

Sensitivity of Distributed Infrastructure System Performance Estimates Under Alternative Tropical Cyclone Wind Field Spatial Correlation Models and Component Fragility Levels

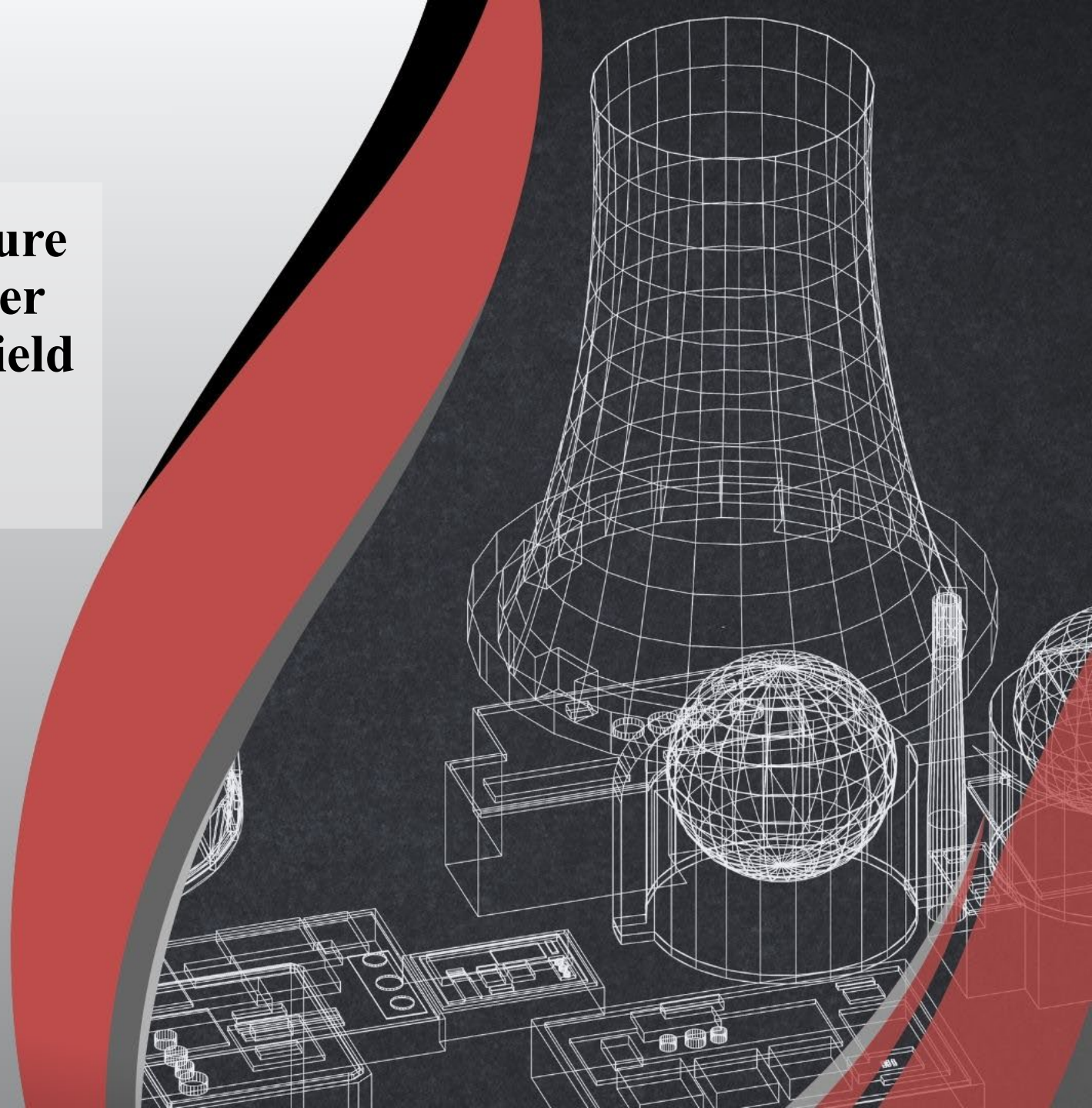
NPH Workshop 2026

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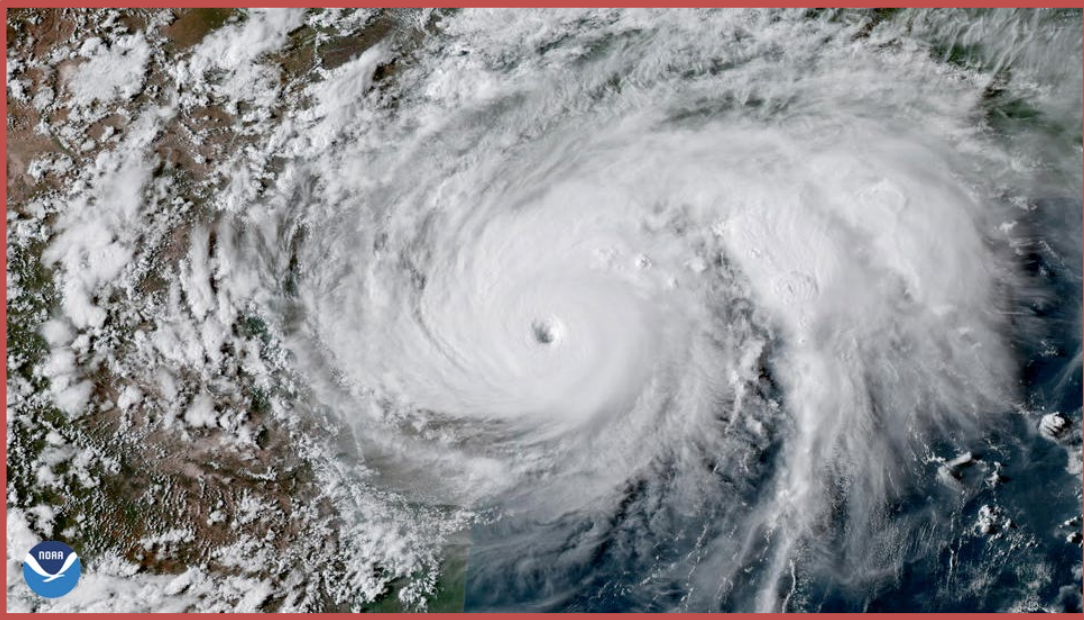
Michelle (Shelby) Bensi, PhD

Associate Professor, Department of Civil & Environmental
Engineering, University of Maryland, College Park



Natural Hazards Affect Large Regions

Wind fields that can extend hundreds of kilometers



Category 4 Hurricane Harvey, Texas coast (NOAA)

Distributed Infrastructure System

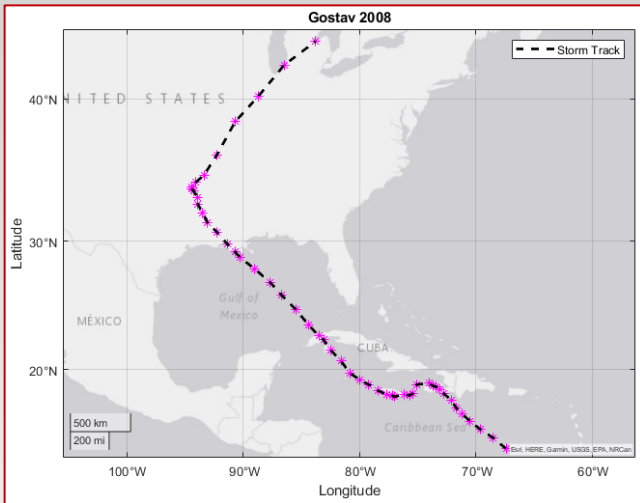


Sources: <https://yaleclimateconnections.org/>

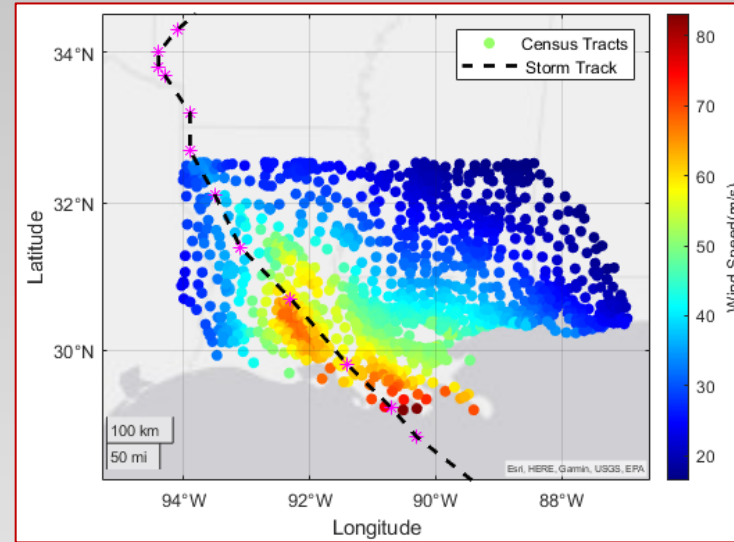
Correlated demands

Spatial Correlation in TC Wind Speed Residuals

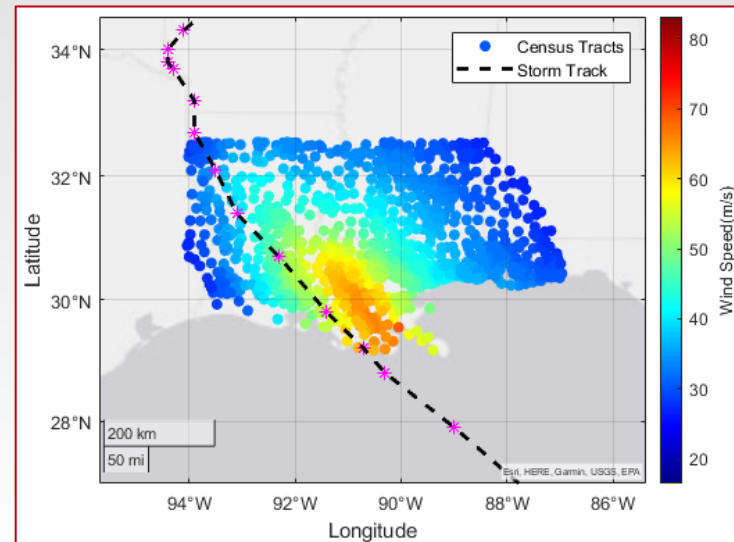
Storm Track



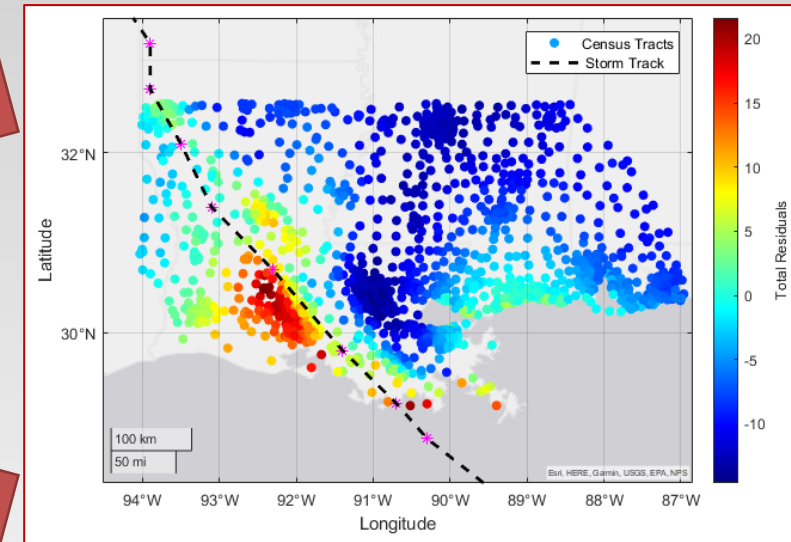
Observation



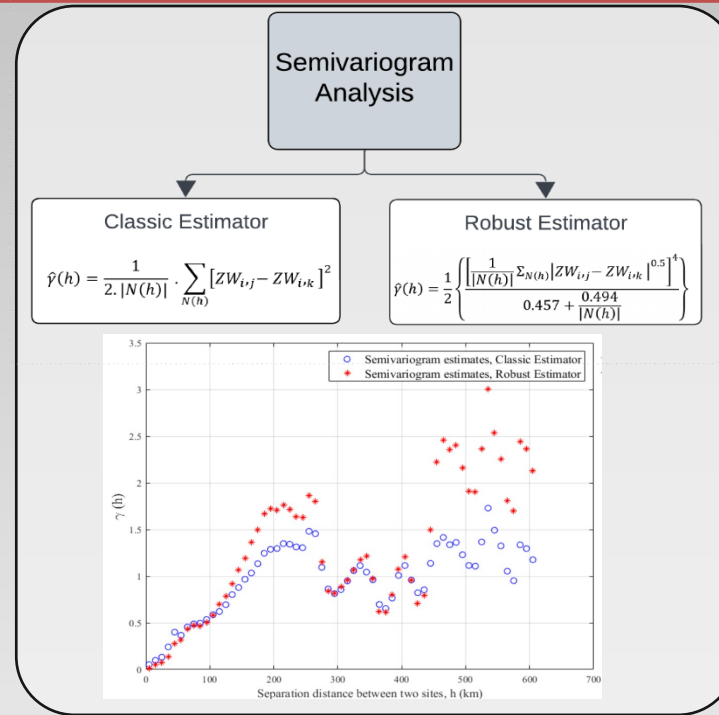
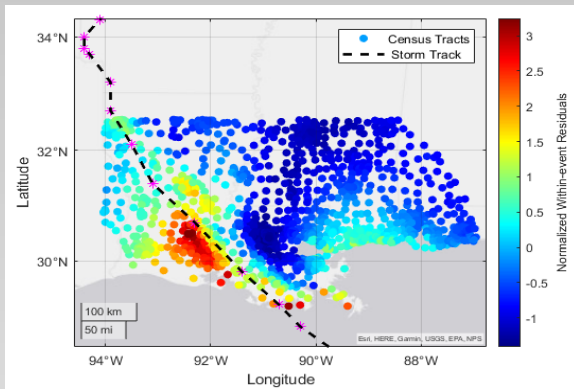
Prediction



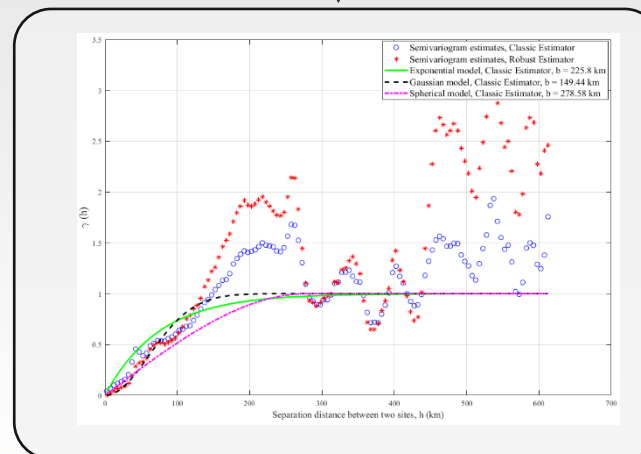
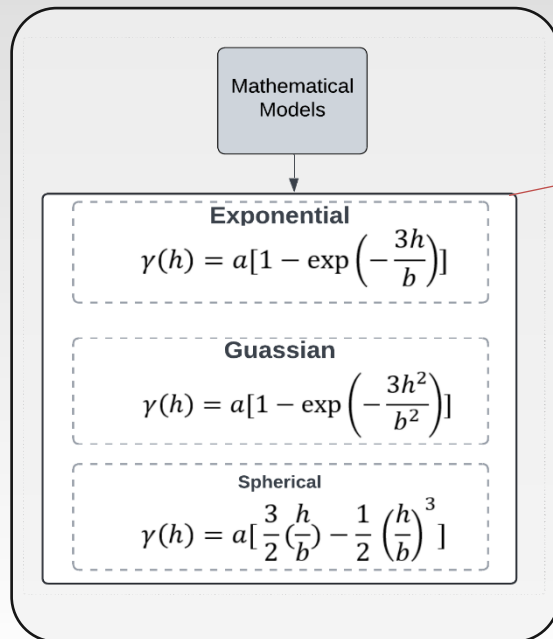
Residuals



Previous Research: Spatial Correlation of Wind Field Residuals



Different shapes

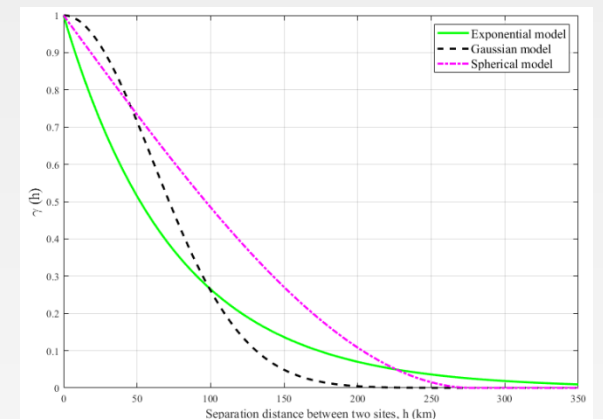


Linear
relationship
between semi-
variogram and
correlation

→

$$\rho(h) = 1 - \gamma(h)$$

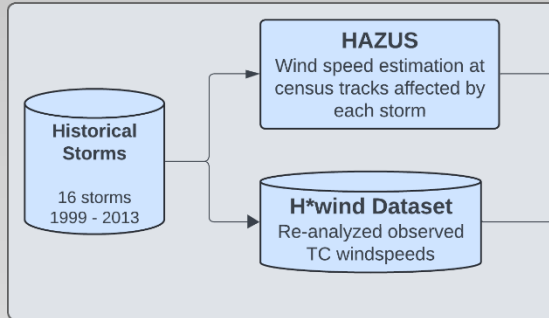
Correlation Function



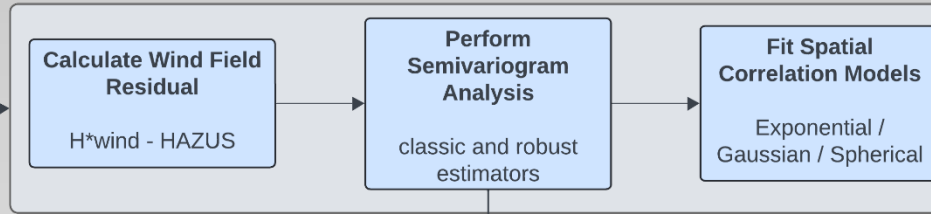
Study Framework

For Storm $i = 1, \dots, 16$

1. Storm selsection and data processing

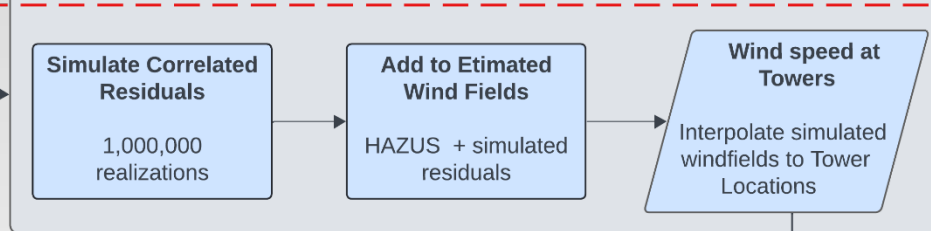


2. Wind Field Residual Spatial correlation



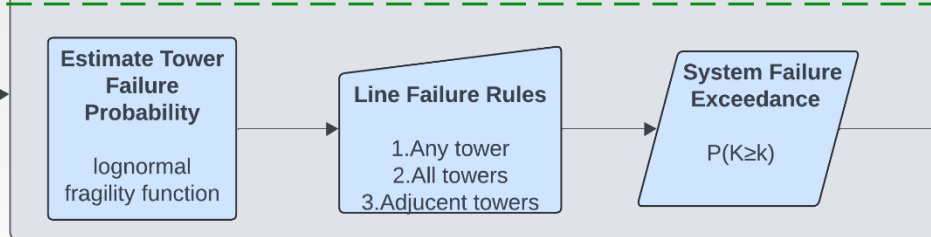
3. Spatially Correlated Wind Field Residual Simulation

For correlation models $j = 1, 2, 3$



System Response

For capacity ratio $c = \frac{\theta}{v_{max}} = 0.25, 0.5, \dots, 2$

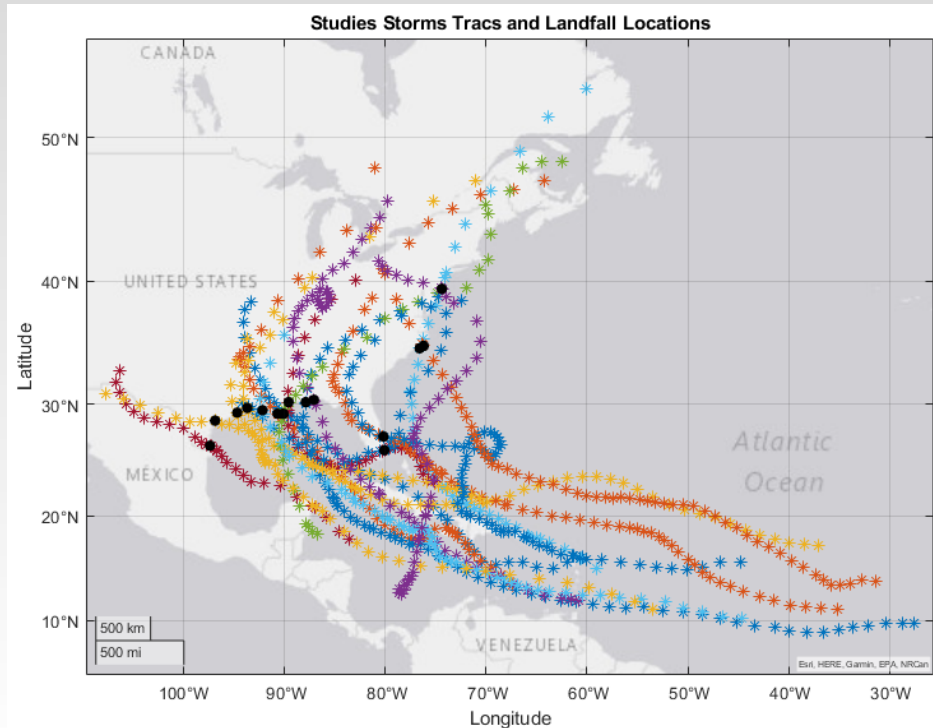
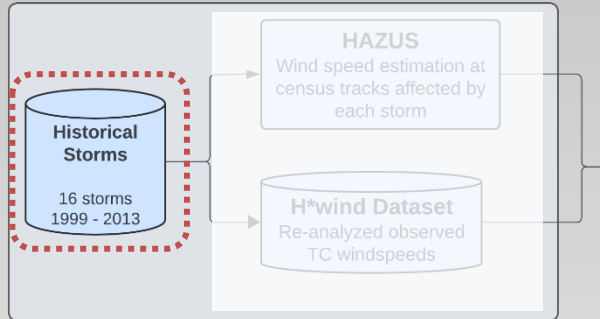


Correlation Model Sensitivity

$$R_i(j, c) = \frac{P_{i,Exp}(K \geq k | c)}{P_{i,Gauss}(K \geq k | c)}$$

Study Cases: Storms Track and Landfall Location

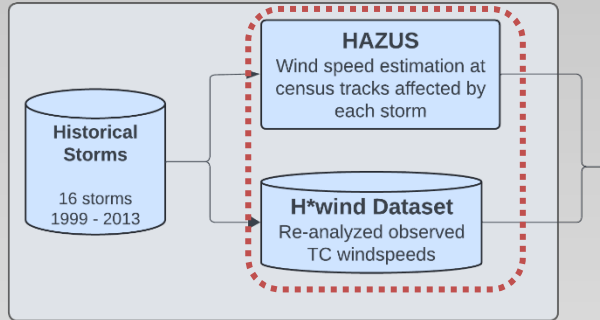
1. Storm selection and data processing



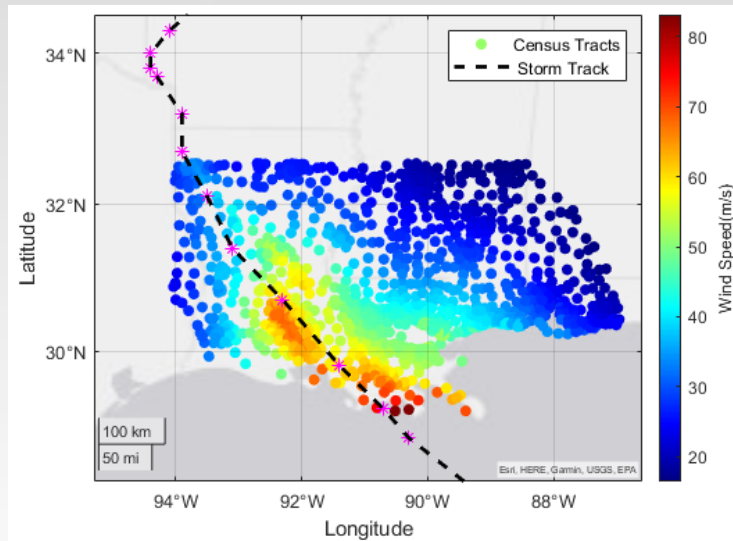
Name	Year	Category (at landfall)
IRENE-NY	1999	3
IRENE-NC	1999	3
LILI	2002	5
ISABEL	2003	5
CLAUDETTE	2003	5
IVAN	2004	5
FRANCES	2004	5
JEANNE	2004	5
KATRINA-LSNA	2005	5
KATRINA-FL	2005	4
RITA	2005	5
DENNIS	2005	5
CINDY	2005	4
GUSTAV	2008	5
IKE	2008	5
DOLLY	2008	4
ISAAC	2012	4
SANDY	2012	4

H*Wind Dataset and HAZUS Model

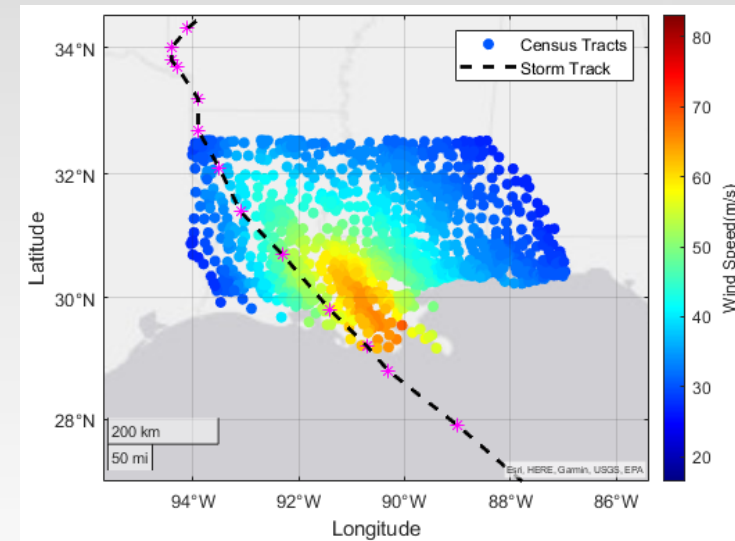
1. Storm selection and data processing



H*wind Dataset

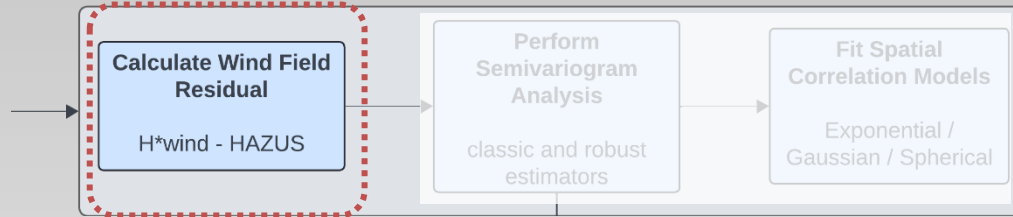


HAZUS Model

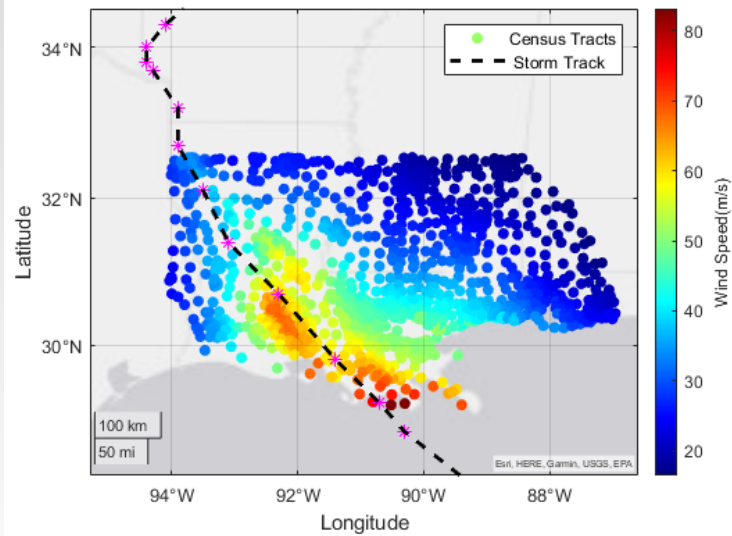


Wind Field Residual Spatial Correlation

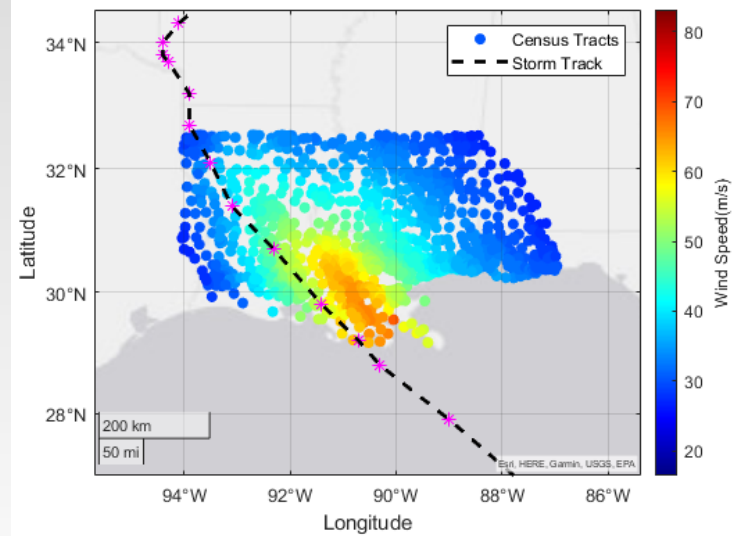
2. Wind Field Residual Spatial correlation



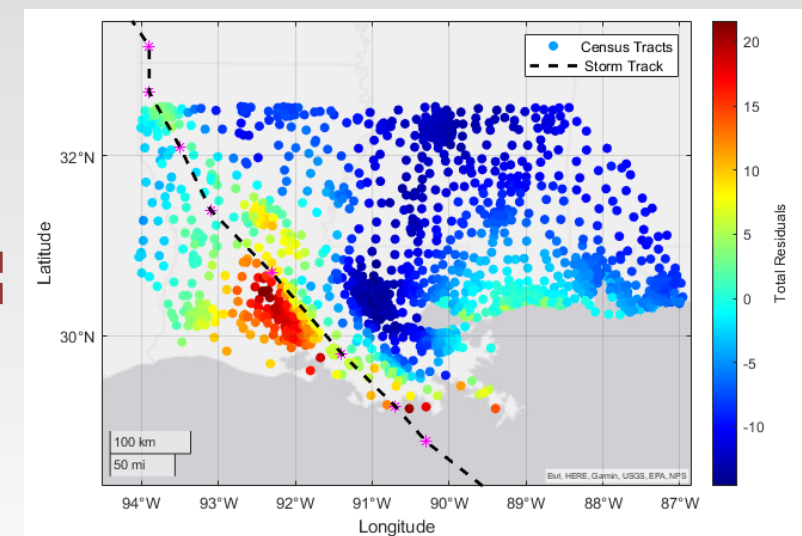
Observation (H*wind)



Prediction (HAZAUS)



Total Residuals



Components of The Total Residual

$$\varepsilon_{i,j}^t = \delta B_i + \delta W_{i,j}$$

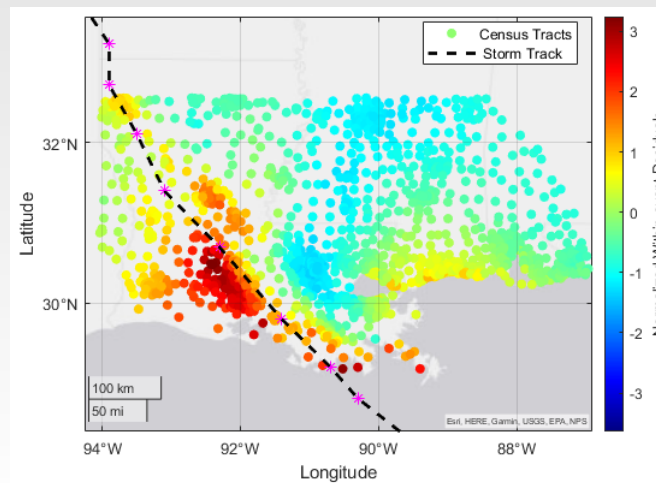
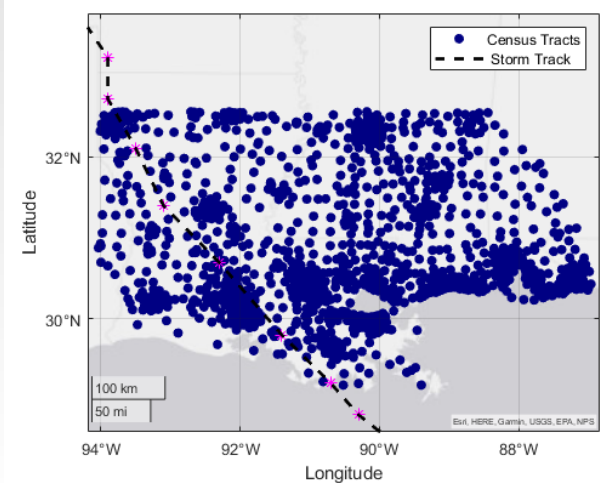
Residual

Residual
=
Between-event Residual
+
Within-event Residuals

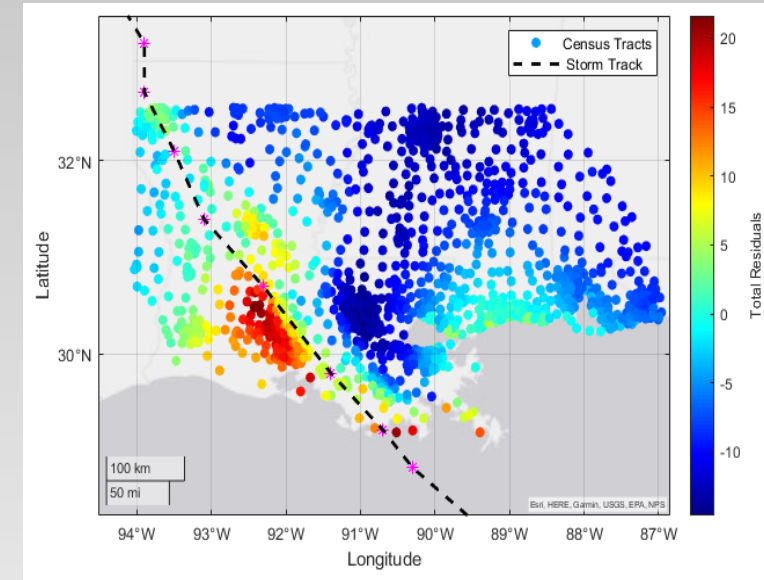
Between-event Residuals

Within-event Residuals

$$\delta B_i = -3.64$$

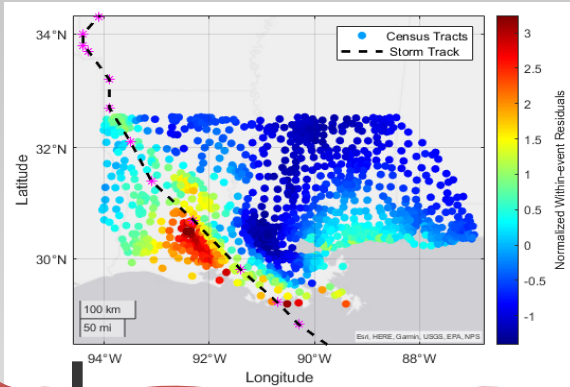


Residuals



Wind Field Residual Spatial Correlation

Within-event Residuals



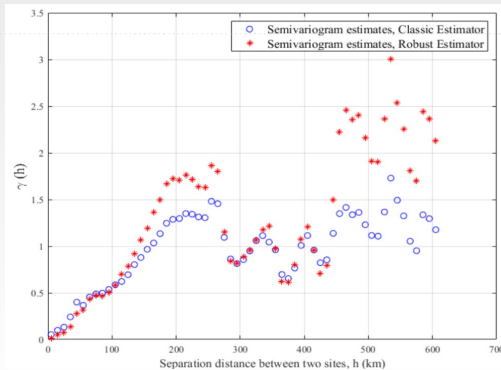
Semivariogram Analysis

Classic Estimator

$$\hat{\gamma}(h) = \frac{1}{2 \cdot |N(h)|} \cdot \sum_{i,j \in N(h)} [ZW_{ij} - ZW_{ik}]^2$$

Robust Estimator

$$\hat{\gamma}(h) = \frac{1}{2} \left\{ \frac{\left[\frac{1}{|N(h)|} \sum_{i,j \in N(h)} |ZW_{ij} - ZW_{ik}|^{0.5} \right]^4}{0.457 + \frac{0.494}{|N(h)|}} \right\}$$



Mathematical Models

Exponential

$$\gamma(h) = a[1 - \exp(-\frac{3h}{b})]$$

Gaussian

$$\gamma(h) = a[1 - \exp(-\frac{3h^2}{b^2})]$$

Spherical

$$\gamma(h) = a[\frac{3}{2}(\frac{h}{b}) - \frac{1}{2}(\frac{h}{b})^3]$$

2. Wind Field Residual Spatial correlation

Calculate Wind Field Residual

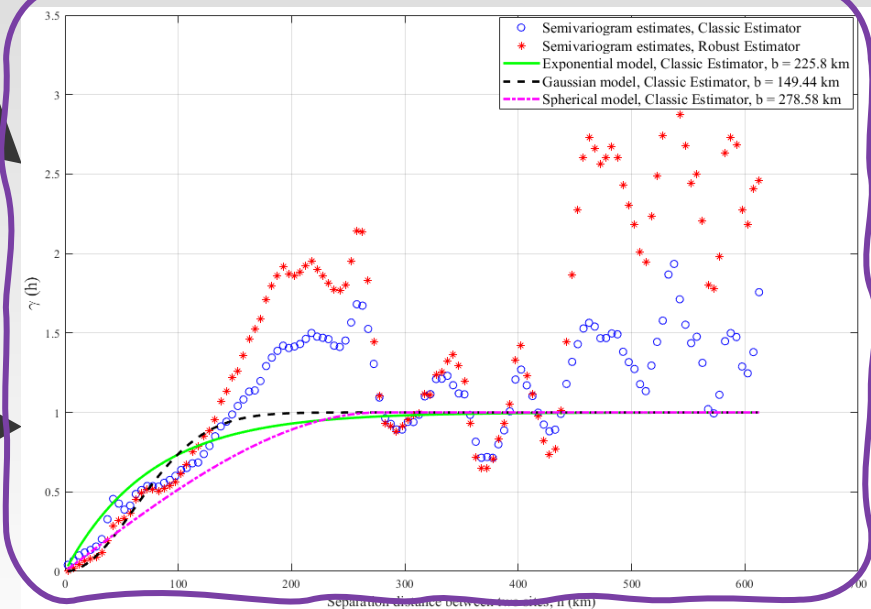
H*wind - HAZUS

Perform Semivariogram Analysis

classic and robust estimators

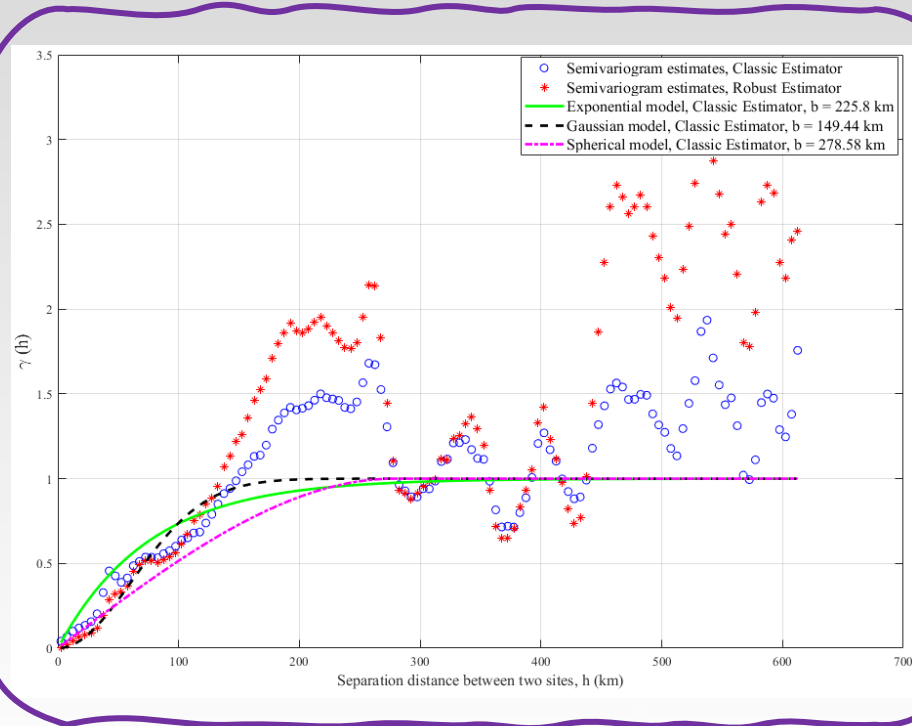
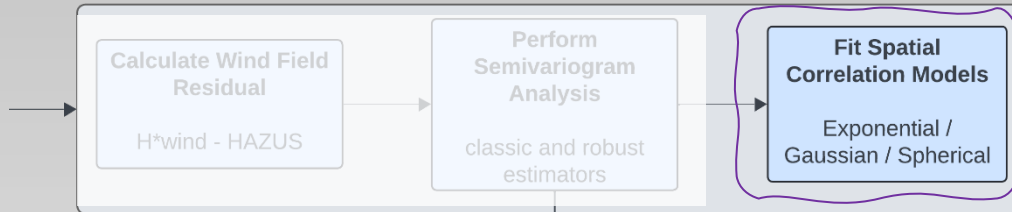
Fit Spatial Correlation Models

Exponential / Gaussian / Spherical



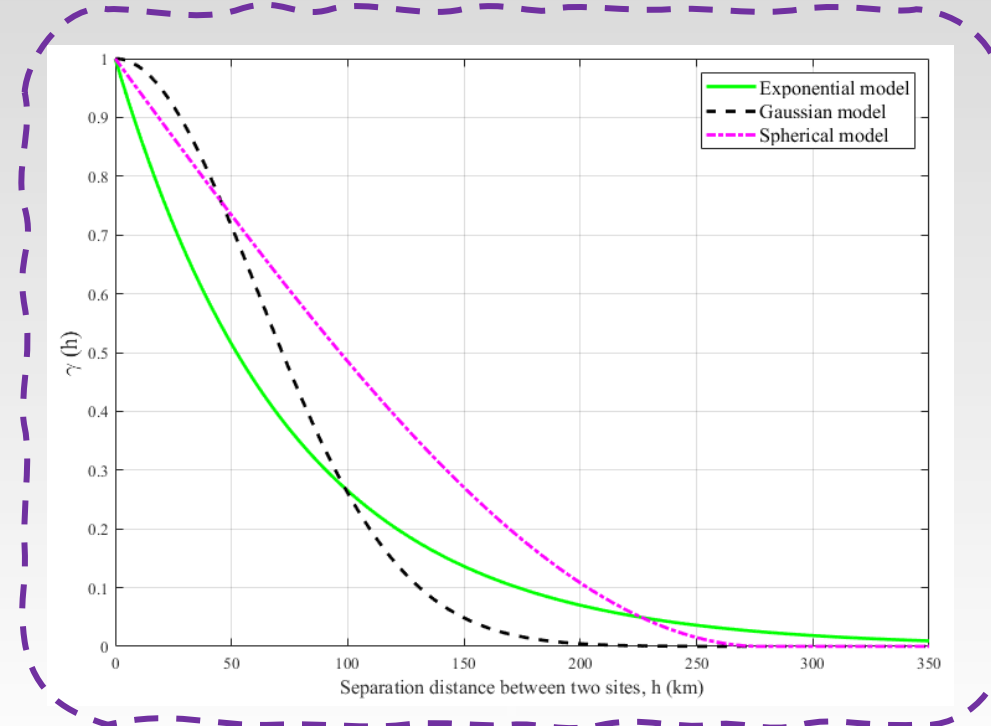
Wind Field Residual Spatial Correlation

2. Wind Field Residual Spatial correlation



Linear
relationship
between semi-
variogram and
correlation

$$\rho_T(h) = 1 - \gamma(h)$$



Simulation of Correlated Wind Field Residuals

For Storm $i = 1, \dots, 16$

2. Wind Field Residual Spatial correlation

Calculate Wind Field Residual

Perform Semivariogram Analysis

Fit Spatial Correlation Models

H*wind - HAZUS

classic and robust estimators

Exponential / Gaussian / Spherical

3. Spatially Correlated Wind Field Residual Simulation

For correlation models $j = 1, 2, 3$

Simulate Correlated Residuals

Add to Estimated Wind Fields

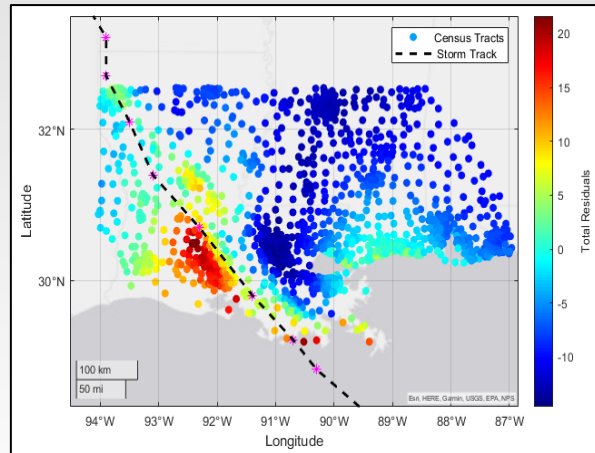
Wind speed at Towers

1,000,000 realizations

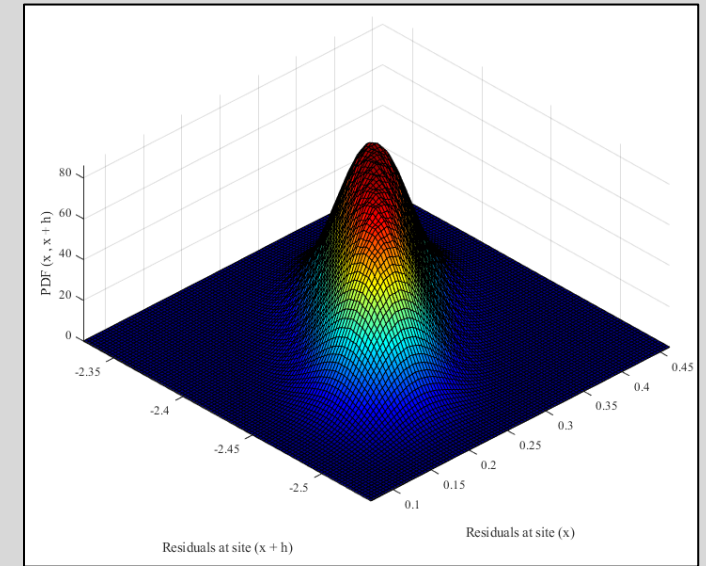
HAZUS + simulated residuals

Interpolate simulated windfields to Tower Locations

Total Residuals



Follow Multivariate Normal Distribution



Mean Vector

$$M = [0, \dots, 0]$$

Covariance Matrix

$$D_T \times R_T \times D_T$$

Standard Deviation Matrix

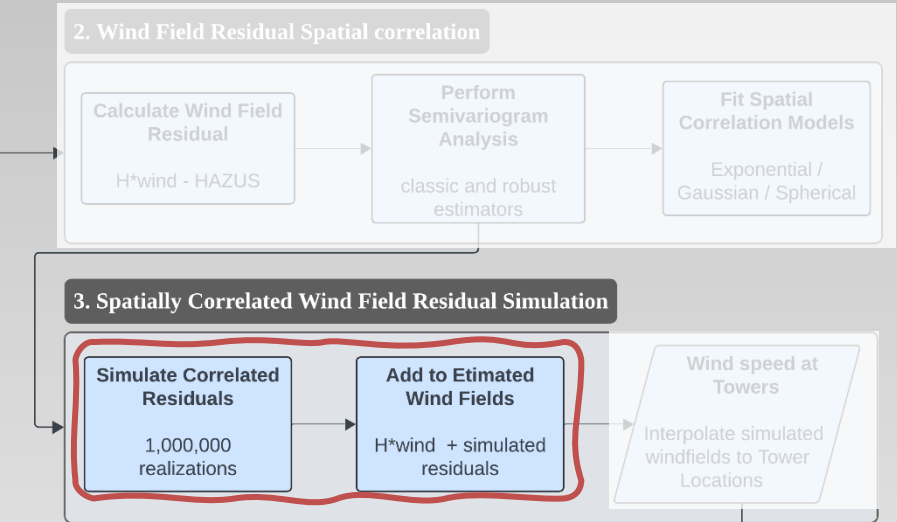
Correlation Matrix

$$\sigma_T = \sqrt{\sigma_B^2 + \sigma_W^2}$$

$$R_T = \frac{\sigma_B^2 + \rho_W(h_{ij}) \cdot \sigma_W^2}{\sigma_T^2}$$

Obtained from previous step

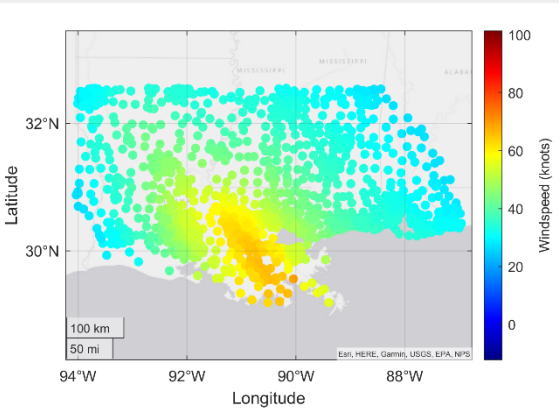
Simulation of Correlated Wind Fields



Gustave (2008)

Wind Field

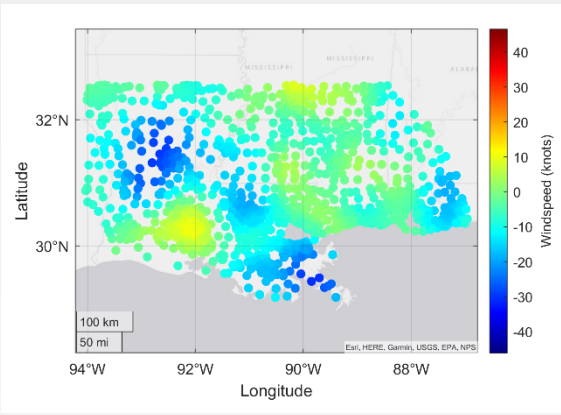
Estimated Wind Field



+

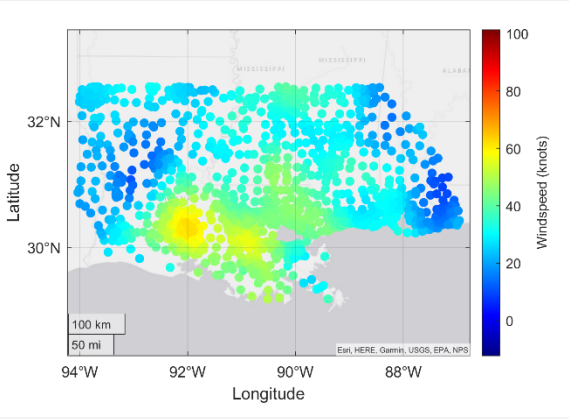
Correlated Wind Field Residuals

Correlated Total Residual



=

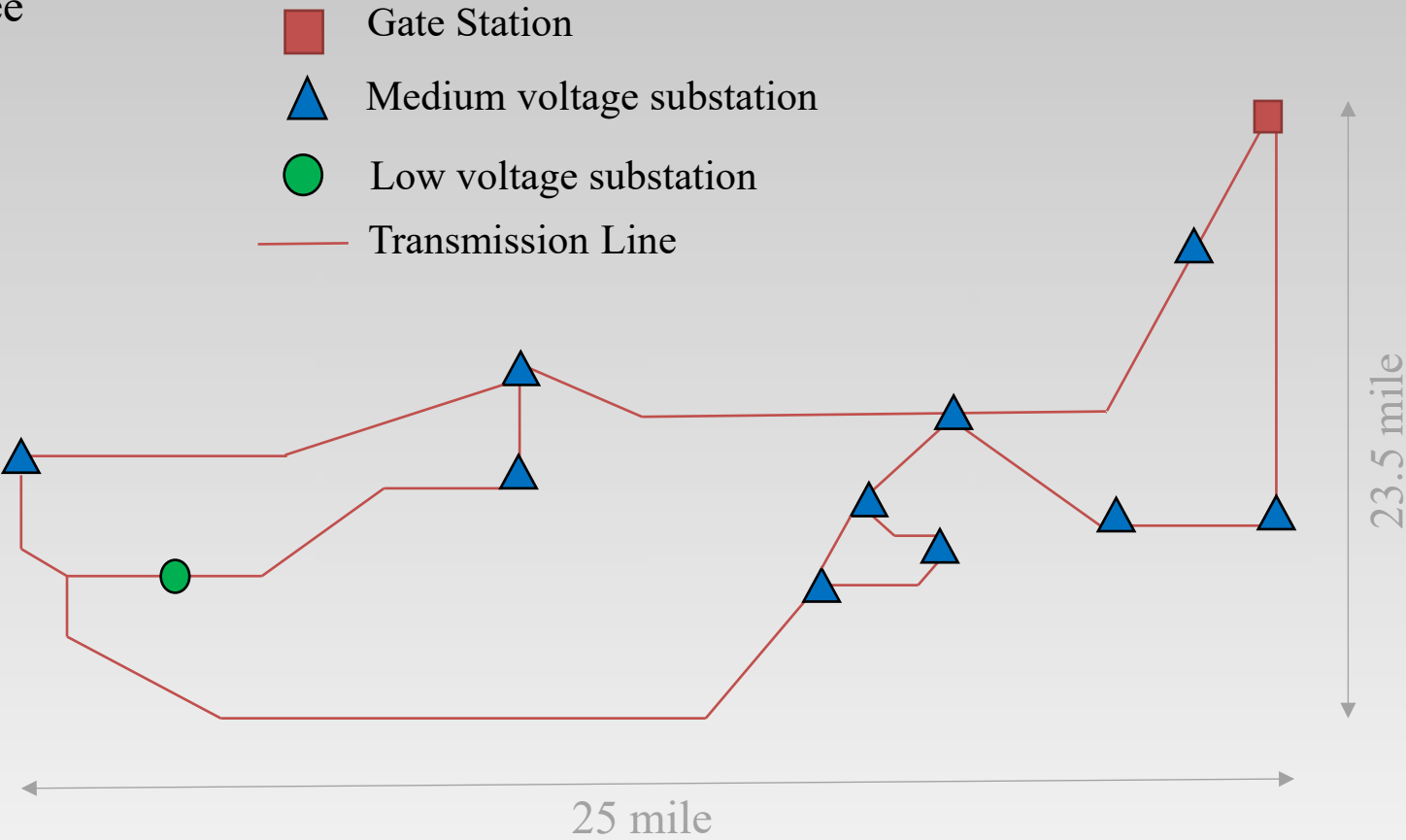
Correlated Wind Field



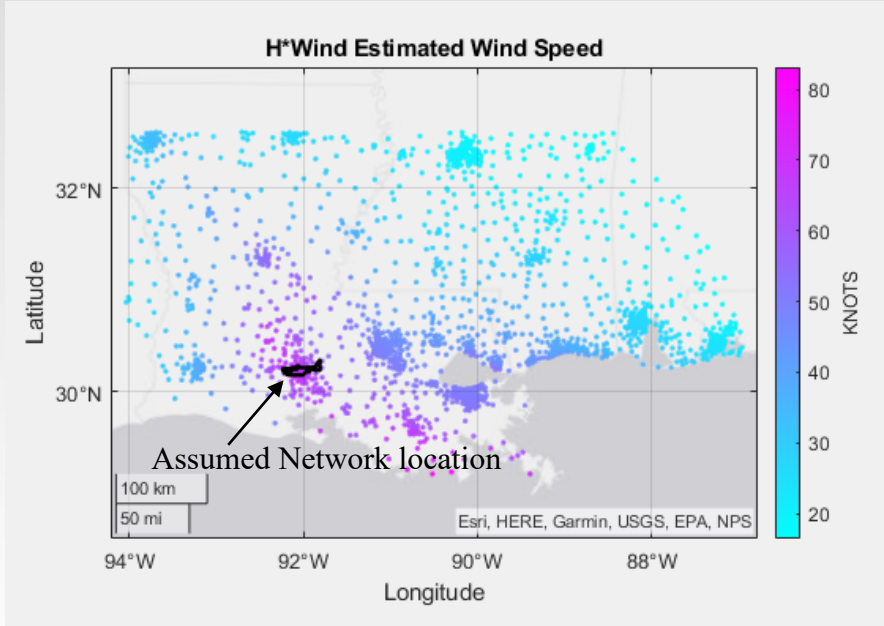
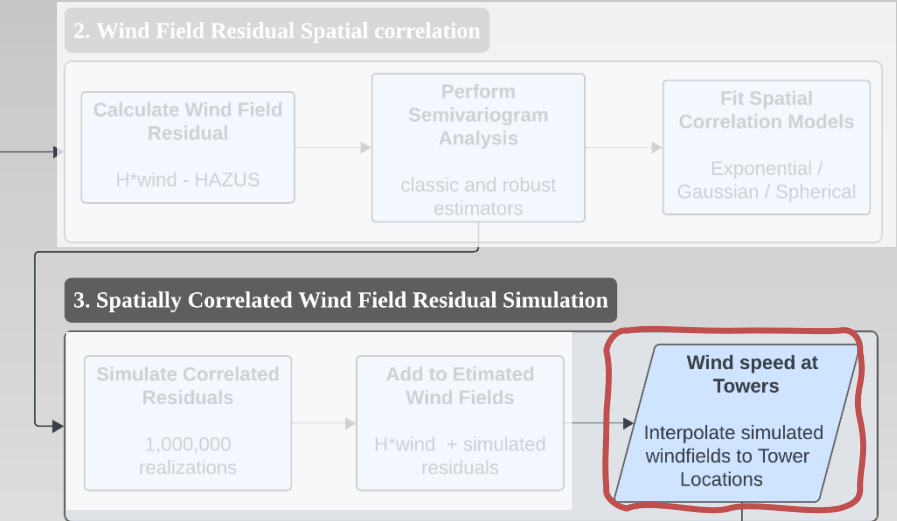
Case Study: Power Distribution Network

Electric power system of Shelby County, Tennessee

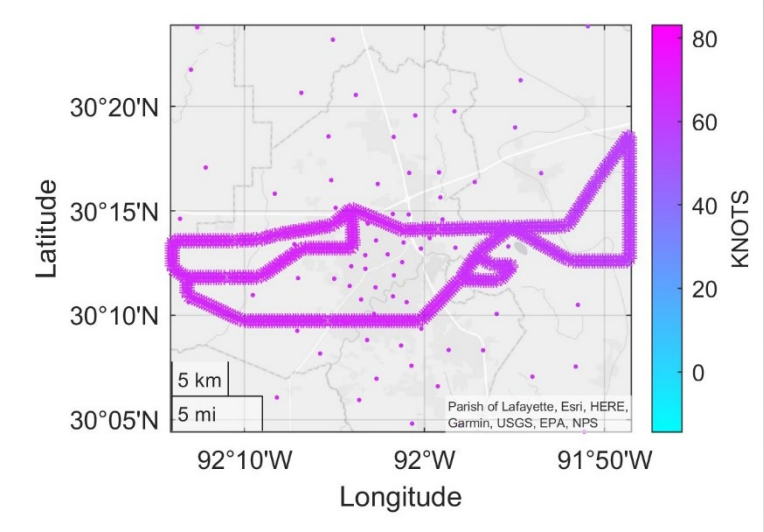
Span of support towers: 240m



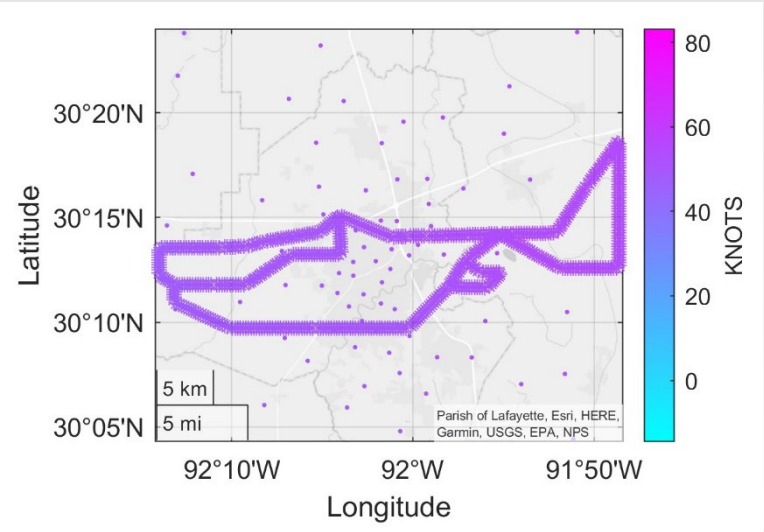
Simulation of Correlated Wind Fields



Observation (H*wind dataset)

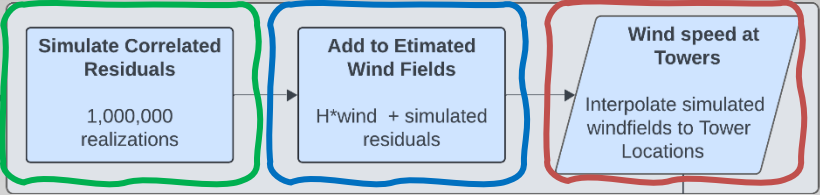


Prediction (HAZUS model)

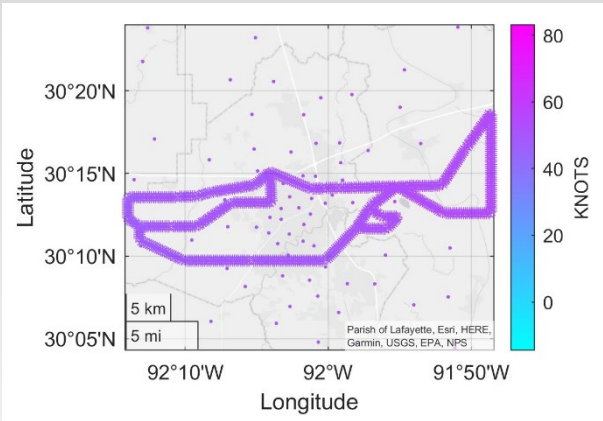


Simulation of Correlated Wind Field Residuals

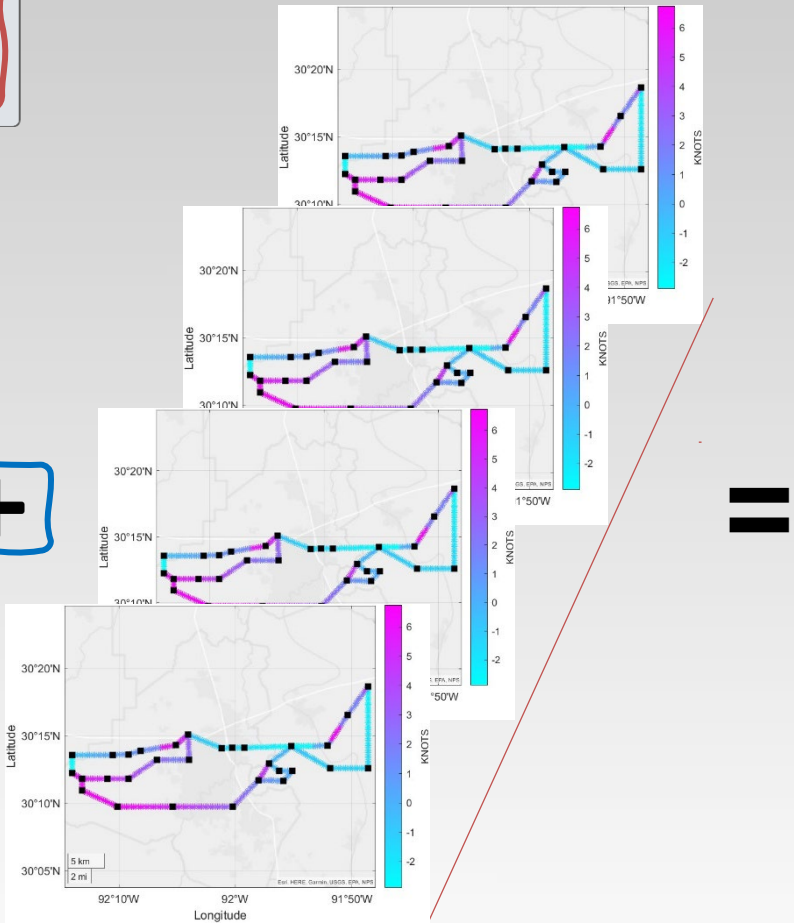
3. Spatially Correlated Wind Field Residual Simulation



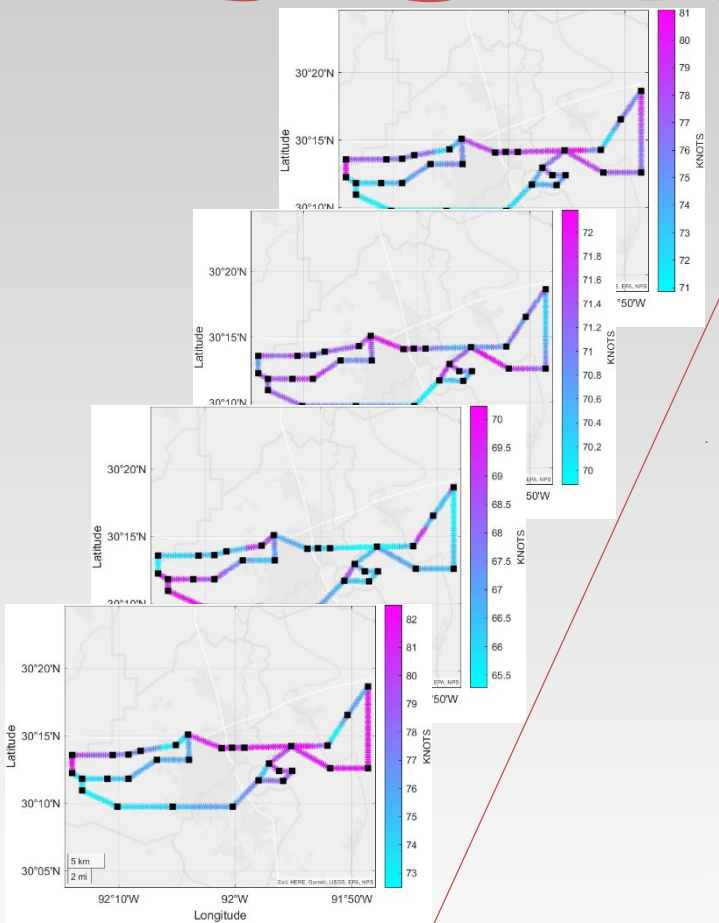
Estimated wind field



Correlated wind field residuals



Correlated wind fields



Fragility Function

Adopted from a reported by Quanta Technologies (Brown, 2009)

Transmission structures subjected to hurricane winds along the Gulf Coast

Approximated it using a two-parameter lognormal fragility model

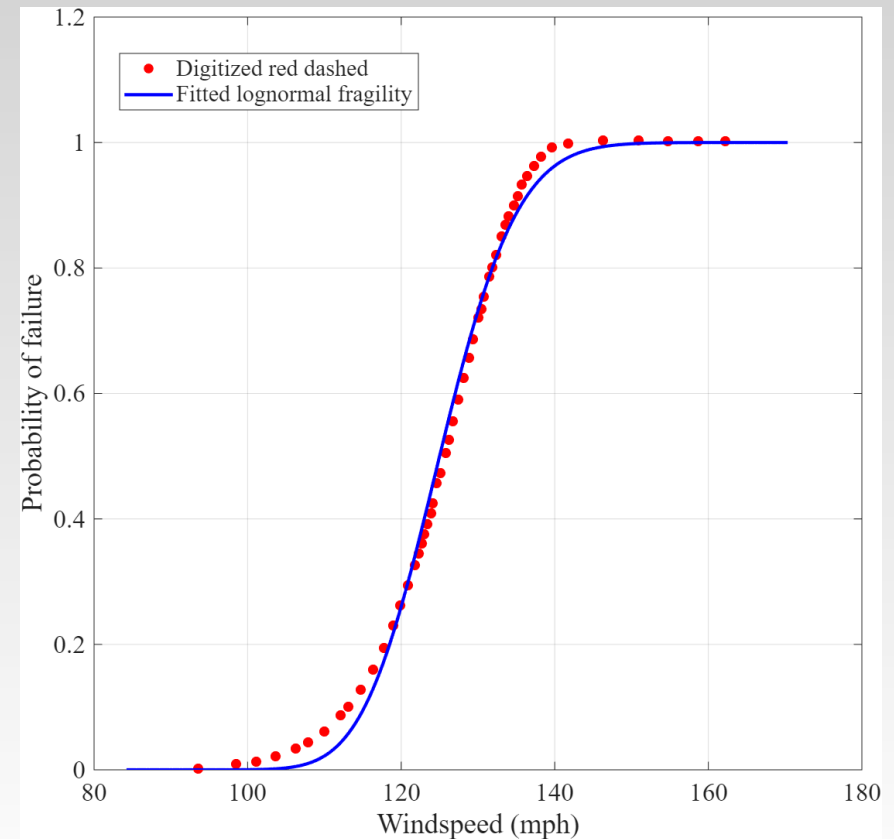
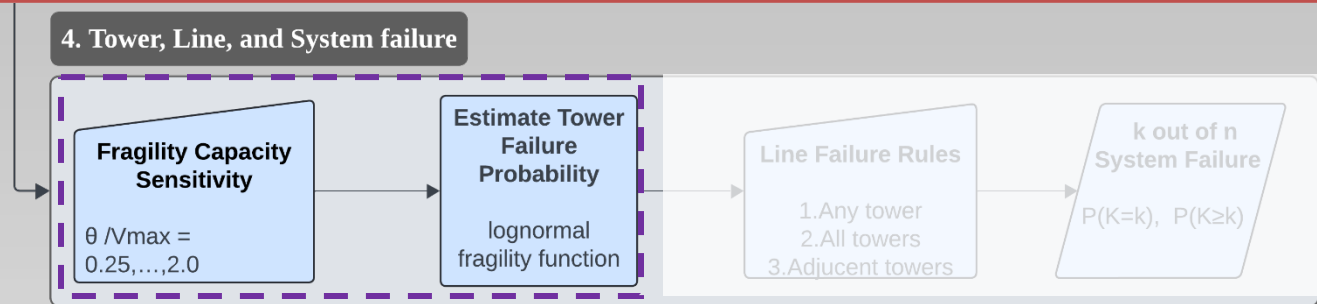
$$P_f(v) = \Phi\left[\frac{\ln(v) - \ln(\theta)}{\beta}\right]$$

$P_f(v)$ Tower failure probability

v wind speed (mph)

θ median capacity

β logarithmic dispersion

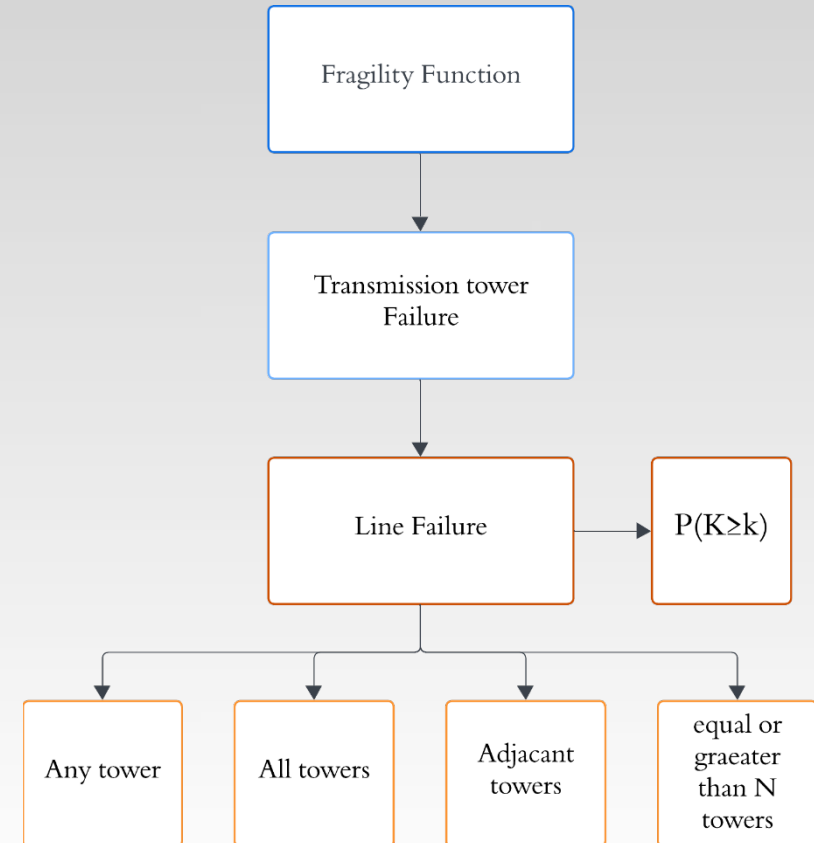
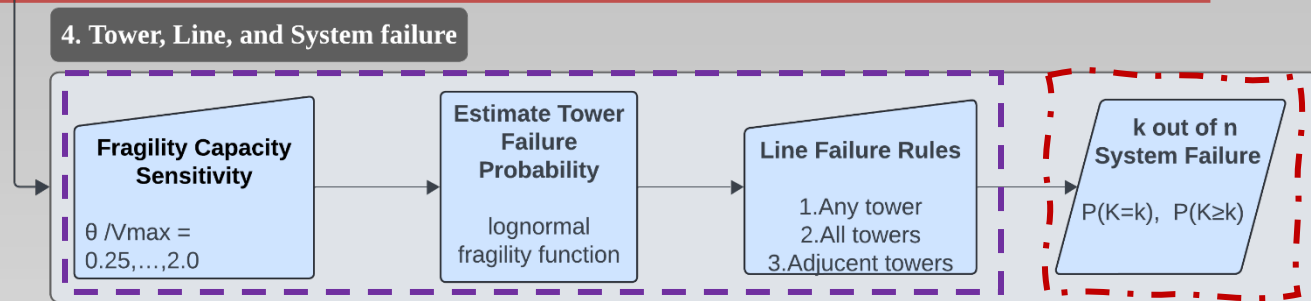


Sensitivity to Median Capacity

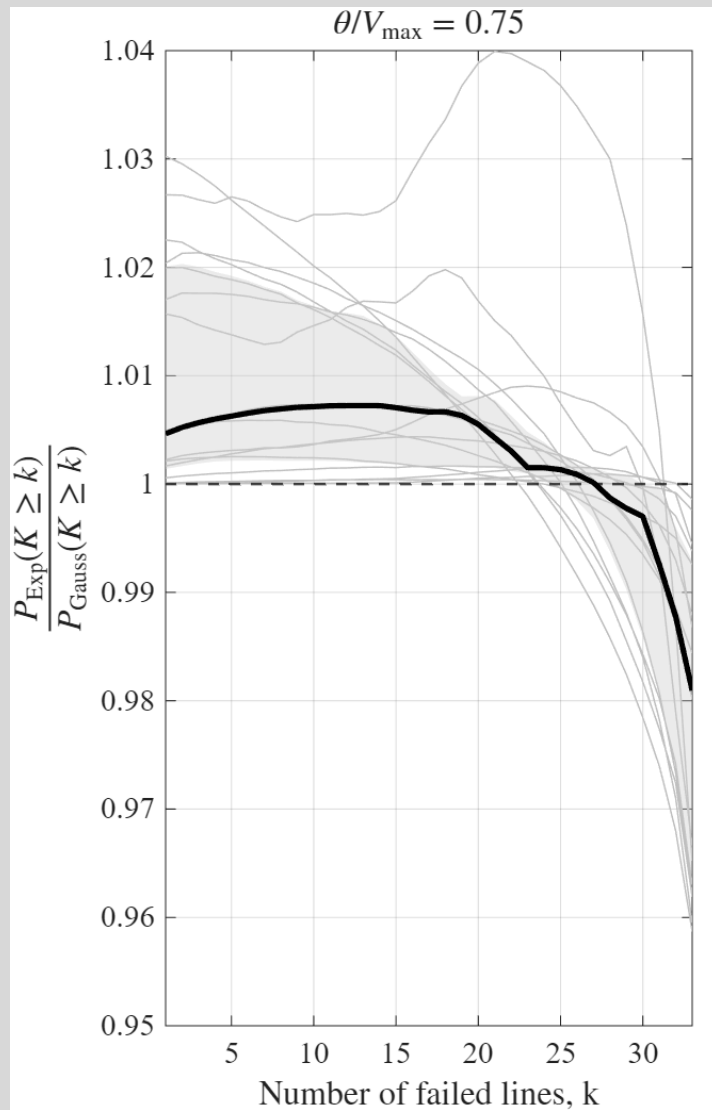
The median capacity of the fragility function, θ , is parameterized relative to a reference maximum wind speed, V_{max} , through the capacity ratio:

$$c_r = \frac{\theta}{V_{max}}$$

$$c_r = [0.25 \ 0.50 \ 0.75 \ 1.00 \ 1.25 \ 1.50 \ 2.00]$$



System Response



System Response

For capacity ratio $c = \frac{\theta}{V_{\max}} = 0.25, 0.5, \dots, 2$

Estimate Tower
Failure
Probability

lognormal
fragility function

Line Failure Rules

1.Any tower
2.All towers
3.Adjucent towers

System Failure
Exceedance

 $P(K \geq k)$

Correlation Model Sensitivity

$$R_i(j, c) = \frac{P_{i, \text{Exp}}(K \geq k | c)}{P_{i, \text{Gauss}}(K \geq k | c)}$$

$$r = \frac{P_{\text{Exp}}(K \geq k)}{P_{\text{Gauss}}(K \geq k)}$$

$r = 1$: no difference

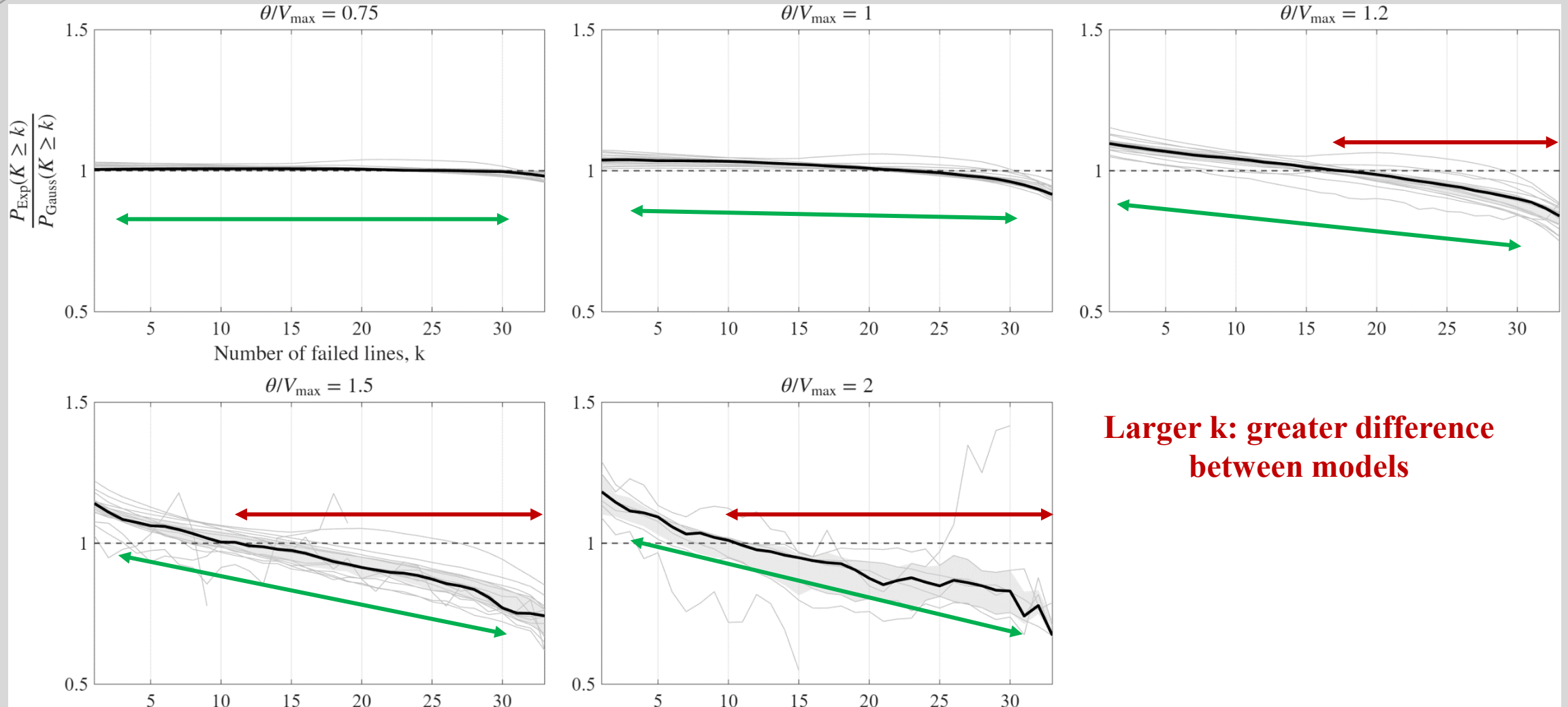
$r > 1$: higher number of failures by
Exponential model

$r < 1$: higher number of failures by Gaussian
model

System Response

Series rule

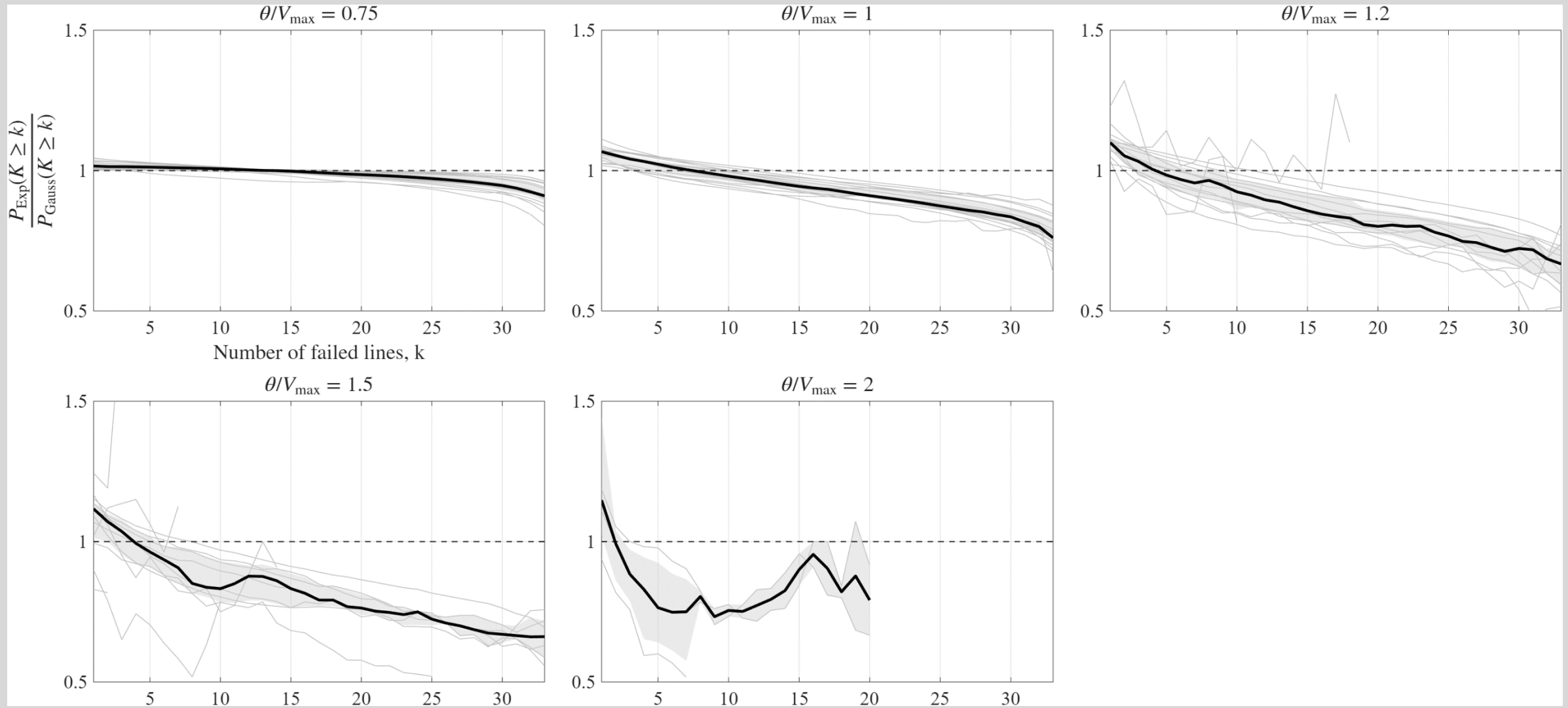
Increasing component capacity $\rightarrow$ increasing sensitivity to correlation model



Larger k : greater difference between models

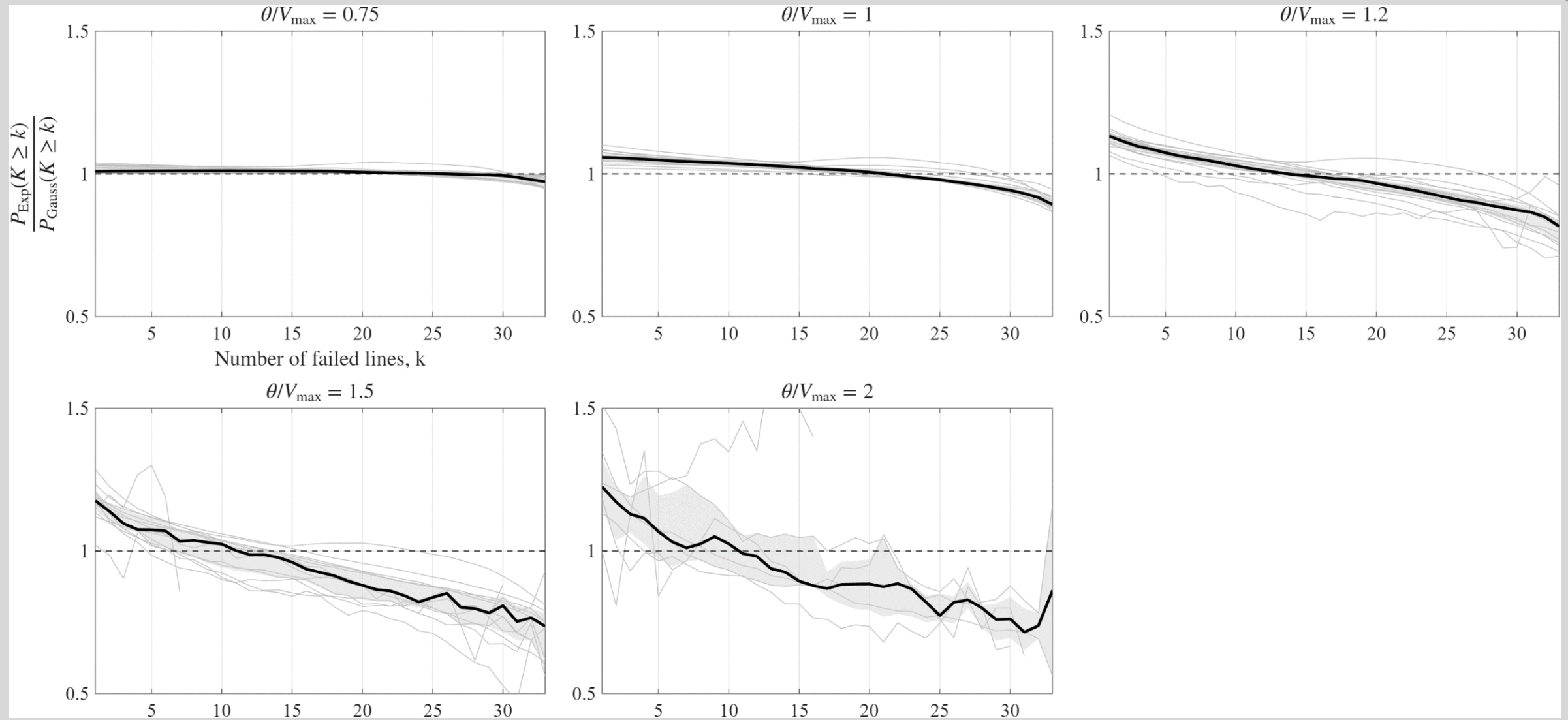
System Response

Parallel rule



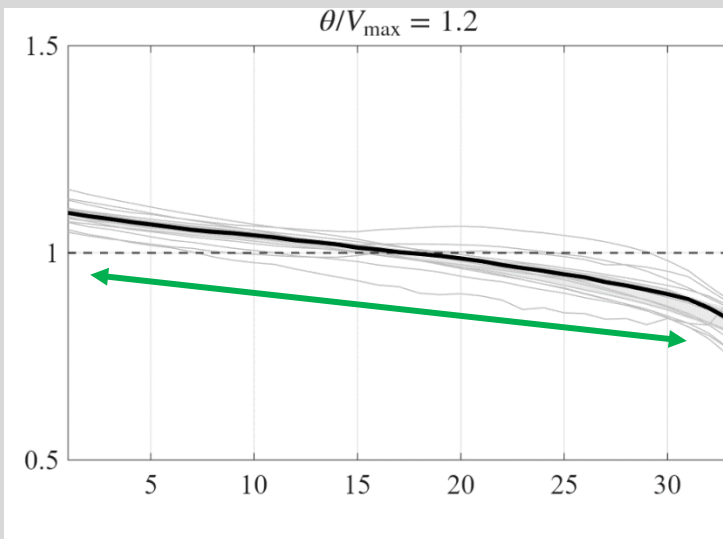
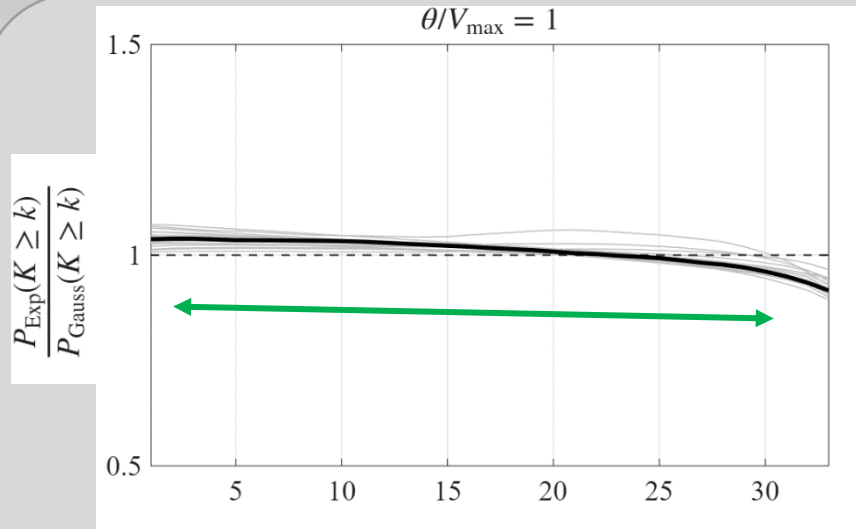
System Response

Adjacent rule



System Response

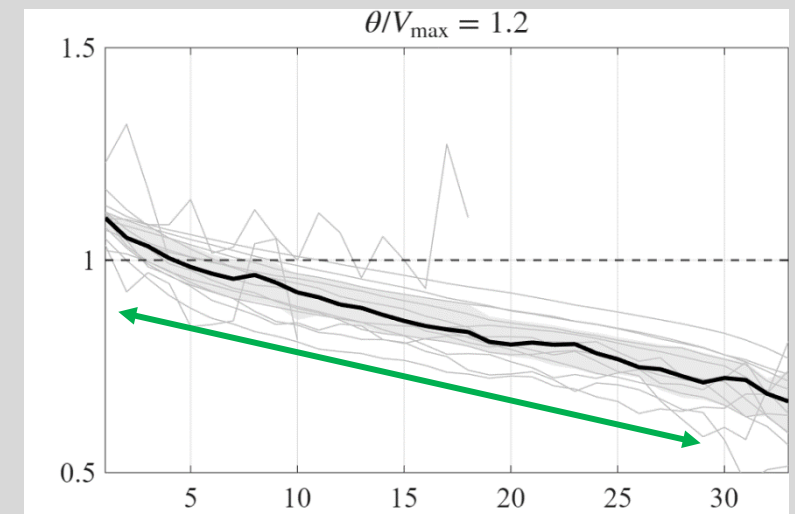
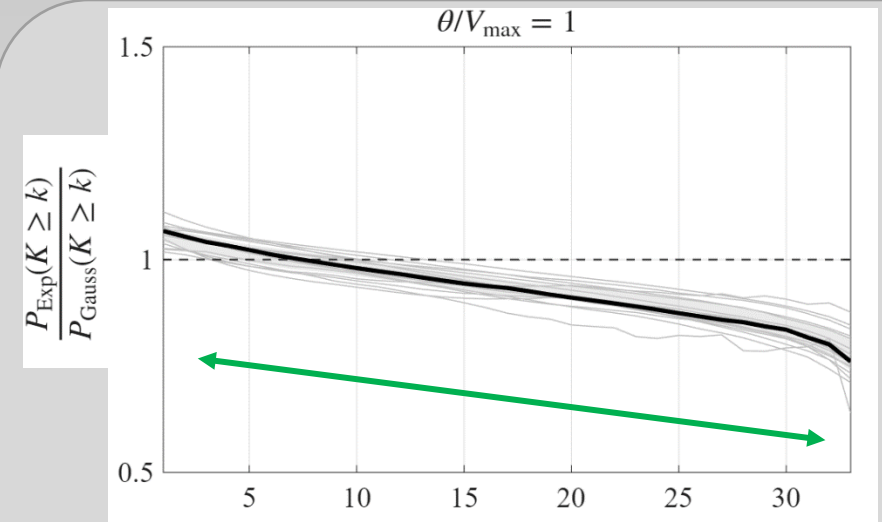
Series rule



System failure logic
changes the importance
of spatial correlation

*Series/parallel refer to
component-to-line failure
logic, not electrical network
topology*

Parallel rule



Key Takeaways

1

TC wind field spatial correlation matters for risk assessment of spatially distributed systems

2

The impact of the type of correlation model depends on the component capacity and the line failure rule

Thank You!

Acknowledgments:

Source of Funding

- National Science Foundation (CAREER Award # 2047966)

Contributors

- Emily Gibson, PhD, P.E.
- Huwei Dong

Questions?