HURRICANE WATER LEVEL PREDICTION USING SURROGATE MODELING

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Problem

Accurate Risk Assessment – real time and static

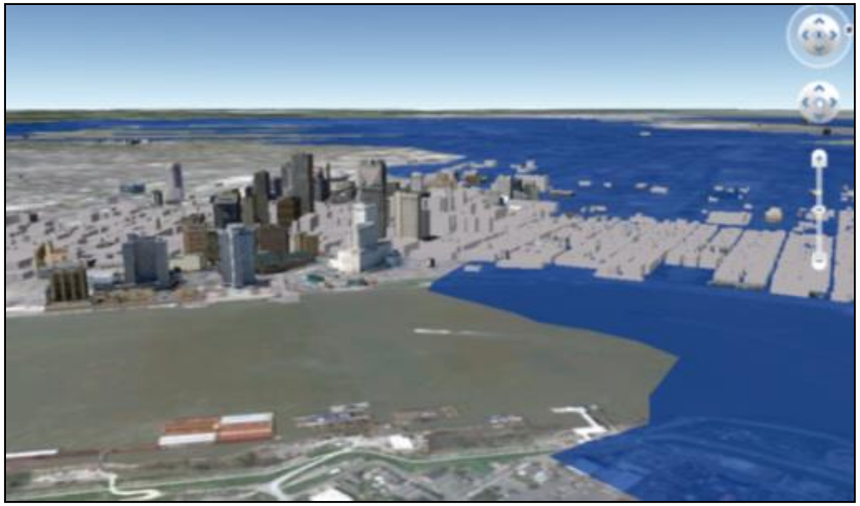
- **Complex physics** and uncertainty demand high fidelity computational models
- Physics-based models are **expensive** and can be infeasible
- Physics are routinely limited
- Climate forecasts can change rapidly and frequently
- Need to **understand uncertainty**
- Want flexibility - Stakeholders perspectives change AFTER modeling is complete, hazards of concern may shift (e.g. vary scenarios, climate change)

Louisiana State Rd. 23 near Myrtle Grove
Tropical Storm Lee (2011)

Galveston 1 day before Ike landfall

Specific Objectives

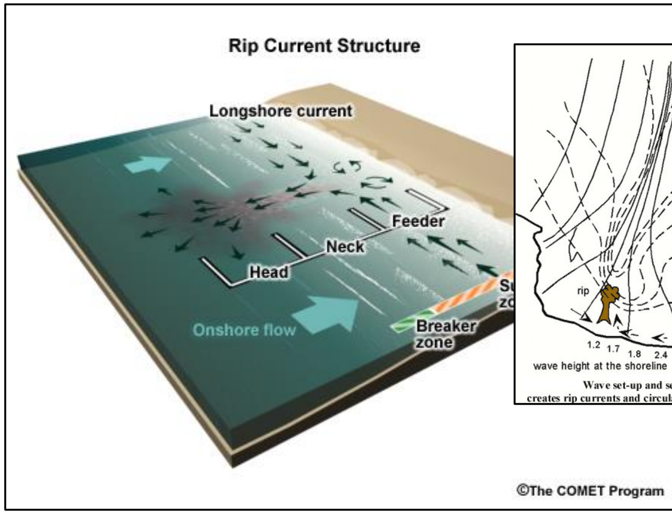
- **High-fidelity Surrogate Models** for Hurricane Response
  - Rapid prediction of response: inundation (surge+tide), wave height, wave period, wave direction, currents, wind speed, wind direction
  - NOAA and Coastal Hazards System data linkage
  - Robust surrogate parameterization
  - Uncertainty



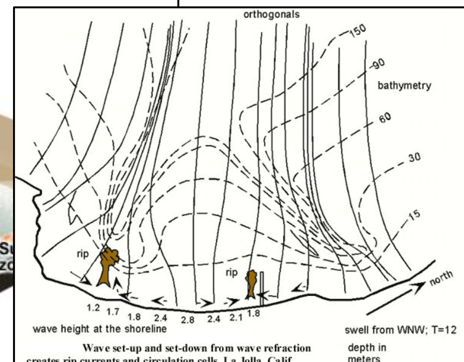
- **Centralized computation/distribution - Coastal Hazards System**
- **Stand-alone PC software - CHRPS**

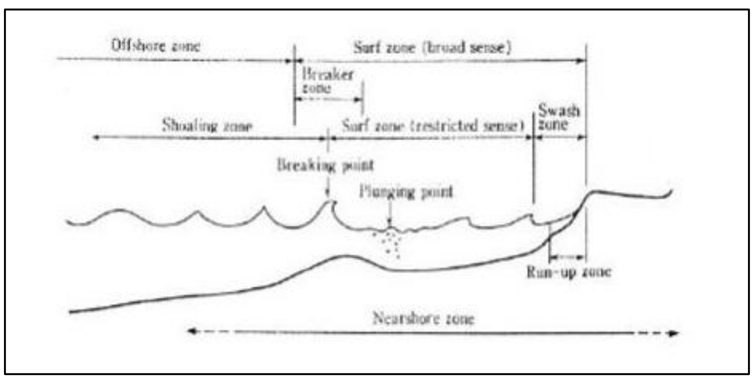
Nearshore Processes are Complex

Nearshore Circulation



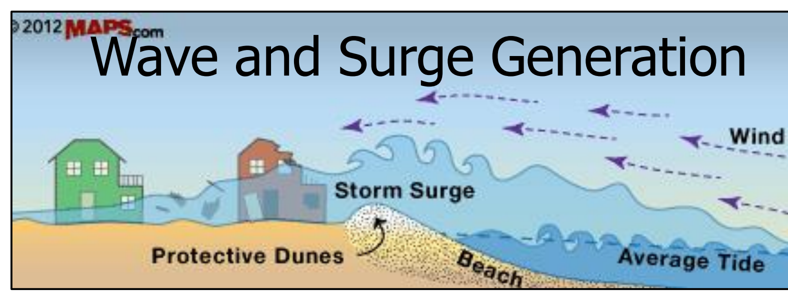
Wave Transformation





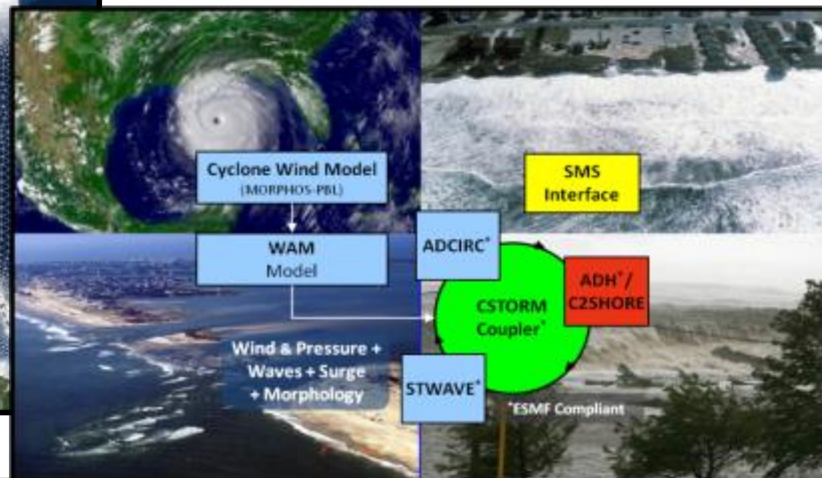
Wave Breaking, Setup and Runup

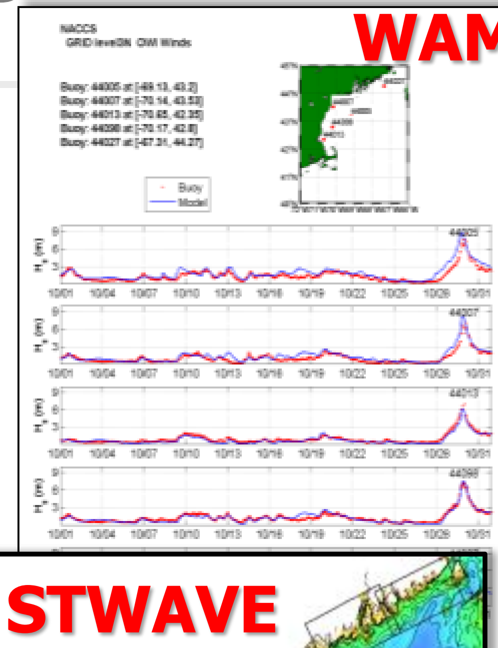
Wave and Surge Generation

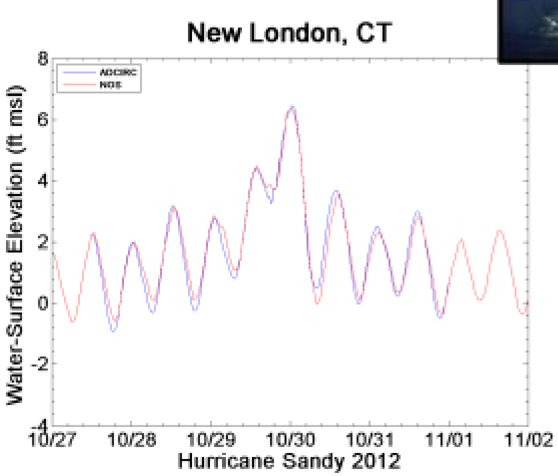


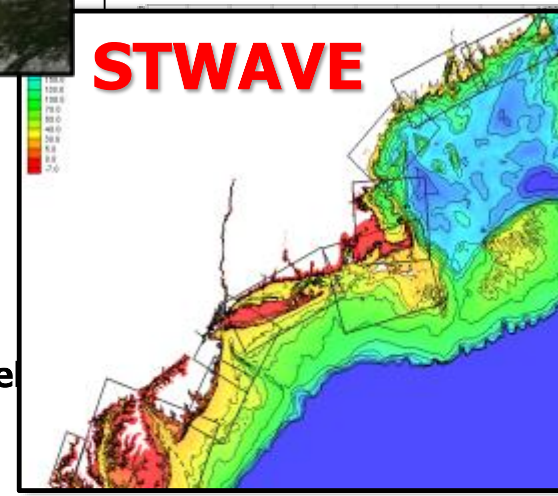
High Fidelity Modeling

CSTORM-MS









CSTORM-MS:
Coastal STORM Modeling System

WAM:
WAve Prediction Model

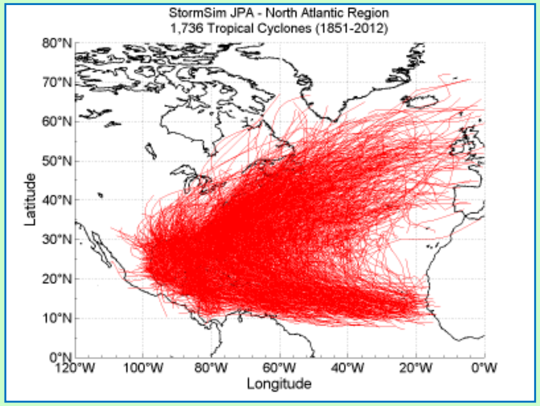
STWAVE:
STeady-State Spectral WAVE model

ADCIRC:
ADvance CIRCulation Model

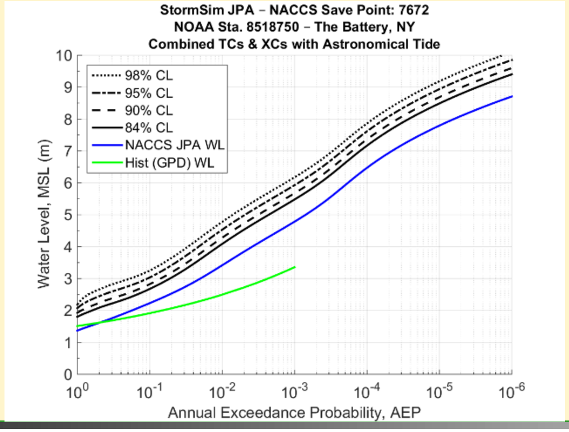
3M nodes, min res ~20 m.

Parameterization of Tropical Cyclones

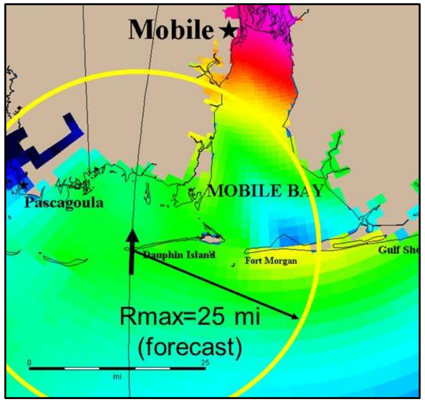
HURDAT database – 1851-present



TS are rare so extreme responses not well represented in measurements



Tropical Storms can be parameterized



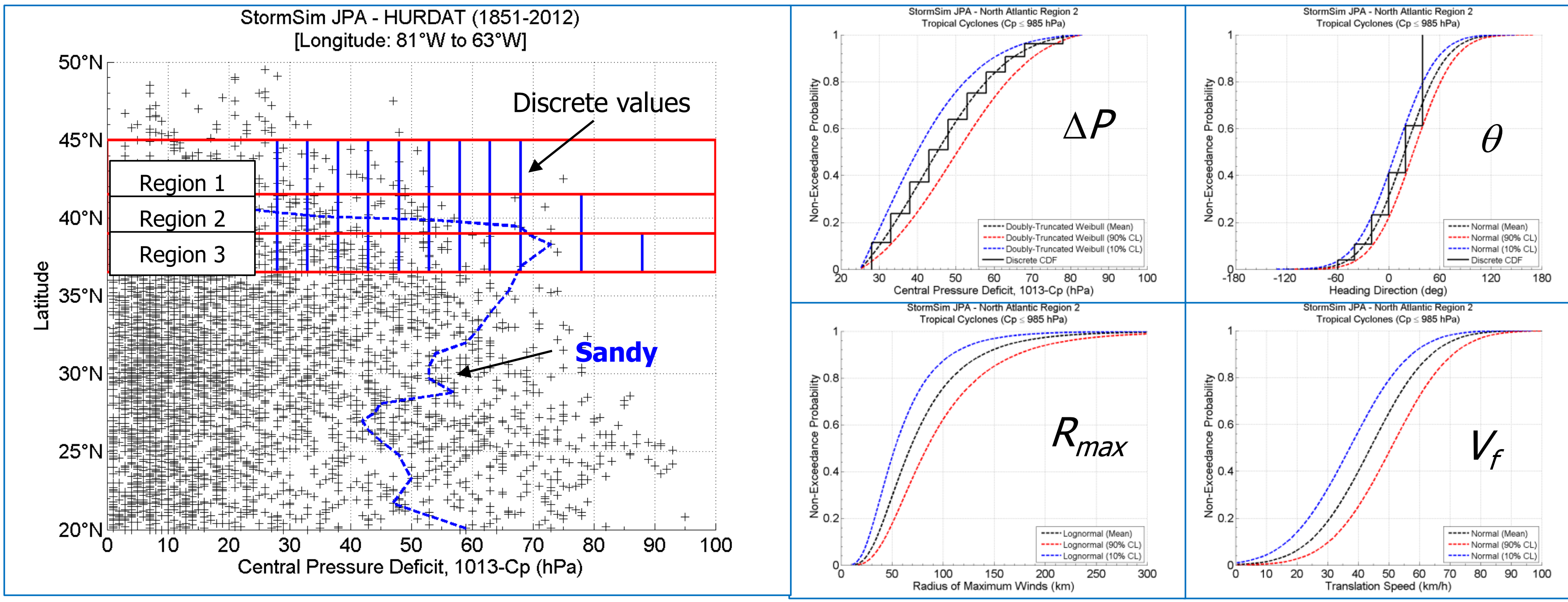
$$\text{Response} = f(\hat{x}) = f\left(X_0, \mathrm{D}P, R_{max}, V_f, q\right)$$

X_0 = Land fall location (lat, lon)
θ = Angle of storm approach
ΔP = Minimum central pressure
V_f = Average forward speed
R_{max} = Radius of maximum winds

Parameterization of Tropical Cyclones

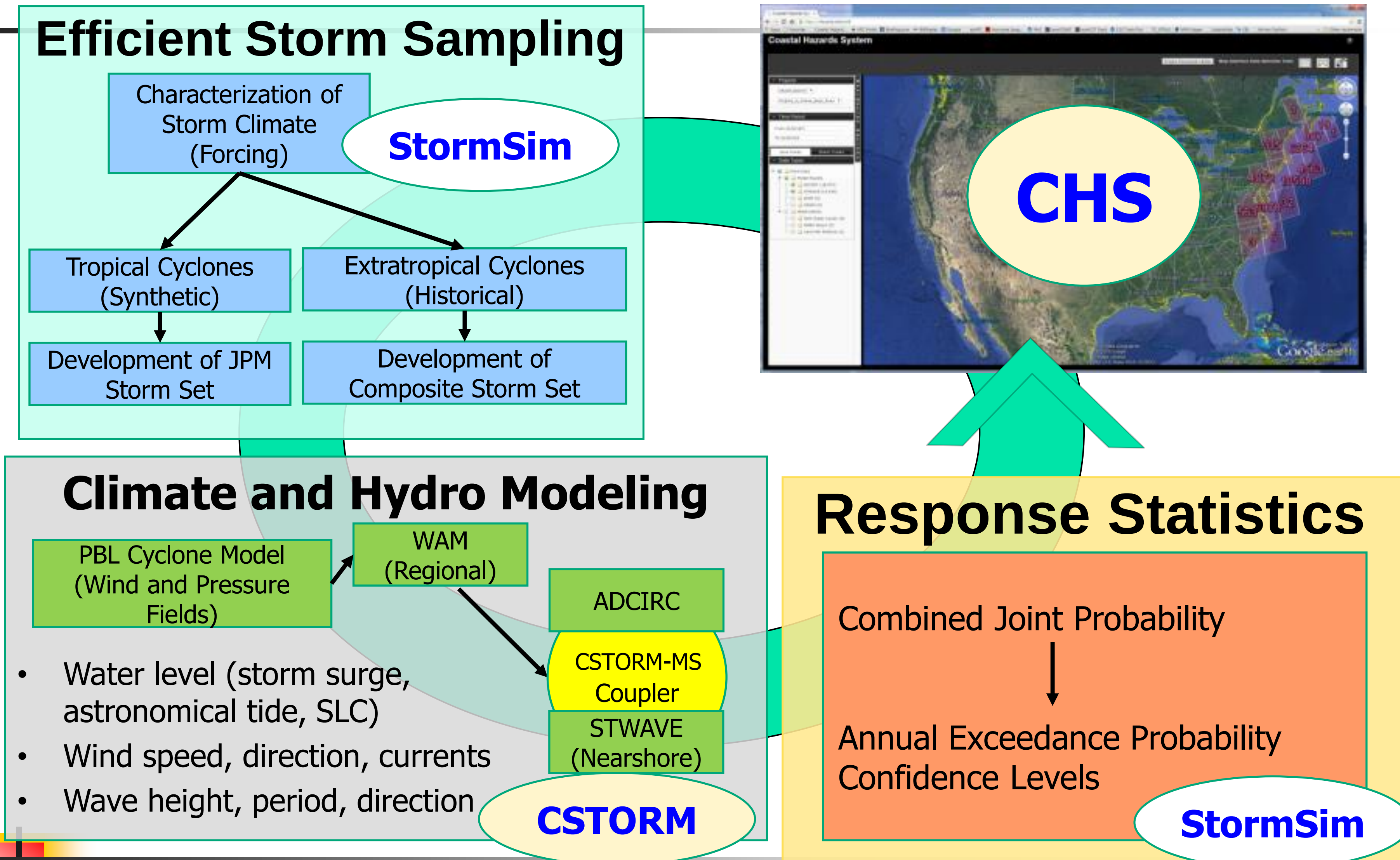
Non-Exceedance Probability Distributions

$$\text{Response} = f(\hat{x}) = f(X_0, \mathrm{D}P, R_{\max}, V_f, q)$$



Hybrid Discretization: Uniform: θ, ΔP ; Bayesian Quadrature: R_{max} , V_f

Coastal Hazards System



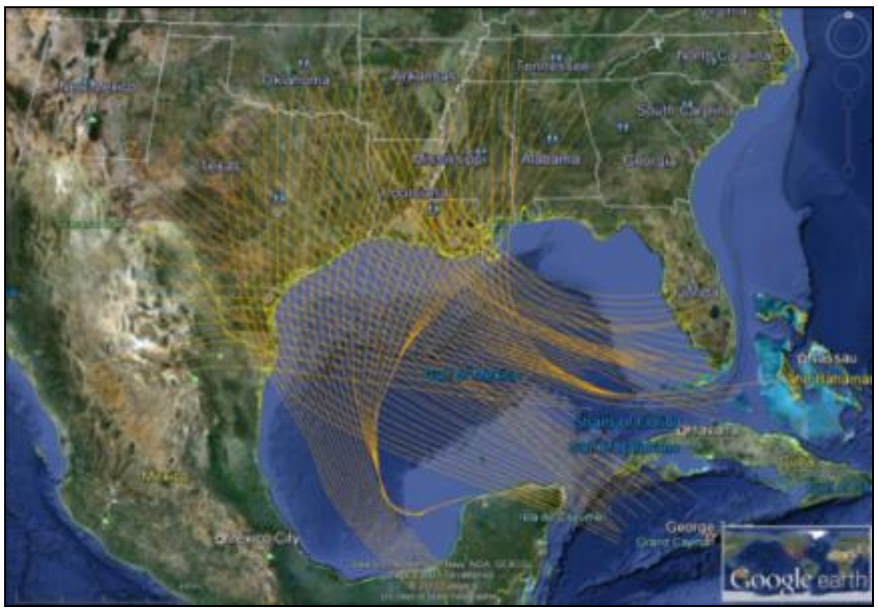
Storm Screening

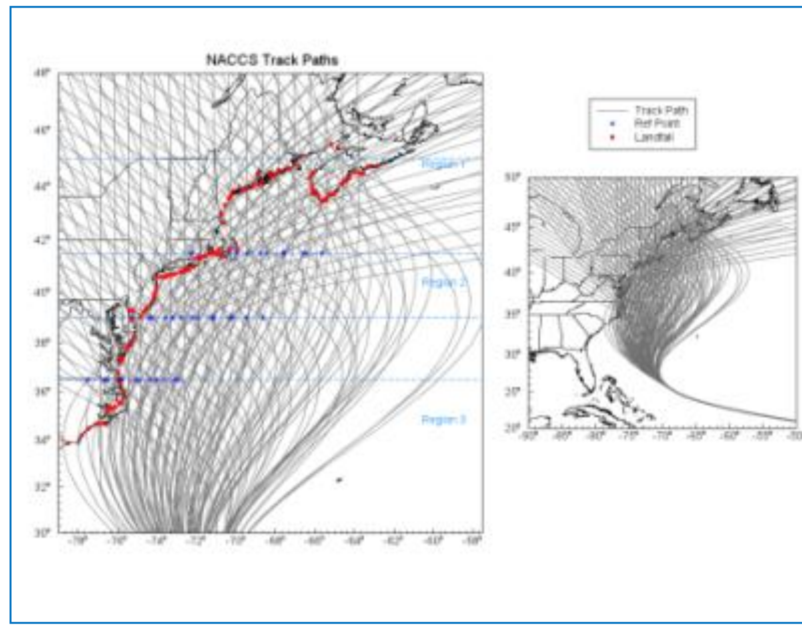
TX/LA/MS/AL/FL – 1187 storms

- C_p: 900 - 975 mb
- V_f: 11 – 33 km/hr
- R_{max}: 11 – 51 km

NACCS – 1150 storms

- C_p: 915 – 985 mb
- V_f: 12 – 88 km/hr
- R_{max}: 25 – 174 km





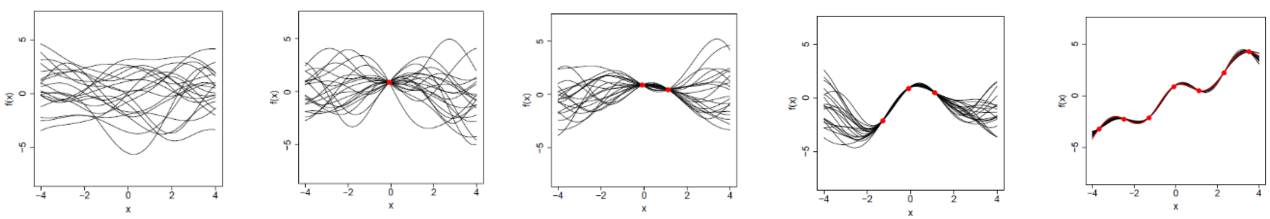
Surrogate Modeling

Surrogate Techniques: Data Driven

- Least squares regression
- Low dimensional spline interpolation
- Dimensional functions
- Polynomial chaos
- Response surface approximations
- **Artificial neural networks**
- **Kriging or Gaussian process emulation**

Gaussian Process Emulator

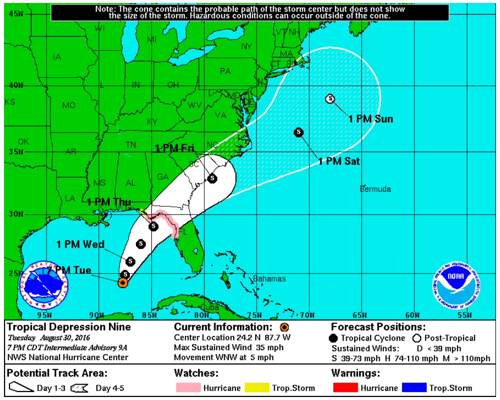
Want $f(x_1),\ldots, f(x_N)$, but only know $f(x_1),\ldots,f(x_n)$, for $n \ll N$.
Need to quantify uncertainty in the estimate?
A statistical inference problem:
    Derive a probability distribution for f given $f(x_1),\ldots,f(x_n)$ (an "emulator")
Popular technique: Gaussian process emulation (Sacks et al. 1989)
Assume $f(x) = m(x) + Z(x)$
$m(x)$ is a parametric function of x (linear, quadratic, spline, …)
Z is a zero mean Gaussian process (the deviation of $f(x)$ from m)
Z is specified with its covariance where the variance σ^2 suggests how far $f(x)$ deviates from $m(x)$



Surrogate Modeling

Inputs

- **Forcing**, input vector **x**
  - Land fall location (lat, lon)
  - Landfall angle of storm approach
  - Minimum central pressure (e.g. 90 nm)
  - Landfall forward speed
  - Radius of maximum winds (e.g. 90 nm)



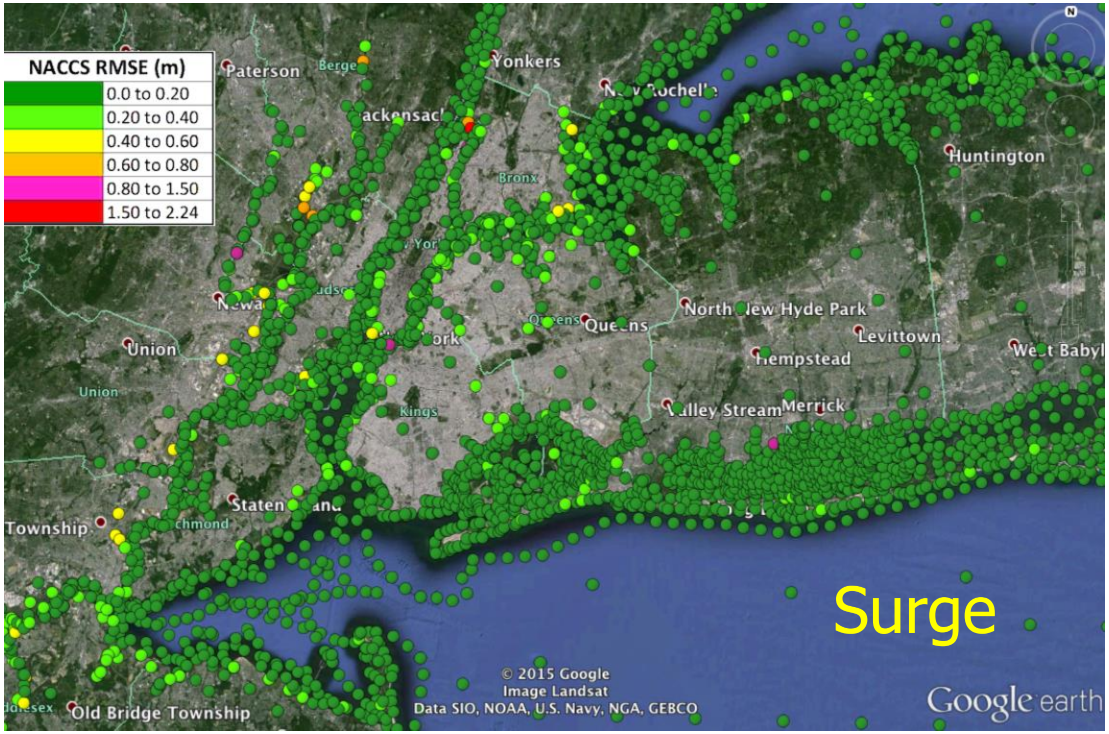
Outputs

- **Response:** Storm **surge**, **wave height**, **wave period,** wave direction, wind speed, wind direction, currents over region

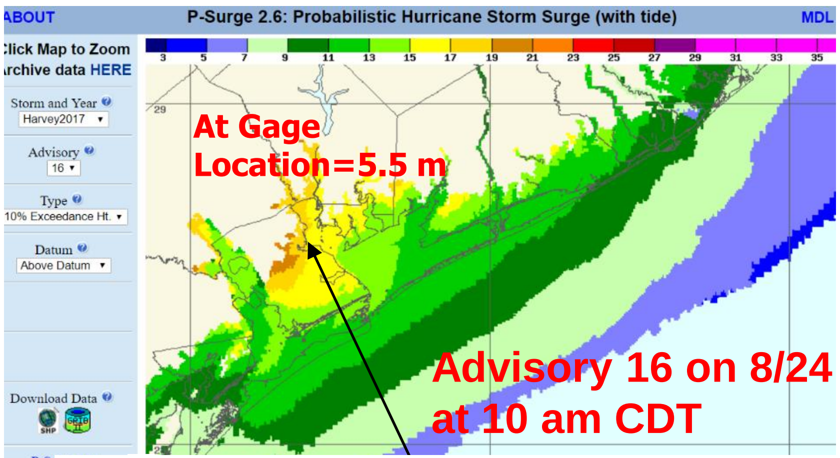
Augment data with dry node information
Reduce dimensionality - Perform PCA to obtain latent space, retain 99.9% of variance – for LA/MS retained ~40 PCs for model trained on peaks and 100 for model trained on time series

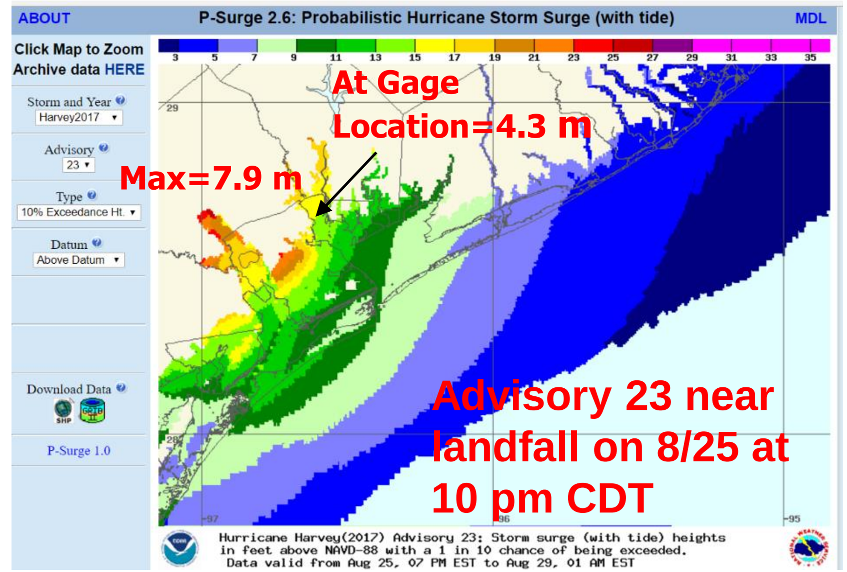
New York Bight LOOCV

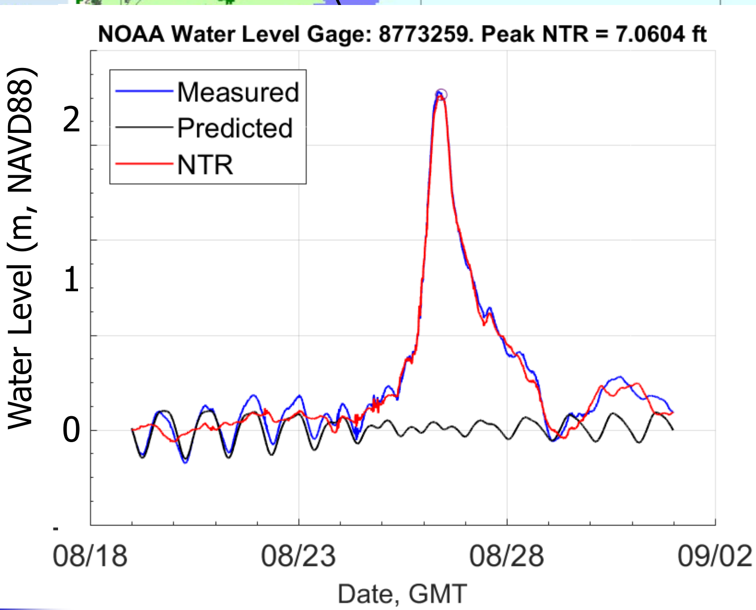
NACCS Surge Training Set Validation
18977 points overall mean RMSE = 0.11 m



NOAA P-Surge Forecast, 10% Exceedance, NAVD88 ft
Hurricane Harvey August 2017





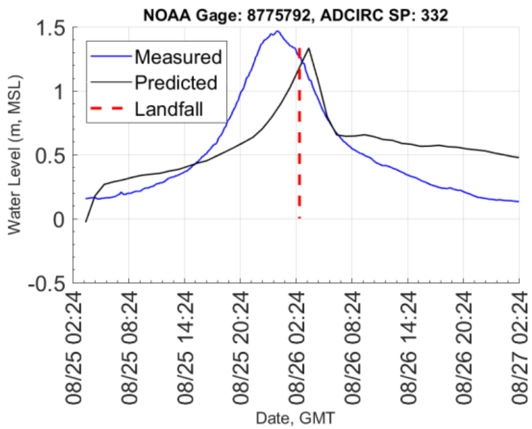


Port Lavaca Gage

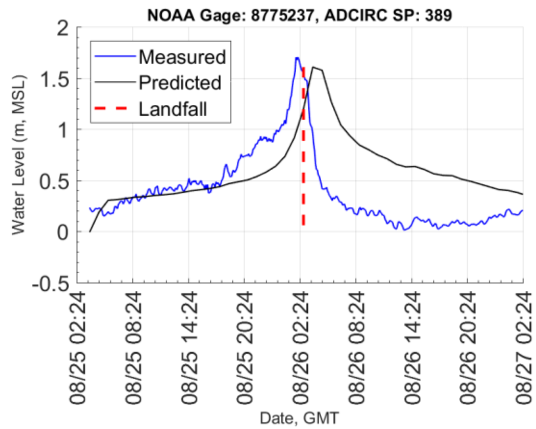
Advisory 16 error: +3.1 m
Advisory 23 error: +1.8 m

CHRP Example simulation for Hurricane Harvey
Validation with Gages for Advisory 16 (36 hours from landfall)

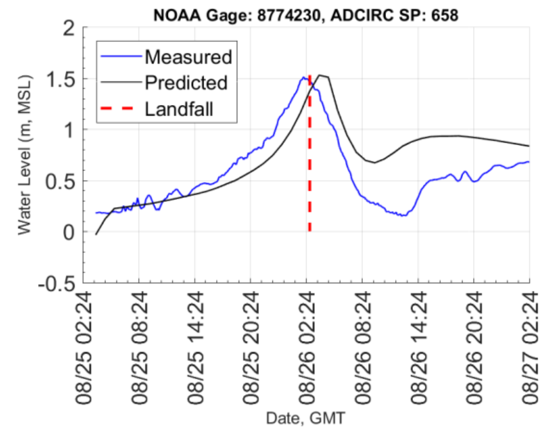
Packary Channel



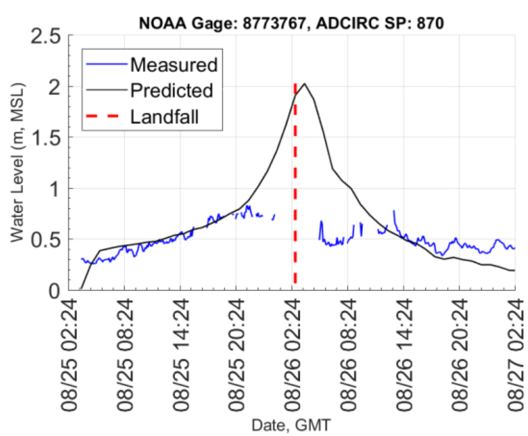
Port Aransas



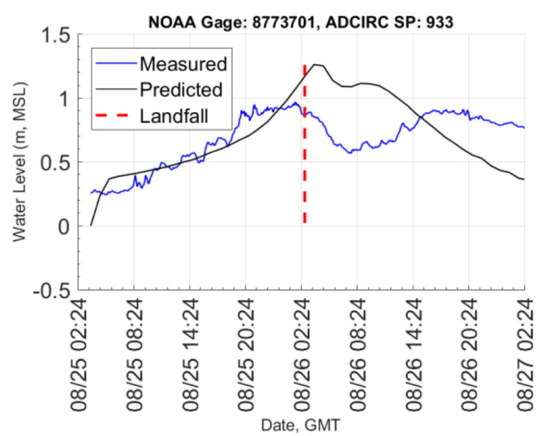
Aransas Wildlife Refuge



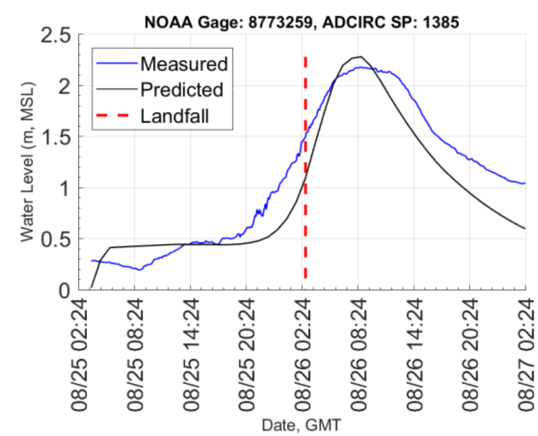
Matagorda Bay Entrance



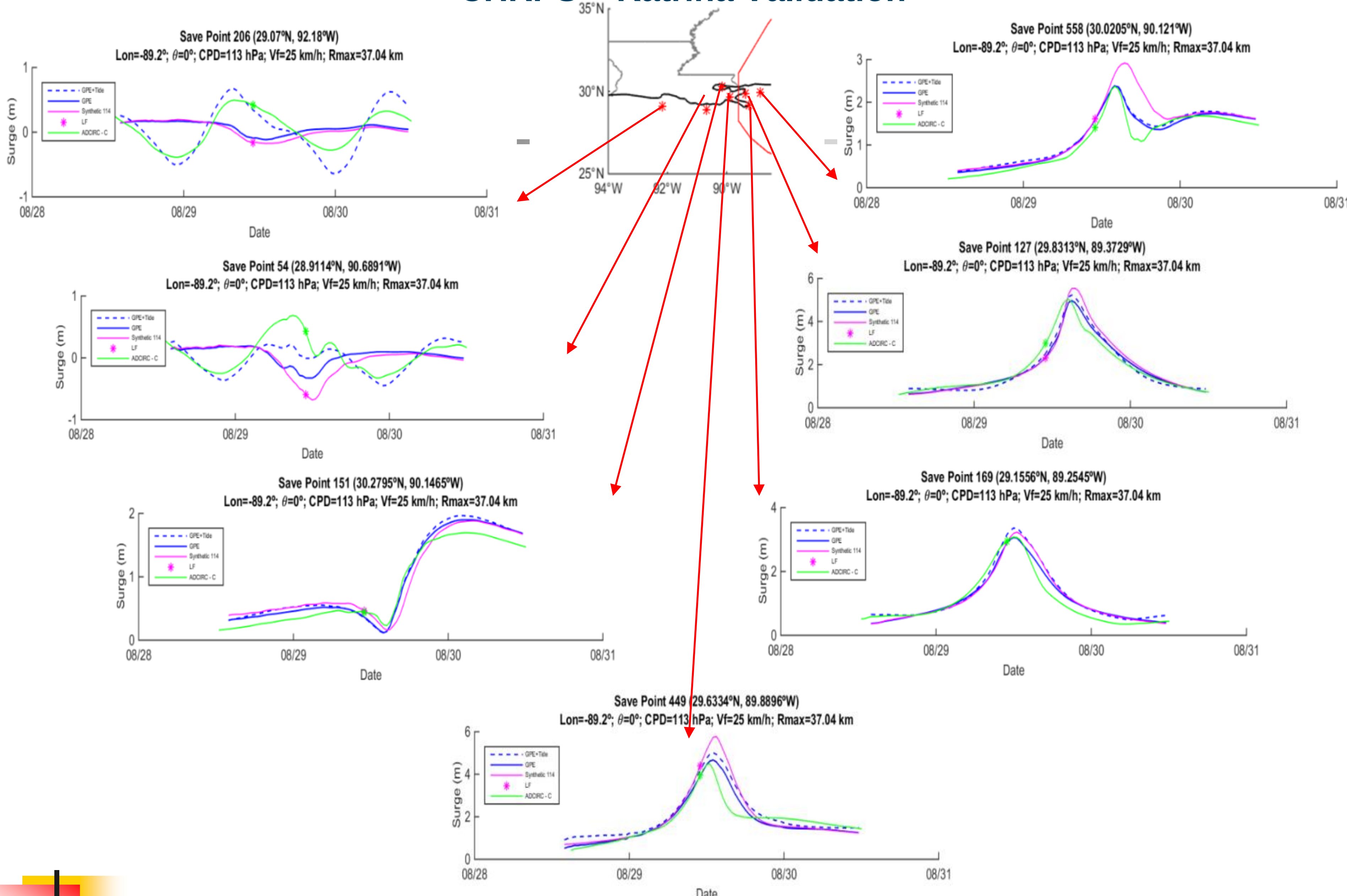
Port O'Connor



Port Lavaca



CHRPS – Katrina Validation



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ERDC Engineer Research and Development Center

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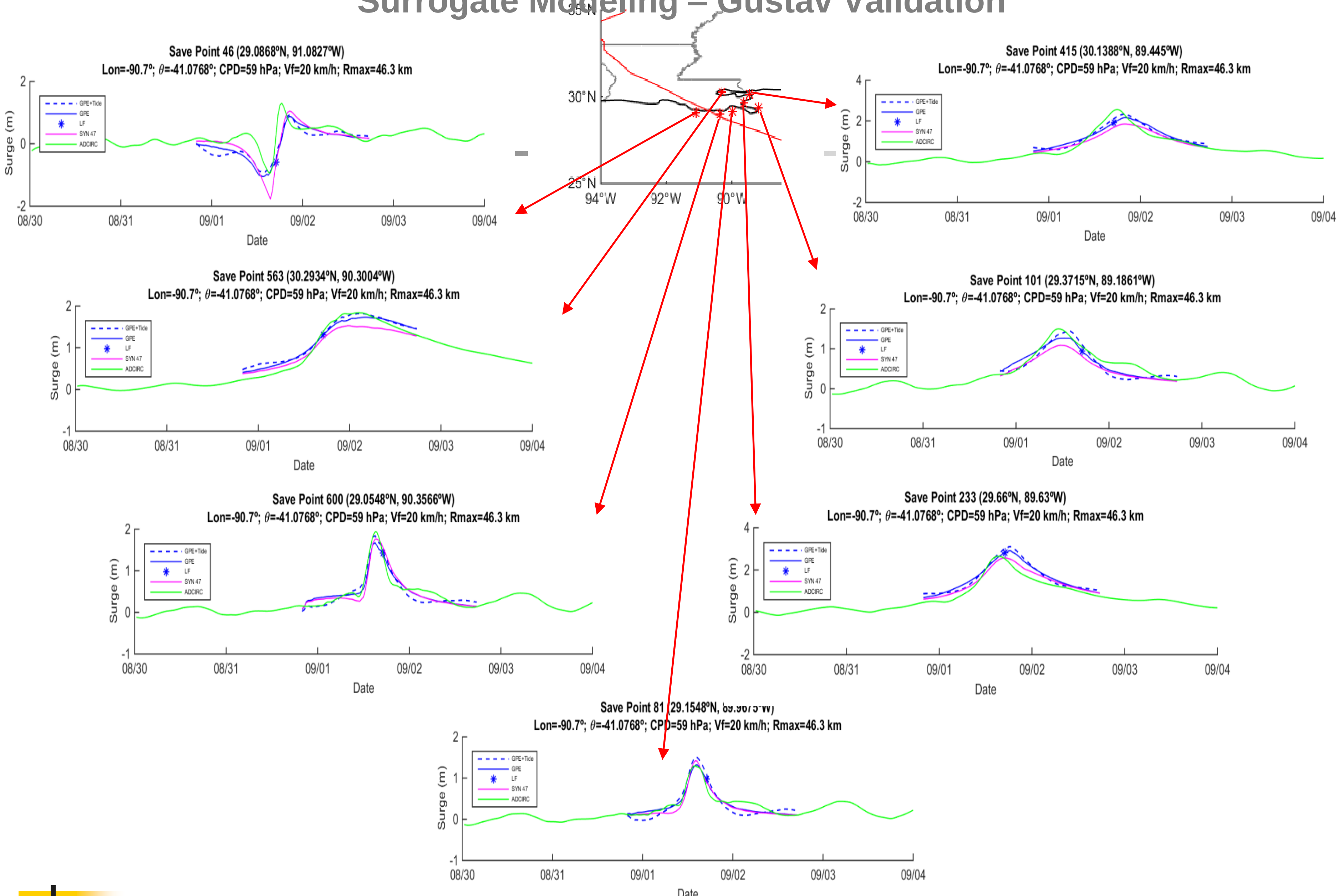
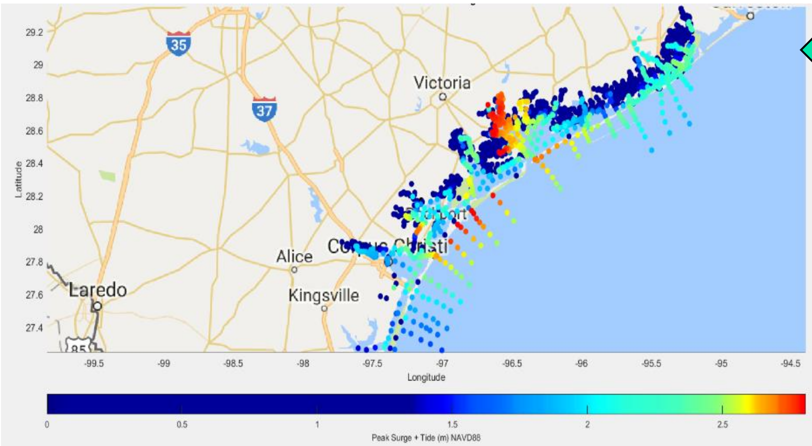
Surrogate Modeling – Gustav Validation

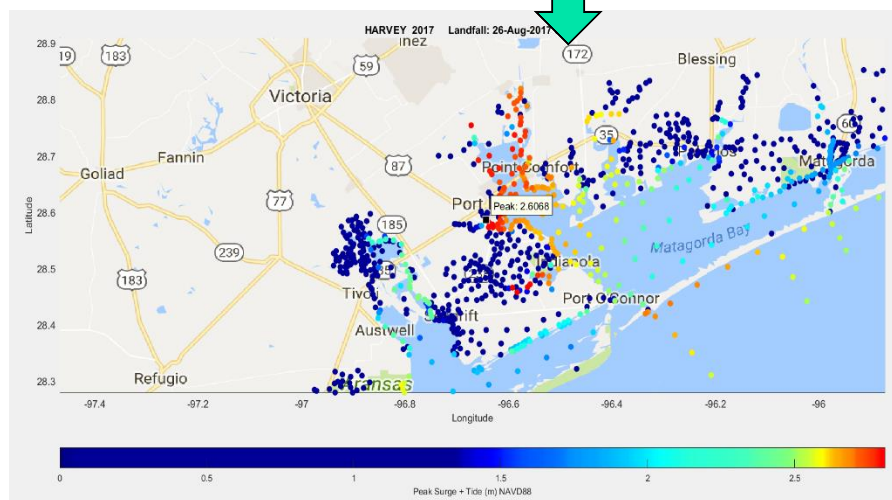


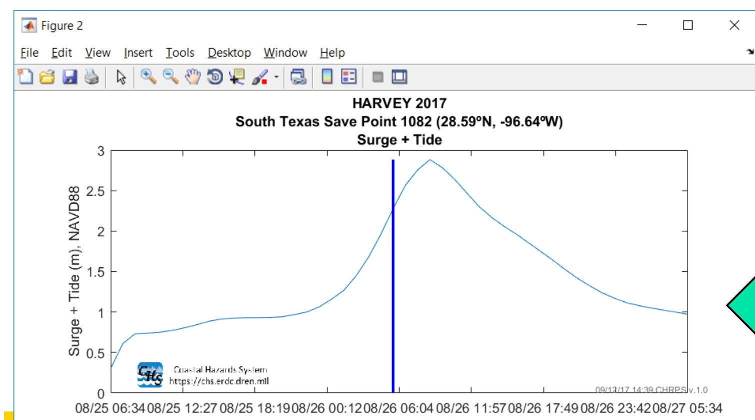
CHRP Surrogate Model Software Interface
Example simulation for Hurricane Harvey



Peak water level output

Zoom in and select a point





Get a plot of time series of surge+tide with landfall indicated

Surrogate Model Uses

- Forecasting in a second
- Import water levels into GIS/GE to illustrate risk
- Scenario analysis
  - Run historical storms with altered parameters
  - Run storms that have not occurred
  - Show the probability of each event separately
  - Varied sea level rise scenarios
- Can be used for risk assessment by running thousands of simulations in probabilistic simulations
- Can add waves, wind, rainfall