Tropical Storm Response Prediction Using Surrogate Models

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Motivation

**Challenge**

- Hurricane landfall location is highly uncertain
- Present predictions are either *stochastic/low fidelity* or *deterministic/medium fidelity/ad-hoc*
- High-fidelity (HF) modeling is resource intensive
- Many scenarios required
- Processes are *nonlinear and complex*
- Model output is very *high-dimensional*

**Support**

- High spatial/temporal correlations
- Regional HF modeling complete in some regions
- Many robust approaches to surrogate modeling
- Strong demand for high fidelity, rapid estimations for emergency management and real time/static risk assessment
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
Unique Leveraging Opportunities

• Disk storage and wide band internet are relatively inexpensive

• Regional high-fidelity modeling is being done for federal projects

• Regional studies represent parameter and probability space with an efficient sample

• Coastal Hazards System data with NACCS, Gulf of Mexico data
Storm Selection

Characterization of Storm Climate (Forcing)

Tropical Cyclones (Synthetic)

Extra-tropical 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)

Response Statistics

Combined Joint Probability

Annual Exceedance Probability

Average Recurrence Interval

Confidence Levels

CHS

- Water level (storm surge, astronomical tide, SLC)
- Currents
- Wind speed, direction
- Wave height, period, direction
Coastal Hazards System

LA/MS – 446 storms
• \( C_p \): 900 - 975 mb
• \( V_f \): 11 – 33 km/hr
• \( R_{\text{max}} \): 11 – 51 km

NACCS – 1050 storms
• \( C_p \): 915 – 985 mb
• \( V_f \): 12 – 88 km/hr
• \( R_{\text{max}} \): 25 – 174 km
Coastal Hazards System

- NACCS: 19k points
- LA/MS/TX: 10k points
- LA grid: 200k points
Surrogate Strategy

Study Overview

CHS Regional storm modeling

Train metamodel
Neural Network
GPE

Validate metamodel

NOAA cyclone track forecast

Predict high-fidelity response
Surrogate Modeling

Data Preparation

- **Parameterize Forcing**, input vector $\mathbf{x}$
  - Land fall location (lat, lon)
  - Angle of storm approach
  - Minimum central pressure
  - Average forward speed
  - Radius of maximum winds
- Response: Peak and time series of storm **surge**, **wave height**, **wave period**, wave direction, wind speed, wind direction, currents
- **Time series**: 46.5 hrs, 30 min time step, 21.5 hrs before landfall to 24 hrs after
- Augment data with **dry node** information
- Output vector $\mathbf{y}$
- Perform PCA to obtain latent space $\mathbf{z}$, retain 99.9% of variance
Surrogate Modeling

Machine learning modeling techniques are basically weighted interpolation assigning a decreasing weight with increasing separation distance.

**Kriging Model**
- Jia and Taflanidis (2013) and Kim et al. (2014)
- Given latent space \( z \) ...
- Kriging to obtain predictions and statistics of prediction error

**ANN Model**
- Kim et al. (2014)
- Multilayer feed forward network
- Levenberg-Marquardt algorithm (LMA) for surface fitting
- 16 - 25 neurons
- Training: 70% of storms
- Validation: 15% of storms
- Testing: 15% of storms
- Performance: correlation coeff > 0.95


Artificial Neural Network

Wave Height and Period Training Set Validation, LA

Predicted Hs (m) vs Targeted Hs (m)
- cc = 0.984
- mse = 0.0141

Predicted Tm (s) vs Targeted Tm (s)
- cc = 0.984
- mse = 0.0655

Average of MSE vs Number of save point

Average of CC vs Number of save point

MSE and CC plots for different training sets.
Artificial Neural Network

Surge

Correlation Coefficient (CC)
- 0.99 to 1.00
- 0.98 to 0.99
- 0.97 to 0.98
- 0.95 to 0.97
- 0.60 to 0.95

LA RMSE (m)
- 0.0 to 0.20
- 0.20 to 0.30
- 0.30 to 0.40
- 0.40 to 0.50
- 0.55 to 0.73
Wave Height and Period Training Set Validation

Freeport, TX

Artificial Neural Network

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>RMSE</th>
</tr>
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<tbody>
<tr>
<td>Surge</td>
<td>0.99</td>
<td>0.40 m</td>
</tr>
<tr>
<td>$H_m0$</td>
<td>0.98</td>
<td>0.15 m</td>
</tr>
<tr>
<td>$T_p$</td>
<td>0.95</td>
<td>0.48 s</td>
</tr>
</tbody>
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- $H_m0$: Correlation coefficient = 0.987, MSE = 0.0311
- $T_p$: Correlation coefficient = 0.961, MSE = 0.14

Mean square error (MSE) and correlation coefficient (CC) for surge, $H_m0$, and $T_p$.
NACCS Surge Training Set Validation – Coefficient of Determination
18977 points overall mean $R^2 = 0.95$
Kriging

NACCS Surge Training Set Validation – Correlation Coefficient
18977 points overall mean RMSE = 0.11 m
Surrogate Modeling

Model Validation
Hurricane Katrina Surge

Artificial Neural Network

Point 03 (Station ID: 8762372)

- surrogate model
- SWAN+ADCIRC
- measured data

Point 04 (Station ID: 8760922)

- surrogate model
- SWAN+ADCIRC
- measured data

Kriging

Save Point 3

Katrina SP03, LACPR 164

Save Point 4

Katrina SP04, LACPR 167

835 points run in 0.018 sec
Hurricane Gustav Surge

Artificial Neural Network

Save Point 4

Save Point 9

Save Point 18

Kriging
Surrogate Modeling

Deployment

USACE Distribution
1. CHS-CHRP – stand-alone program
2. GeoTIFF, SHP files through secure web service

Real-Time Risk
Incorporate into, for example, HEC-FIA for rapid real-time or static hazard, vulnerability and risk assessment, FRM

GIS
Rapid high-fidelity flood prediction and visualization
Summary

- Coastal Hazards System – Regional high-fidelity efficient coastal storm data resource
- High-fidelity storm response surrogate modeling
  - Artificial Neural Network and Kriging
  - Predict surge, significant wave height, peak wave period
  - Model error is reasonably low
  - Computes regional response $<< 1$ sec.
Surrogate Modeling

Thanks for listening...Questions?