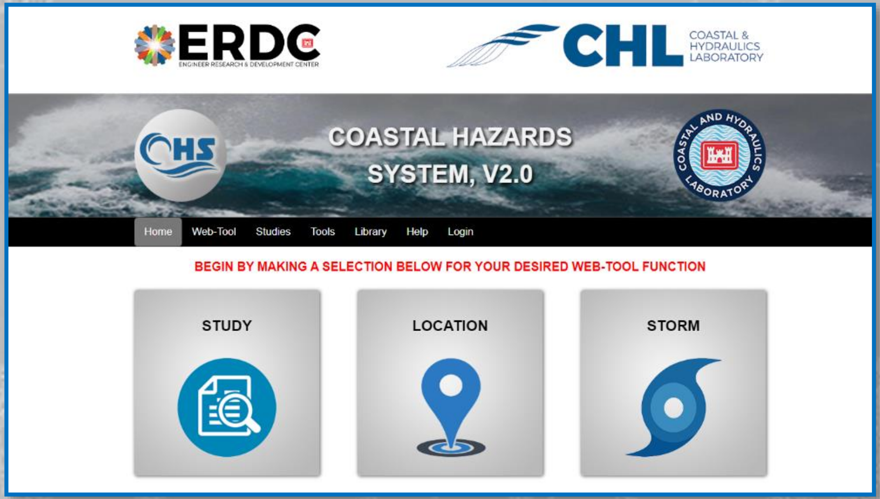
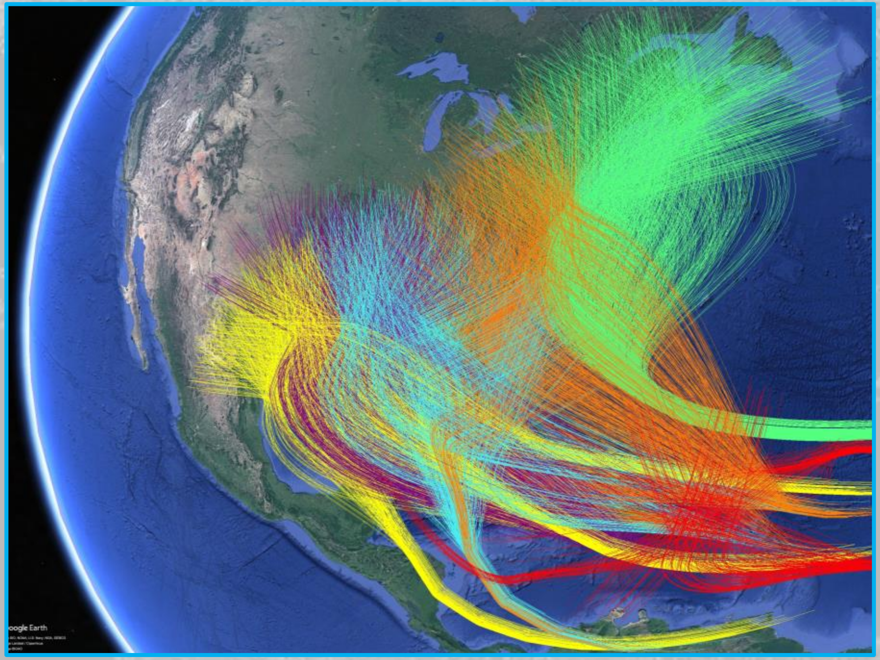
COASTAL HAZARDS SYSTEM –
AN EXPANDABLE AND ADAPTABLE FRAMEWORK FOR COASTAL RISK AND CLIMATE RESILIENCE APPLICATIONS



Norberto C. Nadal-Caraballo, PhD
Senior Research Engineer / Coastal Hazards Group (CHG) Lead

Madison C. Yawn
Research Physical Scientist / CHG Co-Lead

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory

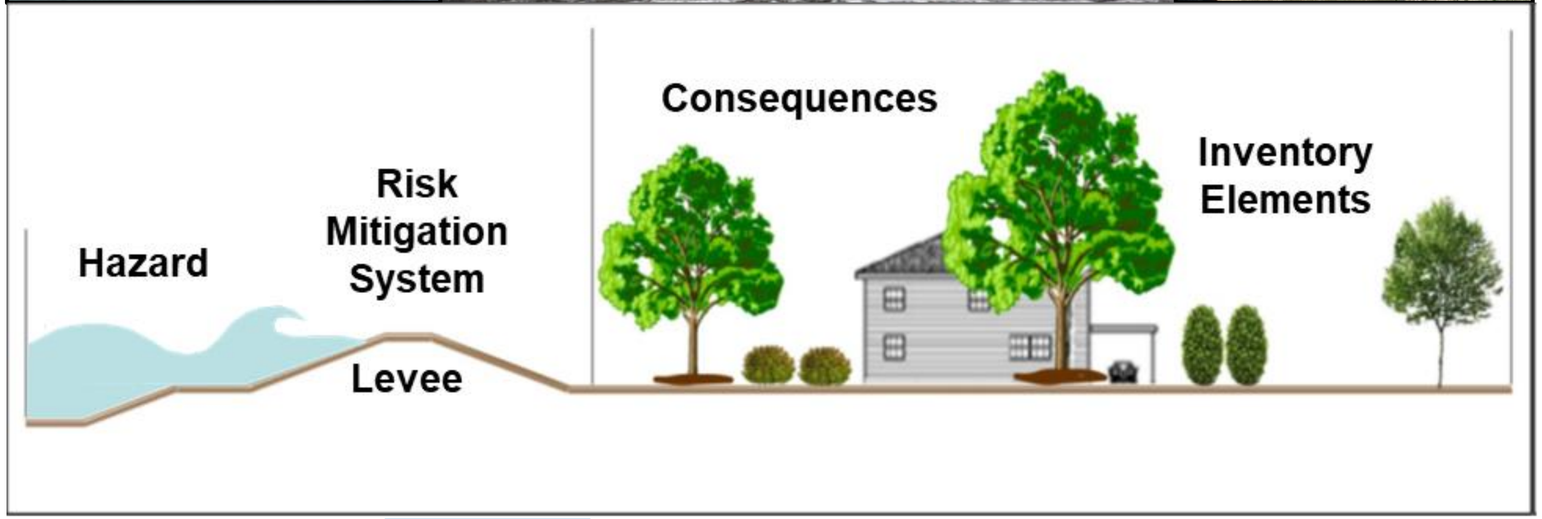


U.S. ARMY
US Army Corps of Engineers ®
ERDC ENGINEER RESEARCH & DEVELOPMENT CENTER
CHL COASTAL & HYDRAULICS LABORATORY
CHS

NEED FOR COASTAL HAZARDS INFORMATION

Commitment to Coastal Resilience

- Federal agencies have missions supporting coastal resiliency (i.e., mitigating, responding to, and protecting against coastal hazards)
- Supporting coastal resiliency includes activities such as:
  - Planning
  - Engineering design (gray and green)
  - Emergency management
  - Risk assessment
  - Flood mapping
- These activities need accurate information describing the magnitude and frequency of coastal hazards
  - Ex: storm surge, waves, rainfall
  - Future climate scenarios
- Information is provided through the Coastal Hazards System (CHS)



Risk = Hazard × Exposure × Vulnerability

Hazard = Magnitude × Frequency

Coastal Hazards System (CHS)

What is the CHS?

A national-scale, multi-agency initiative for accurate, efficient, and consistent quantification of coastal storm hazards along U.S. coastlines and other strategic locations critical to our national security.

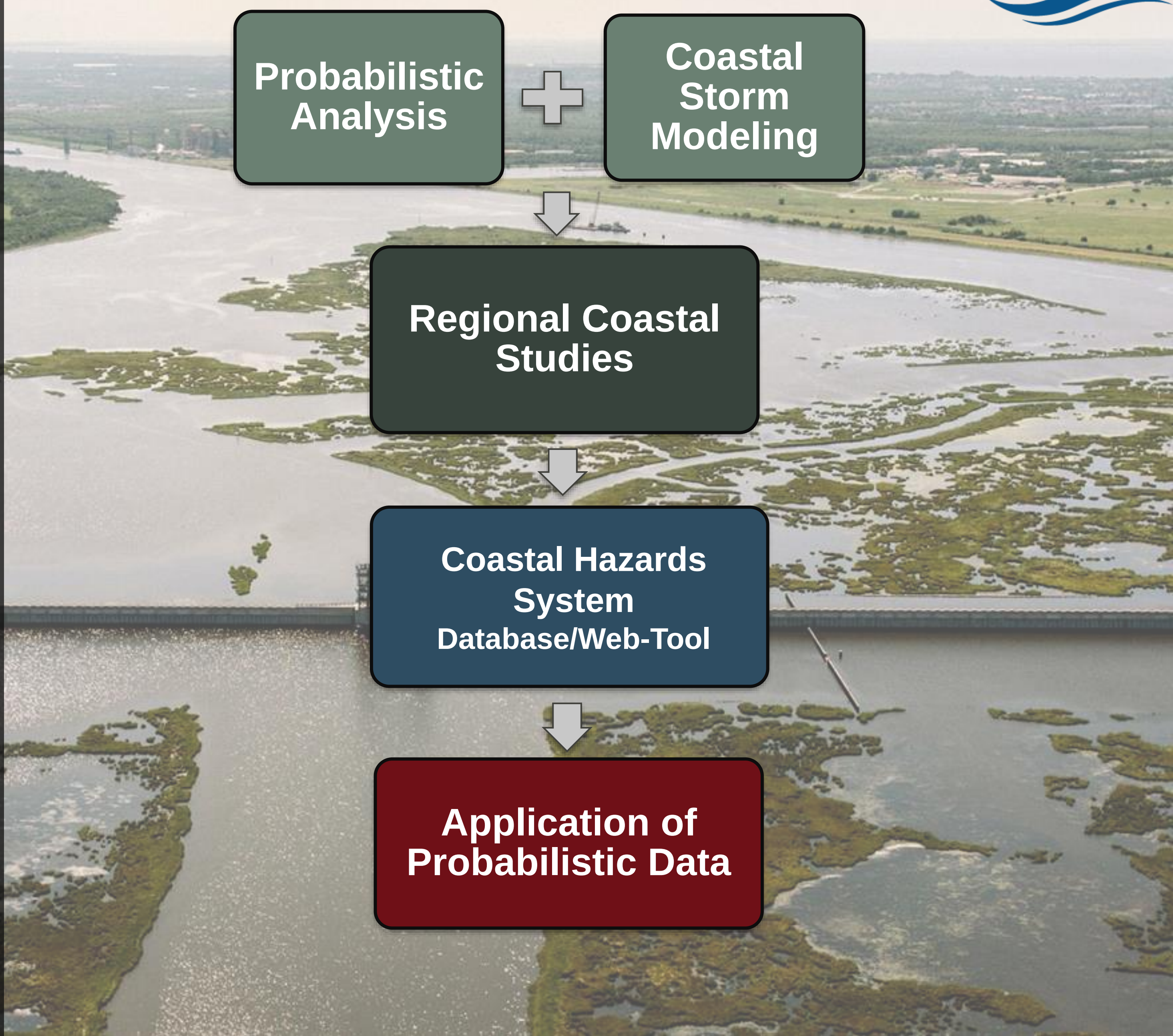
Goal:

Provide high-fidelity, high-resolution state-of-the-art hydrodynamic and probabilistic modeling and companion tools in a multivariate statistical context for coastal planning, engineering, and operations and maintenance.

Impact to the Nation:

Methods, data, and tools within the CHS serve as the basis for coastal engineering by providing high-fidelity, probabilistic coastal hazards on a national scale.

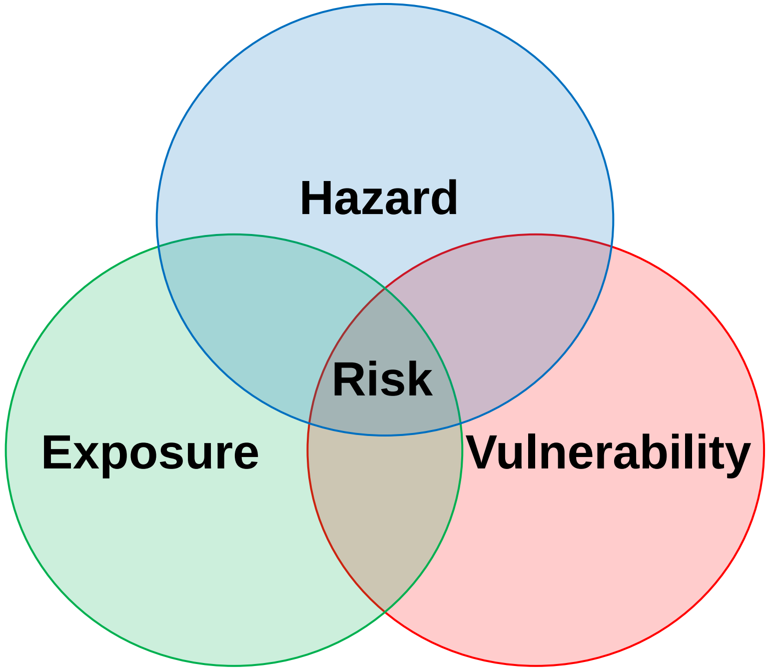
https://chs.erdc.dren.mil



REGIONAL COASTAL HAZARDS

Risk = Hazard × Exposure × Vulnerability

Hazard = Magnitude × Frequency



Primary Hazards

- Storm surge
- Still water level (SWL = surge + tide)
- Sea-level rise (future SWL)
- Wave height, period, direction
- Swell and infragravity (IG) waves
- Currents (water velocity)
- Maximum wind speed

Secondary Hazards

Derived from primary or compound hazards

- Wave runup and overtopping
- Storm surge overflow
- Forces/loading on structures
- Shear stress (levees)
- Sediment transport
- Beach erosion

Compound Hazards

- Rainfall
- Riverine discharge

HOW DO WE QUANTIFY COASTAL HAZARDS?

Approach

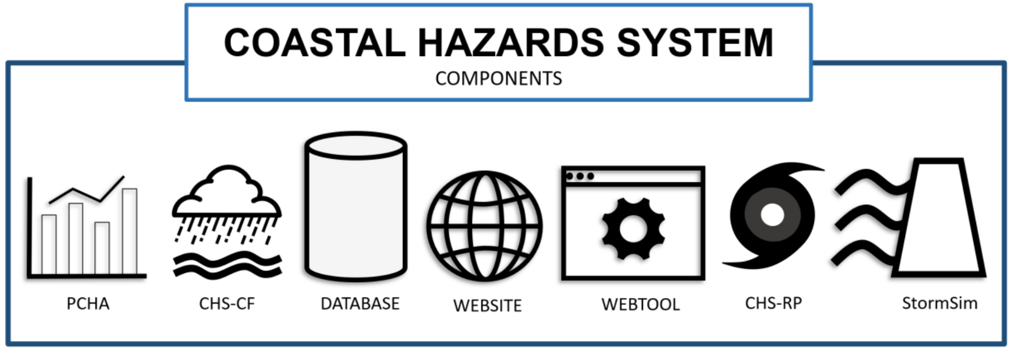
- Conduct comprehensive studies to quantify coastal hazards on a regional scale
  - USACE and FEMA
- Coastal Hazards System (CHS)
  - Publicly available results from coastal studies

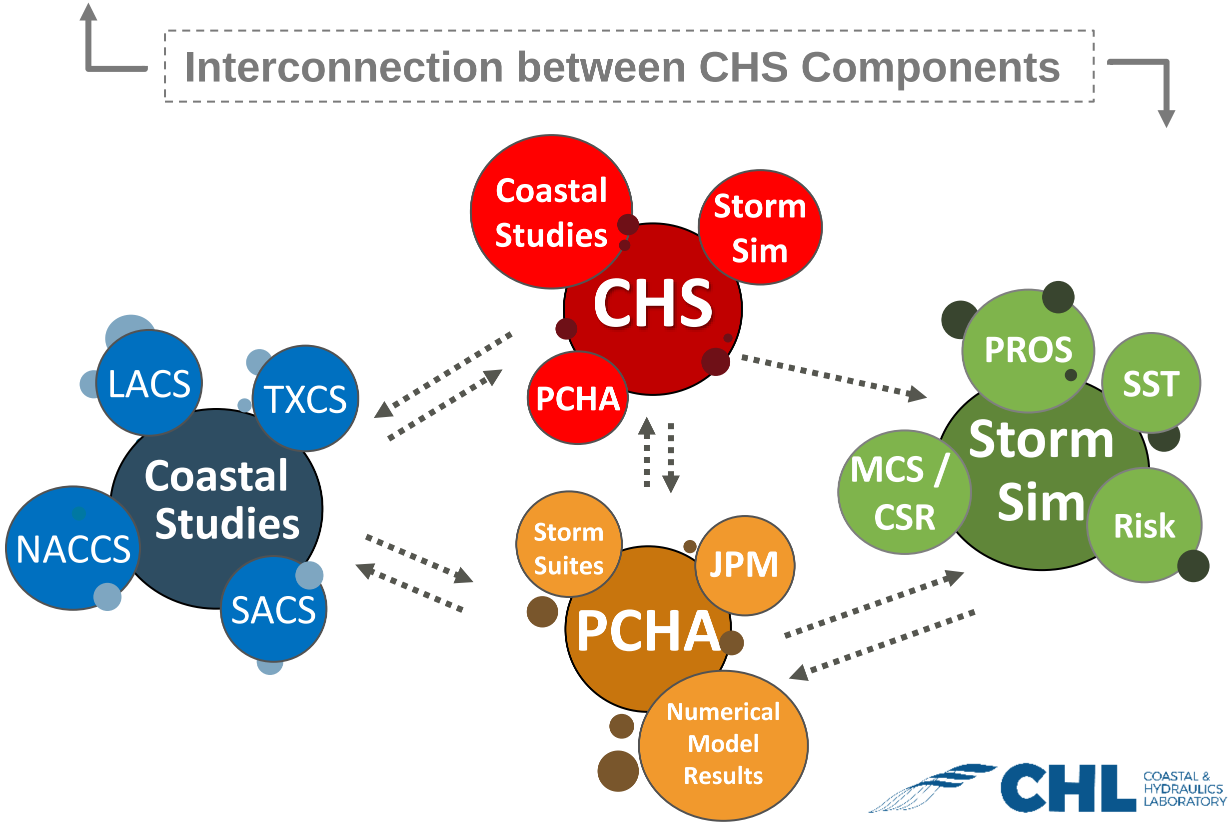
Methodology

- Probabilistic Coastal Hazard Analysis (PCHA) is a statistical and machine learning framework supporting CHS
- Goal: fully cover parameter and probability spaces

Benefit

- Hazard curves describing the full probability space of storm responses, with uncertainty estimates
- Direct input of results to support risk assessments, engineering, reliability, downstream modeling, etc.



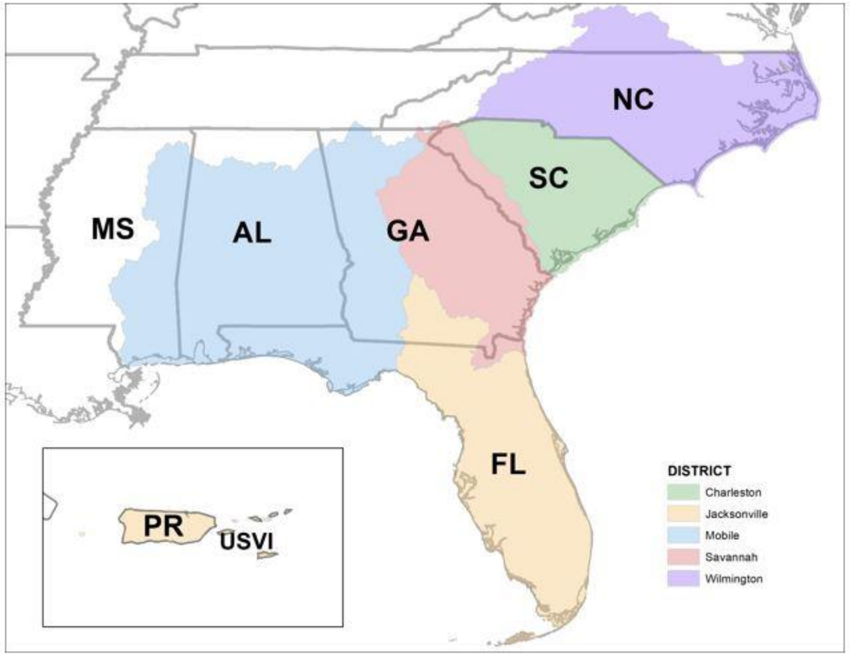


SOUTH ATLANTIC COASTAL STUDY (SACS)

- Water Resources Development Act of 2016 (WRDA 2016) – Section 1204: South Atlantic Coastal Study (SACS)
- Authorizes Secretary of the Army to conduct a comprehensive coastal study within the geographic boundaries of the South Atlantic Division (SAD) to
  1. identify risks and vulnerabilities due to increased hurricane and storm damage as a result of sea level rise;
  2. recommend measures to address the vulnerabilities;
  3. develop a long-term strategy
     - address increased storm damages from rising sea levels
     - identify opportunities to enhance resiliency and increase sustainability in high-risk areas
- Coastal Area of Responsibility (AOR): from the coast to the extent of the tidal influence.

The geographic extent included the three distinct coastal regions within SAD's AOR:

- **Atlantic Coast** – North Carolina to SE Florida
- **Gulf Coast** – SW Florida to Mississippi
- **Caribbean** – Puerto Rico and U.S. Virgin Islands

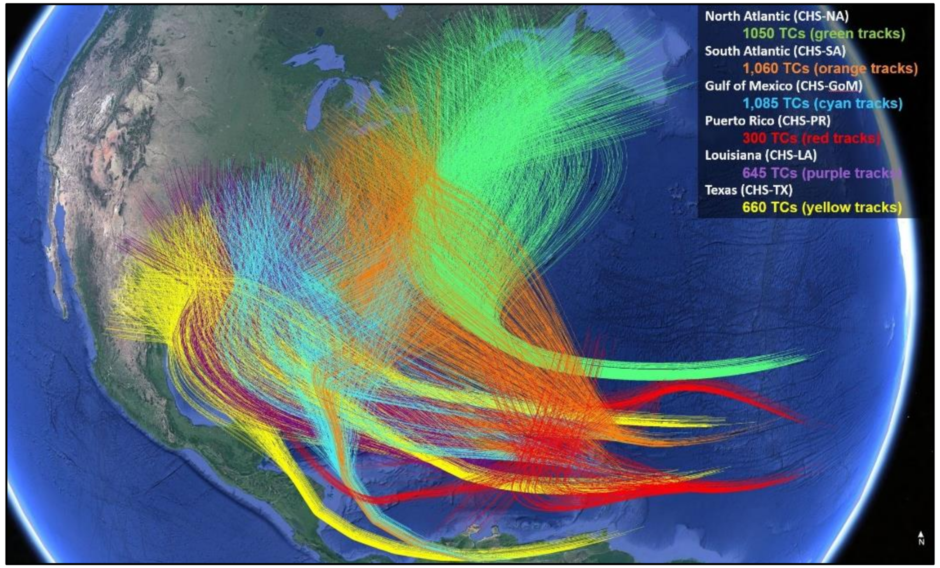


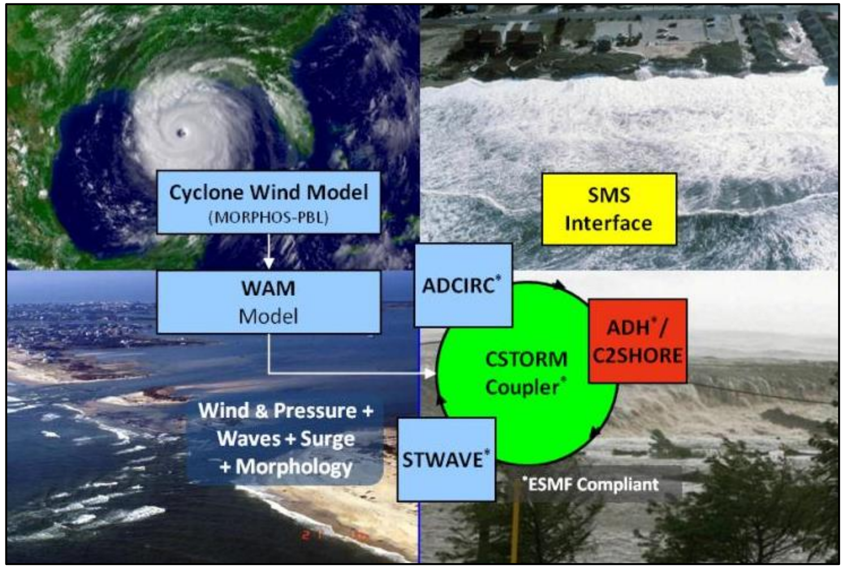
South Atlantic Coastal Study (SACS) Map
(Study extends from the coast inland to the extent of tidal influence)

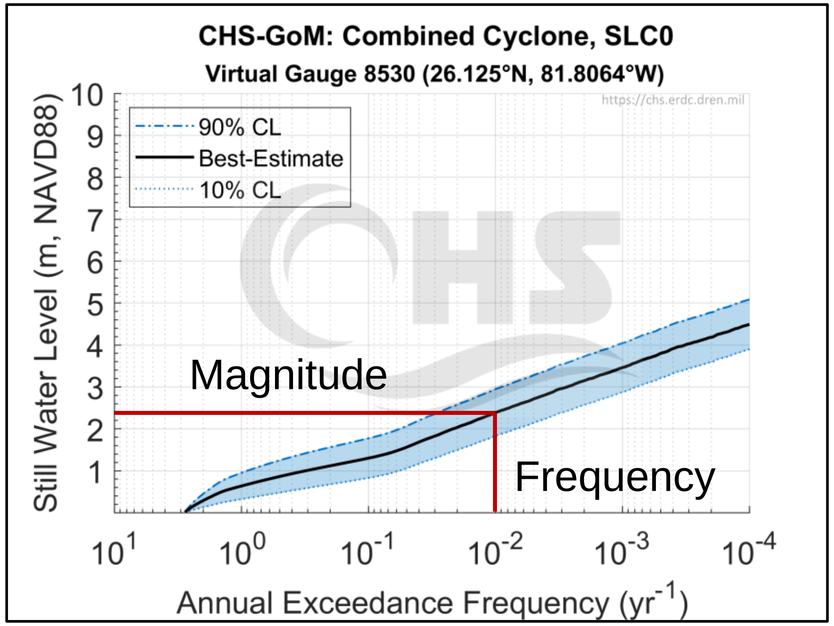
COASTAL HAZARD STUDY WORKFLOW

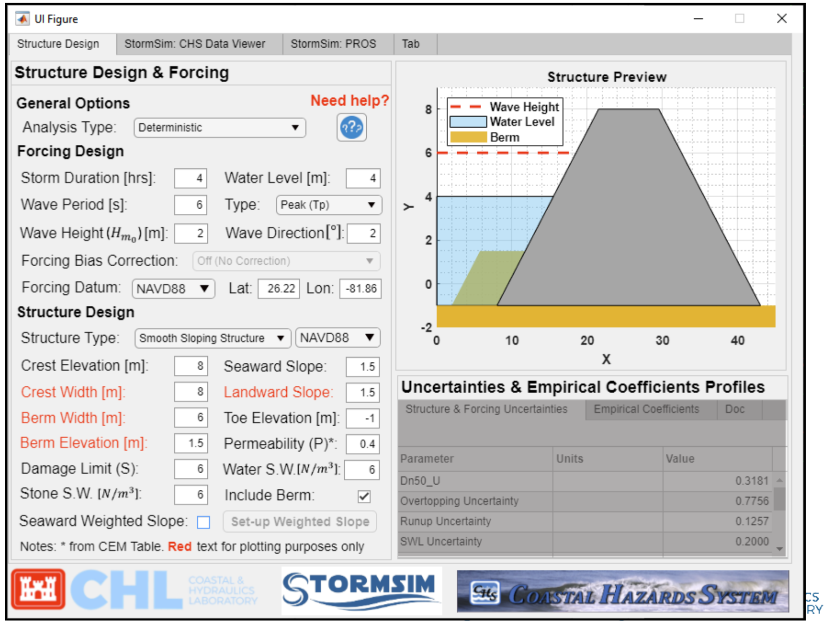
Study Workflow:

- Historical Data
- Storm Suite Development
- Numerical Modeling
- Hazard Analysis
- Data Application





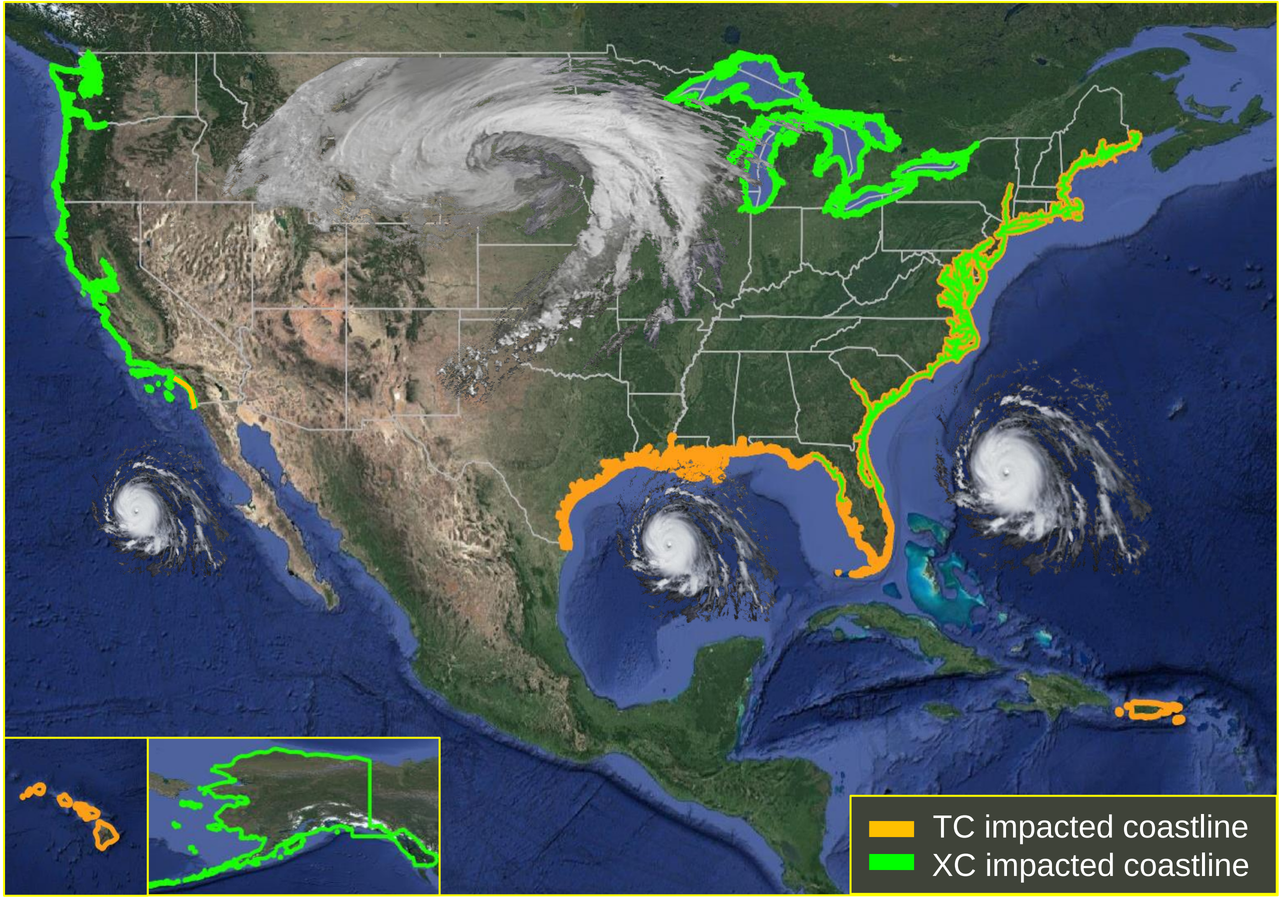




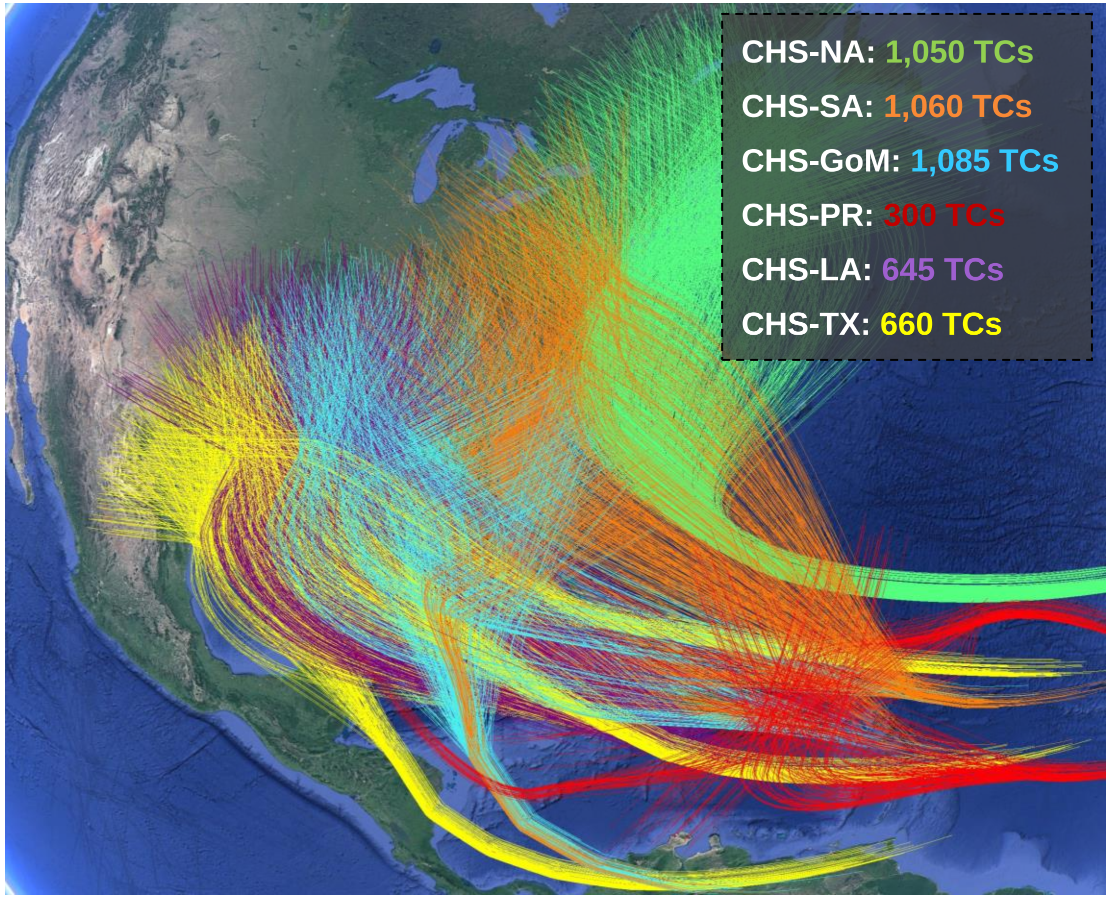
ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

REGIONAL COASTAL HAZARDS

Hazard Magnitude & Frequency ⇒ Dominant Coastal Storm Forcing



Tropical cyclone (TC) and extratropical cyclone (XC) forcing by US coastal region



CHS synthetic TC suites

HOW DO WE QUANTIFY COASTAL HAZARDS?

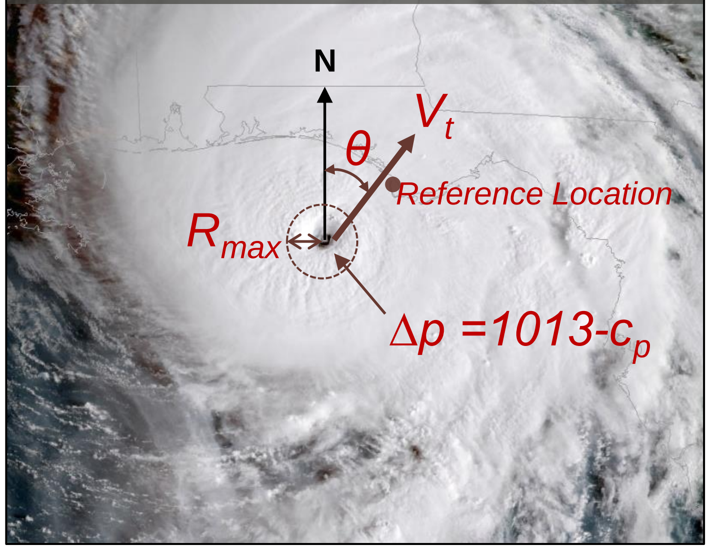
Extratropical Cyclones (XCs)

- Hazard analysis is reliant on historical storm events
- Difficult to physically represent XCs using a set of parameters
- Extreme Value Analysis
  - Stochastic Simulation Technique (SST) to assess XC hazards

Tropical Cyclones (TCs)

- Physical characteristics of TCs can be represented by a set of parameters
- Historical record is too limited for accurate hazard estimation
- Create synthetic TCs to overcome limited observations in historical record
  - Joint Probability Method (JPM) to assess TC hazards

JPM Parameters for TCs



Parameters Defining TCs:

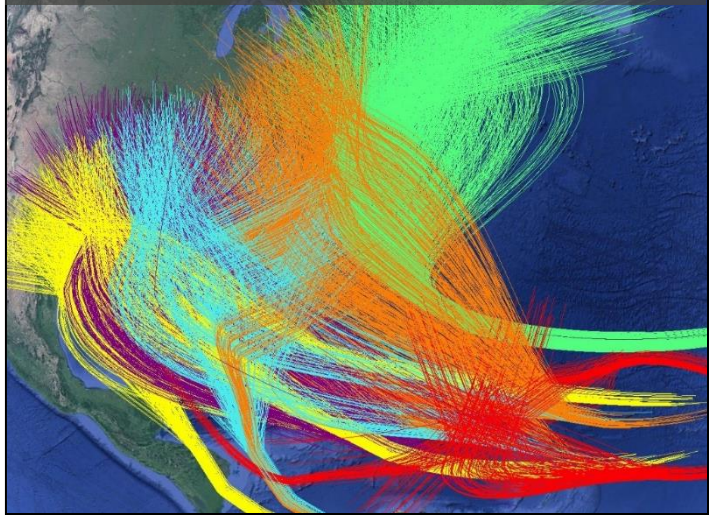
Δp = central pressure deficit

V_t = translational speed

R_{max} = radius of maximum winds

ϴ = heading

CHS Synthetic TC Suites



NACCS
1050 TCs (green tracks)
SACS: NCSFL
1,060 TCs (orange tracks)
SACS: SFLMS
1,085 TCs (cyan tracks)
SACS: PR/USVI
300 TCs (red tracks)
LACS
645 TCs (purple tracks)
TXCS
660 TCs (yellow tracks)

QUANTIFICATION OF COASTAL STORM HAZARDS

Why do we need synthetic TCs?

Observation-based methods

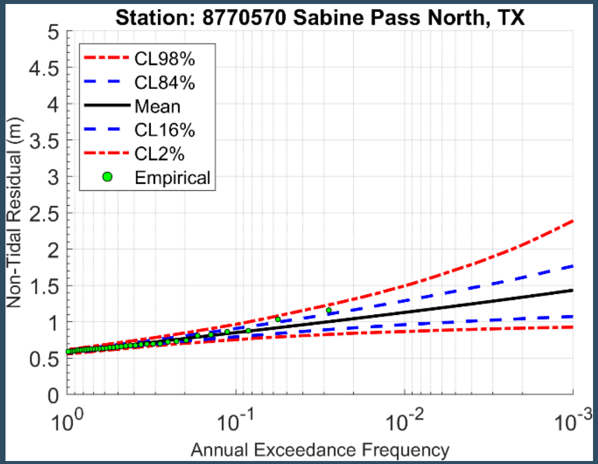
- Ex: Extreme Value Analysis (EVA)
- Low spatial resolution & gaps in available measurement data
- Creates a limited sample of storms and their observed responses at a site
- Understate hazards and risk

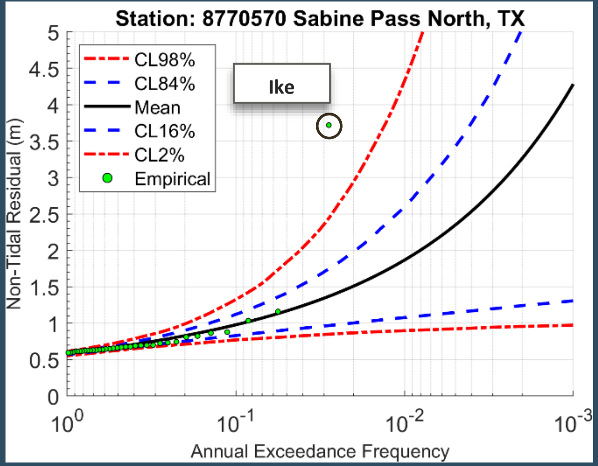
Examples:

- Hurricane Ike – 3.7 m surge
  - Before: AEF ~ 1 in 10^7
  - After: AEF ~ 1 in 700
- Hurricane Sandy – 3.8 m surge
  - Before: AEF ~ 1 in 10^{13}
  - After: AEF ~ 1 in 625

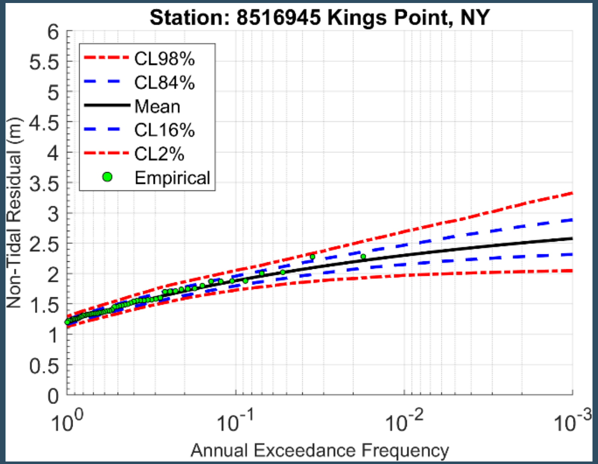
Joint Probability Method!

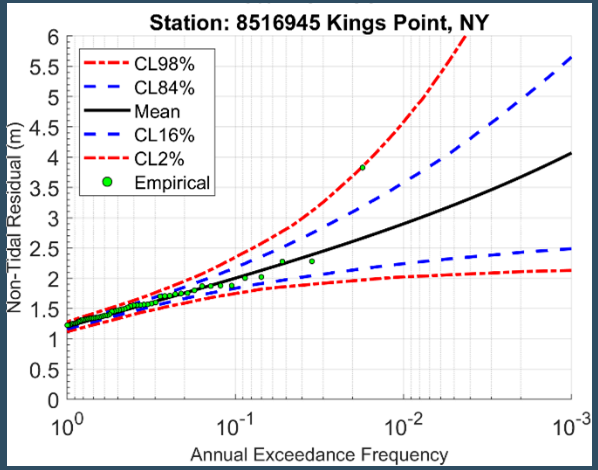
Hurricane Ike





Sandy



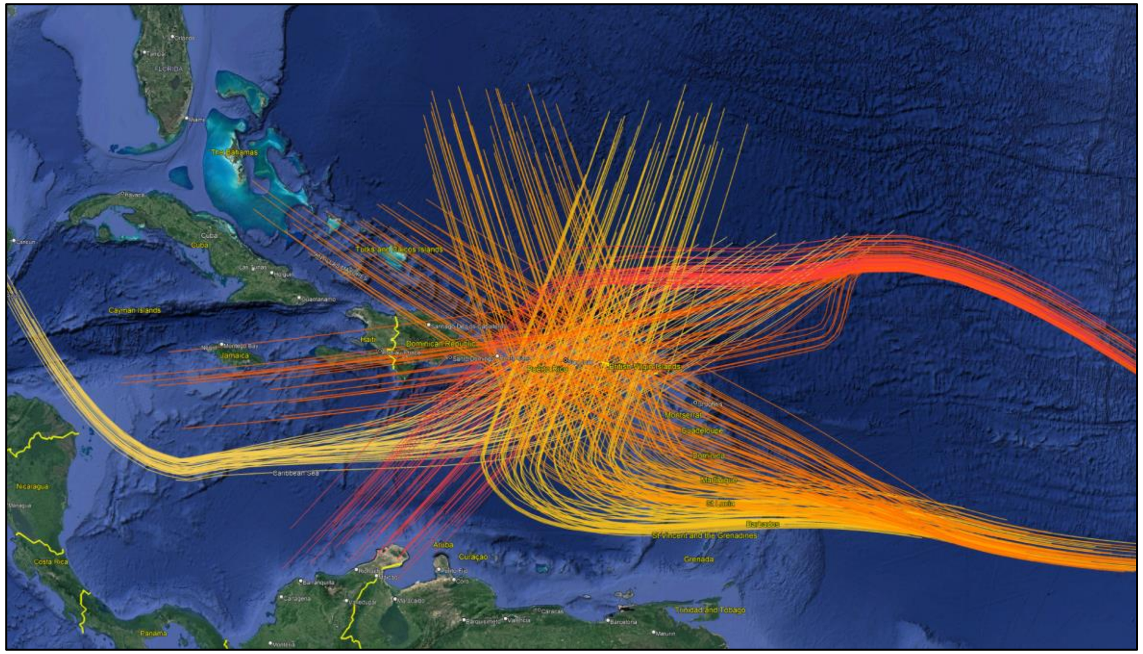


ERDC ENGINEER RESEARCH & DEVELOPMENT CENTER

CHL COASTAL & HYDRAULICS LABORATORY

JOINT PROBABILITY METHOD WORKFLOW

TC Parameter	Range
θ	-140°, -100°, -60°, -20°, +20°, +60° (clockwise from North)
Δp	8, 18, 28, 38, 48, 58, 68, 78, 88, 98, 108, 118, 128, 138, 148 hPa
R_{max}	8 to 143.6 km (from BQ sampling)
V_t	8 to 40 km/h (from BQ sampling)
Total # of TCs	300



General Workflow

- Sample discrete values of TC parameters from historical datasets
- Combinations of discrete values = synthetic TC
  - TC = $[x_0, \Delta p, R_{max}, V_t, \Theta]$
- Develop suite by assigning TCs to idealized tracks
- Assign probabilities to the synthetic TCs
- Simulate TCs in hydrodynamic models
- Compute uncertainty
- Create hazard curves accounting for the storm responses and probabilities

Parameters Defining TCs:

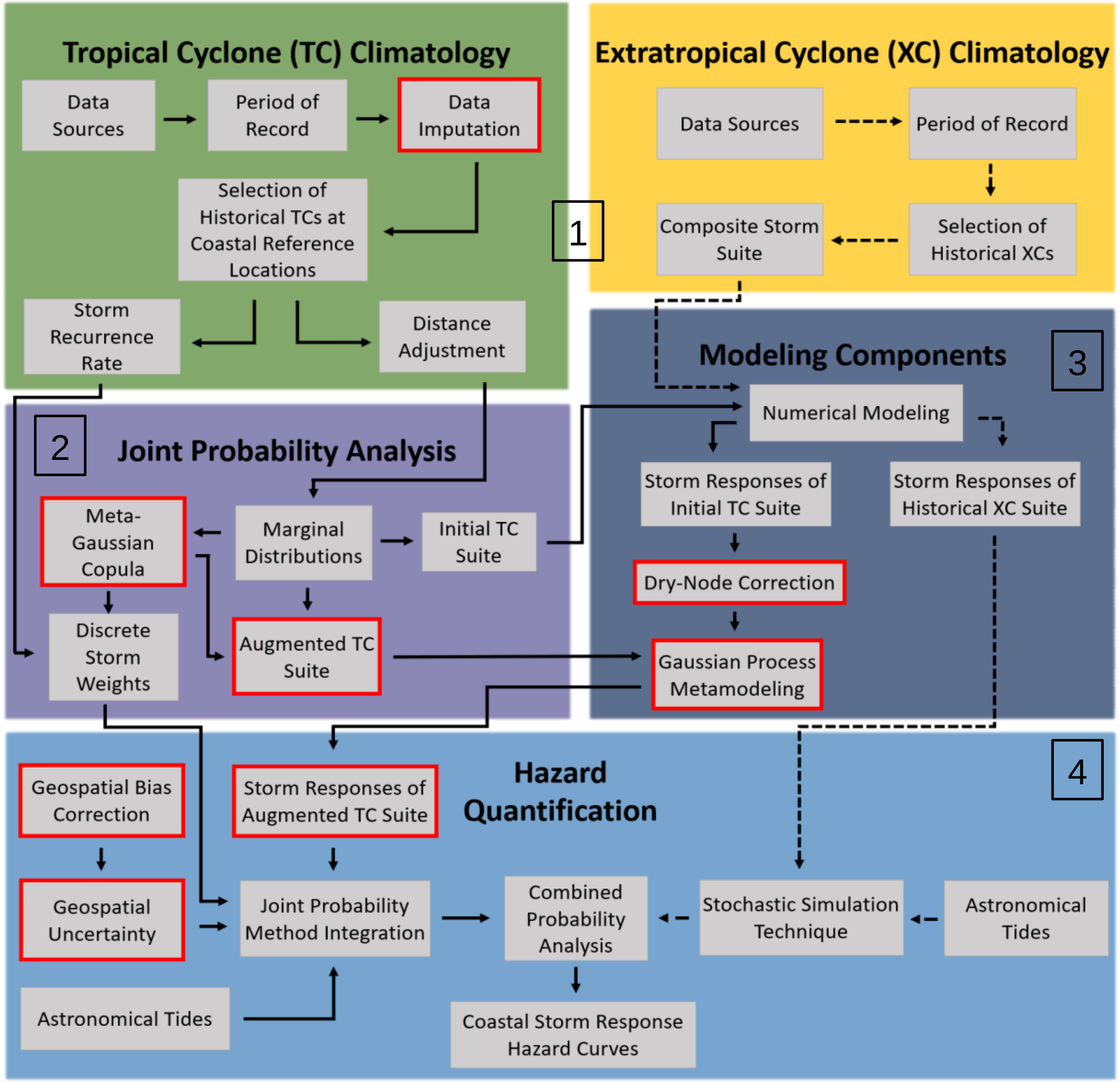
Δp = central pressure deficit

V_t = translational speed

R_{max} = radius of maximum winds

ϴ = heading

PROBABILISTIC COASTAL HAZARD ANALYSIS (PCHA)



Goal

- Develop storm suites that fully characterize hazards
  - Probability space → synthetic storm events cover range of possible storms
  - Physical space → covering range of storm responses

Benefits

- Statistical backbone that supports CHS
- Framework is flexible and model agnostic
  - Expansion to other research areas (i.e., compound flooding)
  - Supports regional and local-scale studies
- Metamodeling techniques used for higher resolution results trained on high-fidelity modeling
- Hazards estimates can be easily updated
  - Evaluate multiple/additional climate scenarios

COASTAL STORM MODELING SYSTEM (CSTORM-MS)

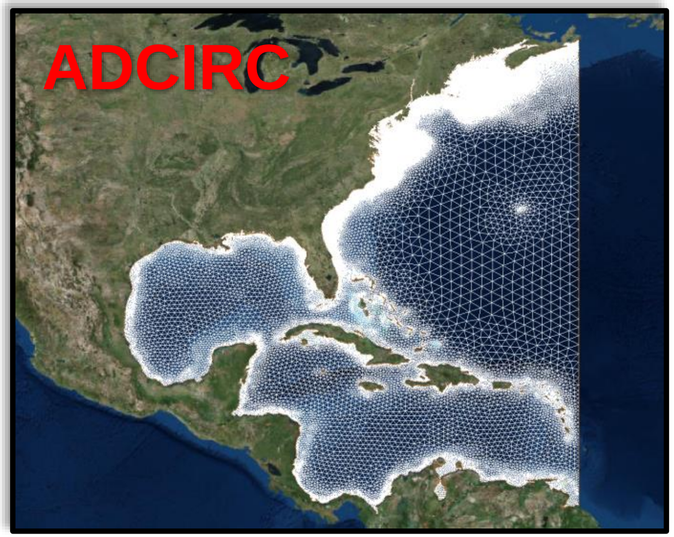
Storm event simulations in CSTORM

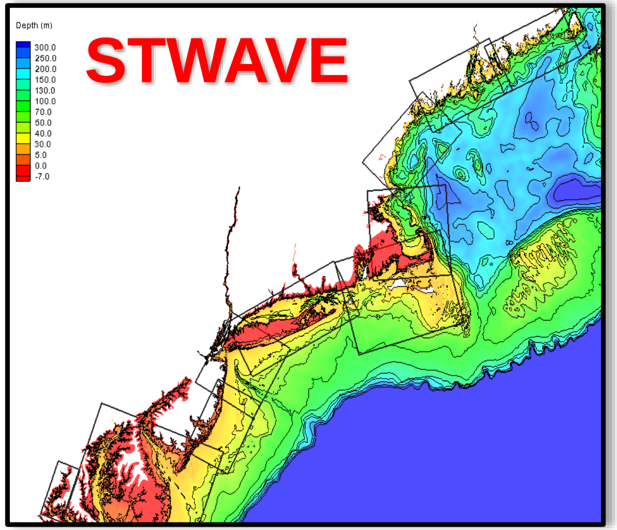
Hydrodynamic Models in CSTORM include:

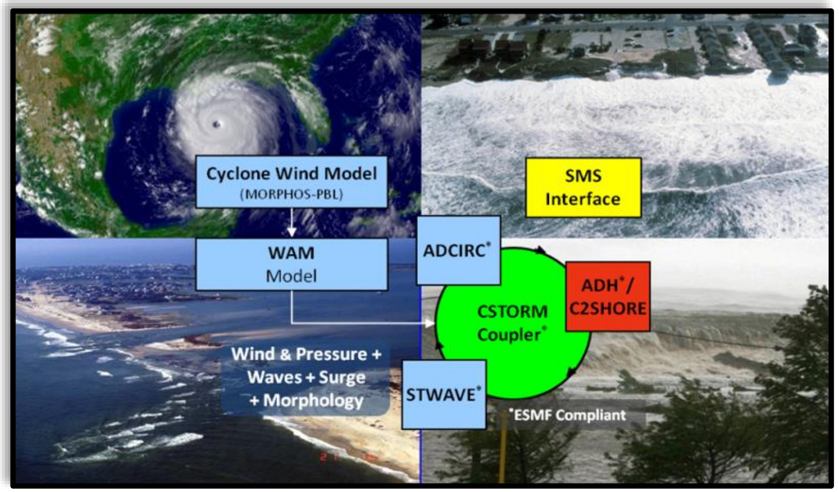
- WAM: WAve Prediction Model
- STWAVE: STeady-State Spectral WAVE
- ADCIRC: ADvance CIRCulation
- SWAN: Simulating WAves Nearshore

Results output at save points:

- Locations of interest where model results and statistics are desired
- Defined by latitude, longitude, and depth
- Generally include tens of thousands of points per study





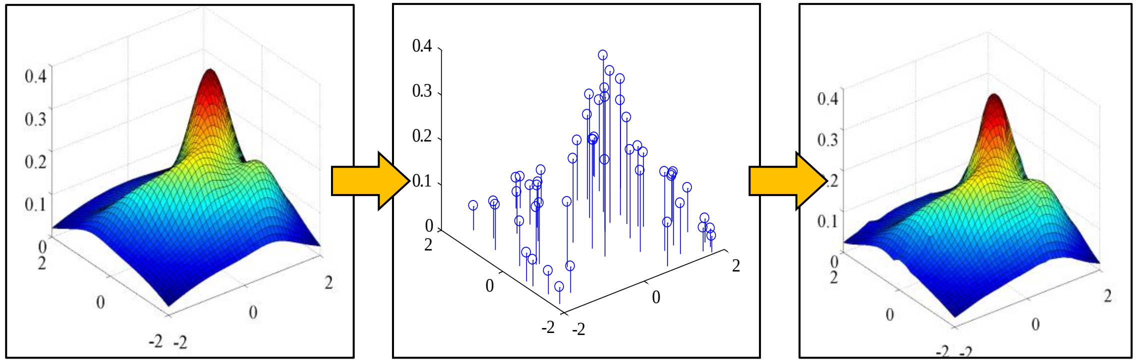


CHS-PCHA WORKFLOW ADVANCEMENTS

Metamodeling Applications

Gaussian Process Metamodeling (GPM)

- Mathematical approximation for the input/output (x/z) relationship of a complex numerical model (frequently referenced as process or computer code).
- Formulated based on a database of simulations for complex process. This database is frequently referenced as experiments or support points.



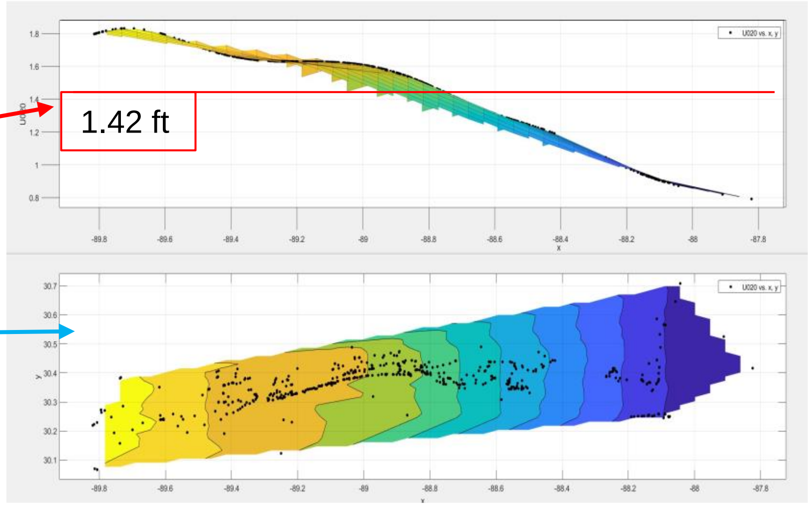
Real model | **Support points** | **GPM approximation (global) + correction (local)**

GPM Applications
- **Data Imputation**
- **Storm Suite Augmentation**
- **Dry Node Correction**

UNCERTAINTY QUANTIFICATION

Estimating numerical modeling error:

- Standard approach: estimate a global uncertainty
- PCHA approach: spatially-varying bias and uncertainty
  - Gaussian Kernel Surface (GKS) approach
- Compute combined bias and uncertainty for SWL hazard estimates
  - Considers relative + absolute values



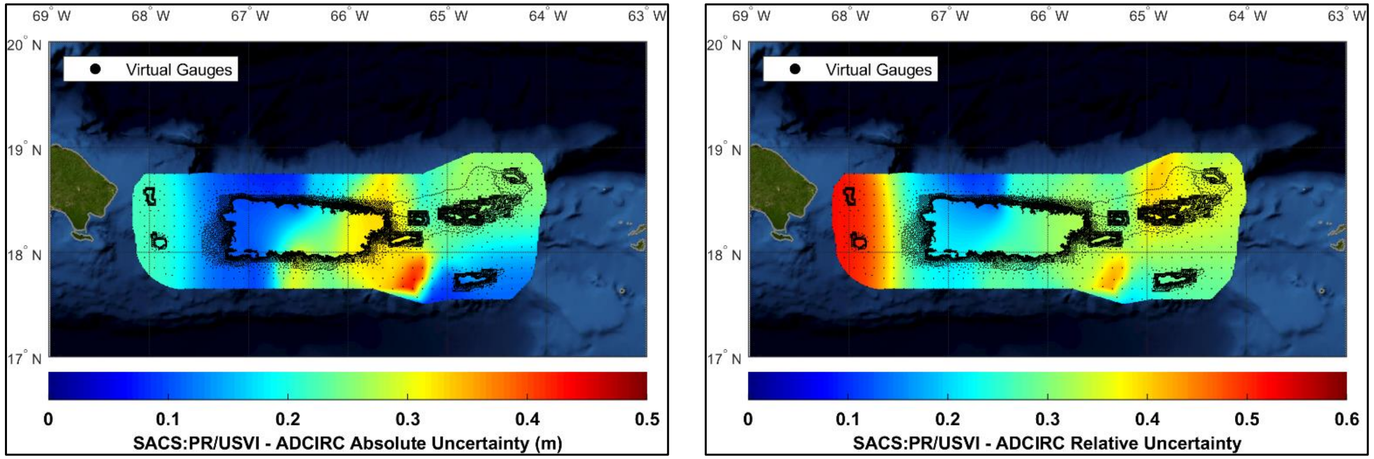
Example Equation:

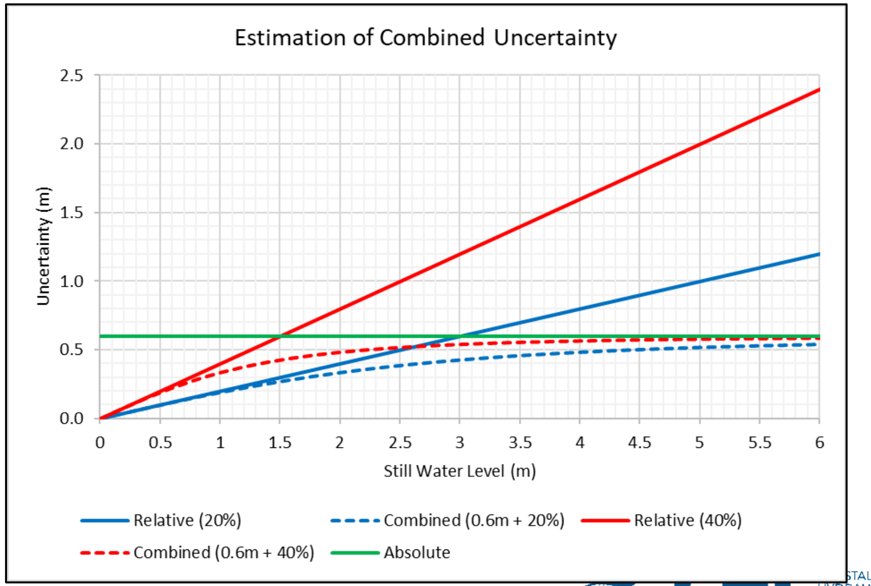
$$c = \frac{1}{\sqrt{\frac{1}{a^2} + \frac{1}{r^2}}}$$

c = combined uncertainty

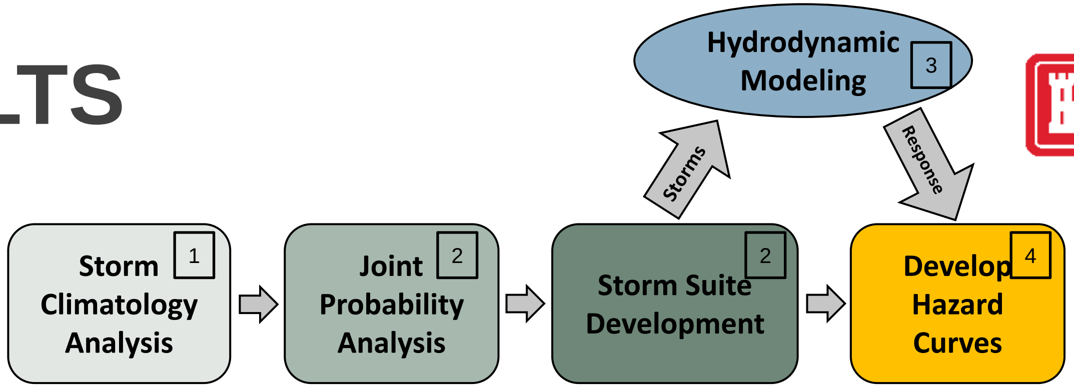
a = absolute uncertainty (ADCIRC + PBL)

r = relative uncertainty (ADCIRC + PBL)





CHS-PCHA HAZARD RESULTS

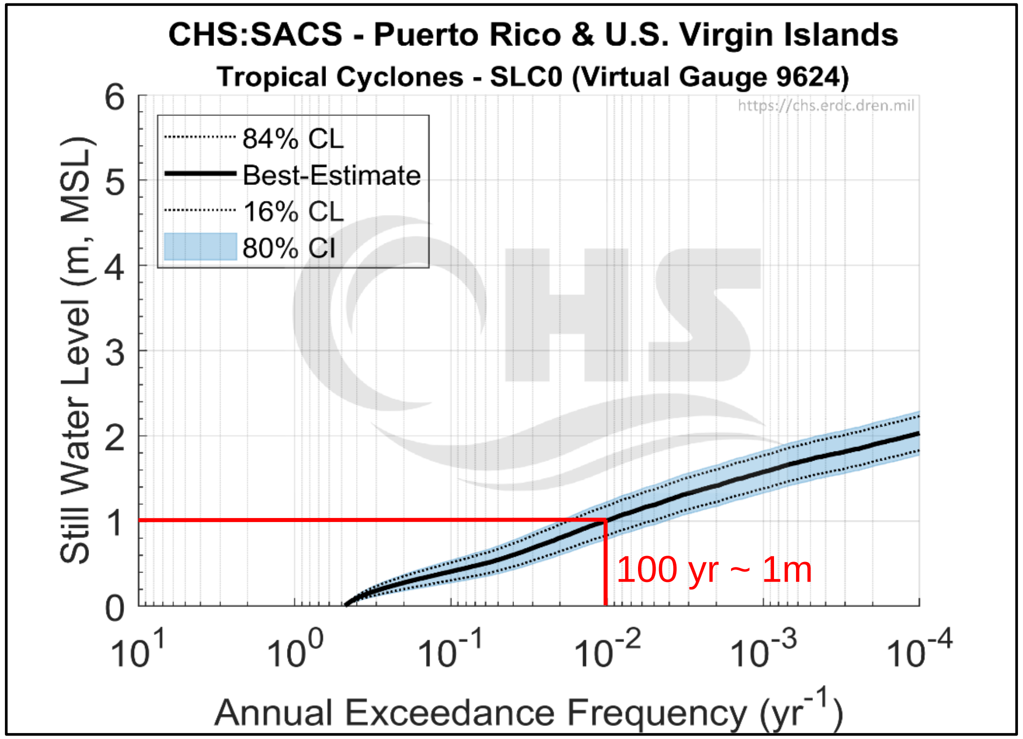


Develop Hazard Curves:

- Apply predicted storm responses and probability masses for the augmented storm suite in JPM integral to create hazard curves
- Annual exceedance frequency estimates
  - Still water level
  - Significant wave height
  - Peak wave period
- Hazard results computed for each storm response at thousands of point locations along coastline

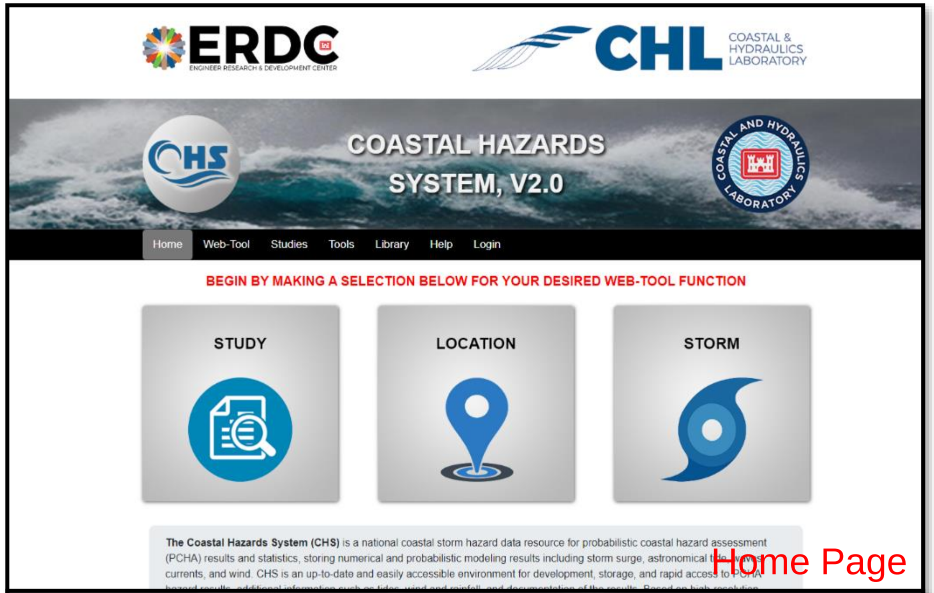
Hazard Curve Information:

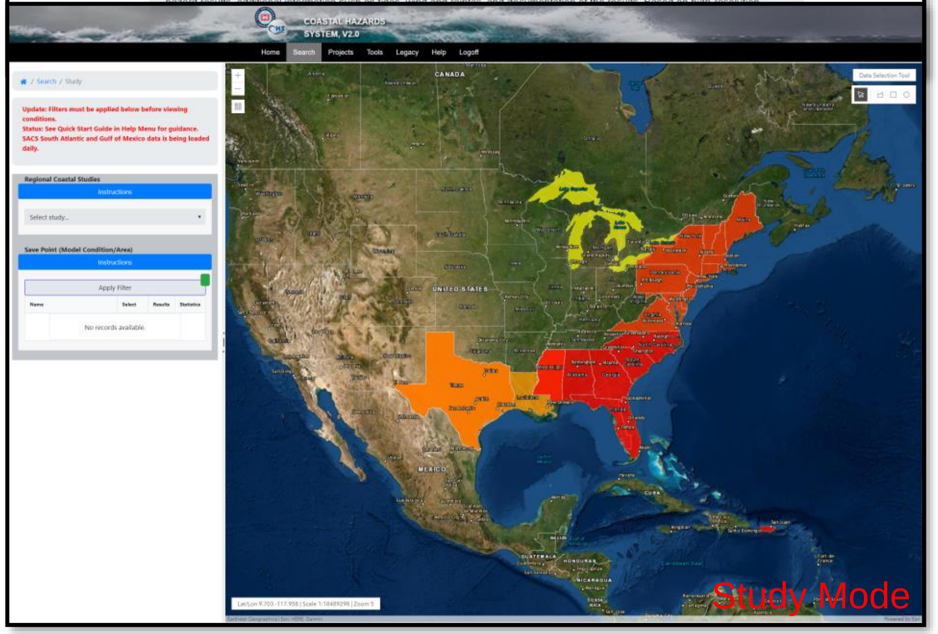
- Provided as a function of annual exceedance frequencies (AEFs)
- Meaning: frequency (# of times) per year a given response is equaled or exceeded
- Inverse of AEFs gives the return period
- Uncertainty represented through confidence limits (CLs)



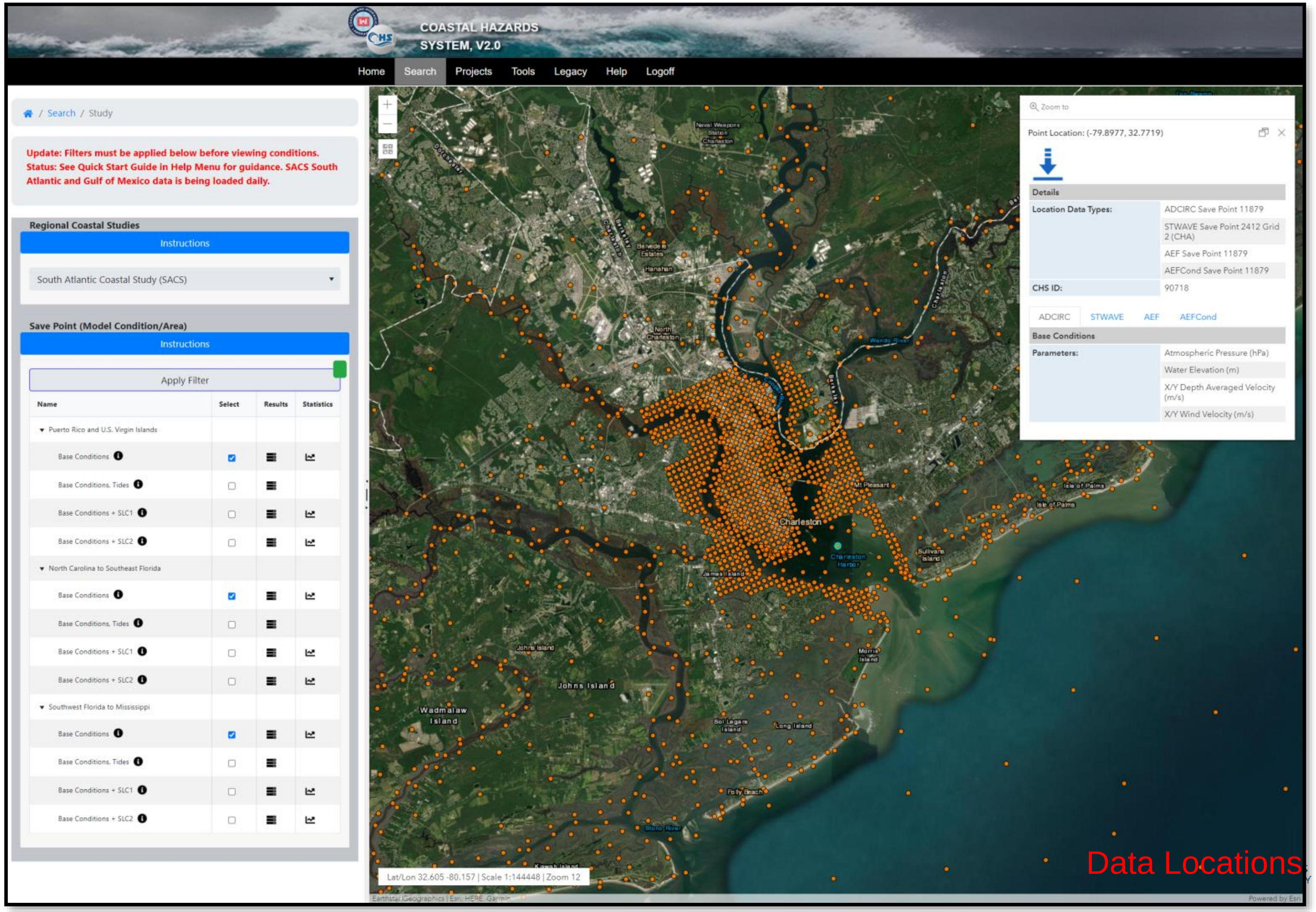
Tropical Cyclone Hazard Curve

CHS – AVAILABLE & ACCESSIBLE DATA

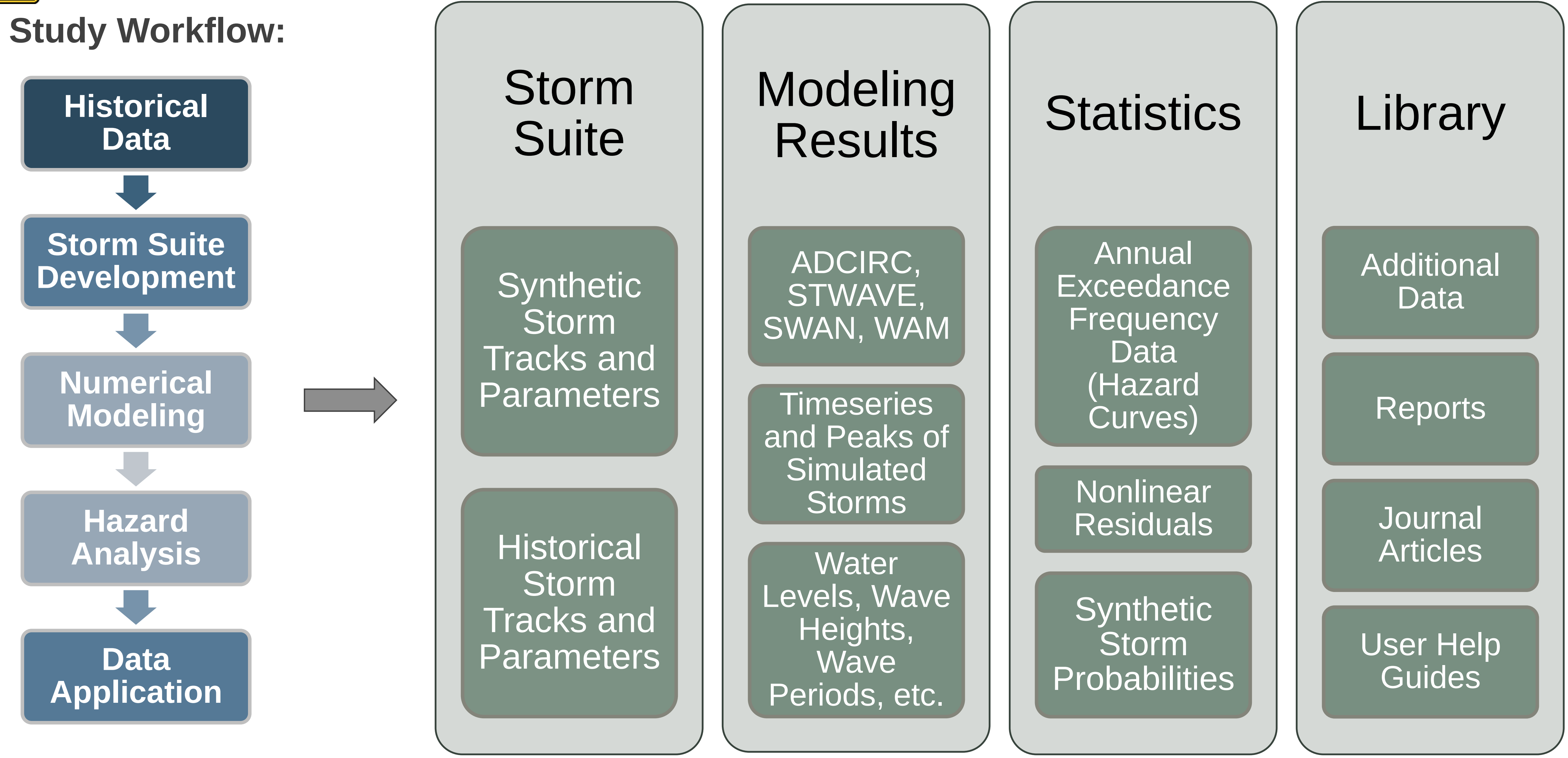




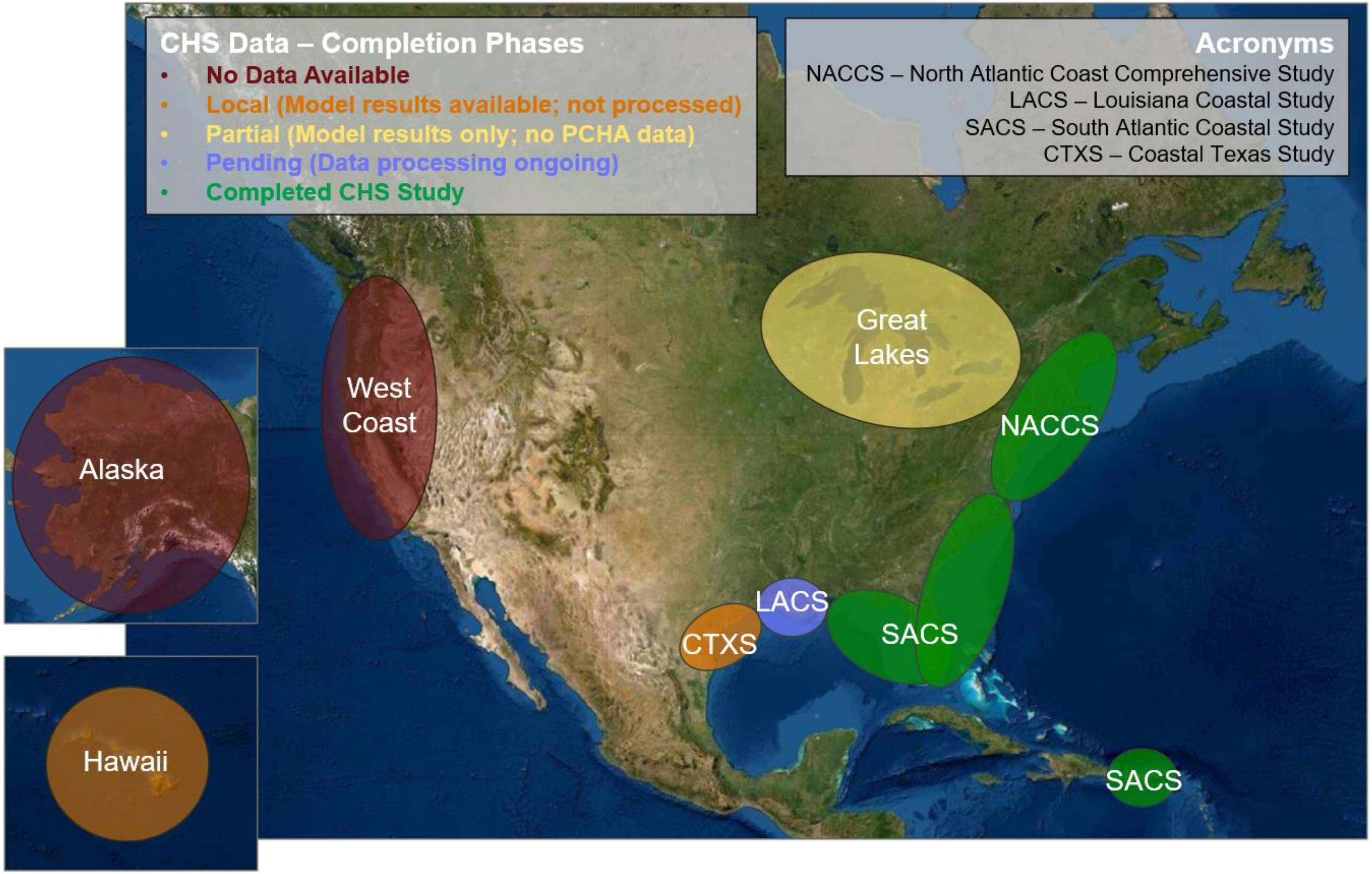
- Web-based platform for users to download statistics results describing the hazards and modeling results of the storm events at save point locations
- https://chs.erdc.dren.mil



REGIONAL COASTAL STUDY DATA

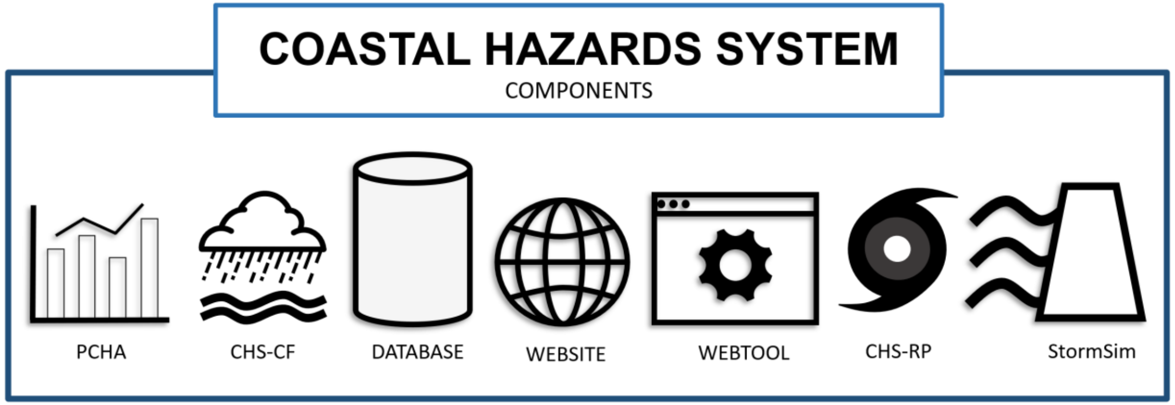


CHS – STATUS OF NATIONAL COVERAGE



COASTAL HAZARDS SYSTEM

A multi-component system with the intent of developing, distributing, and applying coastal storm hazard data

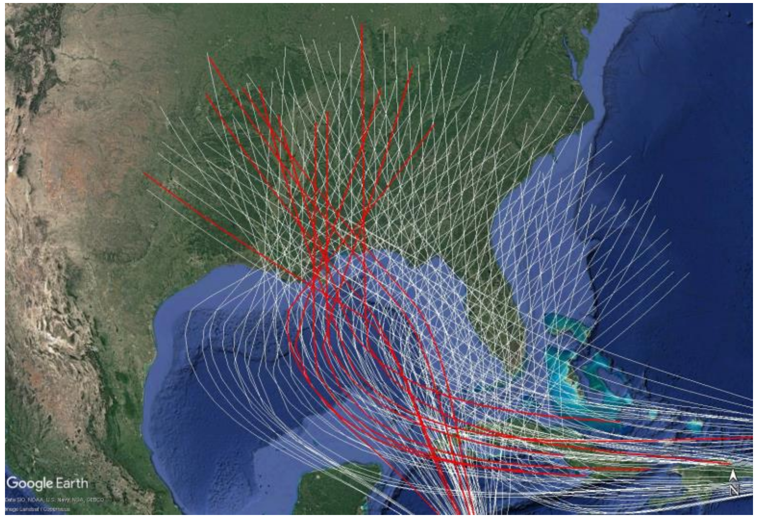


Coastal resiliency support through:

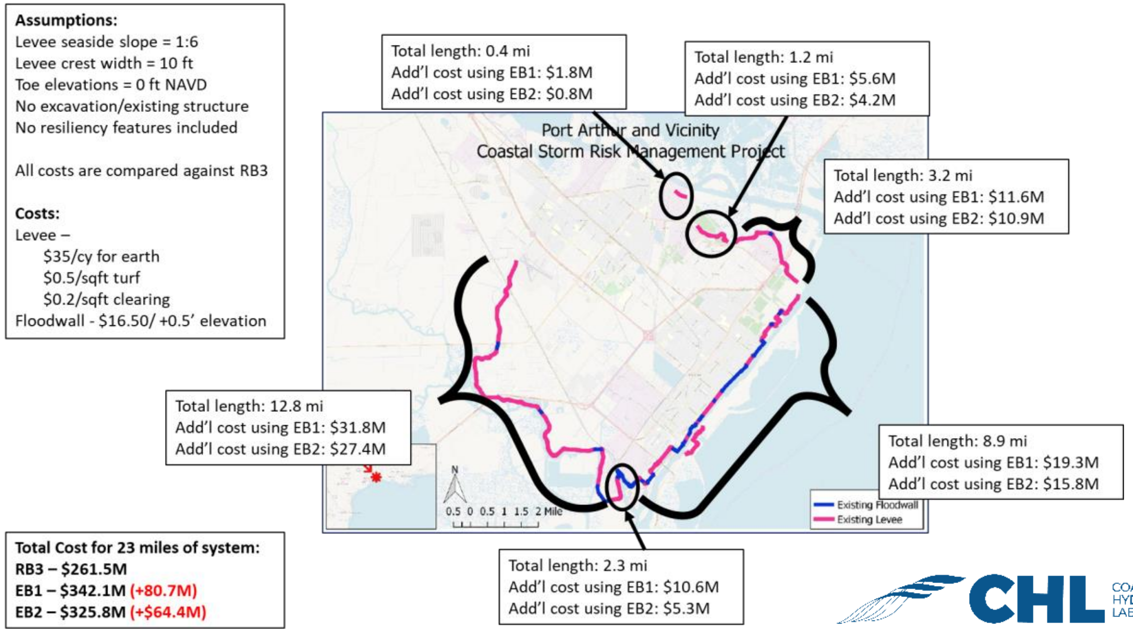
- Storm Suite Development and Hazard Quantification
- Data Storage and Distribution
- Data Application

ENVIRONMENTAL/ECOLOGICAL APPLICATIONS

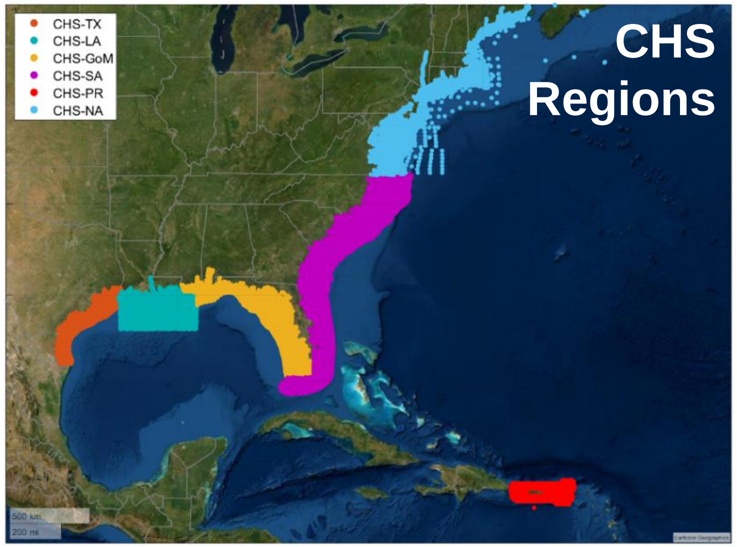
- CHS data can be easily leveraged for downstream studies requiring coastal storm response data:
  - Coastal Storm Risk Management (CSRM)
  - Feasibility Studies
  - Engineering with Nature projects
- Available storm suites, modeling results, and statistics serve as initial conditions or boundary conditions for local-scale projects:
  - Deer Island Aquatic Ecosystem Restoration Project
  - Aberdeen Proving Grounds Coastal Resilience and Natural Infrastructure Project
- Support from PCHA framework
  - Storm selection (sub-sampling)
  - Storm sequencing
  - Climate change/sea level rise evaluation
  - Uncertainty quantification

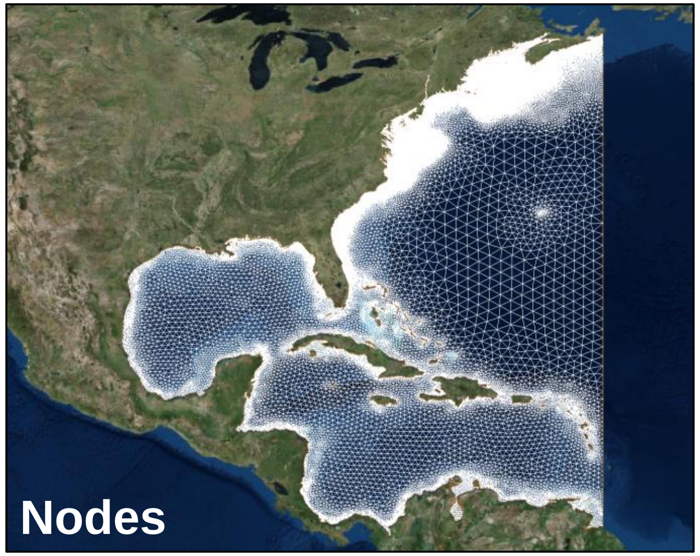


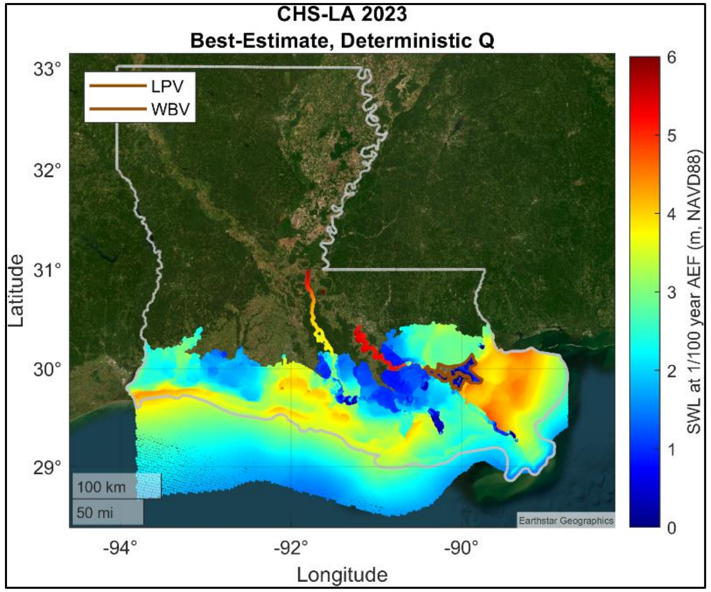
Year	Storm ID	Surge (m)
1	655	0.38
2	1161	0.91
3	1392	0.97
4	1564	0.36
5	1406	0.5
6	1154	3.6
7	48	0.25
8	934	0.22
9	1149	0.55
10	10	2.43

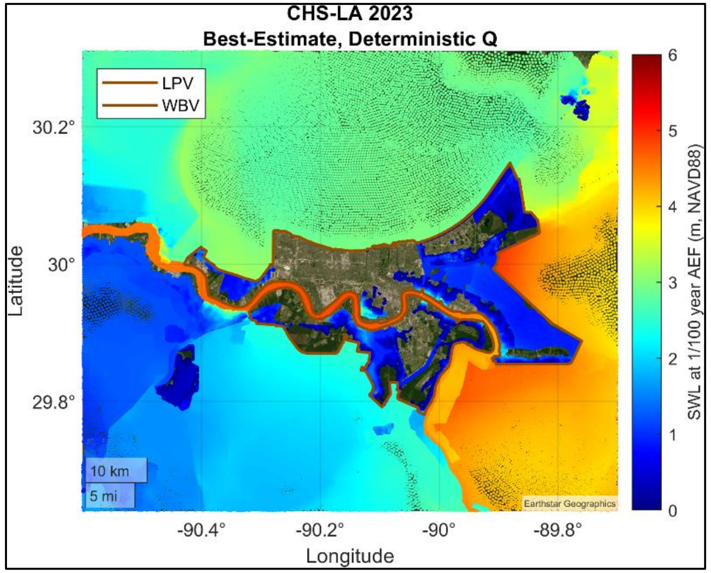


CHS – NODAL HAZARD QUANTIFICATION







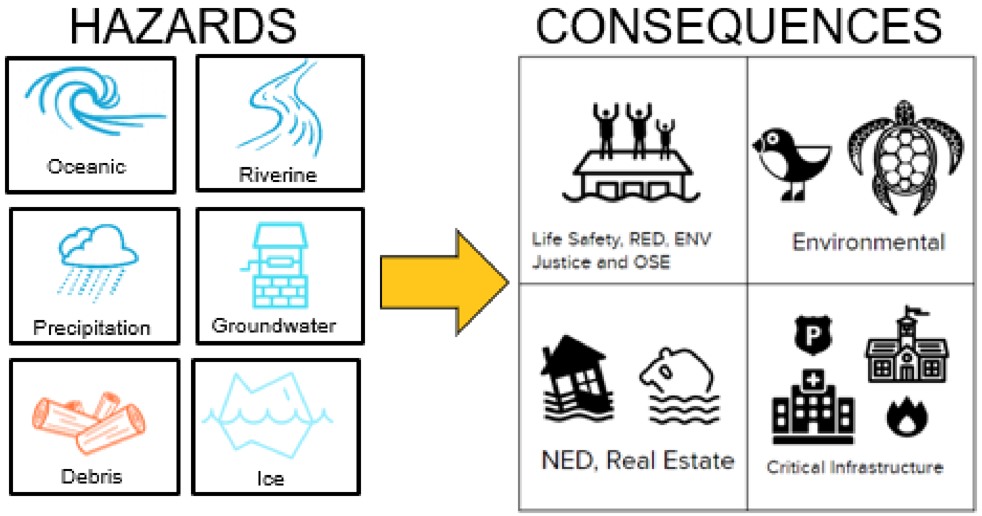


High Resolution Probabilistic Results:

- Main PCHA result is annual exceedance frequency (AEF) estimates
- Updating hazard results at nodal level as part of inter-agency agreement with FEMA
  - Binary to graduated approach for risk
- Increasing resolution of hazard results by orders of magnitude
  - Nodes (millions of points)
  - Save points (thousands of points)
- Timeline for nodal AEF results:
  - Louisiana – December 2022
  - North Atlantic – February 2023
  - Coastal Texas – August 2023
  - Puerto Rico – December 2023
  - South Atlantic – March 2024
  - Gulf of Mexico – August 2024
- Higher-resolution results available for expanded set of applications

COASTAL HAZARD ANALYSIS AND RISK TOOLKIT (CHART)

- Develop a tool that's modular and transparent with appropriate fidelity for decision at hand
- Support CSRM feasibility studies from Scoping to National Economic Development (NED) determination to Chief's Report
- Leverage USACE (and FEMA) investments:
  - Coastal Hazards System, Coastal Storm Damages Prevented, National Structure Inventory, Cloud Compute, StormSim, Cshore/FILSIM
- Support other benefit/consequence categories
  - Other Social Effects (OSE), Regional Economic Development (RED), and Environmental Quality (EQ)
- Multi-year effort with final tech-transfer planned in FY25



COASTAL HAZARDS SYSTEM (CHS)

THANK YOU!

Norberto C. Nadal-Caraballo, PhD
Senior Research Engineer
Norberto.C.Nadal-Caraballo@usace.army.mil

Madison C. Yawn
Research Physical Scientist
Madison.C.Yawn@usace.army.mil