STORMSIM: MULTIVARIATE COASTAL HAZARD RESPONSE STOCHASTIC SIMULATION

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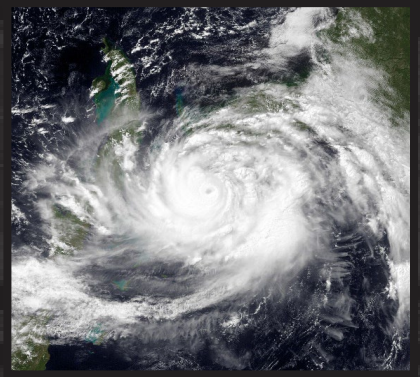

FSBPA
06 February 2025

STORMSIM

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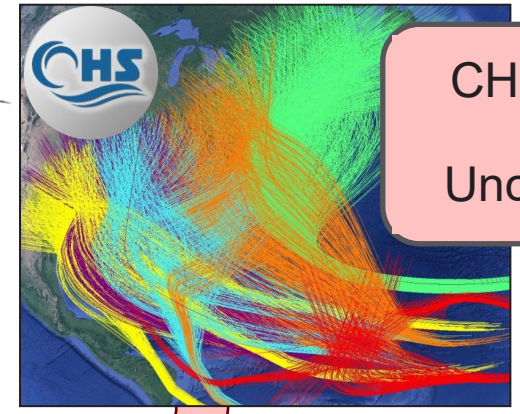
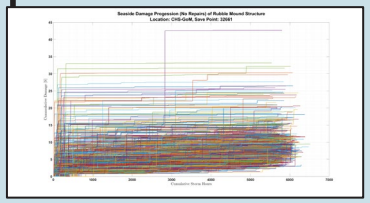
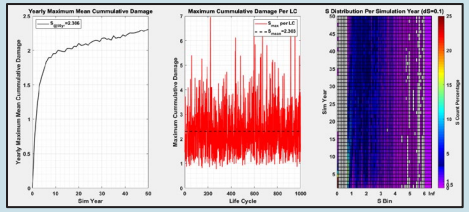
COASTAL STRUCTURES IN STORMSIM

CHS Storms and Uncertainties

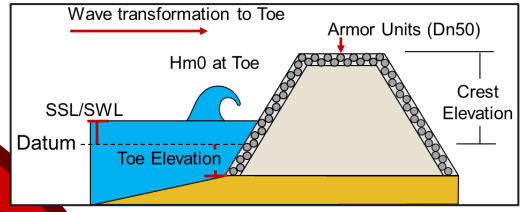


Probabilistic Responses





Define alternatives, scenarios, physics, limit states



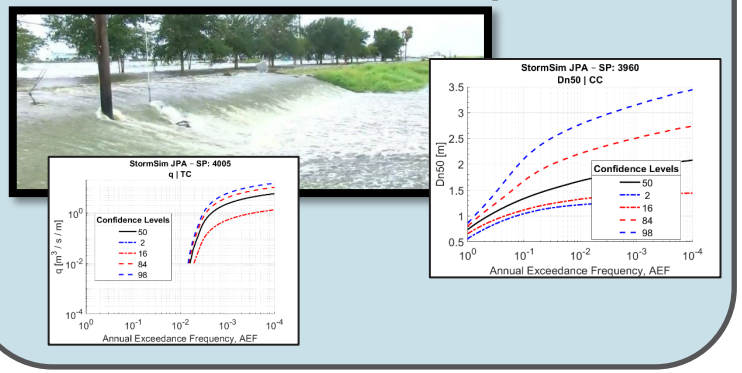
SS-JPM (Tropical Cyclones)

SS-PST (Extratropical Cyclones)

SS – PROS (design)

SS-LCS (performance)

Probabilistic Responses



UNCERTAINTIES

Unrepresented variations in hurricane structures / idealized winds.

Unrepresented variations in hurricane tracks.

Astronomical tide (if small [<10%] compared with surge heights).

Empirical Equation Coefficients from best fits

Skill of atmospheric / PBL model.

Unaccounted variability in Holland B.

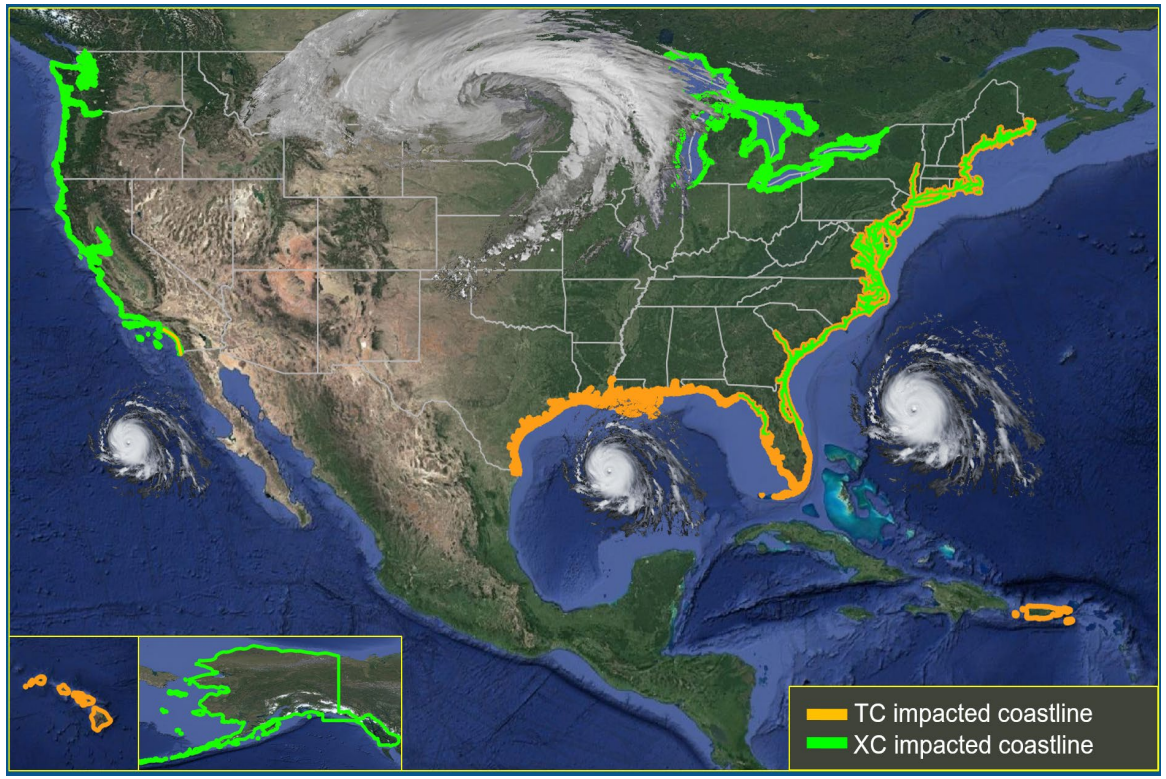
Skill of hydrodynamic model (e.g., ADCIRC).

Climate Change

Gonzalez et al. (2019)

QUANTIFYING COASTAL STORM HAZARDS

Type of probabilistic analysis is region-specific due to different dominant forcing

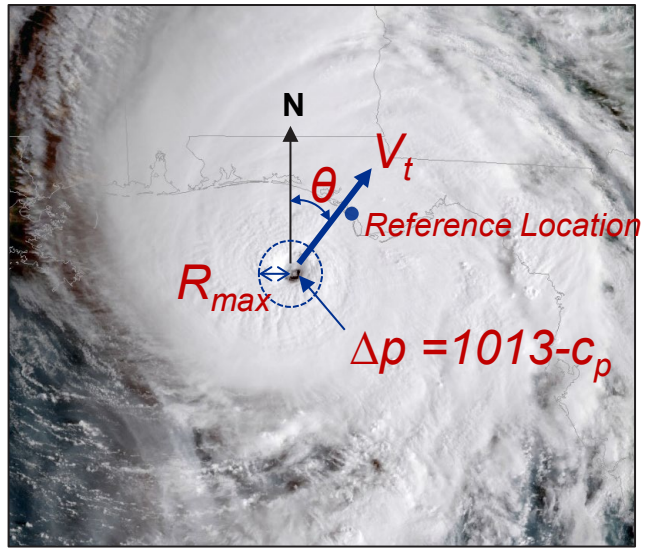


Extratropical Cyclones (XCs)- Extreme Value Analysis

- StormSim Probabilistic Simulation Technique (StormSim-PST)

Tropical Cyclones (TCs) - Joint Probability Method

- Application of synthetic TCs due to limited historical record



Δp = central pressure deficit

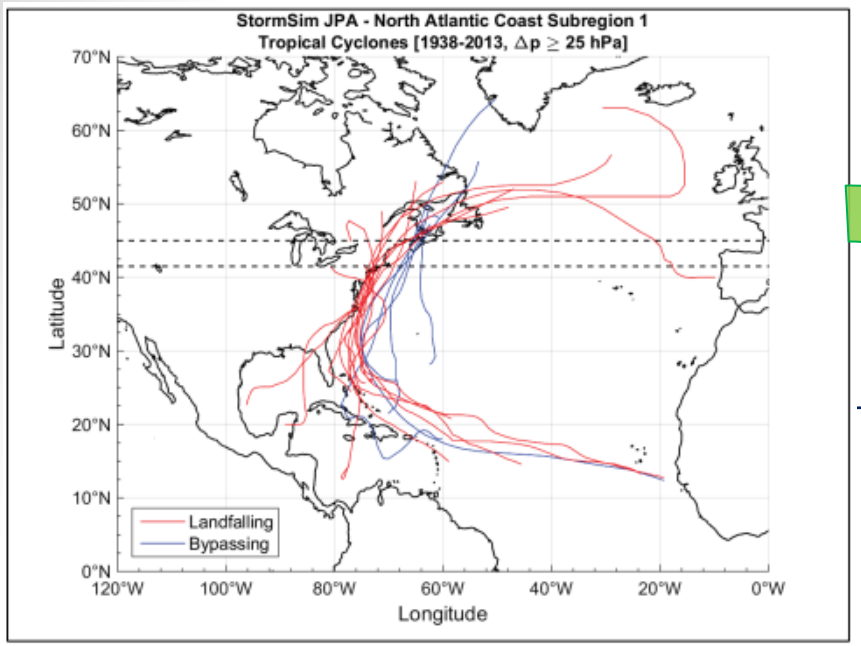
V_t = translational speed

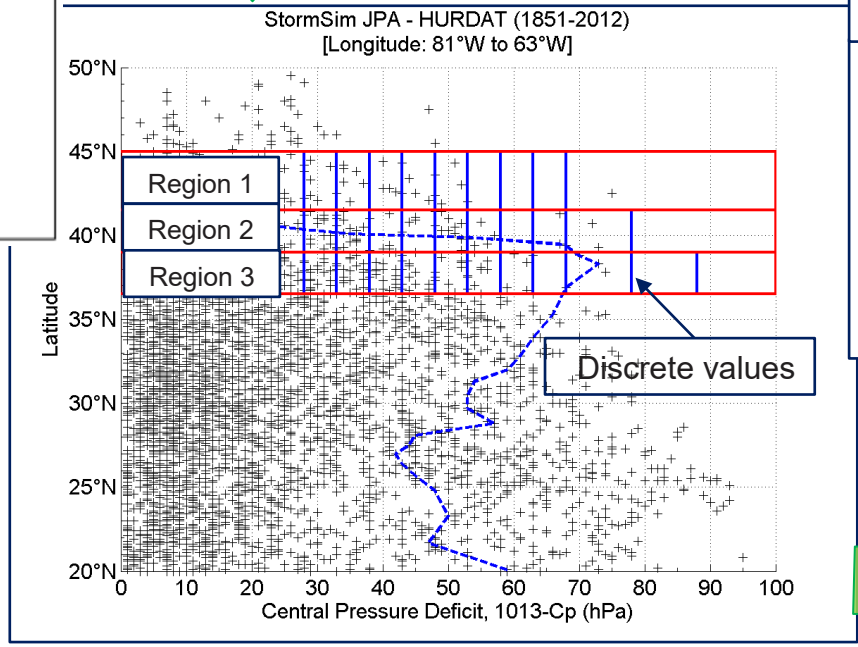
R_{max} = radius of maximum winds

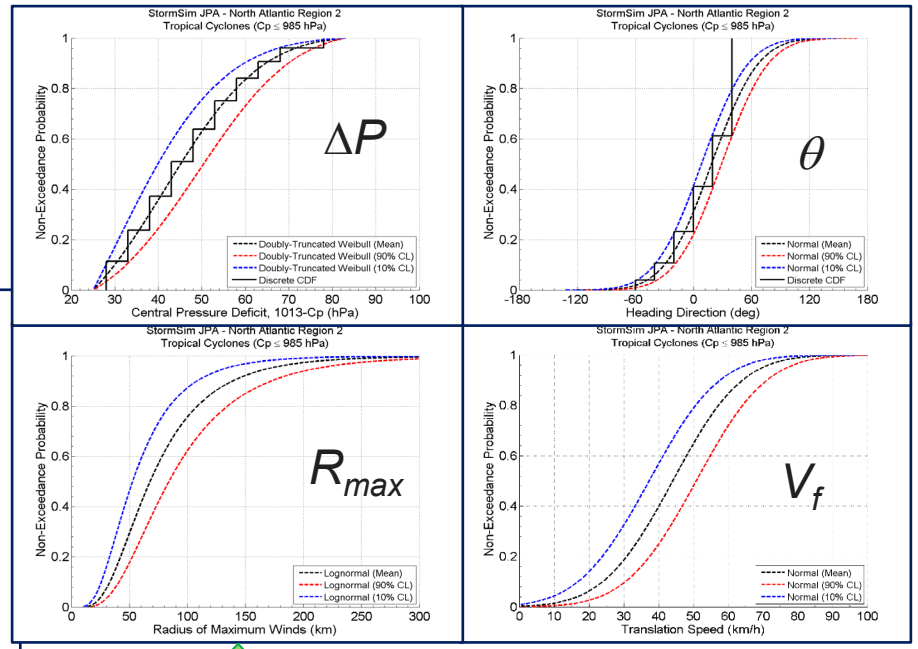
Θ = heading

Nadal-Caraballo et al. (2015)
Nadal-Caraballo et al. (2020)

HISTORICAL STORMS TO SYNTHETIC STORMS

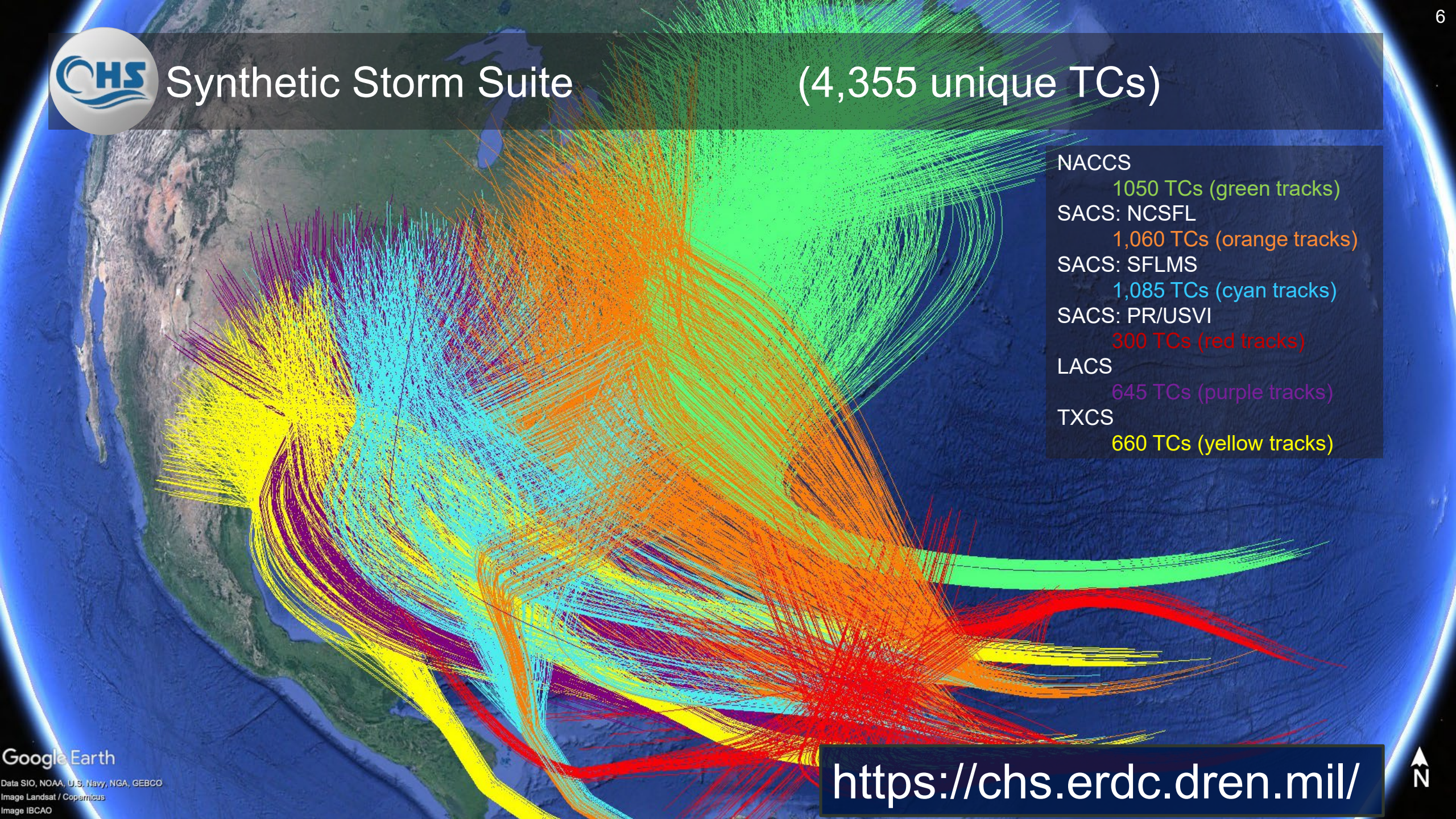






Nadal-Caraballo et al. (2015)
Nadal-Caraballo et al. (2020)

Synthetic Storm Suite (4,355 unique TCs)



COASTAL HAZARDS SYSTEM

Efficient Storm Sampling

Characterization of Storm Climate (Forcing)

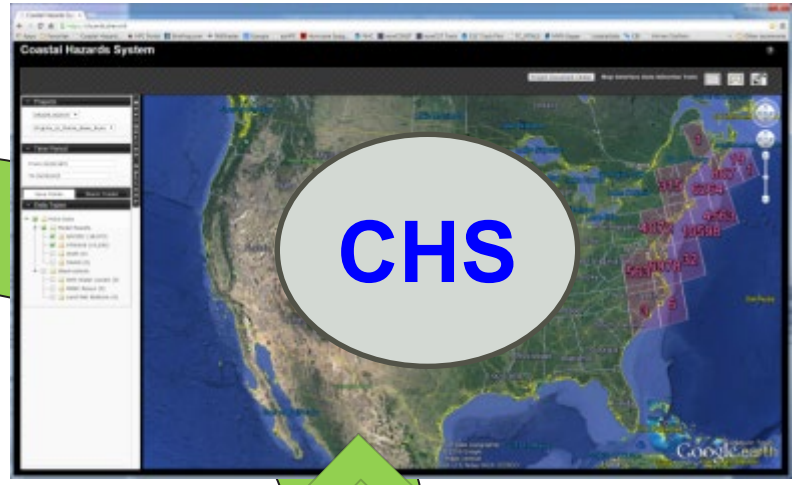
StormSim

Tropical Cyclones (Synthetic)

Extratropical Cyclones (Historical)

Development of JPM Storm Set

Development of Composite Storm Set



Climate and Hydro Modeling

PBL Cyclone Model (Wind and Pressure Fields)

WAM (Regional)

ADCIRC

Coupler

STWAVE (Nearshore)

- Water level (storm surge, astronomical tide, SLC)
- Wind speed, direction, currents
- Wave height, period, direction

CSTORM

Response Statistics

Combined Joint Probability

Annual Exceedance Probability
Average Recurrence Interval
Confidence Levels

StormSim

JOINT PROBABILITY METHOD (JPM)

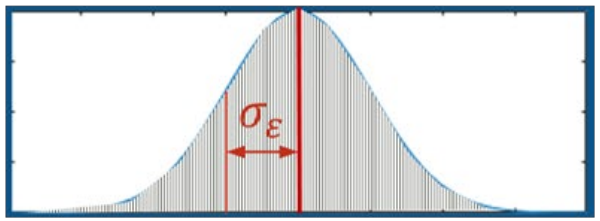
Storm response hazard

Storm | Storm Response | Uncertainty

$WL_{n,i} = WL_n + \sigma_\epsilon Z_i$

TC 1 — DSW_1 — WL_1

TC n — DSW_1 — WL_n



Discretize distribution "*I*" times

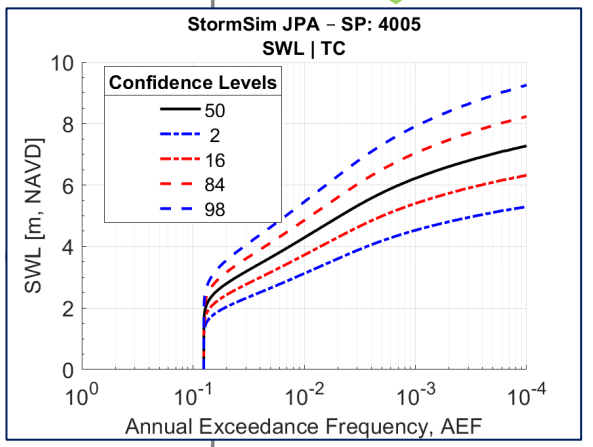
Replicate water level "*I*" times

Adjust Discrete Storm Weights (DSWs)

$\hat{\lambda}_{n_i} = \frac{\lambda_n}{I}$

$WL_{1,1}$ … $WL_{1,i}$

$WL_{n,1}$ … $WL_{n,i}$



Storm is randomly sampled, uncertainty is added to waves and water levels

Integrate hazard using discrete storm weights

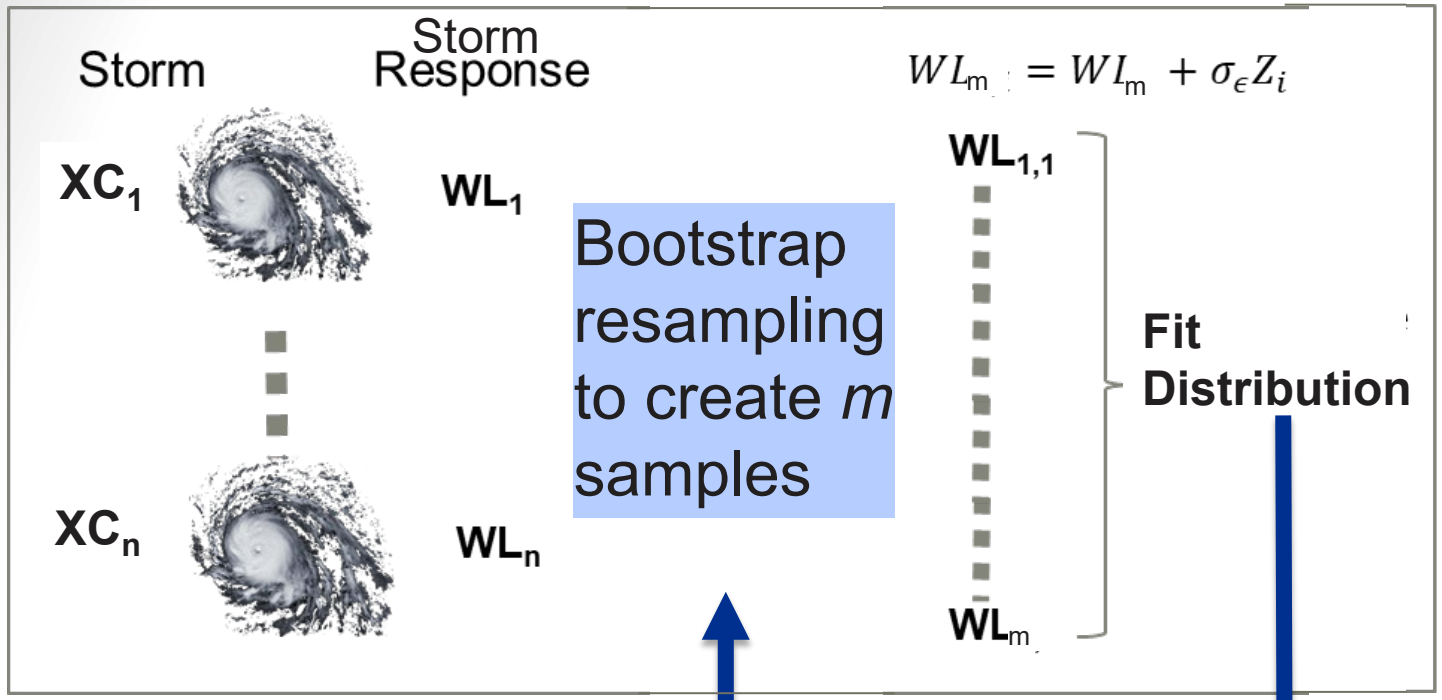
Mean Hazard Curve : $\lambda_{r(\hat{x})>r} \approx \sum_i^n \lambda_i \, P[\{(r(\hat{x}) * \sigma_{int}) \leq \sigma_c\} > r | \hat{x}, \sigma]$

Confidence Limit : CL = $\lambda_{r(\hat{x})>r}$ +(z-score)*$\left(\lambda_{r(\hat{x})>r} \leq \sigma_c\right) * \sigma_{CL}$

Nadal-Caraballo et al. (2015)

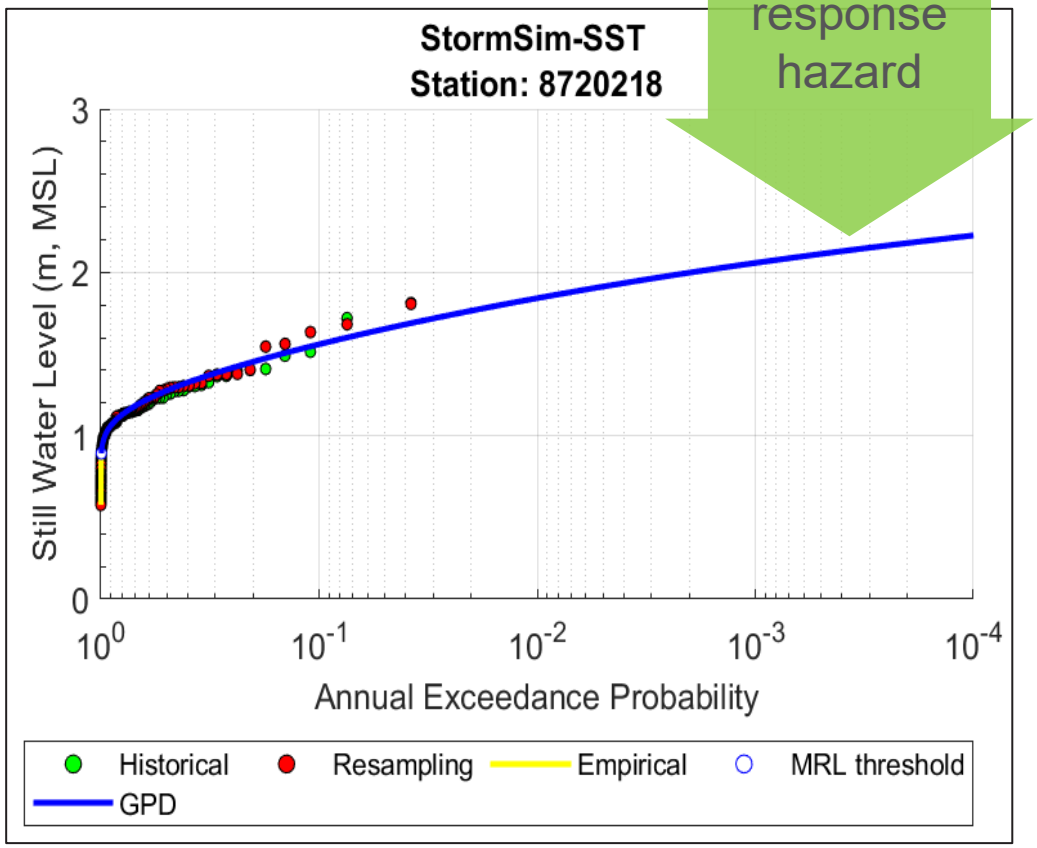
Nadal-Caraballo et al. (2020)

PROBABILISTIC SIMULATION TECHNIQUE (PST)



Storm is sampled using bootstrap resampling, uncertainty is added to waves and water levels

Storm response hazard



Low frequency: Generalized Pareto Distribution (GPD)

High frequency: Empirical distribution

Nadal-Caraballo et al. (2015)

Nadal-Caraballo et al. (2020)

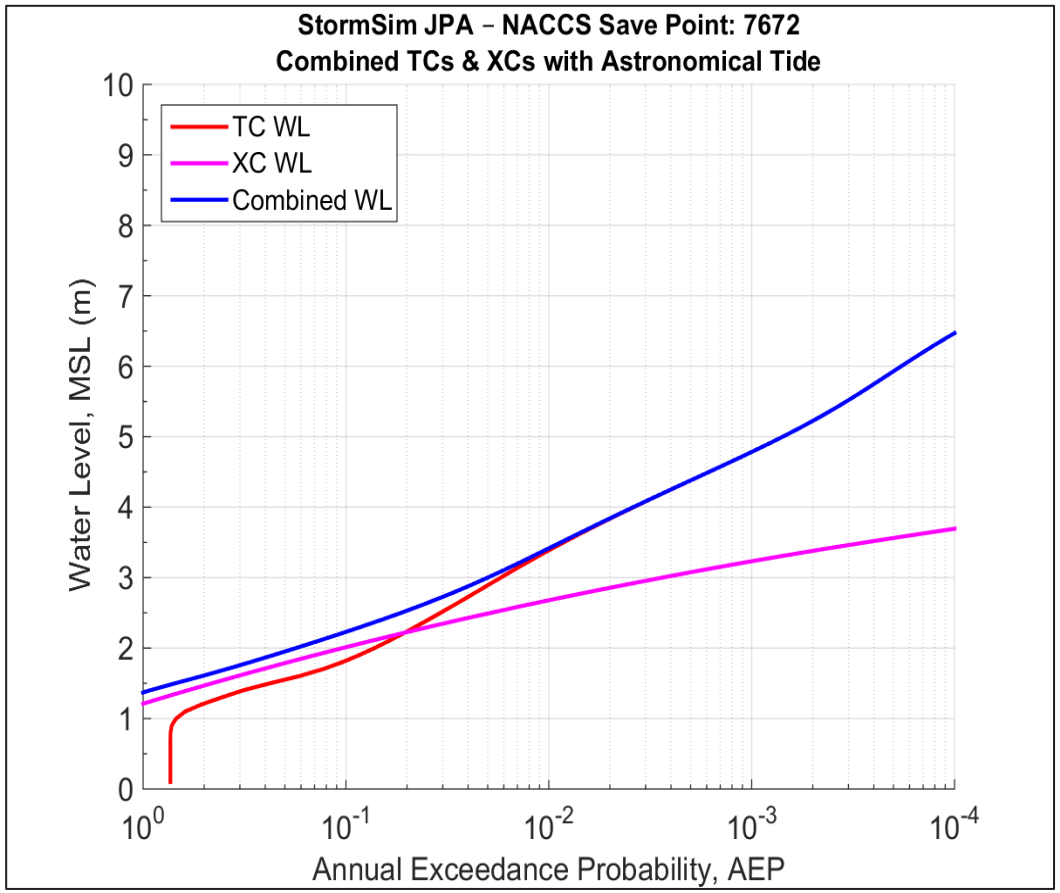
COMBINED JOINT PROBABILITY

Characterization of Storm Climate

High- vs. Low-Frequency Populations

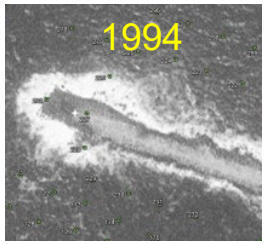
- **Extra-tropical Cyclones (XC)**
  - Annual exceedance probability, AEP ≈ 50% to 2%
  - Average recurrence interval, ARI ≈ 2 to 50 years
- **Tropical Cyclones (TC)**
  - Annual exceedance probability, AEP ≈ 1% to 0.1%
  - Average recurrence interval,
    ARI ≈ 10 to 1000 years (regulatory)
- **Combined Cyclones (CC)**

$$P(CC) = P(TC) + P(XC)$$



Nadal-Caraballo et al. (2015)
Nadal-Caraballo et al. (2020)

COASTAL STRUCTURE RESPONSES



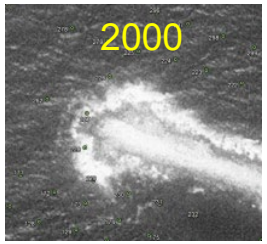
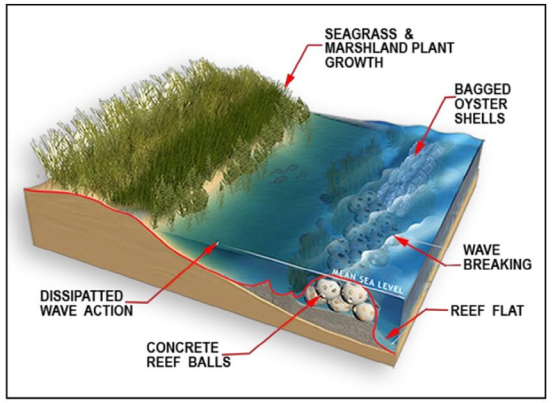


Figure 1. Examples of Coastal Natural and Nature-Based Features



Source: U.S. Army Corps of Engineers, Engineering With Nature, "Natural and Nature-Based Features," at https://ewn.el.erdc.dren.mil/nnbf.html.

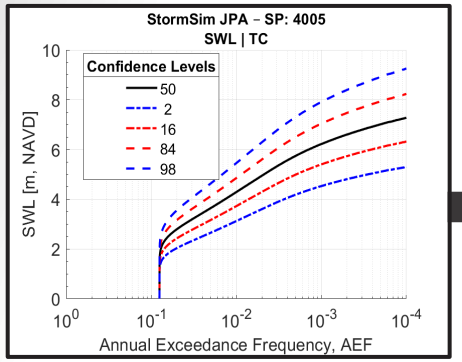
SOME STORMSIM APPLICATIONS

- Poplar, James, Barren DDI
- Neah Bay Breakwater
- Point Judith Breakwater
- Azores Breakwater
- FEMA FIS revision - TX
- FEMA Region V FIS
- S2G Feasibility (2012)
- TX local studies (2012)
- Bayou Caddy, MS
- Navy Task Force EVA
- NACCS
- Herbert Hoover Dike
- NRC Uncertainty
- Coastal Texas Comprehensive Study (2017)
- Coos Bay Jetty
- Dauphin Island Barrier Island Response
- Dyke Marsh
- Turbo Columbia Breakwater
- NASA Wallops Island
- Sabine to Galveston PED
- CTXCS Spine Morphology
- Louisiana Master Plan 2023
- Louisiana Levee Recertification
- Louisiana Watershed Initiative
- FEMA MS reanalysis
- SACS
- NJ Back Bay Study
- Okaloosa PCLA
- FEMA FIS revision - St Tammany Parish
- Mid-Bay DDI
- The Battery PCLA
- Duluth Harbor Pier
- Rhode Island CSRM
- FEMA FIS revision - MS
- FEMA RiskMap 2.0
- Lake Erie Seiche Study
- DC Metro Coastal Study
- Compound Flooding Study
- NRC Pilot Study

- **Levees**
- **Breakwaters**
- **Dunes**
- **Floodwalls**
- **NNBF**

FREQUENCY-BASED VS RESPONSE-BASED

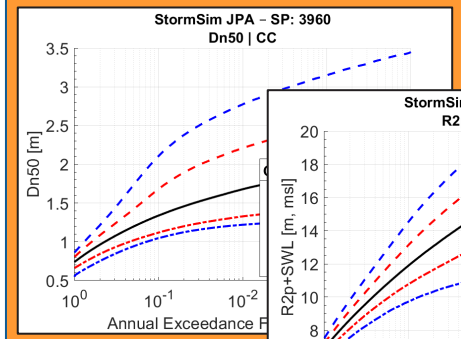
Frequency-based

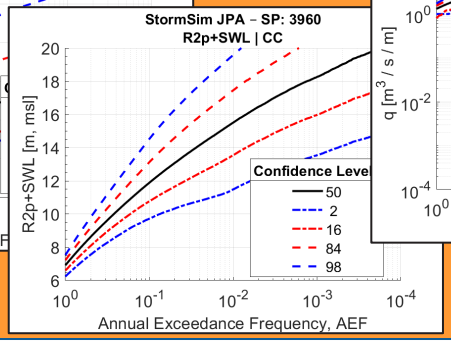


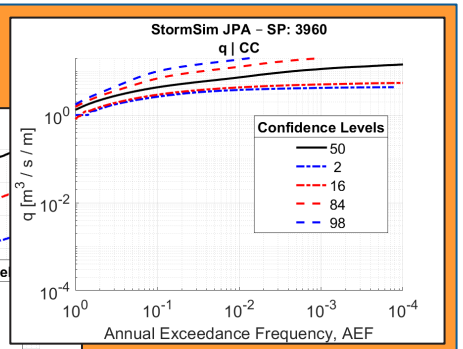
Structure response for given AEP

Response-based

All storms

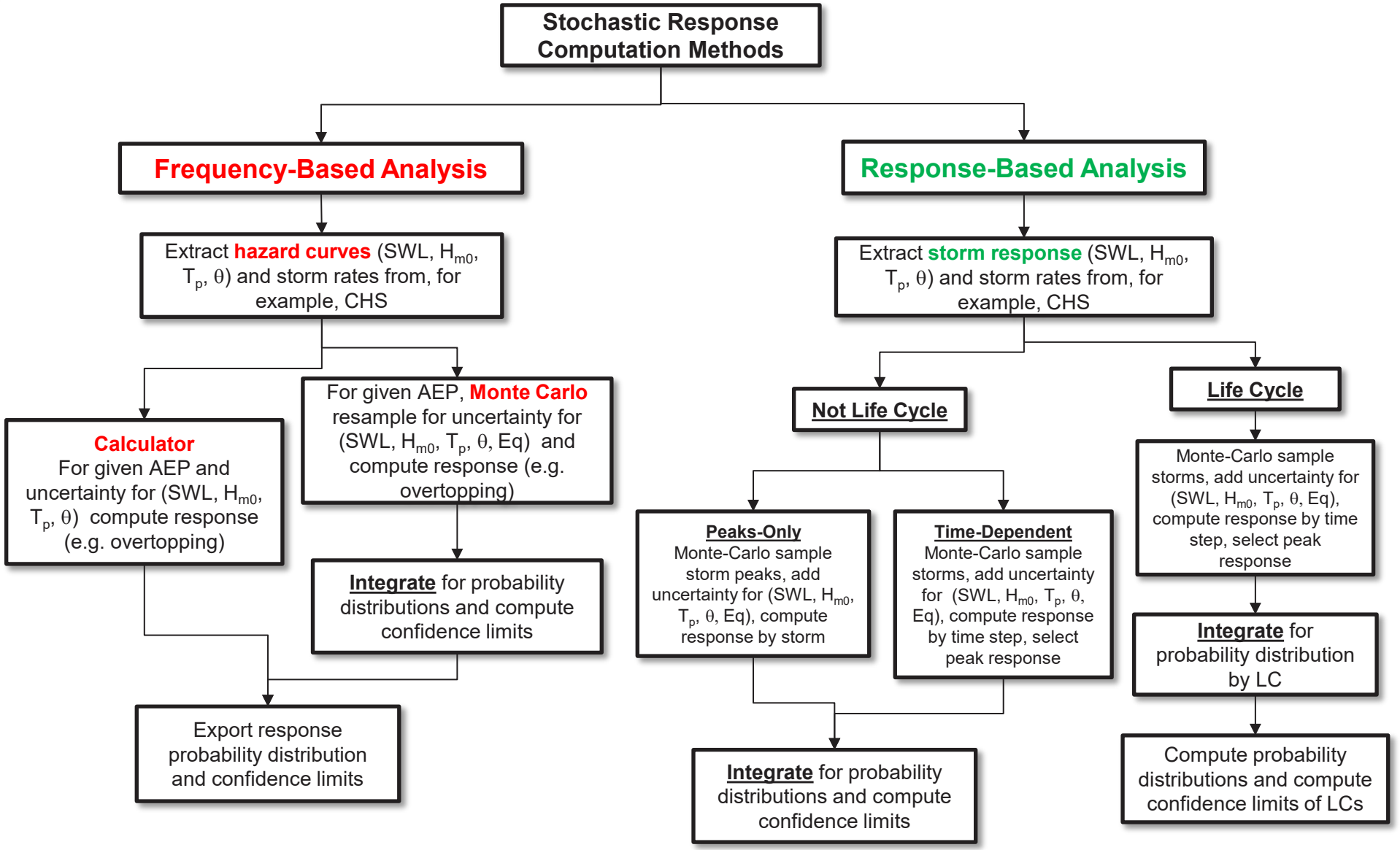






Note: Structure response probability is not equal to the storm response probabilities

Melby et al. (2021)
Stehno (2021)


Stochastic Response Computation Methods
Frequency-Based Analysis
Extract hazard curves (SWL, H_{m0}, T_p, θ) and storm rates from, for example, CHS
Calculator
For given AEP and uncertainty for (SWL, H_{m0}, T_p, θ) compute response (e.g. overtopping)
For given AEP, Monte Carlo resample for uncertainty for (SWL, H_{m0}, T_p, θ, Eq) and compute response (e.g. overtopping)
Integrate for probability distributions and compute confidence limits
Export response probability distribution and confidence limits
Response-Based Analysis
Extract storm response (SWL, H_{m0}, T_p, θ) and storm rates from, for example, CHS
Not Life Cycle
Peaks-Only
Monte-Carlo sample storm peaks, add uncertainty for (SWL, H_{m0}, T_p, θ, Eq), compute response by storm
Time-Dependent
Monte-Carlo sample storms, add uncertainty for (SWL, H_{m0}, T_p, θ, Eq), compute response by time step, select peak response
Integrate for probability distributions and compute confidence limits
Life Cycle
Monte-Carlo sample storms, add uncertainty for (SWL, H_{m0}, T_p, θ, Eq), compute response by time step, select peak response
Integrate for probability distribution by LC
Compute probability distributions and compute confidence limits of LCs

PROBABILISTIC RESPONSE OF STRUCTURES (PROS)

Storm

Storm Response

Uncertainty

S_1

WL_1

S_n

WL_n

JPM

σ_ε

Bootstrap resampling to create *m* samples

PST

Structure Response

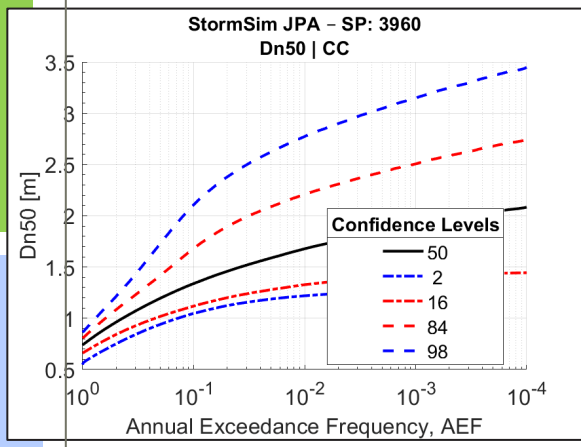
Integrate Hazard Curve

JPM

Fit Distribution

PST

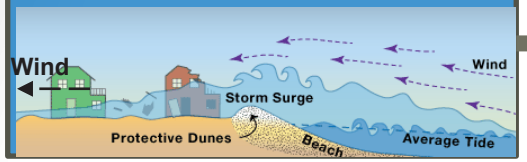
Structure response hazard



Melby et al. (2021)
Stehno (2021)

LIFE-CYCLE SIMULATION (LCS)

Storm forces



Project feature response

Consequence receptor response

Management actions

Sum annual damages and costs

Life-Cycle 1

Year 1: Storm 1 … Storm *n*

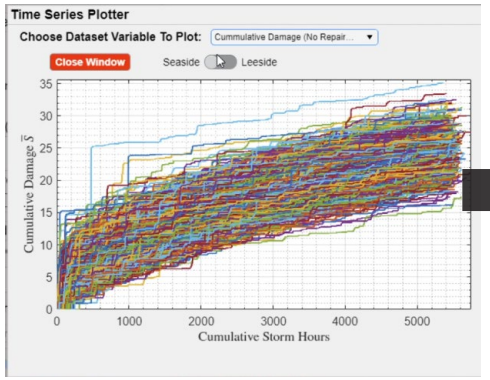
Year 2: Storm 1

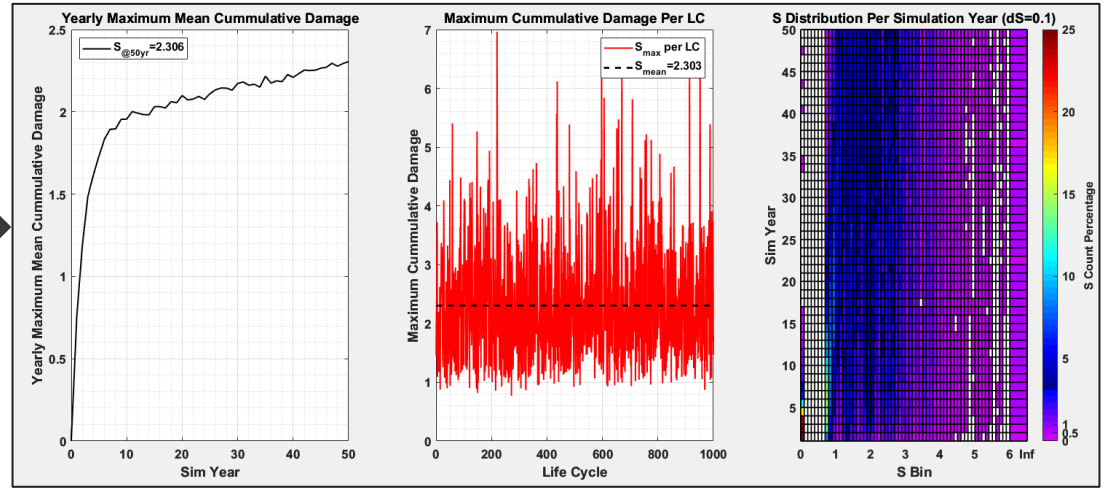
…

Year 50: Storm 1 … Storm *n*

L-C 2 … L-C 957

Expected annual damages





Melby et al. (2011)
Melby et al. (2021)

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THANK YOU

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