Surrogate Modeling for Storm Waves and Surge Forecasts

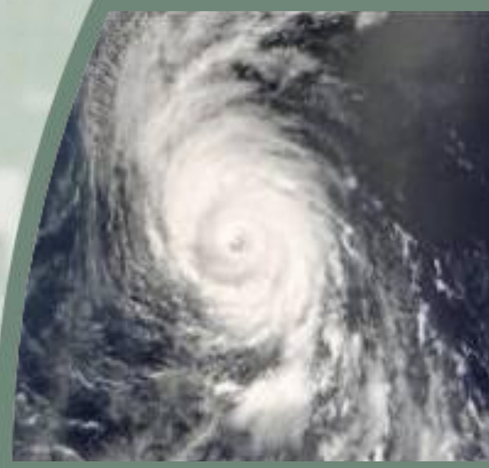
Jane McKee Smith, Jeffrey A. Melby

ERDC Coastal and Hydraulics Laboratory

Alexandros A. Taflanidis, Andrew B. Kennedy

University of Notre Dame

29 October 2013



ERDC
Engineer Research and Development Center

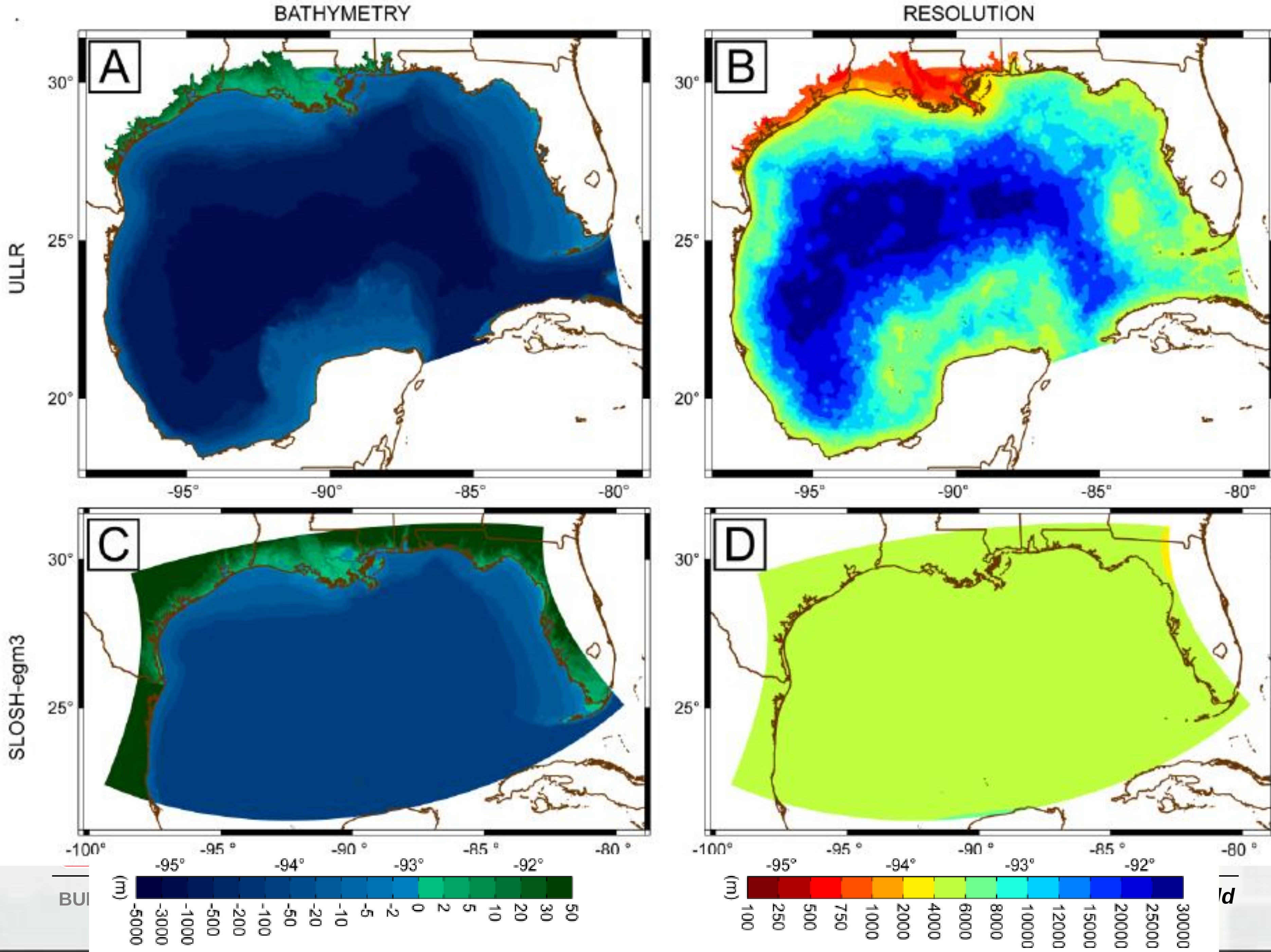
US Army Corps of Engineers®

Motivation

- Need for accurate inundation forecasting is growing
  - Increased coastal development
  - Increased coastal hazard
- Low-fidelity modeling
  - Presently used
  - Probabilistic simulation
  - Inaccurate results in many cases
- High-fidelity modeling
  - Accurate results, with correct forcing
  - Too slow for 100s-1000s of realizations in real time
- Surrogate modeling approach
  - Tap existing databases
  - Good accuracy at low computational cost

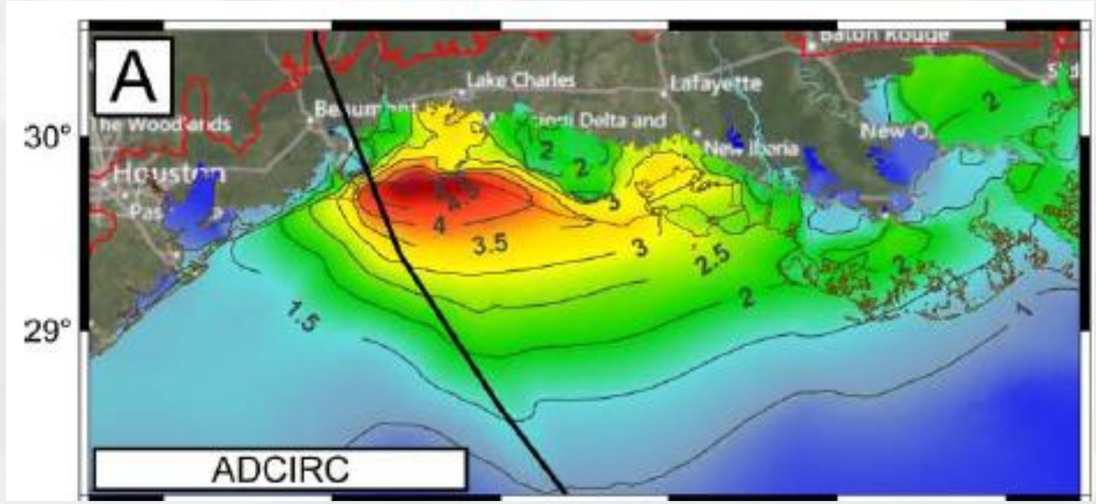
Impact of Low Fidelity Modeling

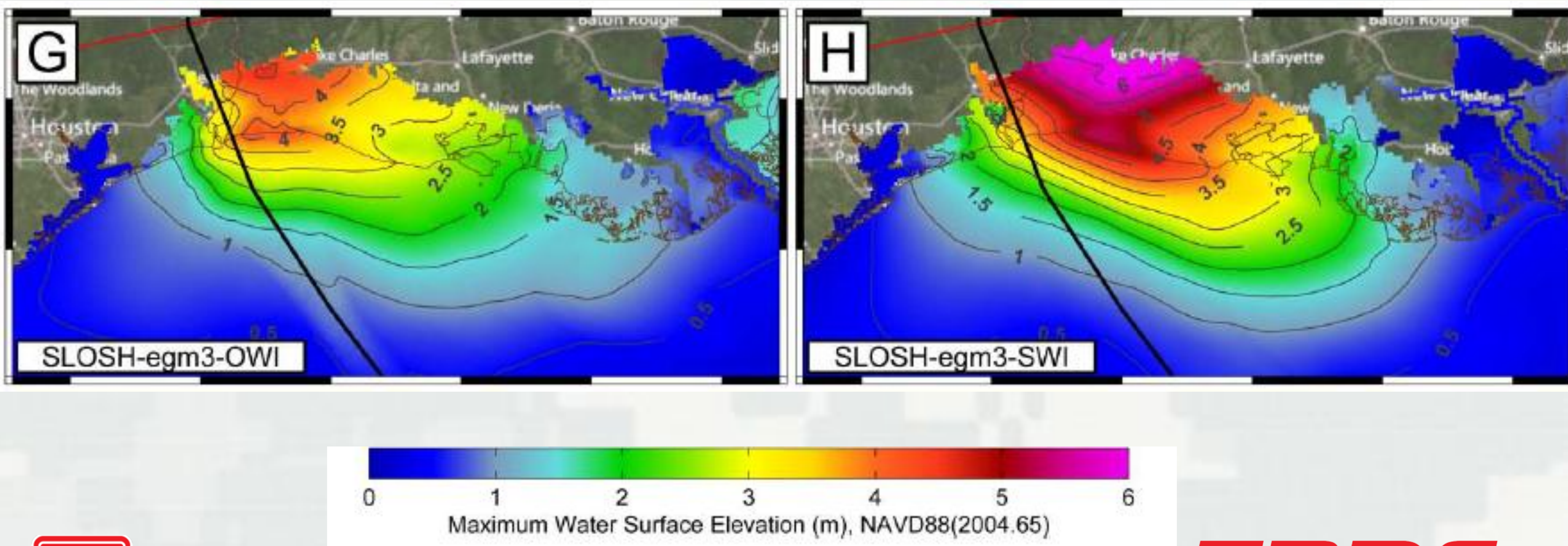
- Kerr et al. 2013 (JGR)
- IOOS project, focused on Gulf of Mexico
- Surge modeling intercomparison
  - ADCIRC
  - FVCOM
  - SELFE
  - SLOSH (no waves or tides, neglects nl advection)
- Hurricanes Rita and Ike



BATHYMETRY
RESOLUTION
ULLR
SLOSH-egm3
A
B
C
D
30°
25°
20°
-100°
-95°
-90°
-85°
-80°
-95°
-94°
-93°
-92°
(m)
-5000 -3000 -1000 -500 -200 -100 -50 -20 -10 -5 -2 0 2 5 10 20 30 50
(m)
100 250 500 750 1000 2000 4000 6000 8000 10000 12000 15000 20000 25000 30000

Rita Surge





BUILDING STRONG®

ERDC

Innovative solutions for a safer, better world

Validation

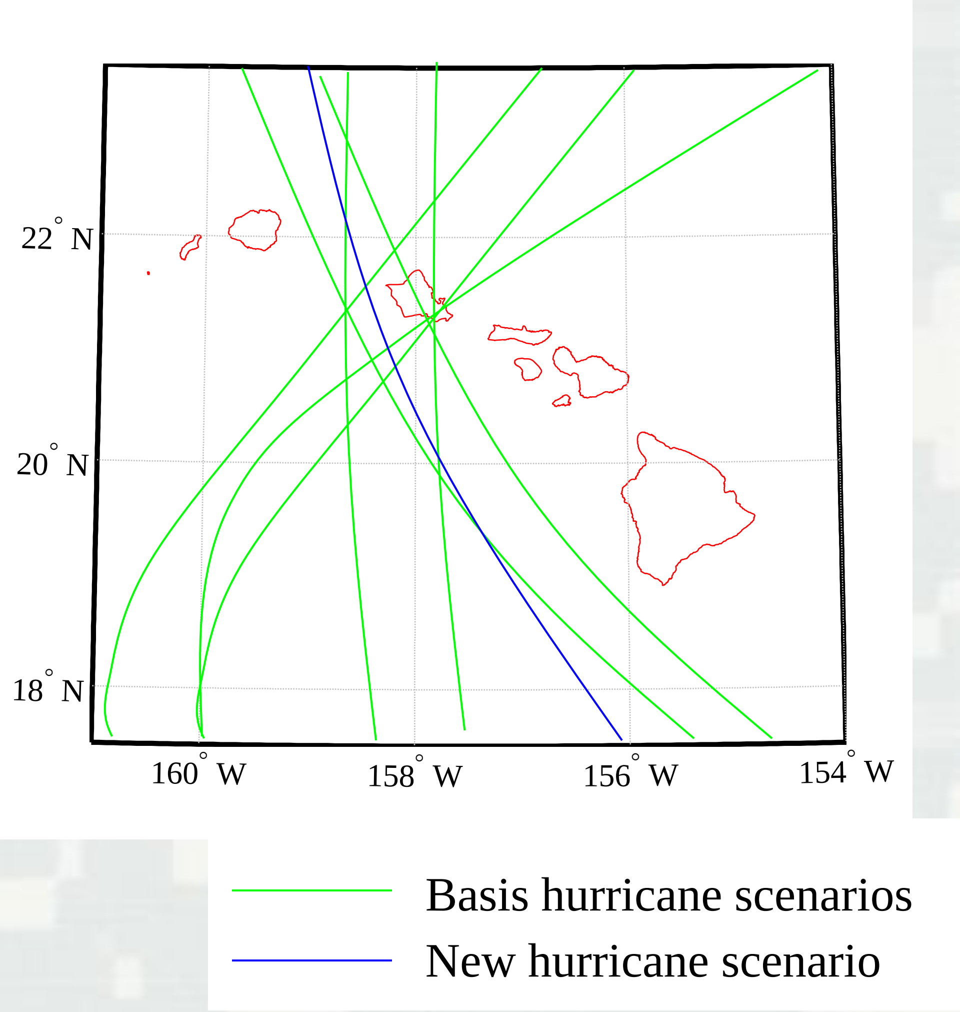
- Rita: 83 HWM, 23 gauge time series
- Ike: 206 HWM, 393 gauge time series
- Errors:
  - ► High-resolution models (> 400,000 nodes, up to 100 m resolution): mean normalized errors 0.33-0.39, correlation coefficients of 0.68-0.74
  - ► SLOSH: mean normalized errors 0.59-0.63, correlation coefficients of 0.50-0.52

Surrogate Modeling

- **Databases of storm scenarios** (high-fidelity modeling). Cover a wide range for characteristics of future regional hurricane/storms.

↓

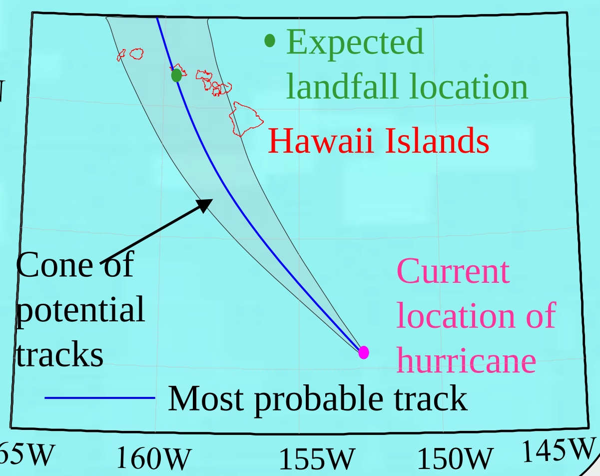
- **Goal:** Use basis scenarios develop an approximate mathematical relationship (surrogate model) for **fast and accurate** prediction of **new** hurricane scenarios.



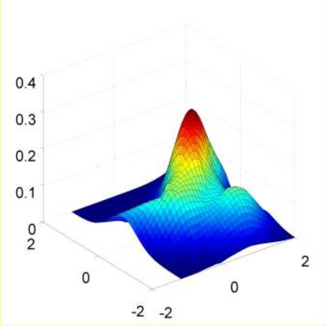
Real-time Hurricane Risk Assessment

4 **stochastic simulation** → Hazard

3 **NWS:** definition of probability distribution for hurricane characteristics $p(x)$



2 **Optimize** surrogate model based on available information



1 **Offline:** Evaluate the high-fidelity model, through high-performance computing

Hawaii: Wave, Surge, and Runup Inundation Database

Wave and surge prediction *(high-fidelity model)*

- High-resolution grids
- SWAN+ADCIRC wave and circulation models
- Validation with tides and Hurricane Iniki

Wave runup prediction

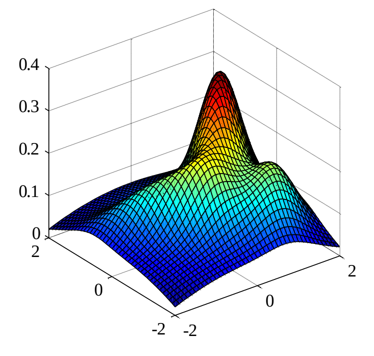
- BOUSS-1D

Wave, surge, and runup inundation database and predictions for new events

- Surrogate modeling

Moving Least Square Response Surface Approximation

Response surfaces: Approximate a function $f(\mathrm{x})$ through NB basis functions



Real Surface

Coefficients for approximation

$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{NB} b_i(\mathbf{x}) a_i\{\mathbf{x}\} = \mathbf{b}(\mathbf{x})^T \mathbf{a}\{\mathbf{x}\}$$

Basis functions

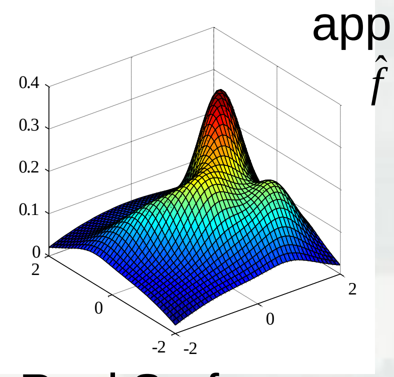
MLS Response Surface Approximation

Response surfaces: Approximate a function *f*(x) through *NB* basis functions

Coefficients for approximation ↓

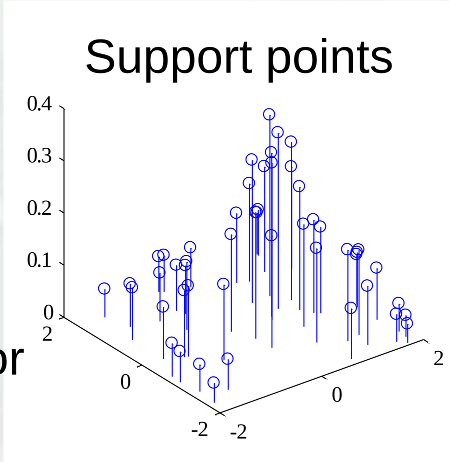
$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{NB} b_i(\mathbf{x}) a_i\{\mathbf{x}\} = \mathbf{b}(\mathbf{x})^T \mathbf{a}\{\mathbf{x}\}$$

↑ Basis functions



Real Surface

Calculate *f*(.) in *NS* support points, and use them to select a{.} by minimizing a weighted square error



Error over all support points ↓

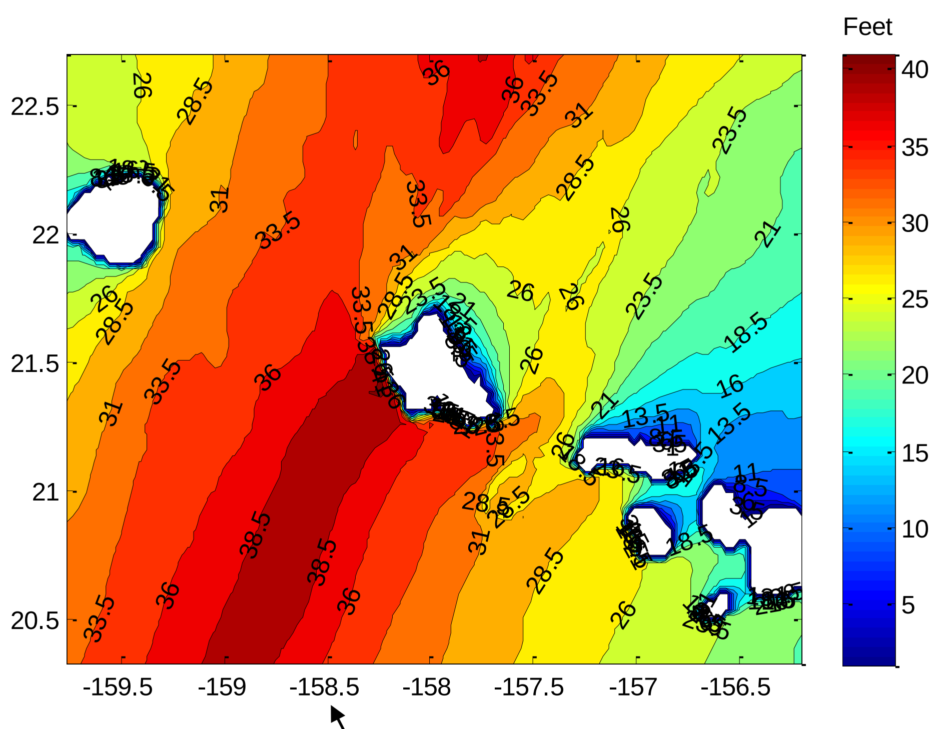
$$J_R\{\mathbf{x}\} = \sum_{I=1}^{NS} w\{\mathbf{x}\}[\hat{f}(\mathbf{x}_I) - f(\mathbf{x}_I)]^2$$

$$= \sum_{I=1}^{NS} w\{\mathbf{x}\}[\mathbf{b}(\mathbf{x}_I)^T \mathbf{a}\{\mathbf{x}_I\} - f(\mathbf{x}_I)]^2$$

↑ weights

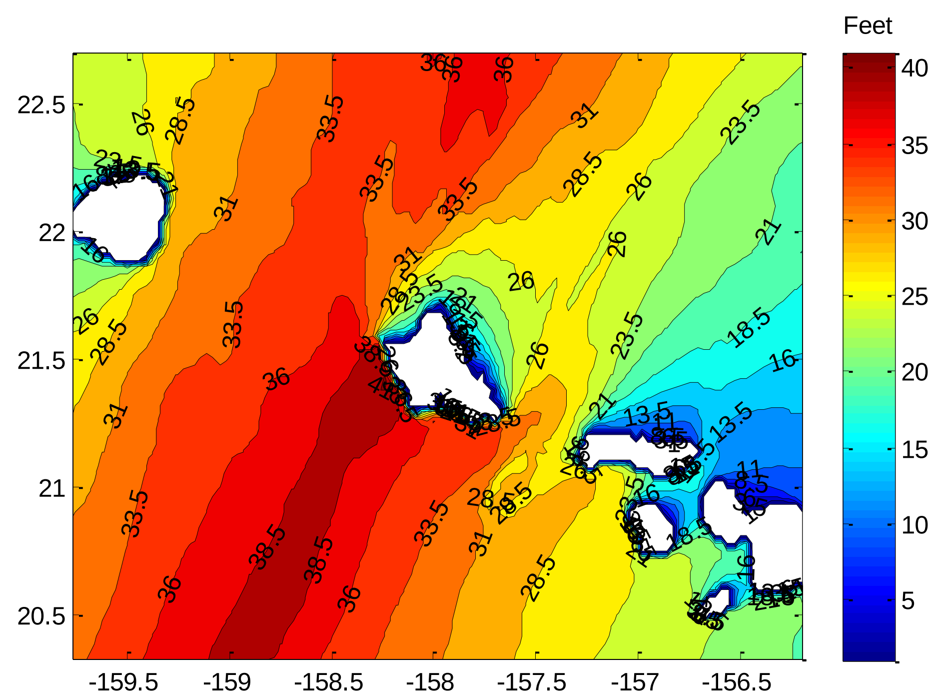
Wave Height Forecast: Hawaii

High-fidelity model predictions



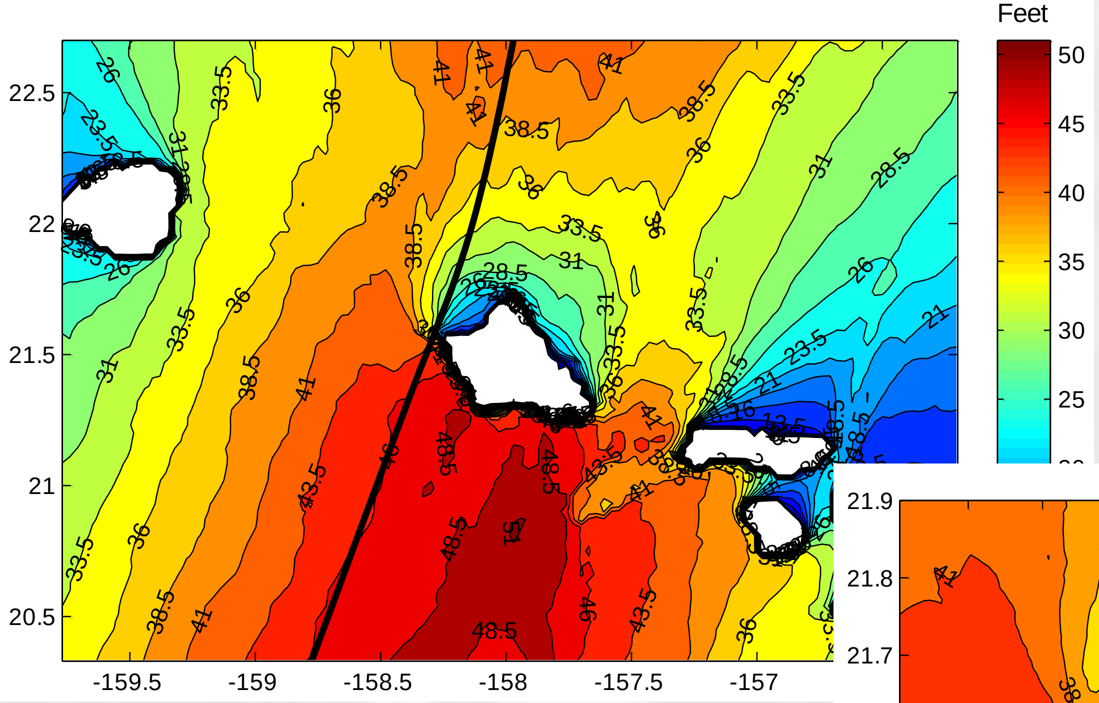
2000 computational hours per scenario

Surrogate model predictions

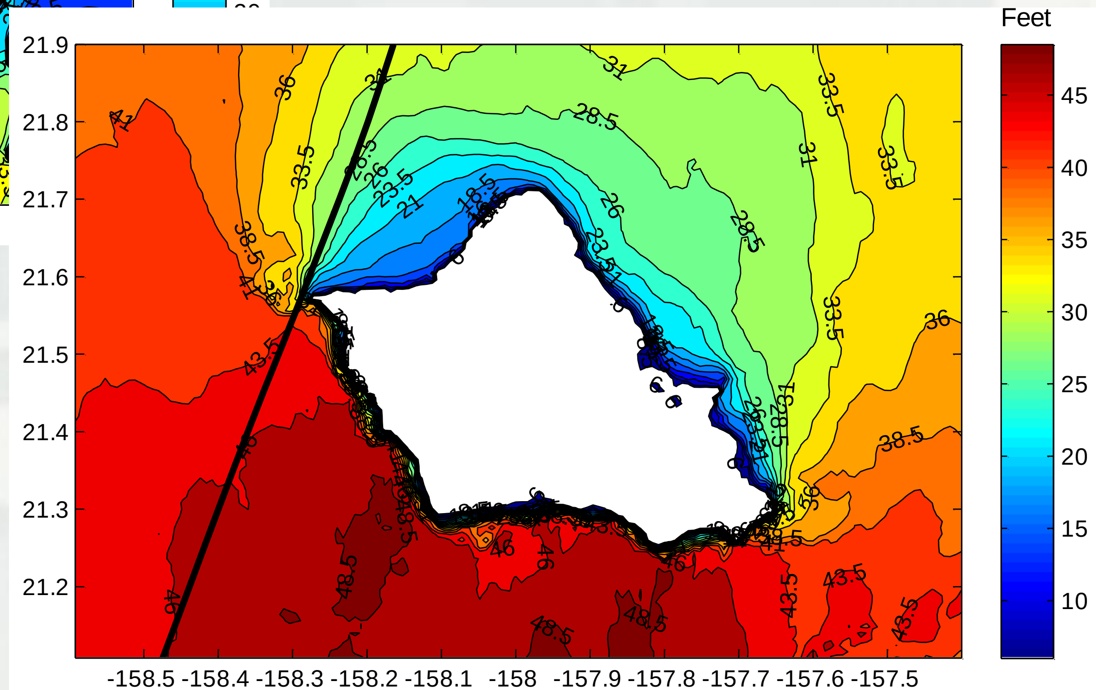


0.08 sec per scenario

Probabilistic Risk Assessment

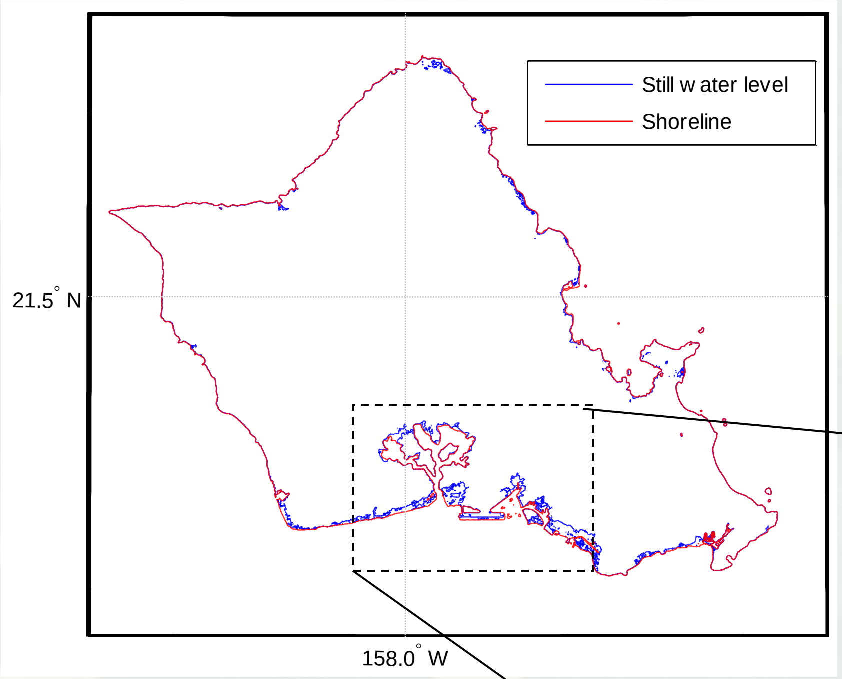


Significant wave height with probability of exceedance 10%

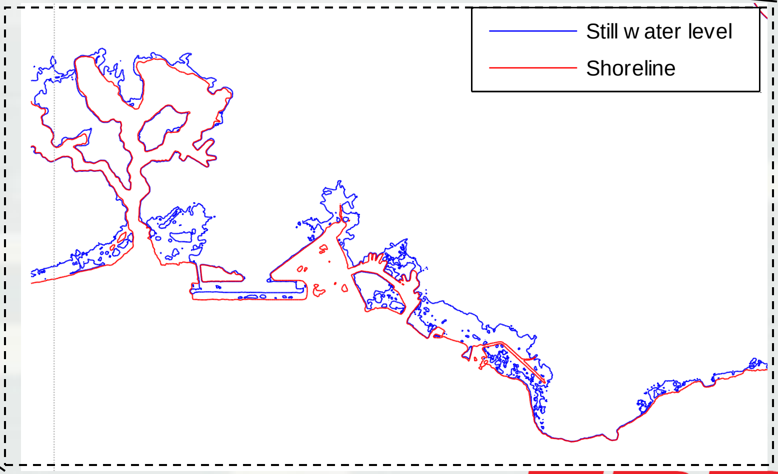


Once surrogate model has been optimized can be efficiently used for risk assessment

Probabilistic Risk Assessment



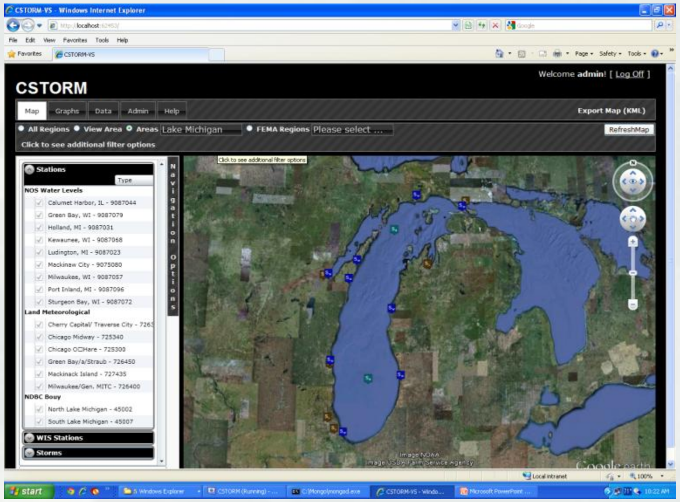
Still water level with probability of exceedance 10%

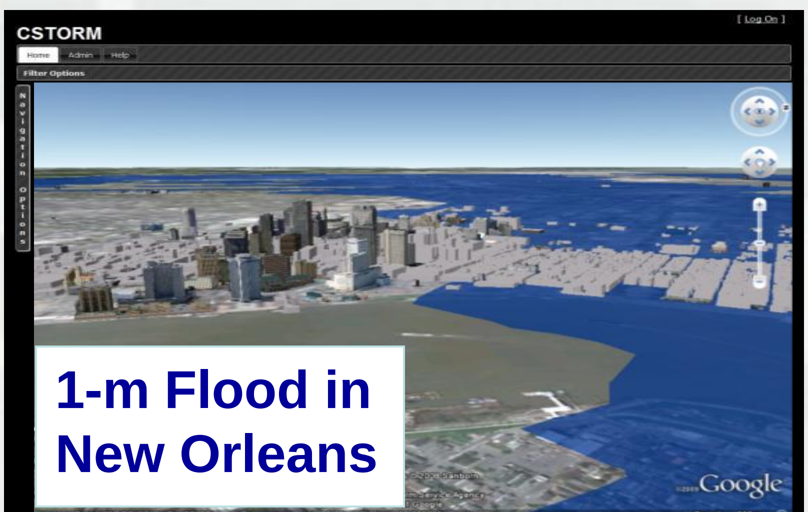


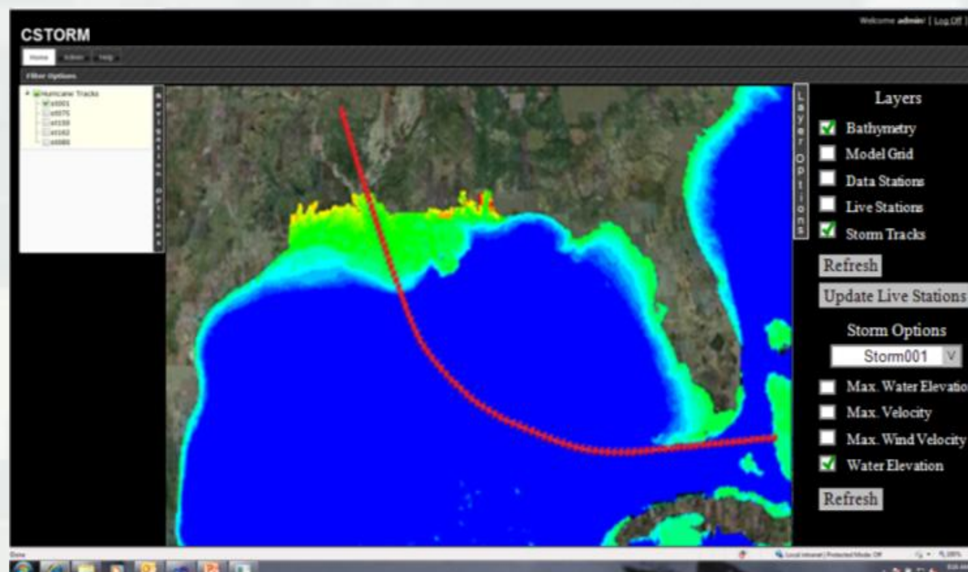
CSTORM-DB

Coastal Storm Database and Visualization System

- Leveraging USACE regional coastal studies
- Gathering historical measurements and high-fidelity climate, surge, and wave modeling results
- Creating national storm database
- Web tool with Google Earth map interface
- Data mining and analysis tools (plotting, extremal analysis)
- Surrogate modeling from database (high-fidelity surge prediction layer)





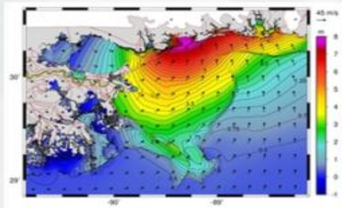


Current Implementation: New Orleans

- 446 storm database. Grid for surge predictions includes 568,000 points (very large dimensional).

- Main challenge
  - Very high dimensional input, makes optimization and implementation of surrogate model less efficient

- Solutions
  - Principal component analysis: exploit correlation of output to reduce computational effort
  - Kriging: improvement over response surfaces. Does not involve computational expensive matrix inversions at the implementation stage, reducing computational burden.



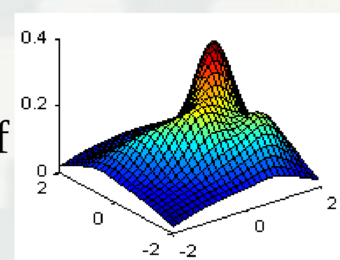
Initial database, established though high-fidelity modeling

Parameterize hurricane scenarios in database

Correct nodes that have remained dry for some storms

Perform PCA to obtain latent space

Develop kriging model in latent space. Obtain mean predictions and variance of error related to these predictions



For each new scenario

Establish kriging approximation in latent space

Transform back to original space

[If needed] Address uncertainty in scenario to calculate risk (Monte Carlo Simulation)

Preliminary Results

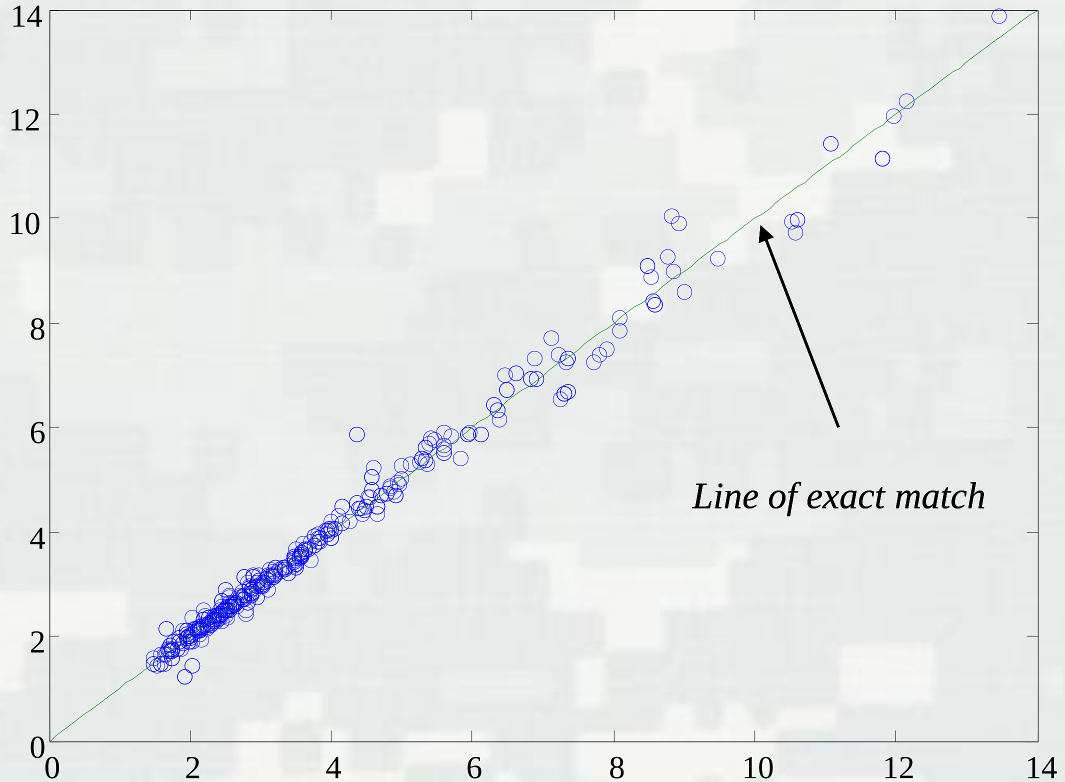
- Accuracy of developed surrogate model
  - 4% average error in predictions of storm surge when considering points in the New Orleans grid that were inundated at least in 50% of the storms in the initial database
  - Error increases to 5% when extending to points that were inundated for only 10% of the storms in our initial database

- Misclassification (predicting an area is flooded when it is not and vice versa) is just 2% over the entire New Orleans grid.

Surge Predictions

High fidelity model surge (ft) predictions

2000 computational hours per scenario

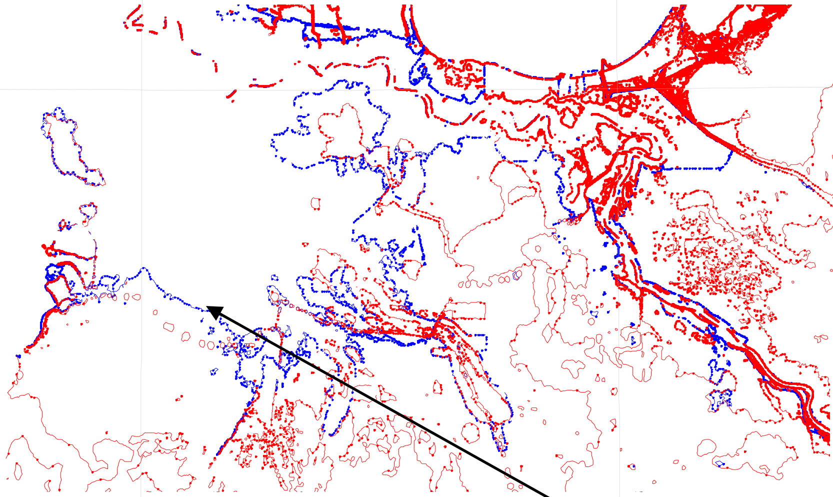


Surrogate model surge (ft) predictions

0.1 sec per scenario

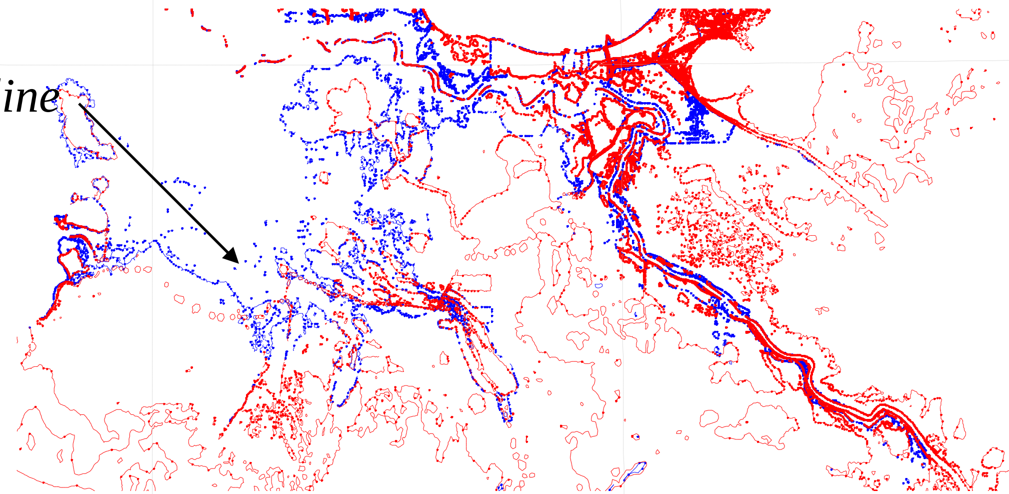
Inundated Areas Predictions

High-fidelity model predictions



Inundation line

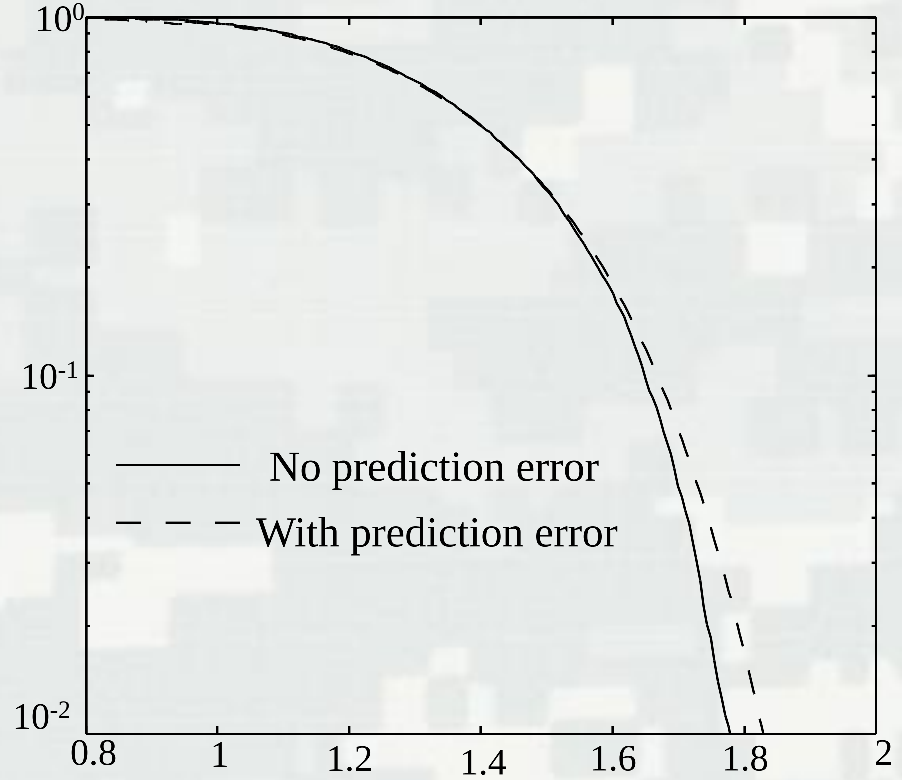
Surrogate model predictions



Good match for predicting inundated areas

Risk Assessment Results

Probability of exceeding threshold



Threshold for surge (m)

Including the prediction error of metamodel influences the risk assessment results for low-probability events

Conclusions

- Surrogate modeling provides framework for dynamic and fast evaluation of waves, surge and inundation
- High-fidelity, high-resolution models to simulation hundreds of hurricanes provides basis
- Deterministic or probabilistic estimates
- Results in seconds to minutes

Modeling Gaps:

Overland wave propagation

- **wetlands**
- **urban areas**

Morphology evolution

Coupling of surge and rain/runoff models

Field measurements