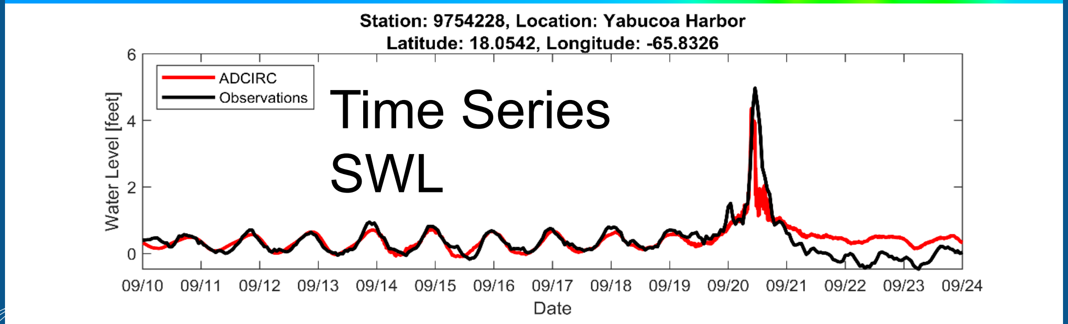
PCHA Example: SACS PR-USVI

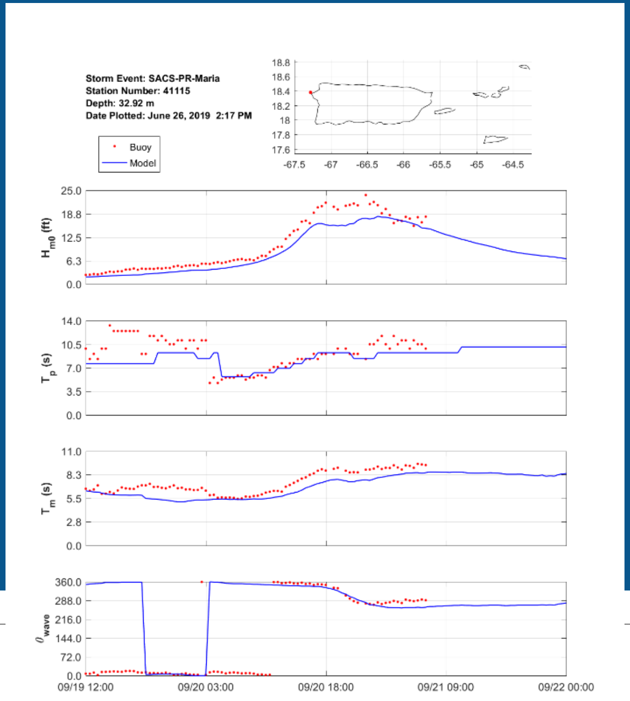
Hurricane Maria

CSTORM-MS COASTAL STORM MODELING SYSTEM

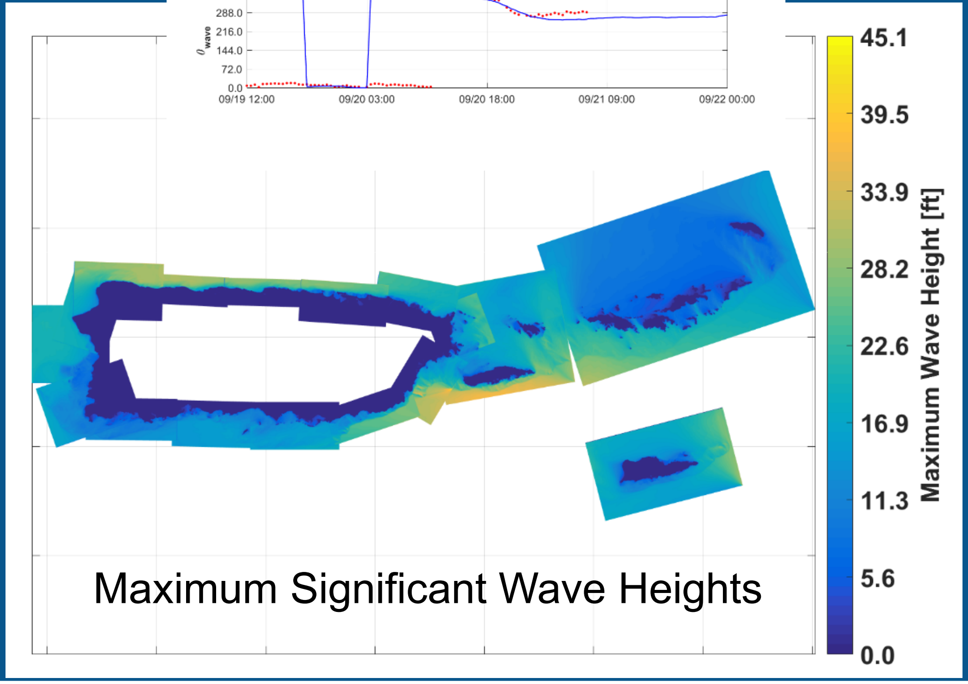
Hydrodynamic Modeling







Time Series Waves

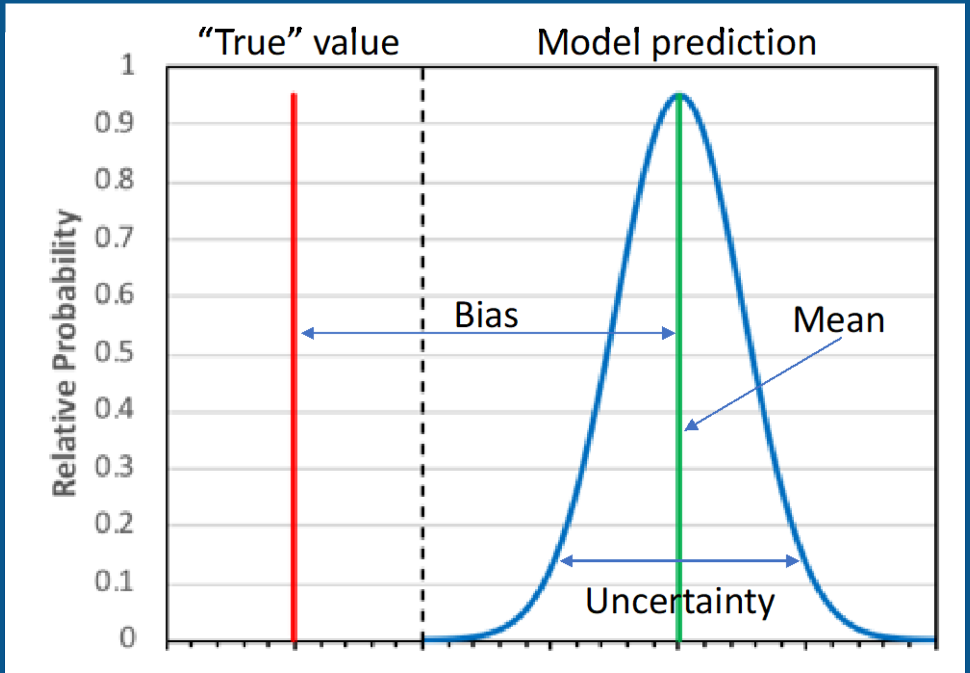


Joint Probability Method

Hazard Curve Integration

Quantification of Uncertainty

- **Bias** – measure of model accuracy; defined as the average error or difference between model predictions and the "true" values.
- **Uncertainty** – represents the likely extent or spread of the model error.



$$f(X) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)^2}$$

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

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

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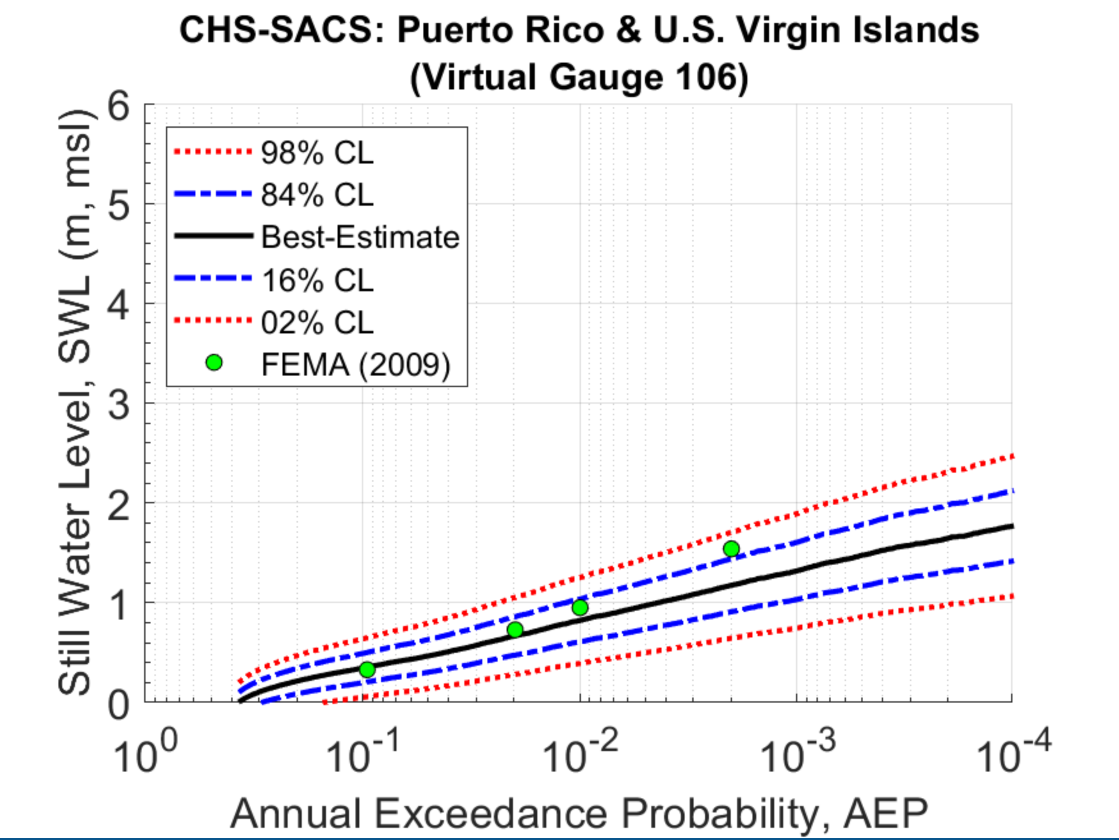
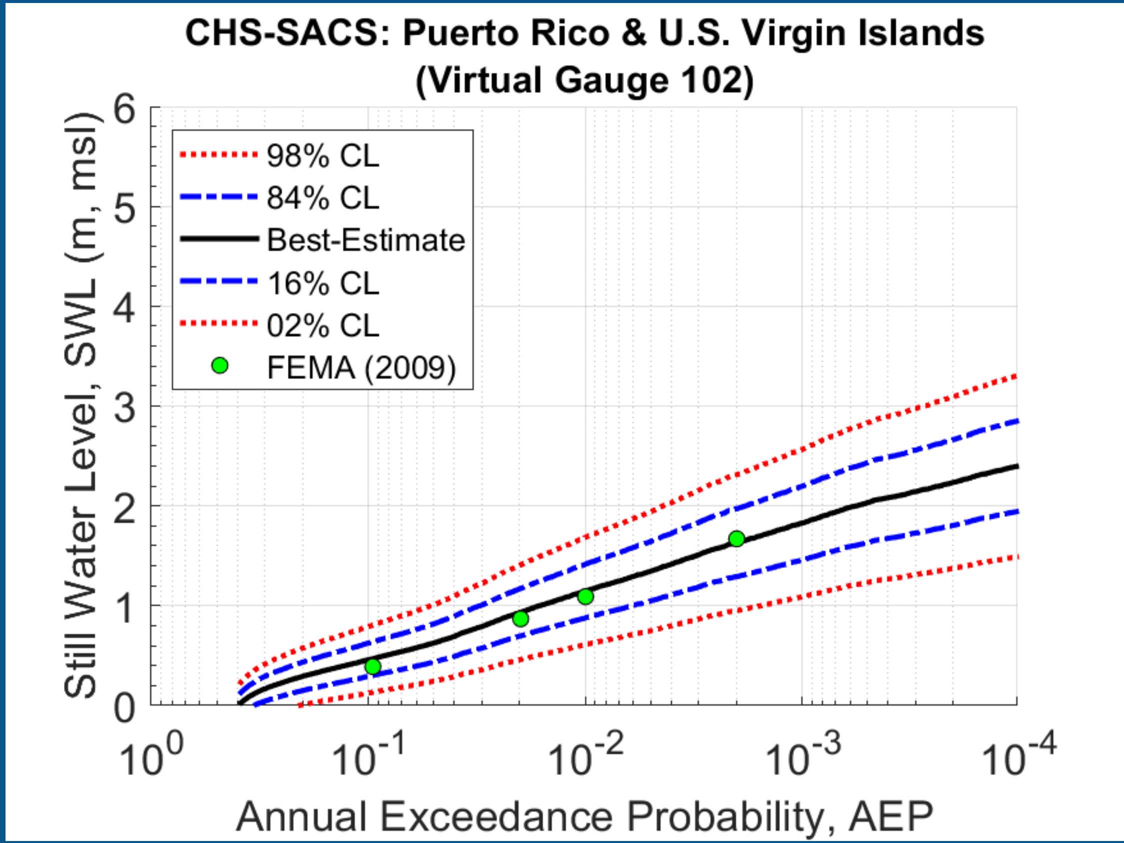
PCHA Example: SACS PR-USVI

Hazard Curve Integration





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USACE Coastal Flooding Hazard Studies

Comprehensive Studies

- North Atlantic Coast Comprehensive Study (NACCS)
- Coastal Texas Study (CTXS)
- South Atlantic Coastal Study (SACS)

Focus Studies

- Sabine to Galveston – Pre-construction, Engineering & Designs (PED)
- Coastal Texas – Galveston Bay Coastal Spine Feasibility Study
- New Jersey Back Bays Coastal Storm Risk Management (CSRM) Study
- Nassau County CSRM Study
- NY-NJ Harbor and Tributaries Feasibility Study

Data, Models, and Methods…

Data Partition (Intensity) → **Storm Recurrence Rate** → **Marginal Distribution Fitting of TC Parameters** → **Synthetic Storm Set with Computed Probability Mass** → **Hazard Curve Integration**

Hydrodynamic Modeling

Data Partition (Intensity)

- All Intensities
- High Intensity, Medium Intensity, Low Intensity

Storm Recurrence Rate

- UKF Mean, EKF Mean, GKF Mean, GKF Mean +/- SD
- UKF Mean, EKF Mean, GKF Mean

Marginal Distribution Fitting of TC Parameters

TC Parameter
- Central pressure, Cp
  - Gumbel
  - GDP
  - Weibull
- Translational speed, Ts
  - Normal
  - Lognormal
  - Gumbel
  - Weibull
- Heading direction, Hd
  - Normal
- Radius of maximum winds, Rmax
  - EBTRKS
    - Normal
    - Lognormal
    - Gumbel
    - Weibull
  - Statistical model
    - Lognormal

TC Parameter
- Central pressure, Cp
  - LTWD
  - DTWD
- Other Parameters same as “All”

Synthetic Storm Set with Computed Probability Mass

- Bayesian Quadrature, Response Surface, Stochastic Track Model, PCHA, Monte Carlo Simulation
- Bayesian Quadrature, Response Surface, Stochastic Track Model, PCHA, Monte Carlo Simulation

Hazard Curve Integration

- Gaussian redistribution, Error incorporation: Proportional, Constrained, Constant, Mean
- Gaussian redistribution, Error incorporation: Proportional, Constrained, Constant, Mean

Hydrodynamic Modeling

PBL
WAM
WAVEWATCH III
ADCIRC
SLOSH
STWAVE
SWAN

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Questions?

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