# Analysis & Optimization of Electricity Infrastructure Hardening Measures

Workshop for Research in
Electricity Infrastructure Hardening

Gainesville, FL

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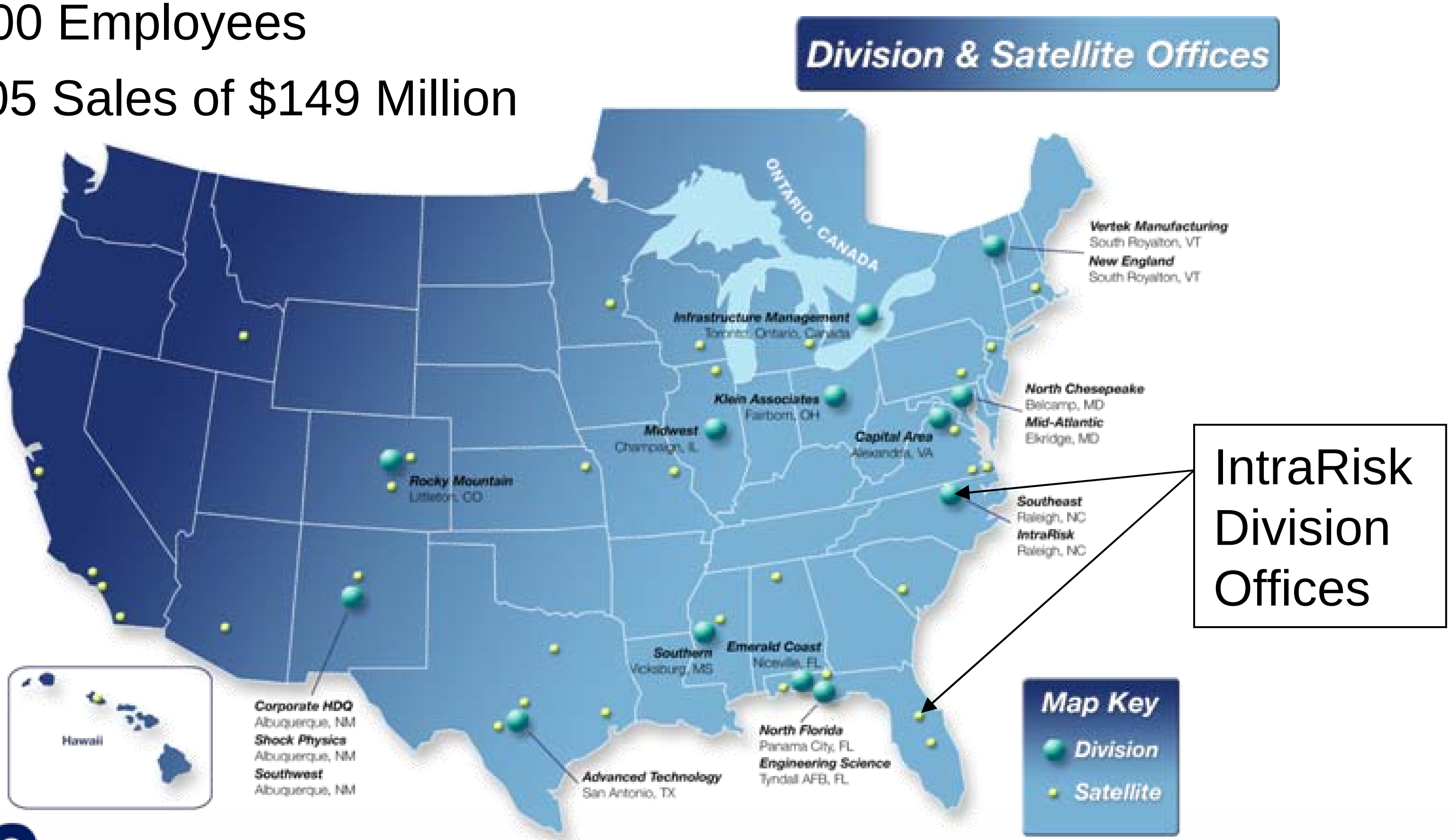
APPLIED RESEARCH ASSOCIATES, INC.
An Employee-Owned Company

# Outline

- ARA Overview
- Stochastic Damage Modeling with Example Applications
- Tree Blowdown
- Coastal Flooding
- Research Recommendations

# Applied Research Associates, Inc.

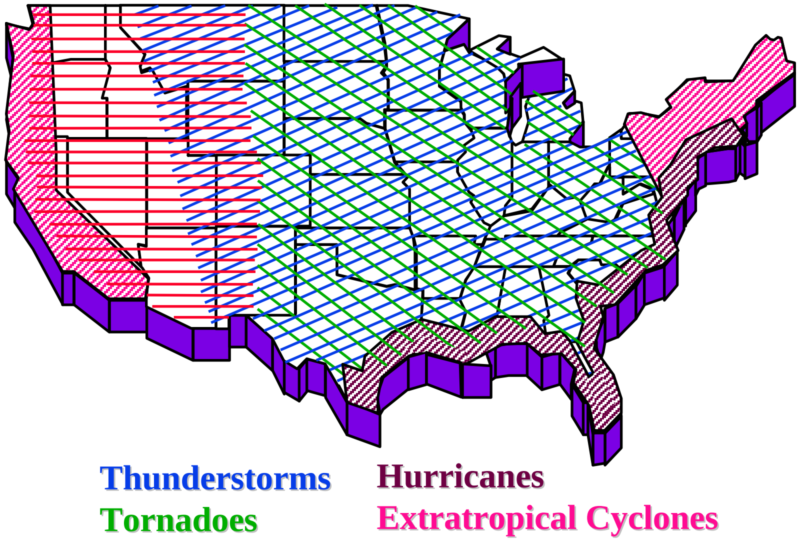
- Founded in 1979 – Employee Owned
- 1,100 Employees
- FY05 Sales of $149 Million



# Wind Engineering Capabilities

- Over 80 person-years of wind engineering experience
- Over 200 wind engineering publications
- Validated wind hazard and vulnerability models for accurate risk assessment
- Over 20 wind engineering software tools

**ARA's Wind Hazard Models**




- Extensive post-storm damage investigation experience

# Significant Projects/Activities

- Transmission line risk studies in U.S., Canada, & Caribbean
- Tornado risk assessments for nuclear power plants
- FEMA hurricane loss evaluation methodology (HAZUS)
- ASCE 7 design wind speeds for Gulf & Atlantic coasts
- USACE risk-based levee design criteria development
- Florida Residential Construction Mitigation Program
- Building code studies in FL, NC, SC, and TX
- ASTM wind borne debris standards
- Worldwide hurricane climatology studies for wind tunnels

# Stochastic Damage Modeling

- Transmission and distribution systems are highly vulnerable to hurricanes
- Regional response and recovery efforts are severely impacted by power outages
- Utilities must find the best balance between costs of hardening, maintenance costs, and outage impacts
- Historical data and lessons learned are necessary but not sufficient for optimal decisions

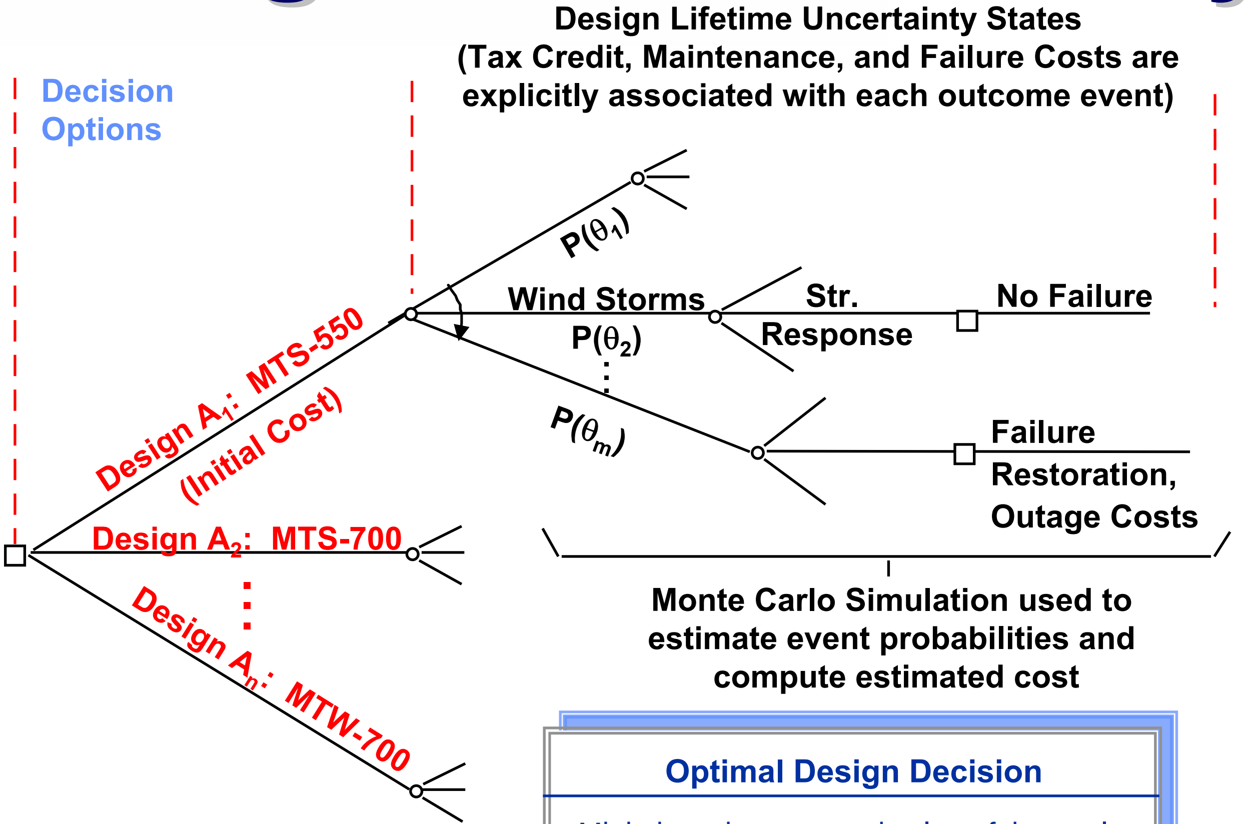
→ Stochastic damage models are needed to optimize electricity infrastructure hardening measures

# Hardening Measures

- Strengthening
  - Pole and tower designs
  - Conductors and conductor connections

- Maintenance
  - Invest additional resources in inspecting and repairing degraded system components
- Redundancy
  - Multiple paths

# Optimal Transmission Line Design Decision Analysis




| Outcomes | Costs |
|---|---|
| . | . |
| . | . |
| . | . |
| $X(\bar{A}_1,\theta_q)$ | $u_{1q}$ |
| . | . |
| . | . |
| . | . |
| $X(\bar{A}_1,\theta_r)$ | $u_{1r}$ |
| . | . |
| . | . |
| . | . |
| $X(\bar{A}_1,\theta_t)$ | $u_{1t}$ |

$$E\left[u\left(A_1\right)\right]=\sum_{i=1}^{t}P\left(\theta_i\right)u_{1i}$$

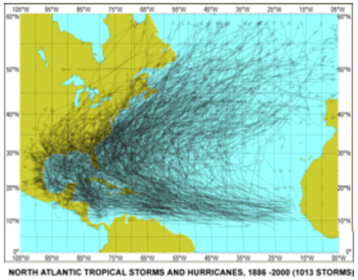
**Optimal Design Decision**

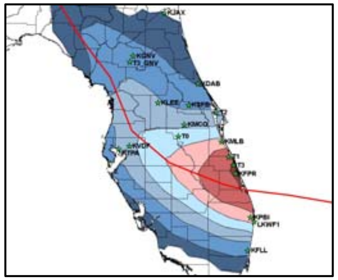
Minimizes the expected value of the total lifetime costs, discounted to present worth

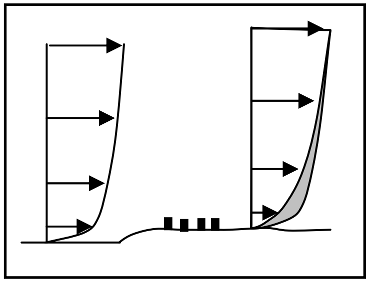
$$E\left[u\left(A^*\right)\right]=\min_{j=1,n} E\left[u\left(A_j\right)\right]$$

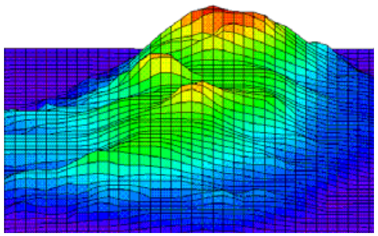
# Modeling Components

Event Risk* | Wind Fields* | Terrain | Trees | Topography



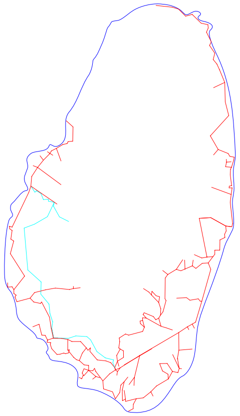



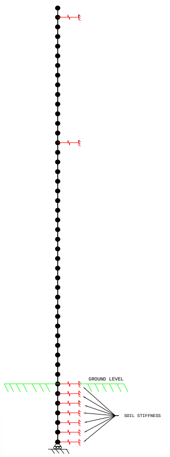


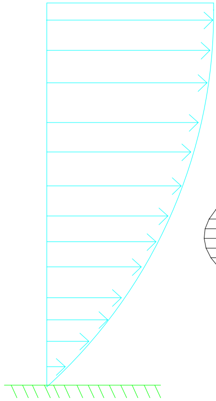


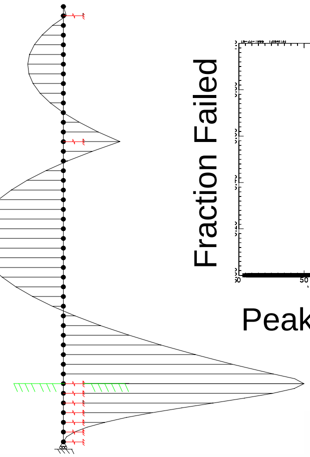
*Hurricane, Thunderstorm, Tornado, Winter storm

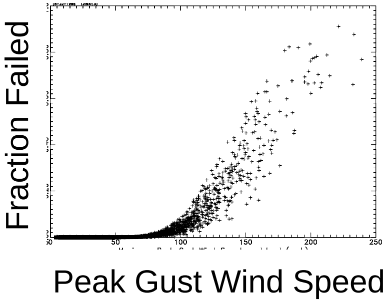
Line Locations | Structures | Wind Loads | Failure Probabilities | Economics

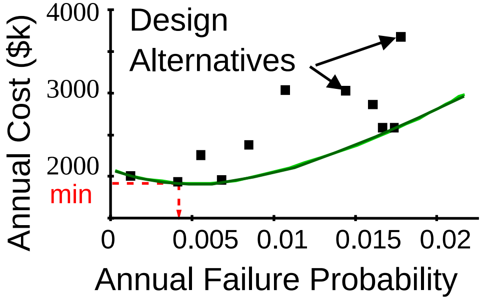










# Optimum Risk-Based Design

Hurricane Simulation (Windspeed, Direction as Function of Position)

↓

Transmission Line Geometry (Length, Orientation, Geographic Location)

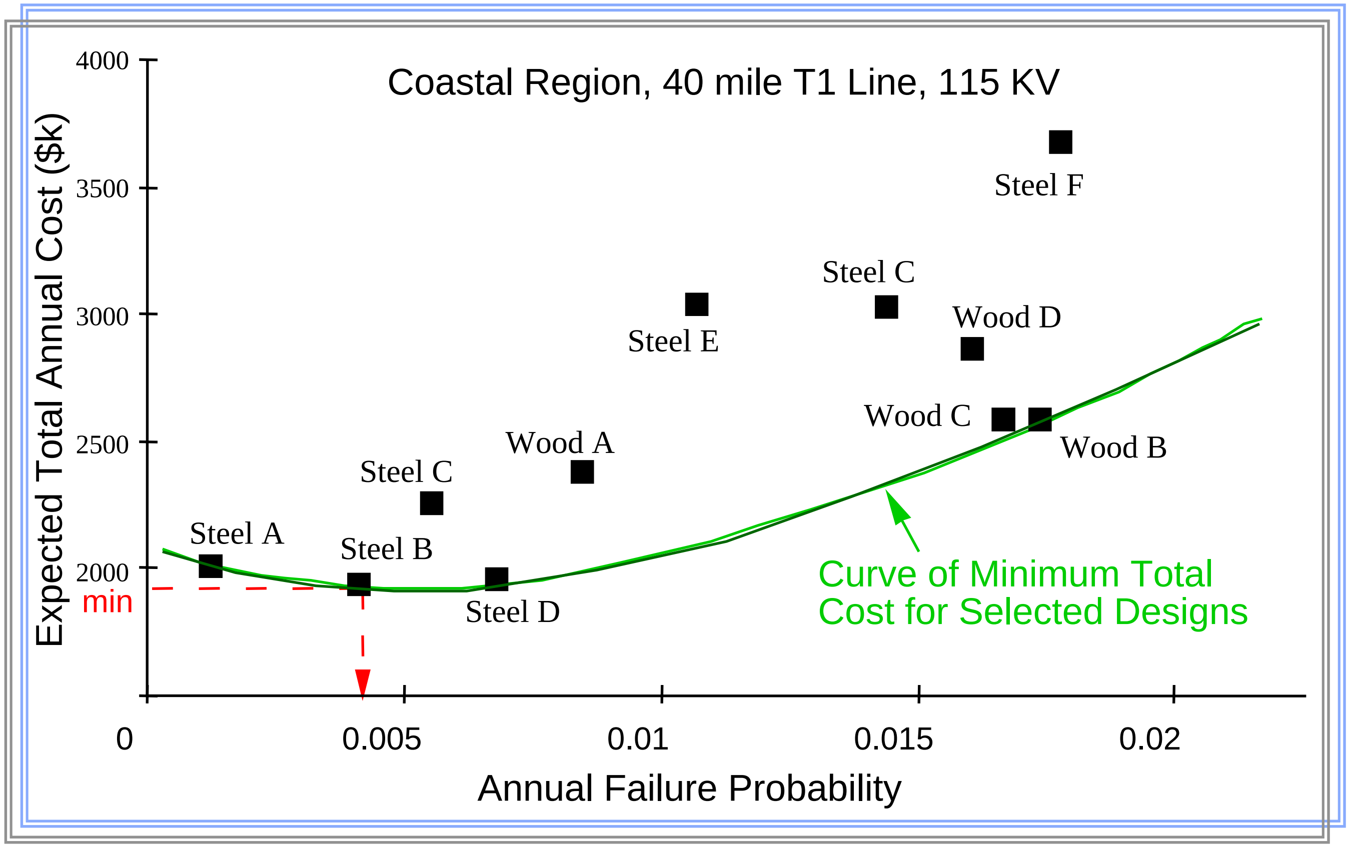
↓

Wind Load Estimates and Failure Probabilities for Design Alternatives

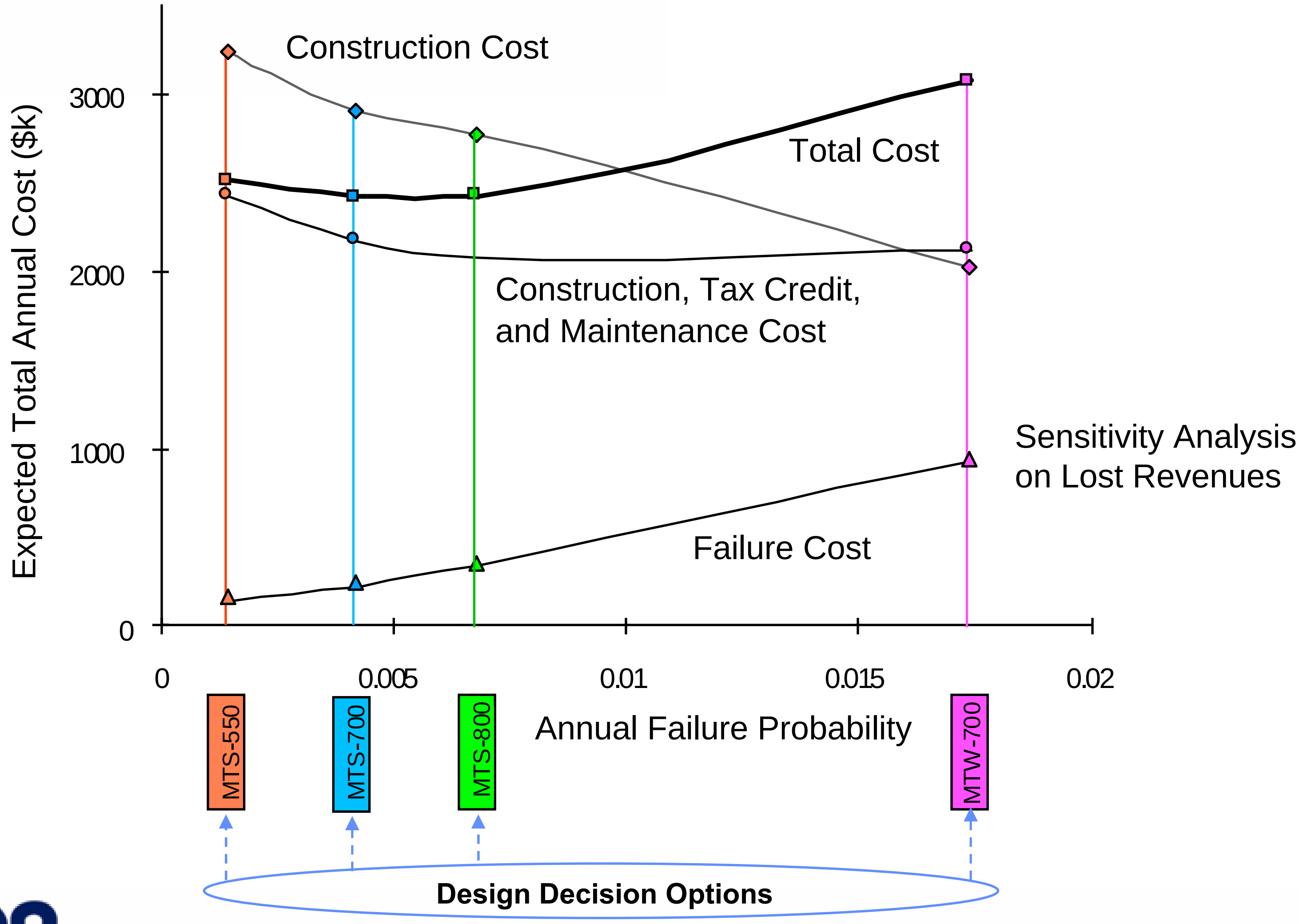
↓

Aggregate all Costs and Discount to Present Worth

→



# Minimize Total Lifetime Cost

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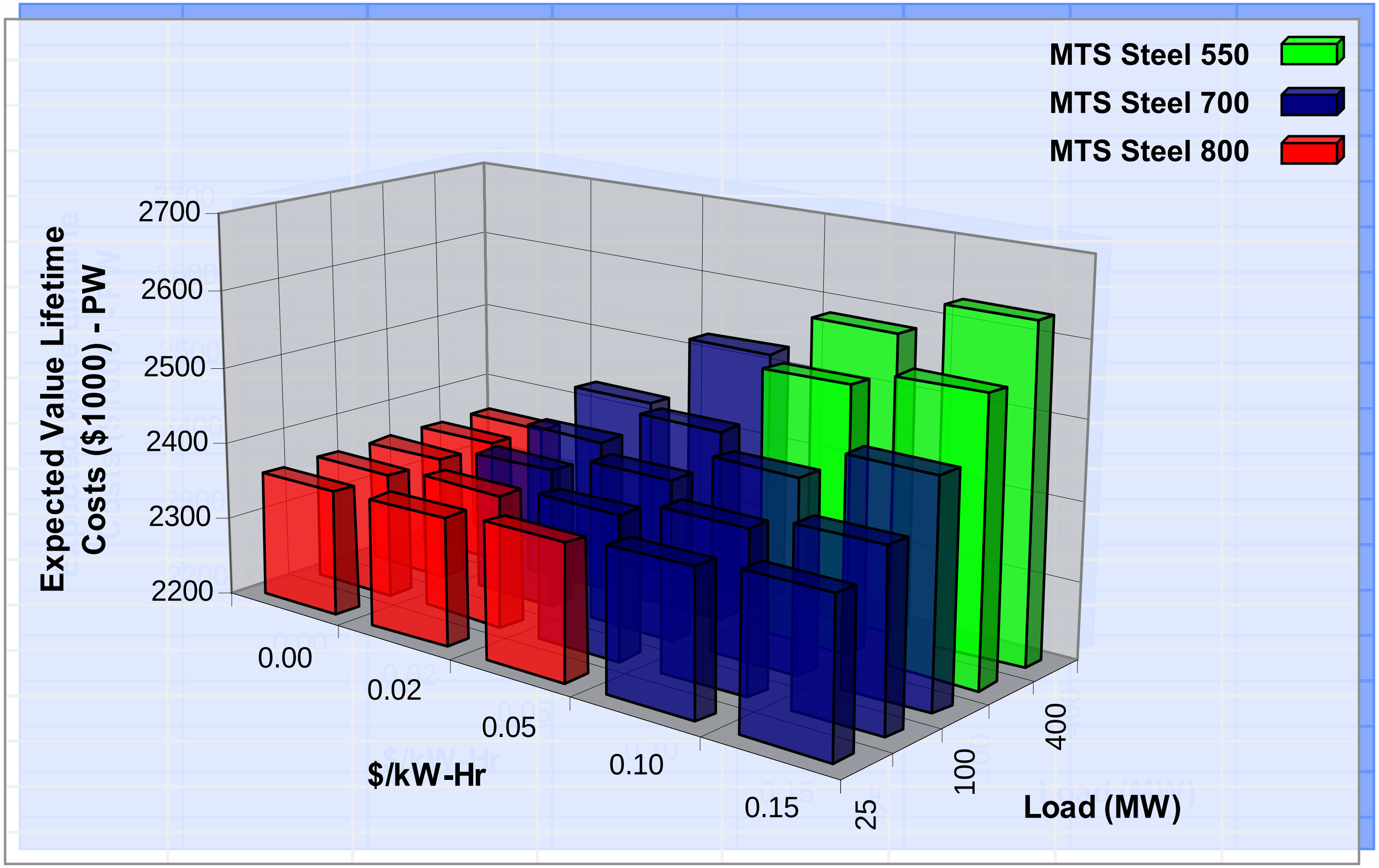
# Decision Threshold Analysis on Failure Cost Sensitivity

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# Tree Blowdown

- Load and resistance model based on research performed by the USFS in the 1950’s and additional work performed by ARA in the 1980’s
- Models probability of uprooting or stem failure as a function of
  - Tree characteristics and tree density
  - Peak gust wind speed
- Tree inventory database developed for contiguous U.S. and implemented in HAZUS-MH Hurricane Model for
  - Tree damage to property
  - Tree debris removal estimation

# Tree Load and Response Model

Tree is modeled as a SDOF

$$m_e\dddot{x} + c\ddot{x} + kx = F_D(t)$$

Stiffness:

$$K = \frac{3EI_{bh}}{H_{bh}^3}\overline{K}\psi(c_s, f_1)$$

Period of vibration:

$$T = a_1 + b_1\frac{H_{bh}^2}{d_{bh}} + \varepsilon$$

$$\frac{F_D}{\frac{1}{2}\rho U^2} = \frac{d_c^3}{h}\frac{1}{W_{dbf}}\Psi_D$$

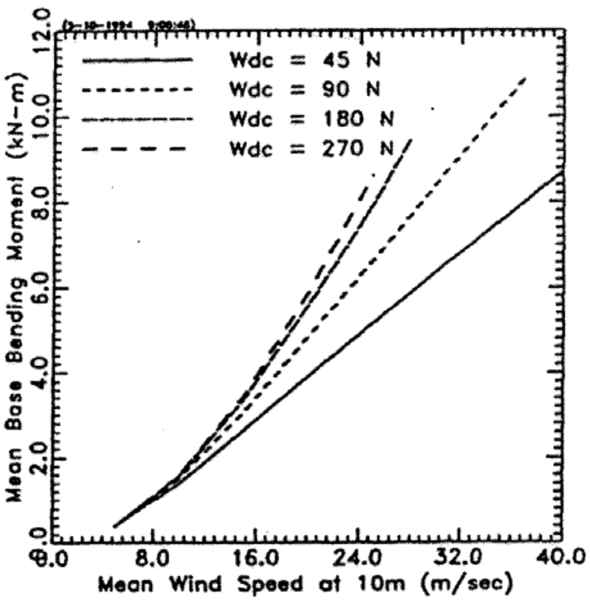
$$\Psi_D = \frac{k_2k_2\left(\frac{R}{W_{dc}}\right)^{-1.5}}{k_1 + k_2\left(\frac{R}{W_{dc}}\right)^{-1.5}}$$

where the drag parameters k1 and k2 are modeled as lognormal random variables that depend on the modulus of rupture

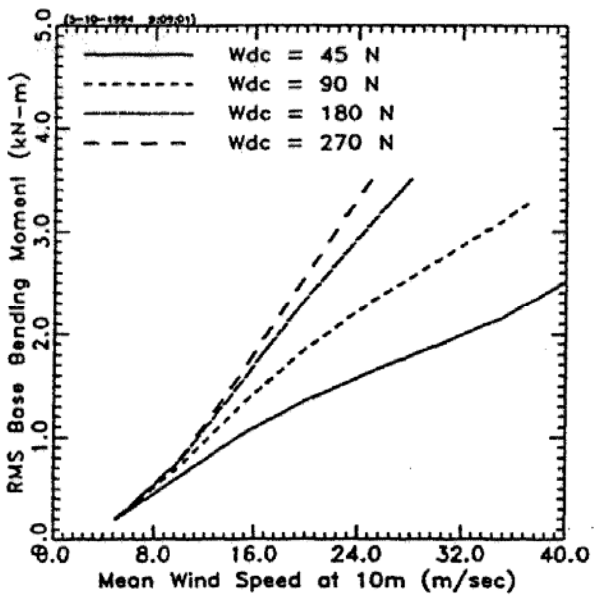
# Example Simulation Results

Base Bending Moments (kN-m)

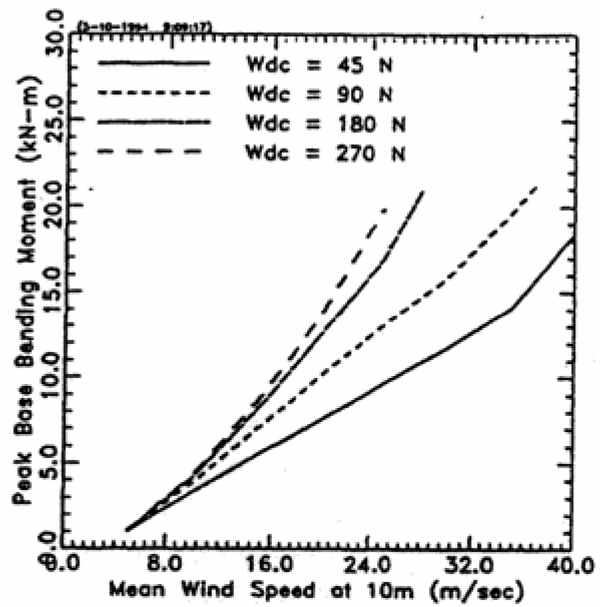
Mean



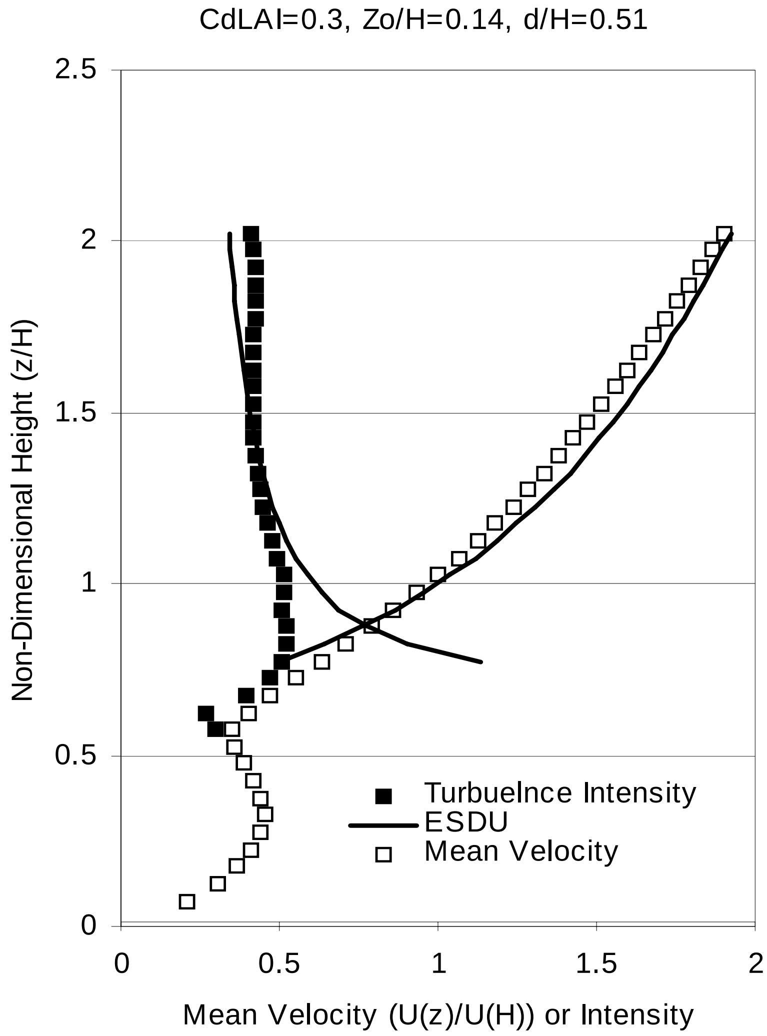

RMS




Peak



# Model Flow in Tree Canopies

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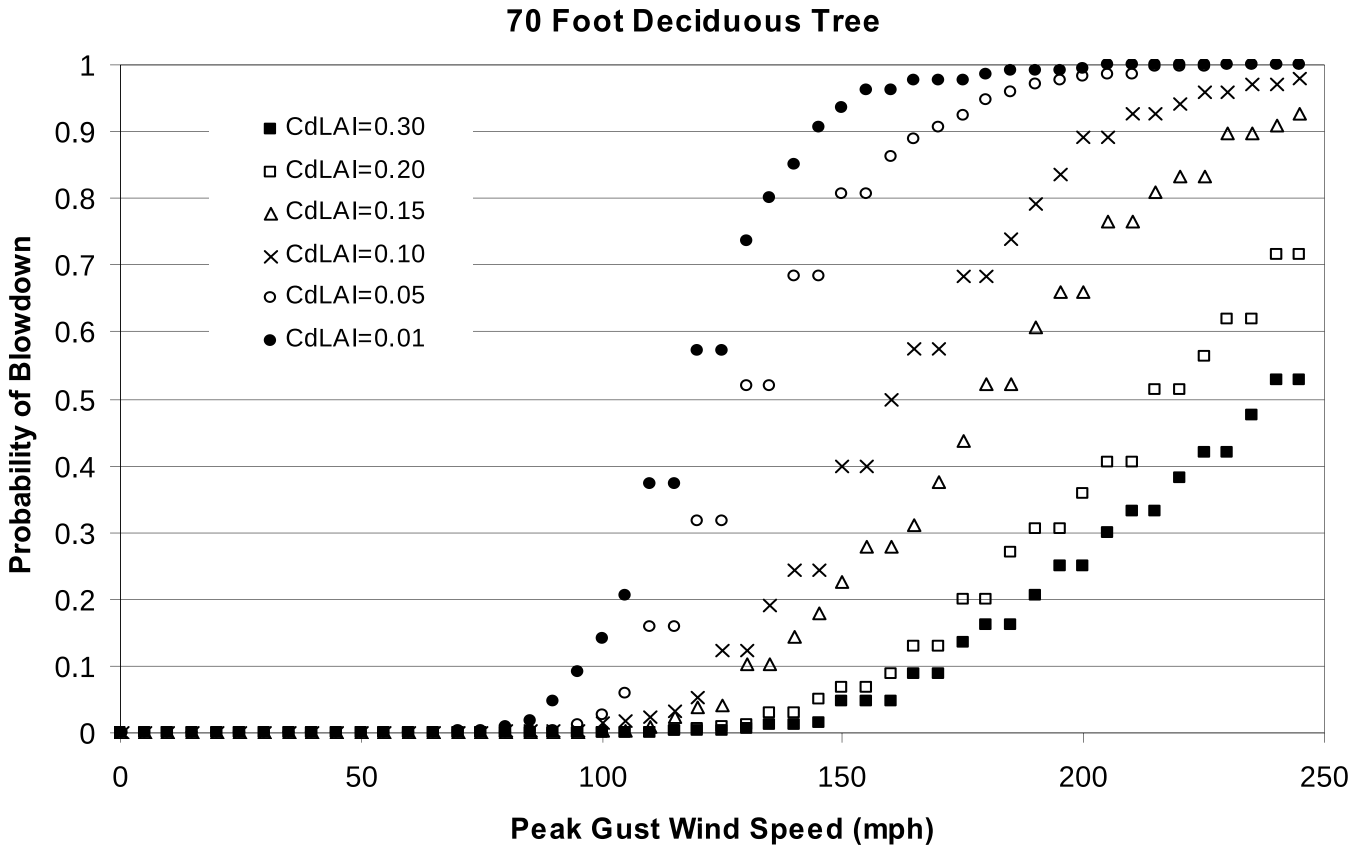
# Simulation Approach

1. Sample tree parameters
2. Choose value of $C_d LAI$ for "forest"
3. Compute effective velocity parameters
4. Generate time series of wind speeds (10 minutes)
5. Compute value of $C_d A$ for sampled tree
6. Compute minimum failure wind speed and convert to open terrain equivalent
7. Repeat 100 times
8. Compute effective number of stems/Hectare

$$\gamma = \frac{10^4 C_d LAI}{C_d A}$$

# Example Probability of Blowdown

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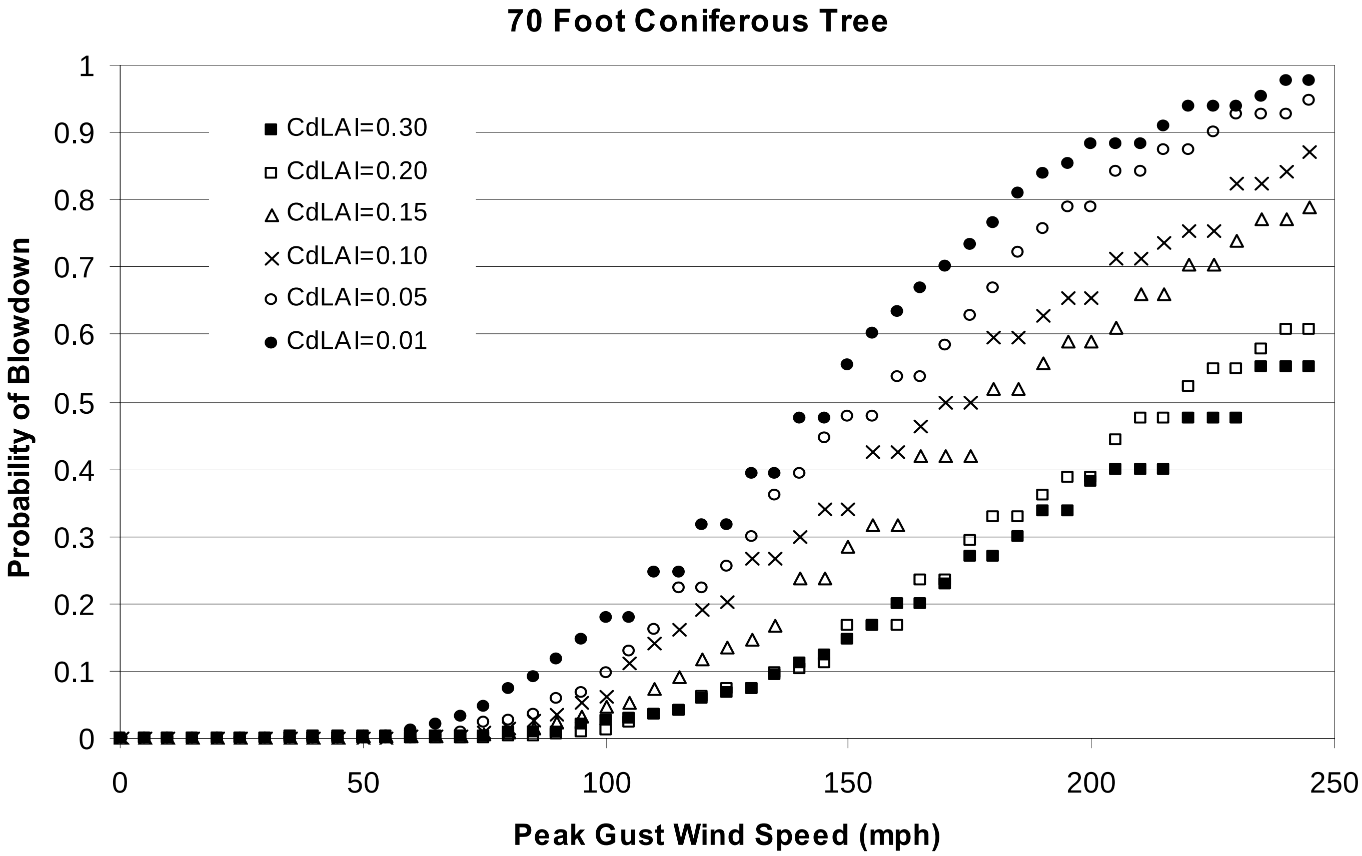
# Example Probability of Blowdown



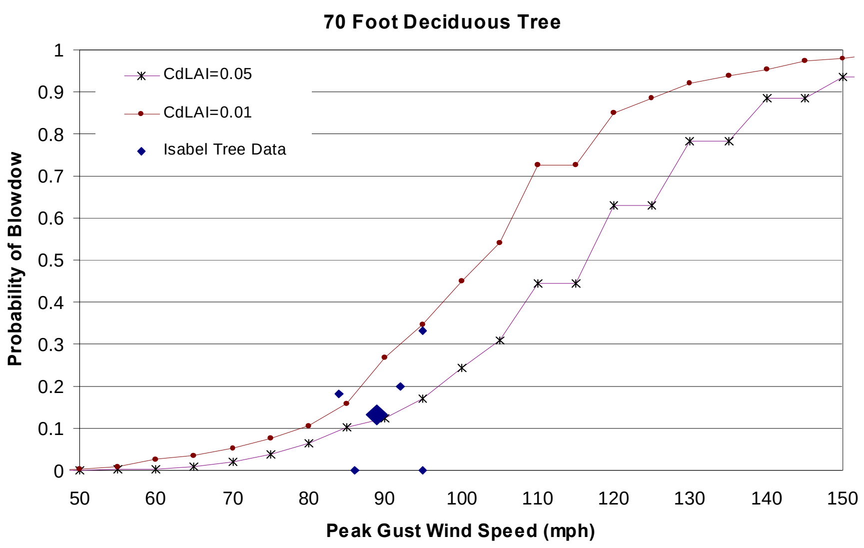
# Validation of Tree Blowdown

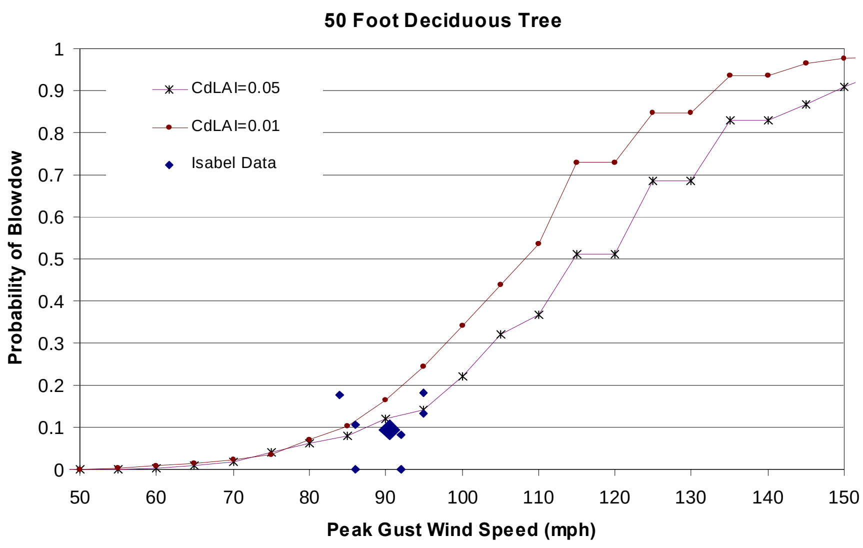
- Data collected following Hurricane Isabel (2003)
  - Eight randomly selected areas in Northeastern North Carolina
  - Number of trees on each lot
    - By height class
    - By tree type (deciduous or coniferous)
    - By performance (uproot, stem failure, no failure)

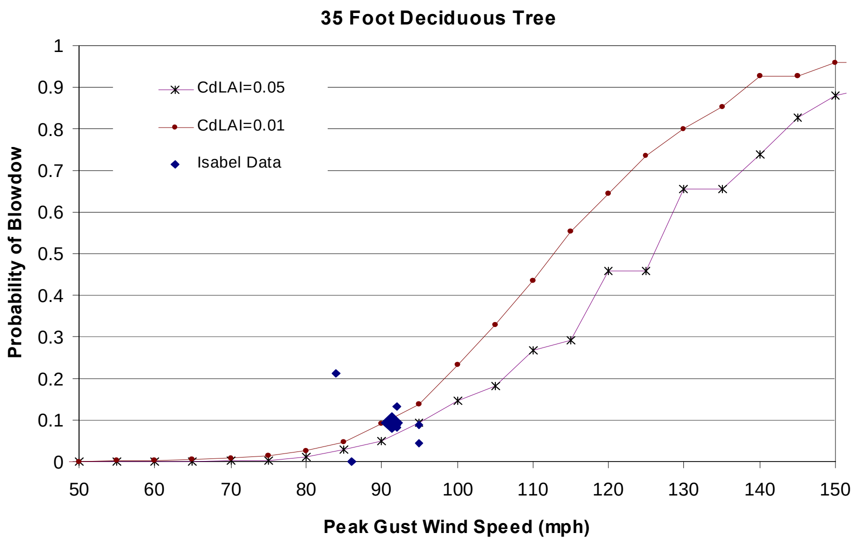
# Summary of Data Collected

| Location | Peak Gust Wind Speed (mph) | Number of Lots Surveyed | Total Number of Trees | % of Trees Blown Down |
|---|---|---|---|---|
| Ahoski 1 | 86 | 20 | 54 | 3.7% |
| Ahoski 2 | 86 | 28 | 113 | 5.3% |
| Elizabeth City 1 | 95 | 34 | 171 | 5.8% |
| Elizabeth City 2 | 95 | 45 | 217 | 8.8% |
| Manteo 1 | 92 | 9 | 178 | 18% |
| Manteo 2 | 92 | 32 | 150 | 11% |
| South Mills | 92 | 27 | 150 | 19.3% |
| Windsor | 84 | 28 | 125 | 8.8% |
| Total | | 223 | 1158 | 10.8% |

# Deciduous Trees

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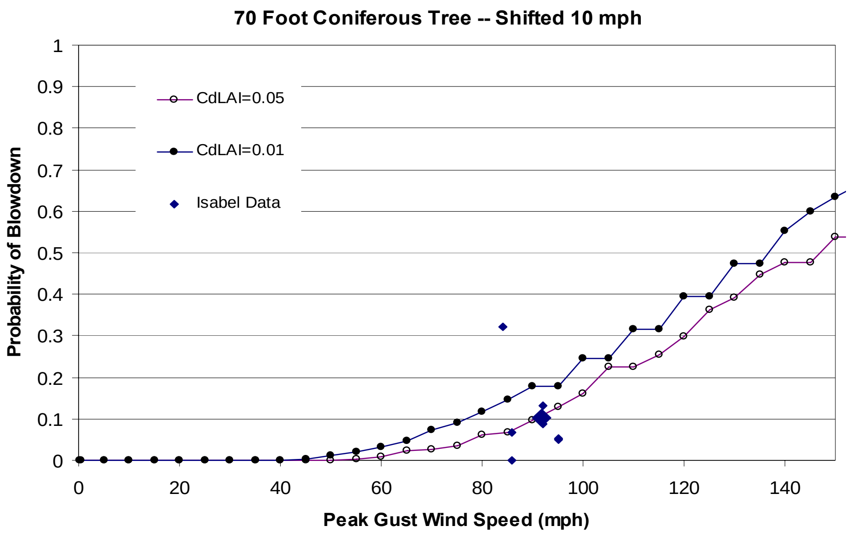
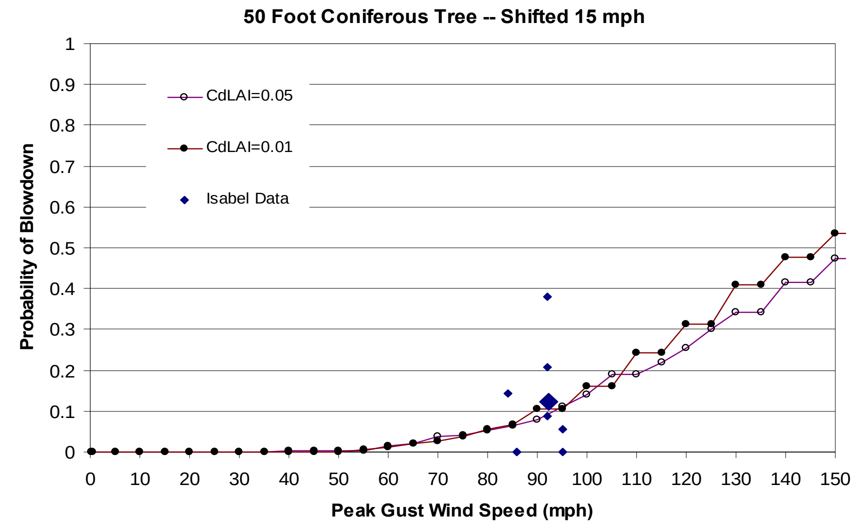
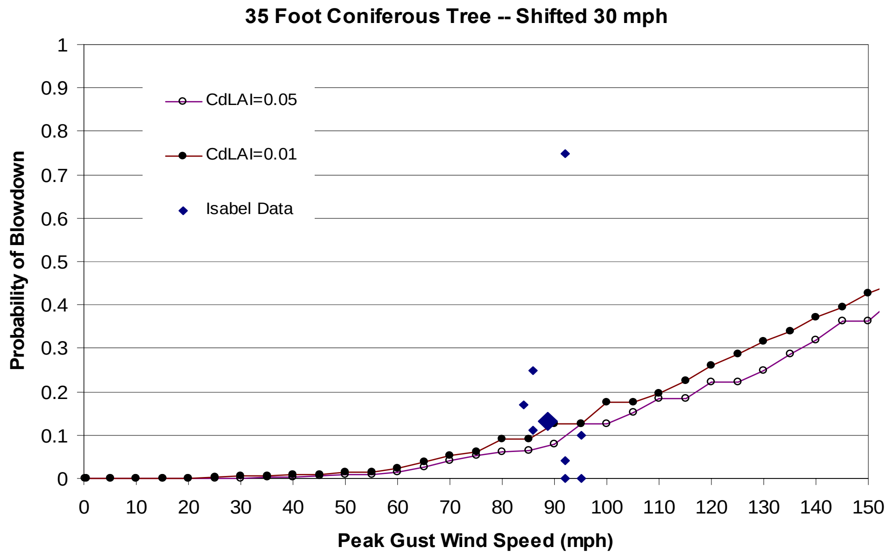
# Coniferous Trees

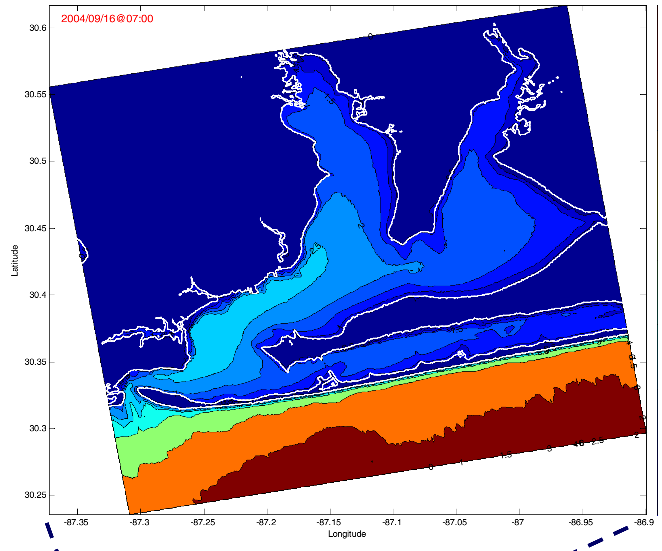


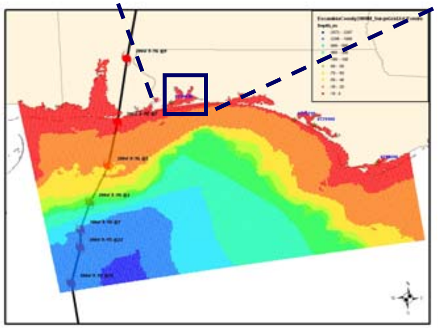



# Coastal Flooding Risk Analysis

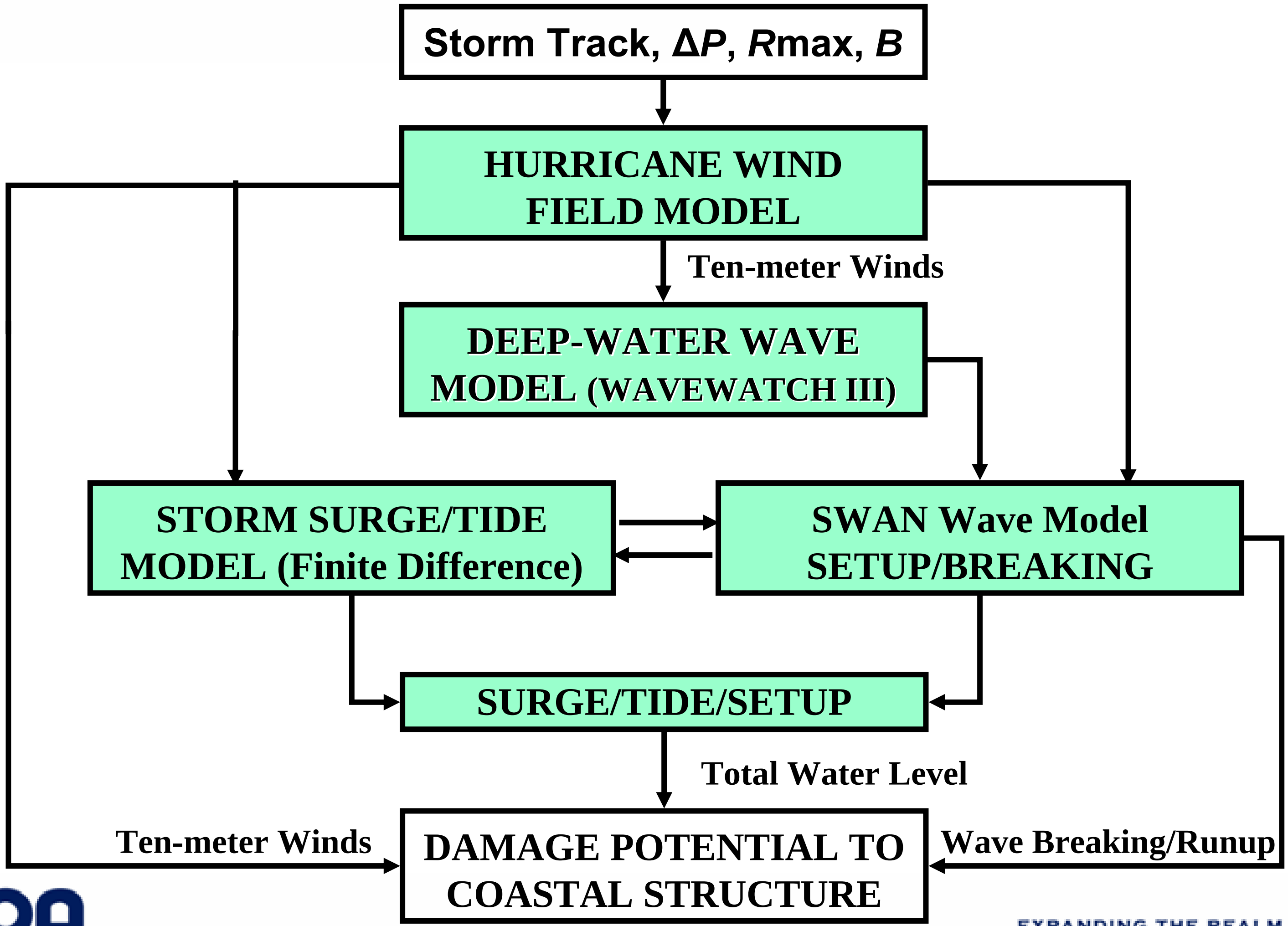
- Model components
  - Storm surge
  - Astronomical tide
  - Wave set-up and run-up
- Applications
  - Planning, design, & mitigation
  - Emergency response
  - Insurance



Hurricane Ivan storm surge and waves in Escambia Bay

# Coastal Flooding Model Overview

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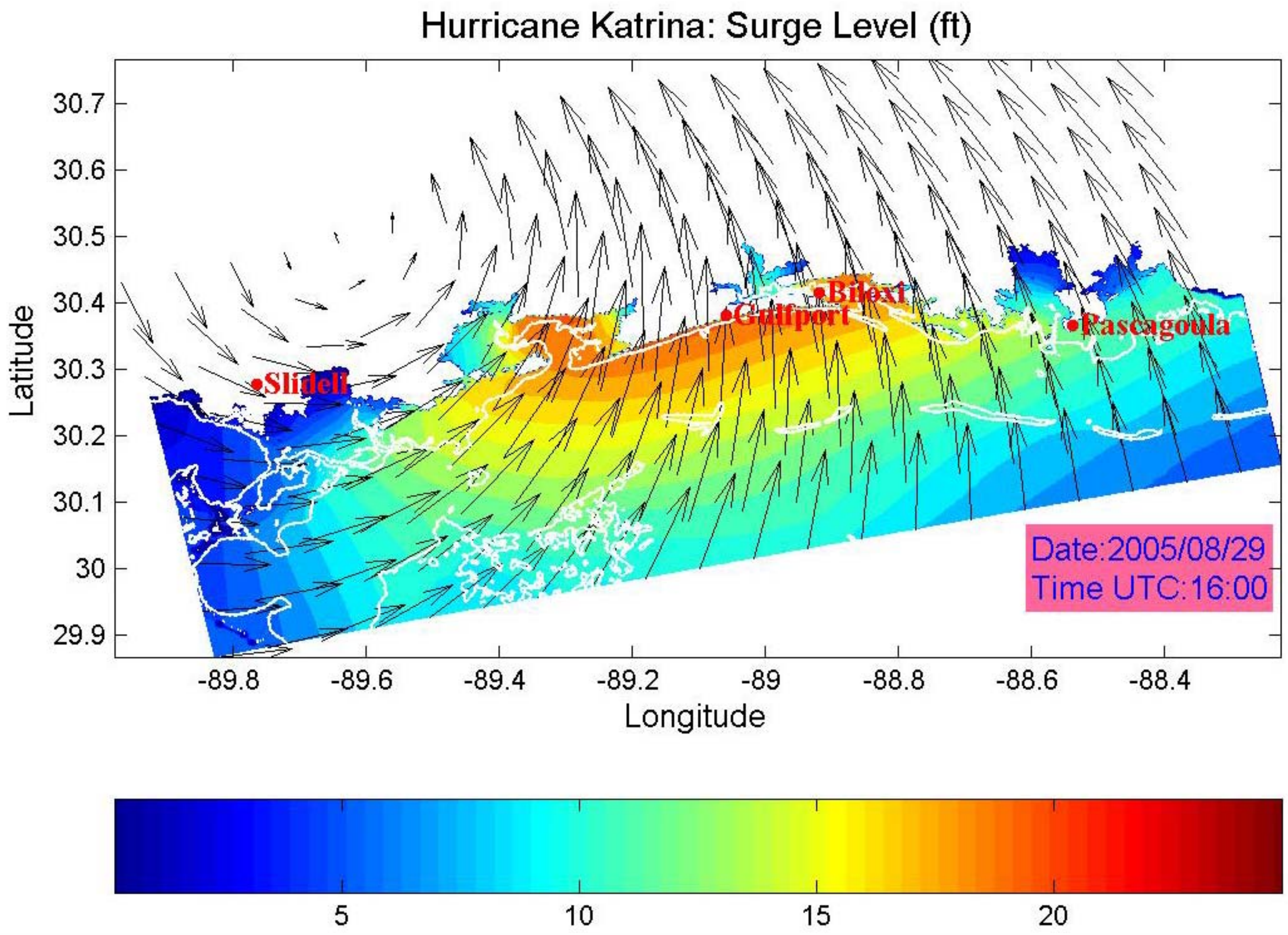
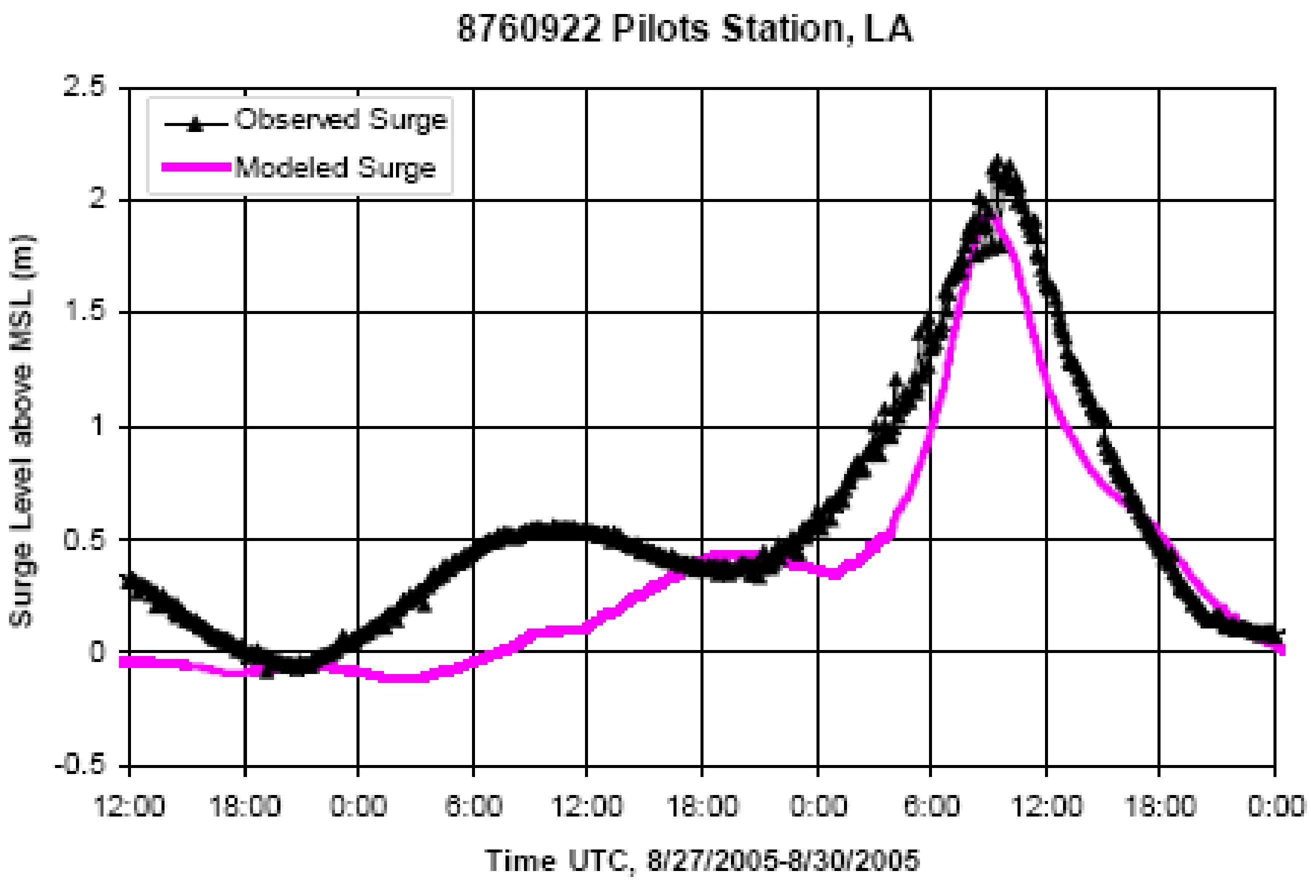
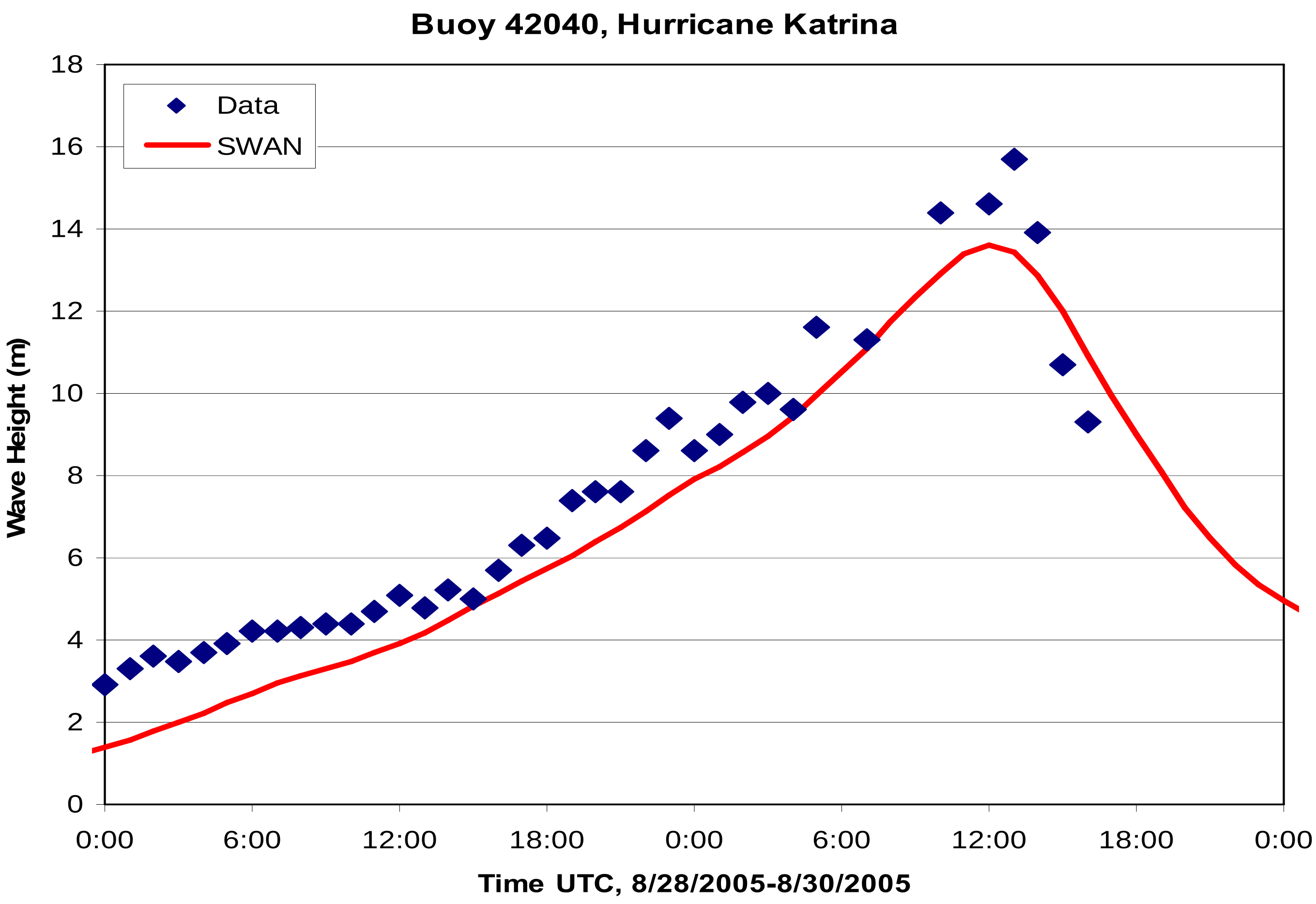
# Hurricane Katrina Storm Surge



# Katrina Storm Surge Prediction



# Katrina Wave Height Prediction



# Research Recommendations

- Transmission line optimization studies
  - Optimization of new construction and maintenance
  - Impacts of response and recovery costs and indirect economic losses on design and maintenance decisions
- Distribution line optimization studies
  - Regional analysis via statistical analysis at block level
  - Analysis of above ground vs. below ground installation
  - Develop and validate models for tree damage to distribution lines
- Coastal flooding impacts on power plants, substations, and T&D systems