Modeling Hurricane Impact on Texas Electrical Infrastructure

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Outline

- Introduction
- Model Description
  - Hurricane Modeling
  - Impact Modeling
  - Outage Probability
- Results and Analysis
- Conclusion

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Introduction: Hurricane Risk Assessment

- Hurricanes have devastated the eastern seaboard causing severe structural damage to electrical infrastructure
- Severe outages caused by lack of preparedness highlight the necessity for early risk assessment [1]
- Computational modeling can be used to analyze potential hurricane's impact on the electrical grid
  - Improves resilience efforts and helps develop faster restoration processes

[1]

[1]

[1] A. Kwasinski, F. Andrade, M. J. Castro-Sitiriche, and E. O'Neill-Carrillo,"Hurricane maria effects on puerto rico electric power infrastructure,"IEEE Power and Energy Technology Systems Journal, vol. 6, no. 1, pp.85–94, 2019.

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Introduction: Hurricane Wind Threat

- The scope of our model focuses on the threat that high-speed hurricane winds pose for electrical grids
- US DOE hurricane Sandy & Irene report identifies extreme hurricane winds as primary threats
  - "Devastating" wind damage in both hurricanes, collectively causing significant harm to 22,815 transmission poles and 191 electrical substations [2]
- NERC report on hurricane Harvey similarly identifies significant damage caused by high hurricane wind speeds across Texas' electrical grid [3]

[2] Office of Electricity Delivery and Energy Reliability. "Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure." U.S. Department of Energy, Apr. 2013.

[3]"Hurricane Harvey Event Analysis Report." North American Electric Reliability Corporation, 9 Mar. 2018.

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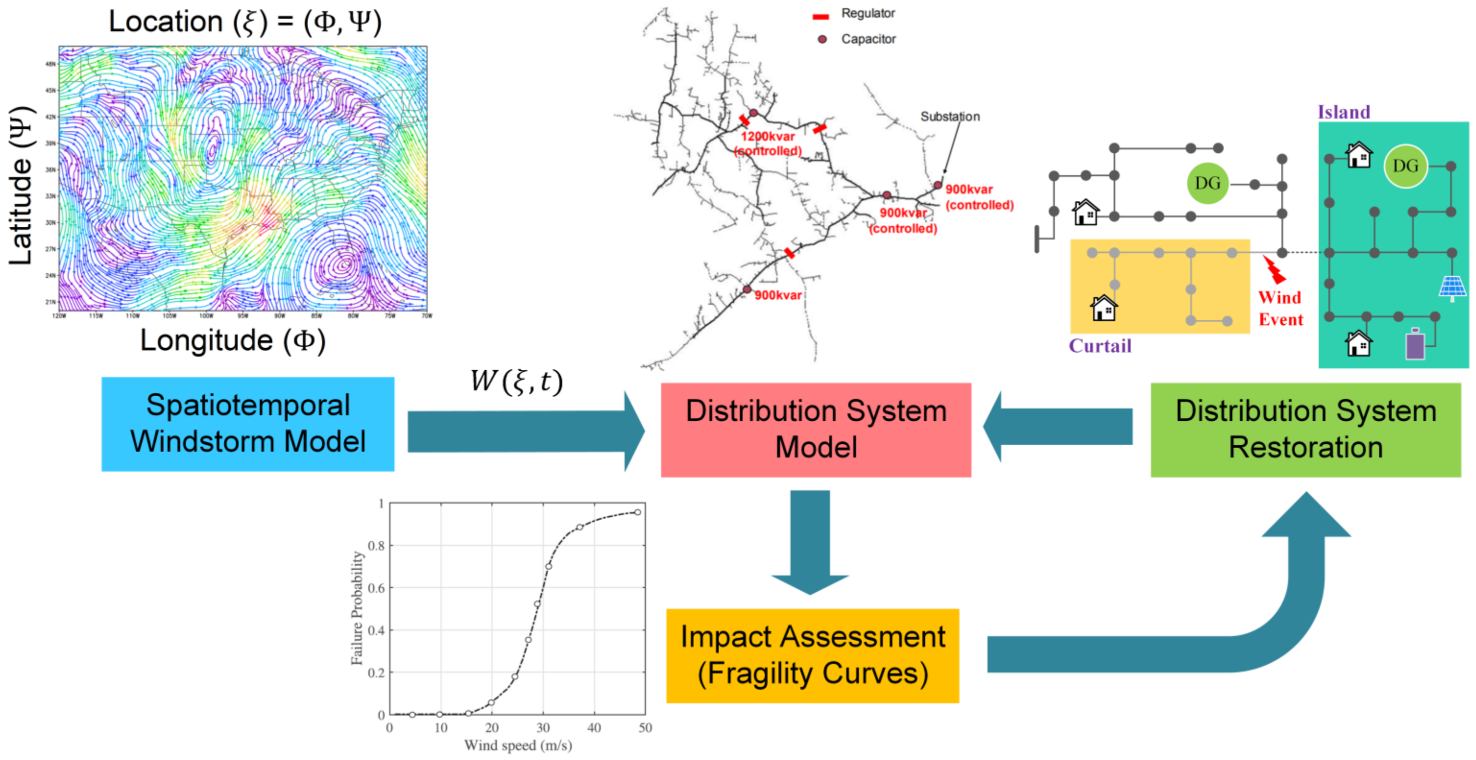
Model Overview

- Meteorological model implemented

- Distribution and hurricane models combined for impact assesment

- Outage probabilities are calculated

- Resiliency gaps are identified



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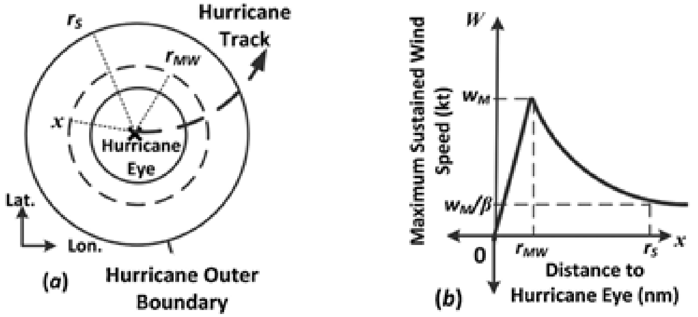
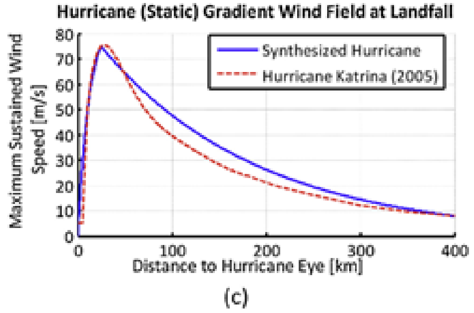
Spatiotemporal Windstorm Model: Static Wind Field

- Create static wind field at a singular point in time
- Static wind field can be modeled if three parameters are known: r_{mw}, r_s, w_m. **(see figures (b) and (c))**. [4]
- Once these three values are known, wind speed at any distance ‘x’ from the center of the hurricane can be approximated. Assumed that K=1.14 and β=10. (**see top figure and (a)**) [4]

$$W(x) = \begin{cases} \xi(1 - \exp[-\psi x]) & 0 \le x < r_{mw} \\ w_m \exp\left[-\left(\frac{\ln(\beta)}{r_s - r_{mw}}\right)(x - r_{mw}\right) & r_{mw} \le x \le r_s \\ 0 & x > r_s \end{cases} \quad [4]$$

$$\xi = K \times w_m; \quad \psi = \frac{1}{r_{mw}} \ln\left(\frac{K}{K-1}\right), \qquad K = 1.14$$

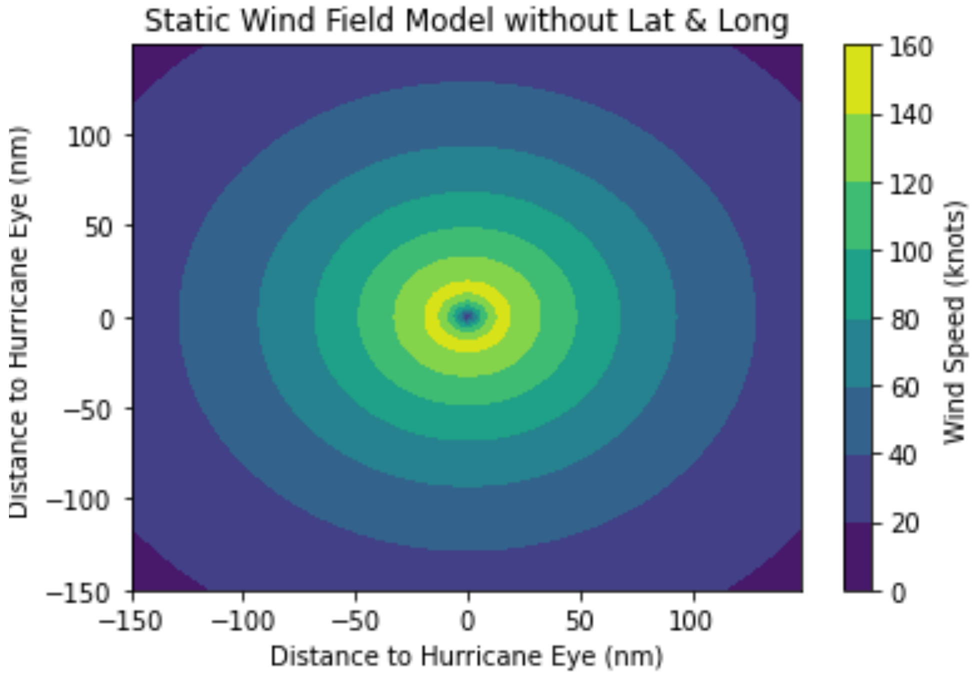


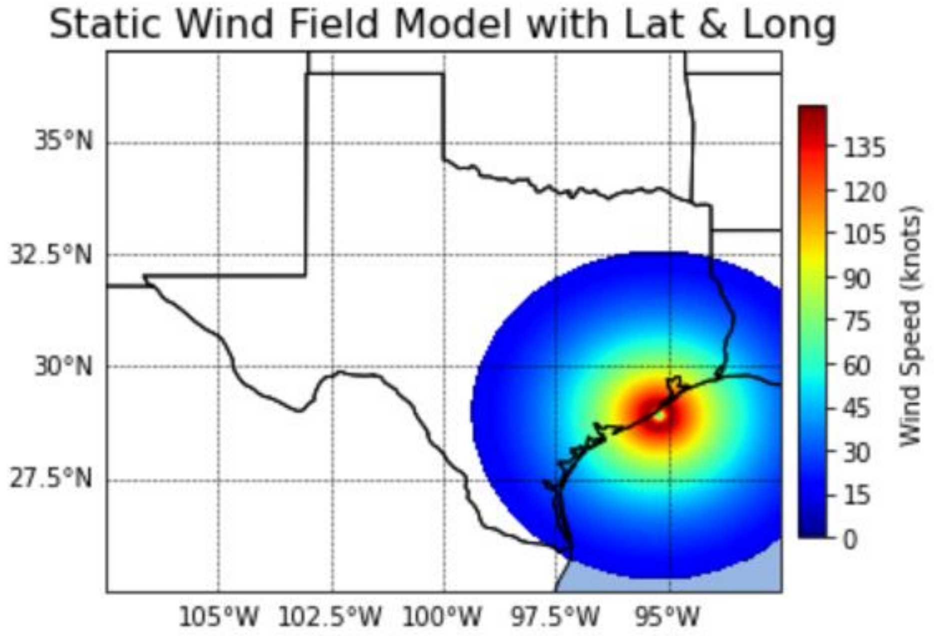


[4]

[4] P. Javanbakht and S. Mohagheghi, “A risk-averse security-constrainedoptimal power flow for a power grid subject to hurricanes,”ElectricPower Systems Research, vol. 116, pp. 408–418, 2014. [Online]. Available:https://www.sciencedirect.com/science/article/pii/S0378779614002727

Static Wind Field Model





- Left: purely represents hurricane without latitudinal/longitudinal representation
- Right: latitudes and longitudes are introduced to model hurricane progression over time (dynamic wind field)

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Spatiotemporal Windstorm Model: Dynamic Model

- Convert the static wind field model to dynamic wind field model by modeling hurricane path

- Dynamic wind field can be modeled if the path of the hurricane (*lat*, *long*) and the land decay factor (α) is known, as well as the initial values of the three parameters (rmw, rs, and wm) [4]
  - Each point in the path is every 2 hours for a total of 12 hours
  - Assumed that α=0.04

- Once these two values are known, the dynamic wind field can be modeled through generating a static wind field for every point in the path
  - New values of rs, rmw, and wm are generated for each time step

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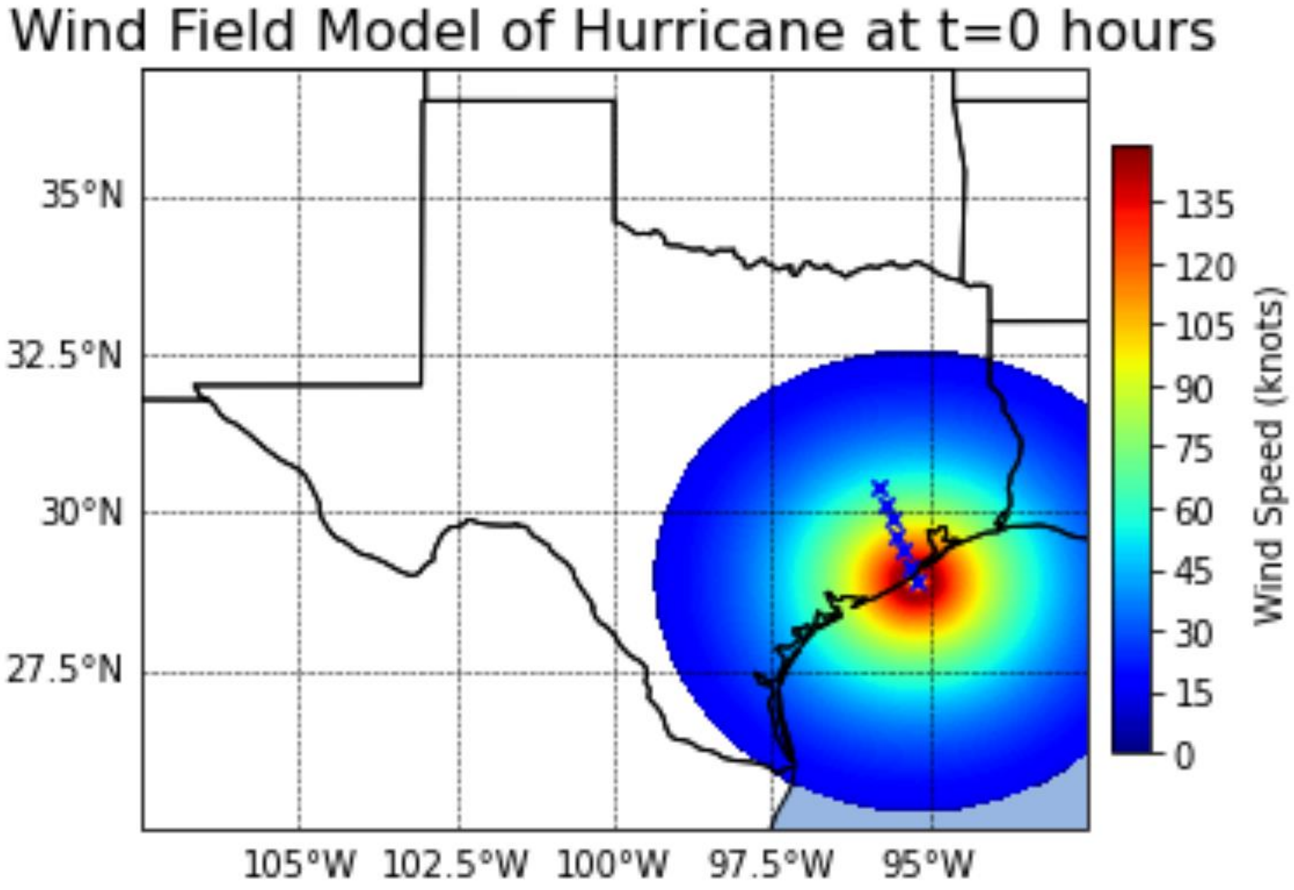
Results: Dynamic Spatiotemporal Windstorm Model

- Hurricane size varies with each timestep and is based on KDE of $\mathbf{r}_s$



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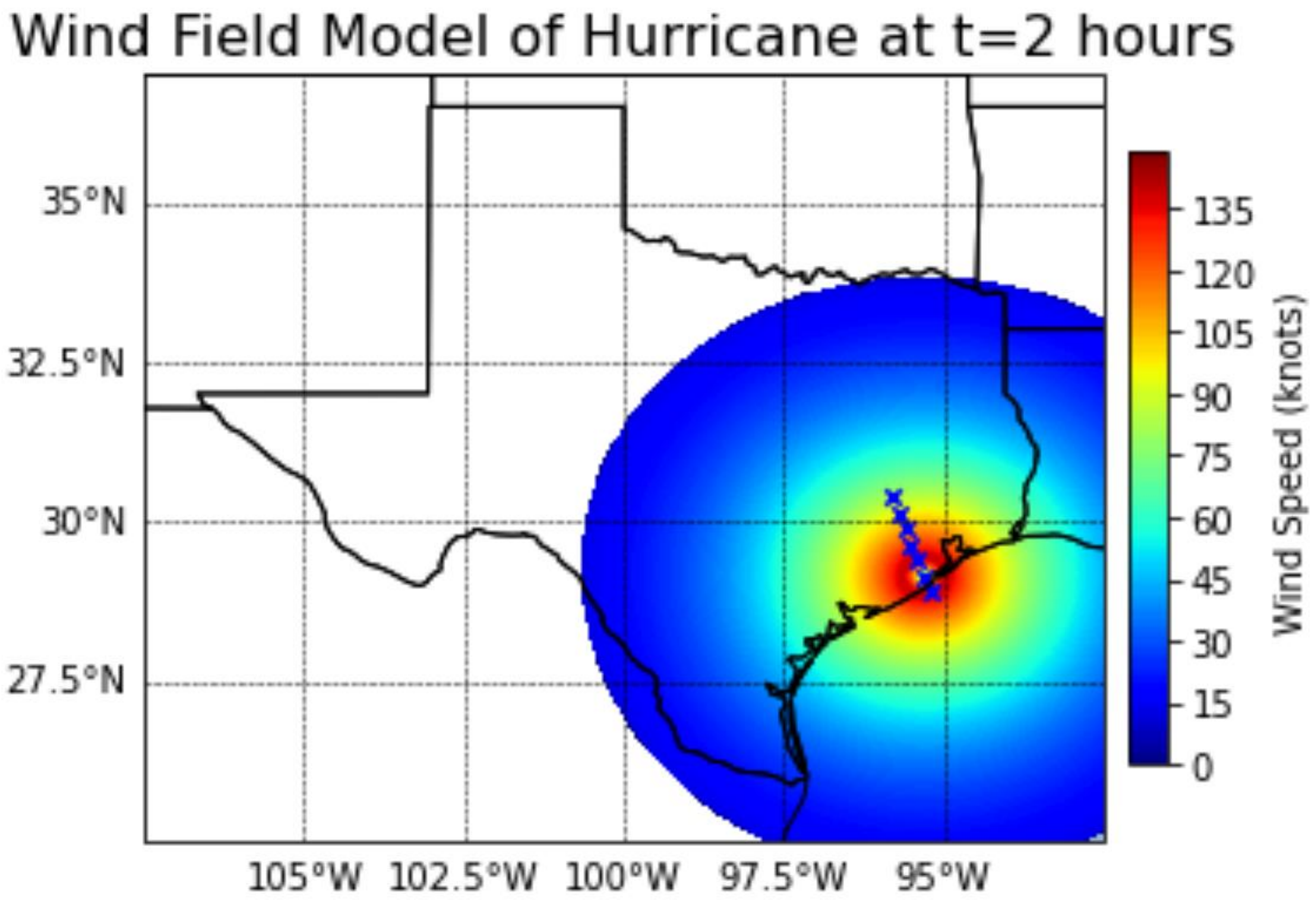
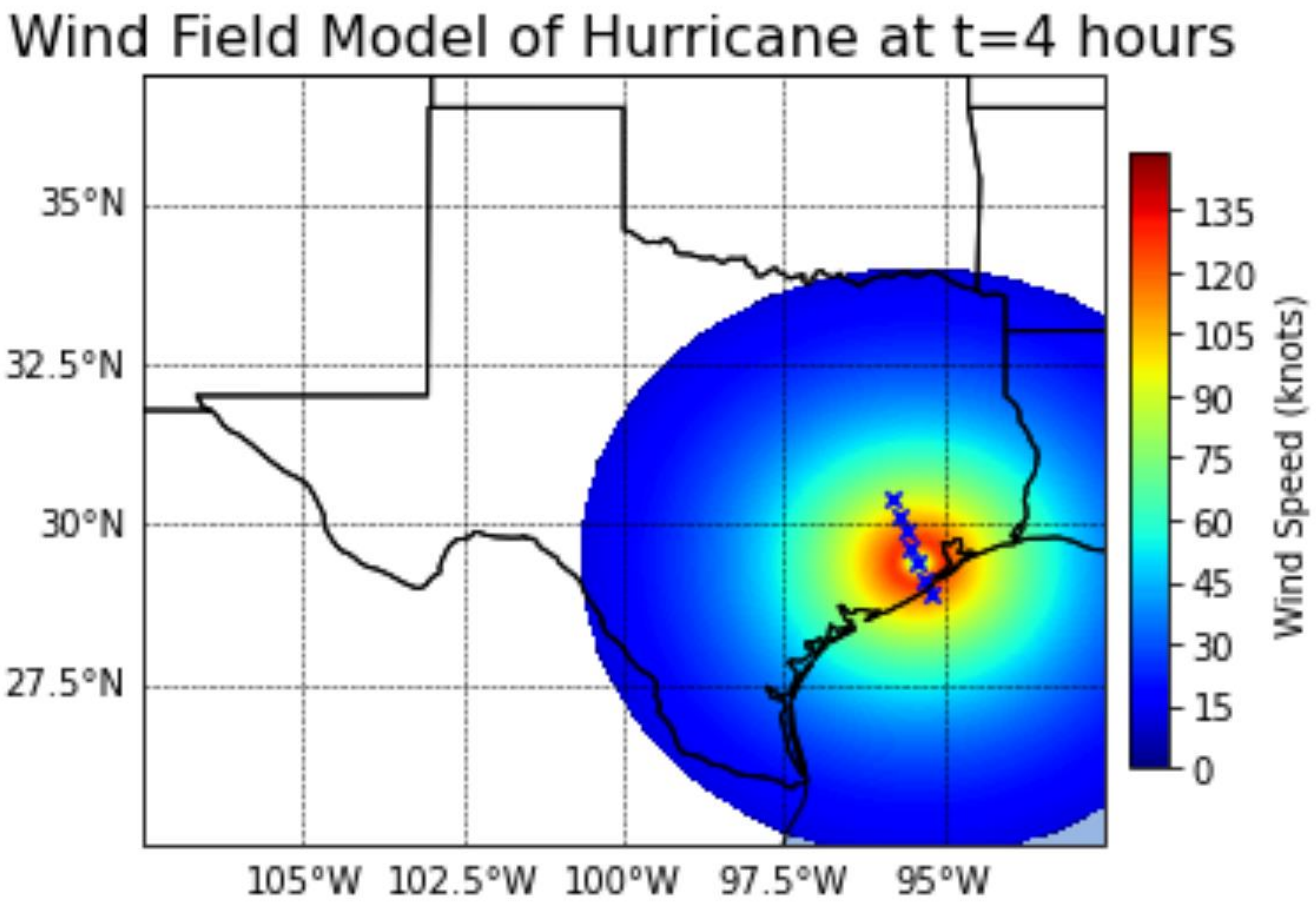
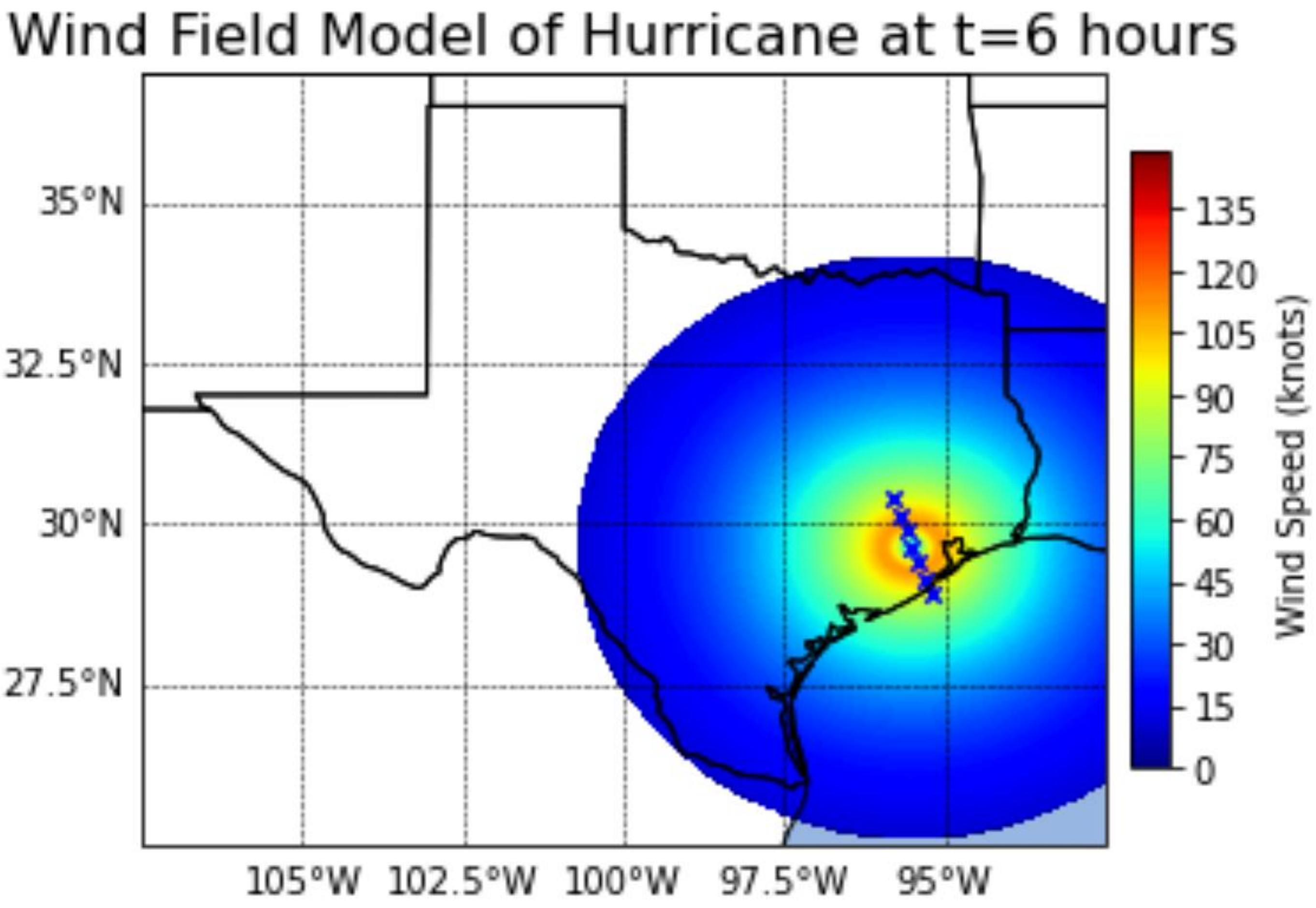
Results: Dynamic Spatiotemporal Windstorm Model



Results: Dynamic Spatiotemporal Windstorm Model



Results: Dynamic Spatiotemporal Windstorm Model



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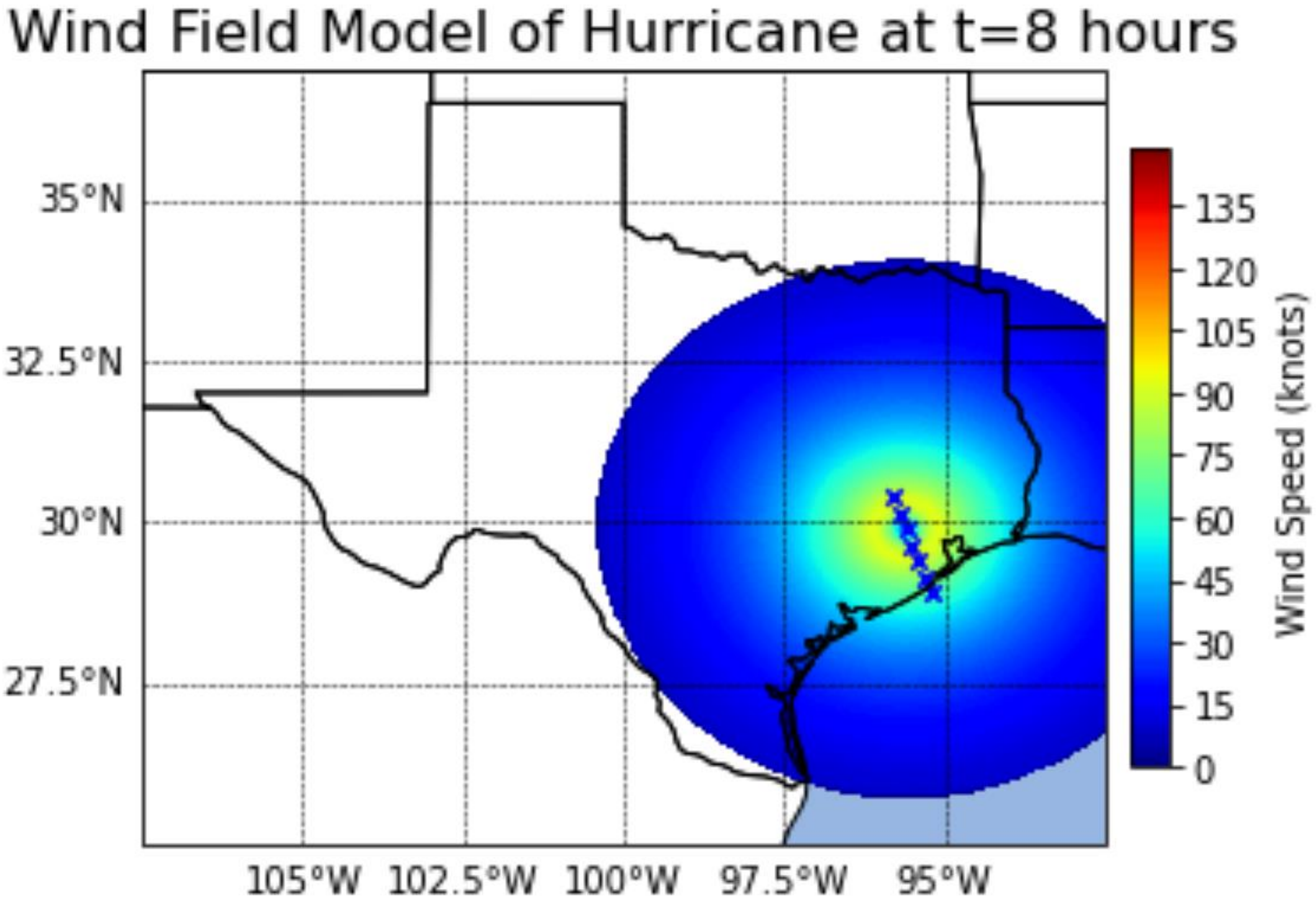
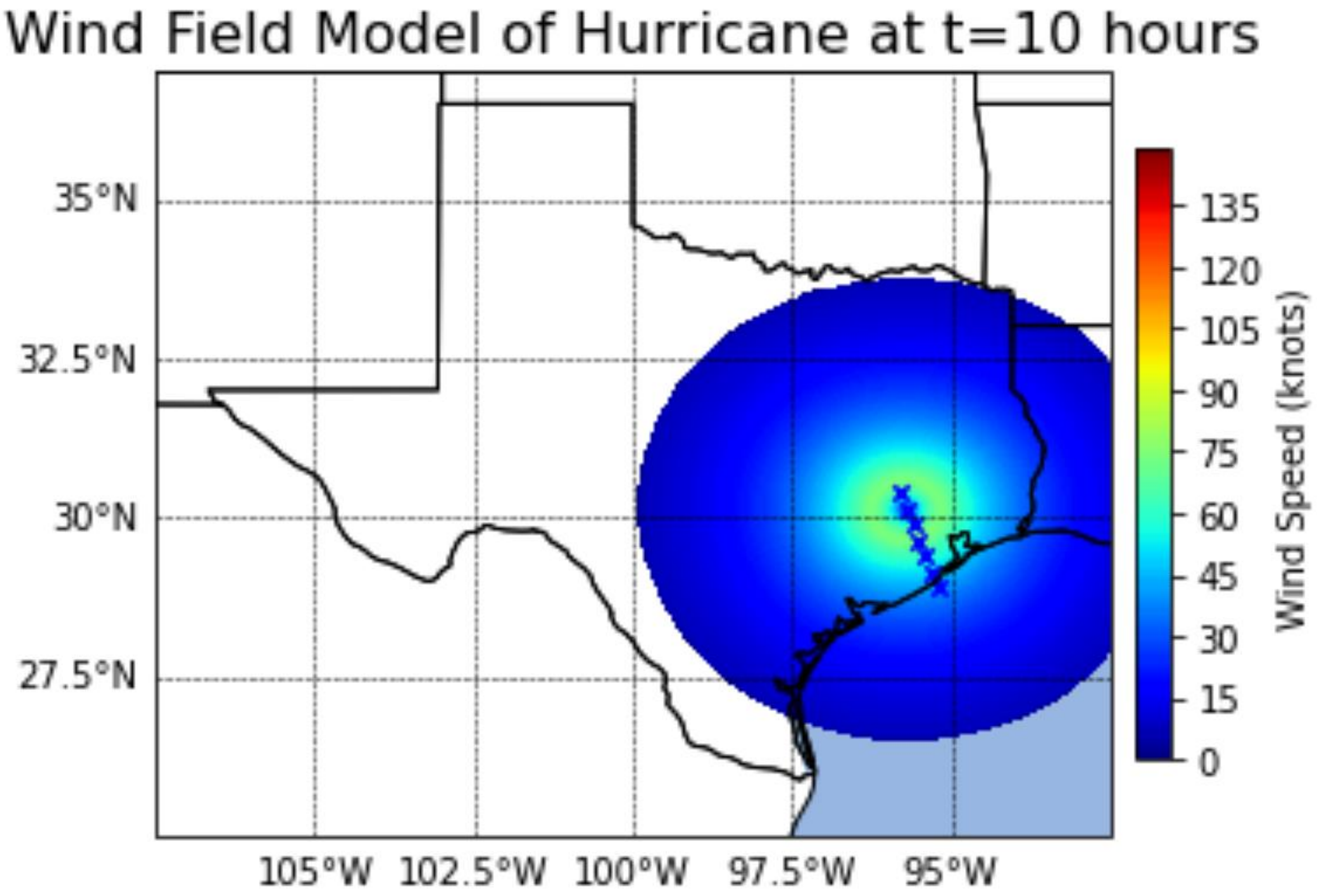
Results: Dynamic Spatiotemporal Windstorm Model



Results: Dynamic Spatiotemporal Windstorm Model



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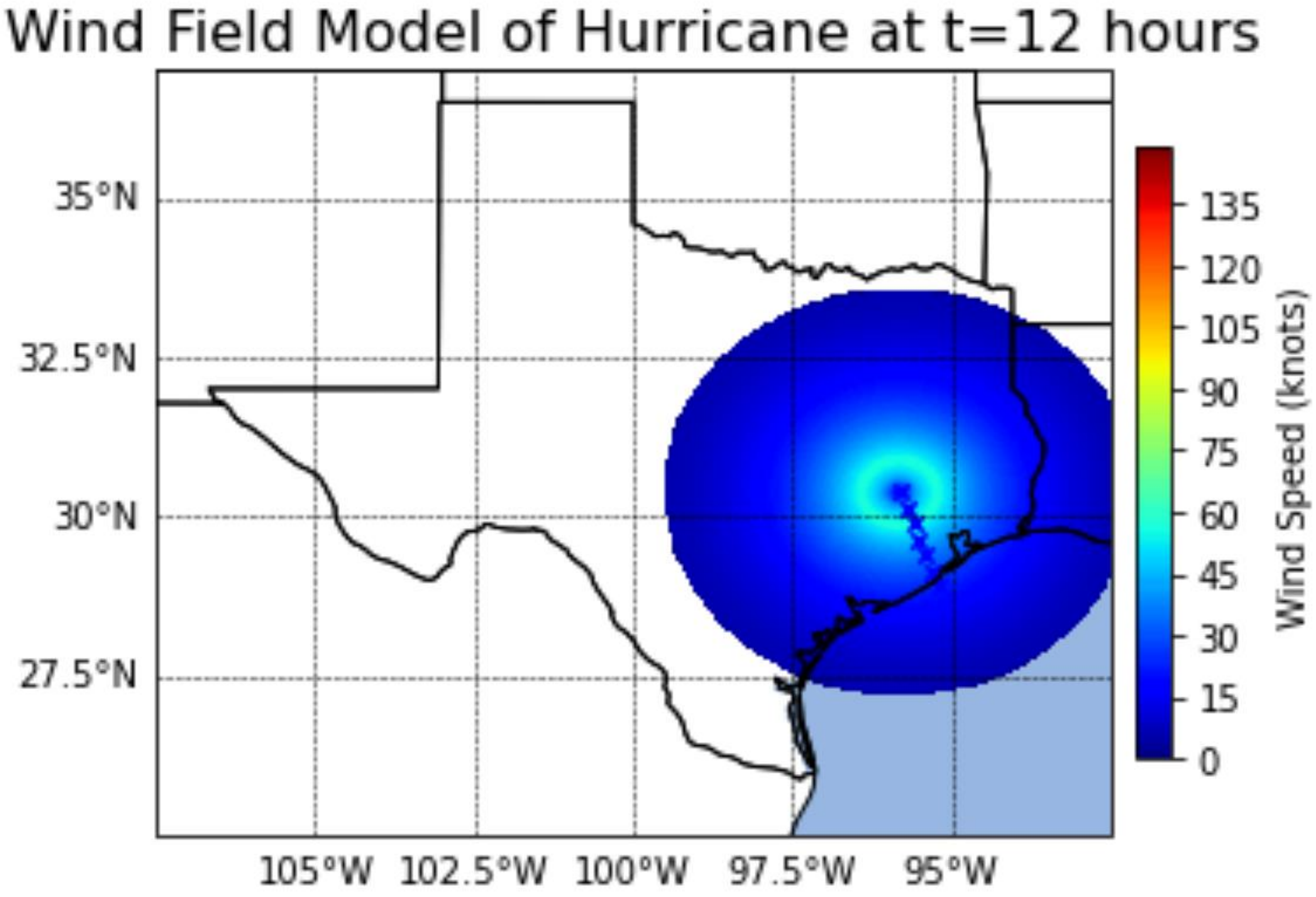
Results: Dynamic Spatiotemporal Windstorm Model



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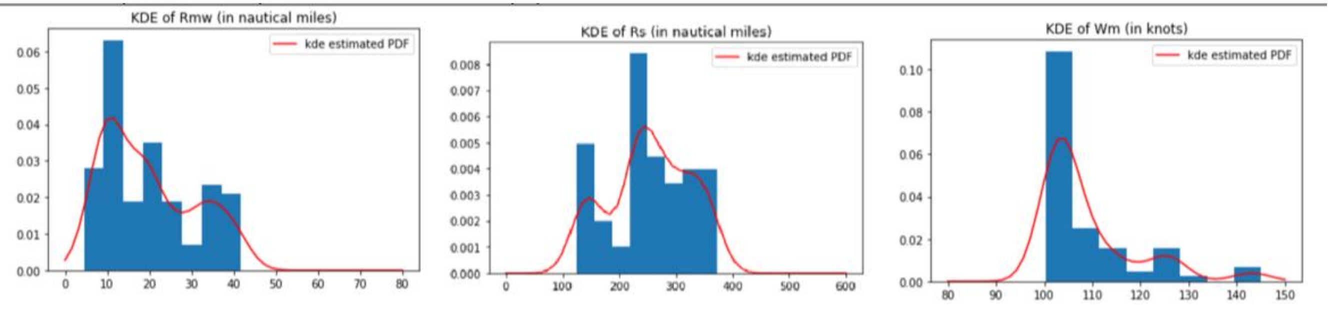
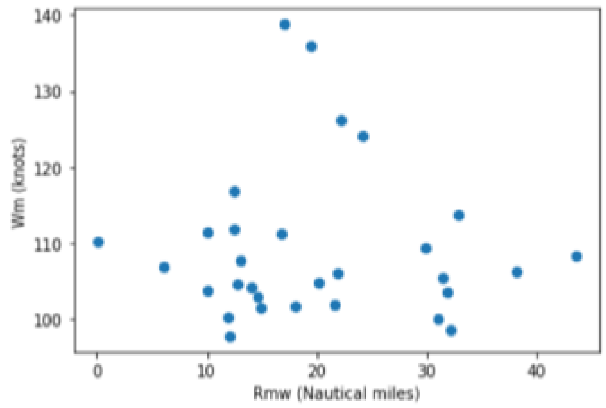
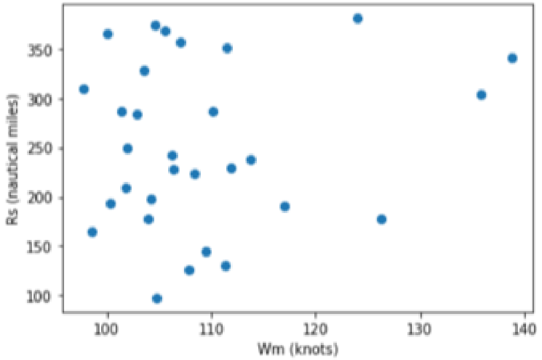
Spatiotemporal Windstorm Model: Multiple Tracks, Scenarios

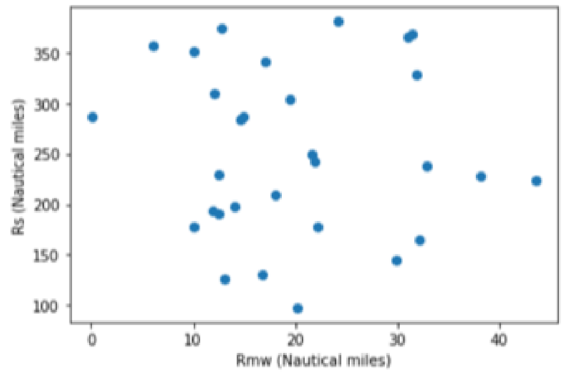
- Third step is to generate different possible scenarios for the hurricane and dynamically mod each scenario



- Different scenarios are generated through assigning a different initial value of {r_s, r_{mw}, w_m} based on kernel density estimates (shown in fig.)
  - **Generated 10 scenarios per track with 3 tracks for a total of 30 scenarios**
- Can generate different scenarios by randomly sampling from the KDEs because the three variables are not correlated with each other [4]



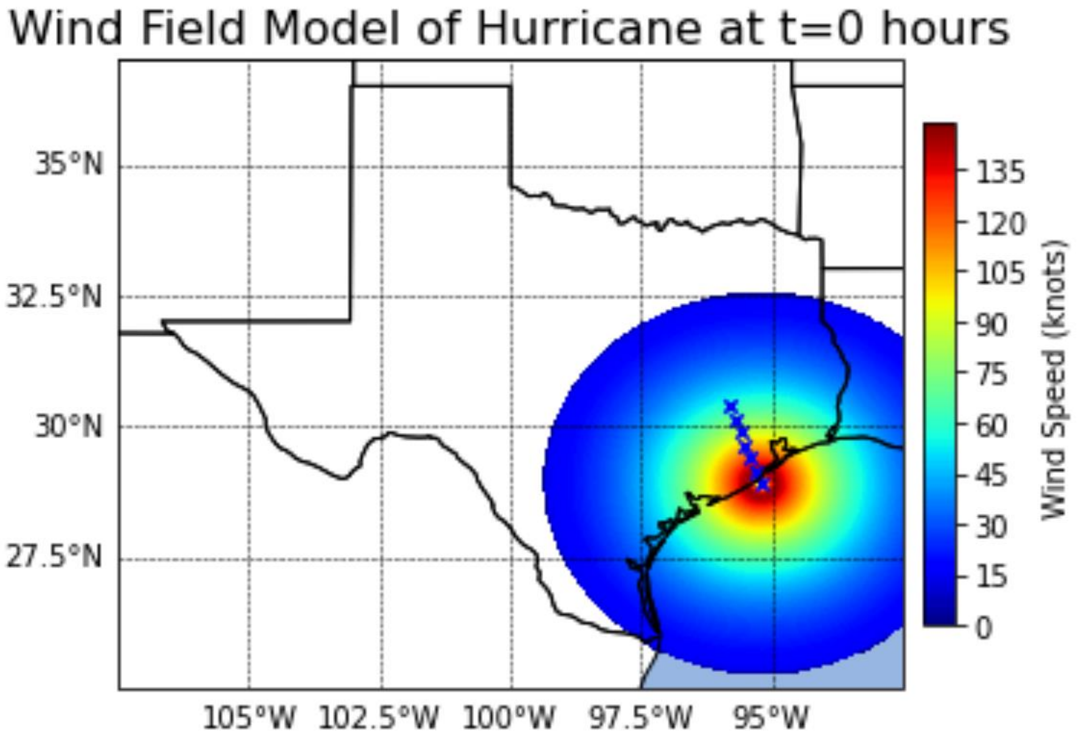




	0 hrs	2 hrs	4 hrs	6 hrs	8 hrs	10 hrs	12 hrs
Track 1 (N,W)	(28.9, 95.2)	(29.14, 95.3)	(29.39, 95.4)	(29.63, 95.51)	(29.88, 95.61)	(30.12, 95.71)	(30.37, 95.82)
Track 2 (N,W)	(28.9, 95.2)	(29.13, 95.35)	(29.35, 95.5)	(29.58, 95.65)	(29.8, 95.8)	(30.03, 95.95)	(30.25, 95.10)
Track 3 (N,W)	(28.9, 95.2)	(29.1, 95.39)	(29.3, 95.58)	(29.5, 95.78)	(29.7, 95.97)	(29.89, 96.17)	(30.09, 96.36)

Impact Modeling

- Model Texas electrical grid with meteorological simulations to assess impact on electrical infrastructure



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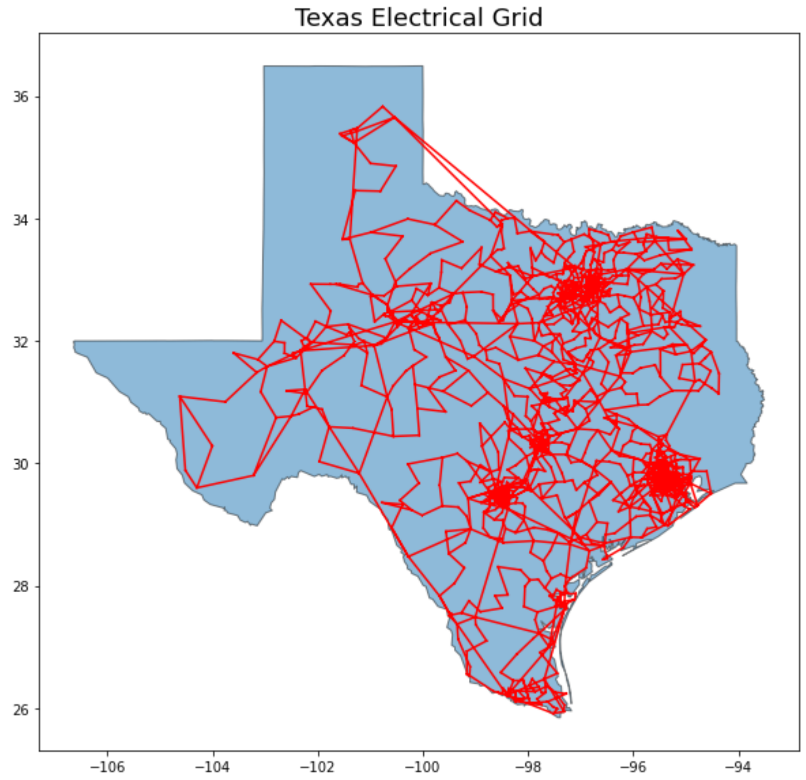

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Hurricane Impact Matrix

- Hurricane Impact Matrix proposed in [4] can be applied to generate maximum windspeed values for each transmission line in the electrical grid
  - Applied for each transmission line 'j' and hurricane scenario 'h'

$$\boxed{him_{j,h} = \begin{cases} w_{m_h} & d_{min}(j,h) \leq r_{mw_h} \leq d_{max}(j,h) \\ max\begin{pmatrix} w_{d_h}(d_{min}(j,h,)|m_h) \\ w_{d_h}(d_{max}(j,h,)|m_h) \end{pmatrix} & otherwise \end{cases}} \quad [4]$$

d_{min} and d_{max} are defined as the minimum and maximum distances from any point on transmission line 'j' to the eye of the hurricane

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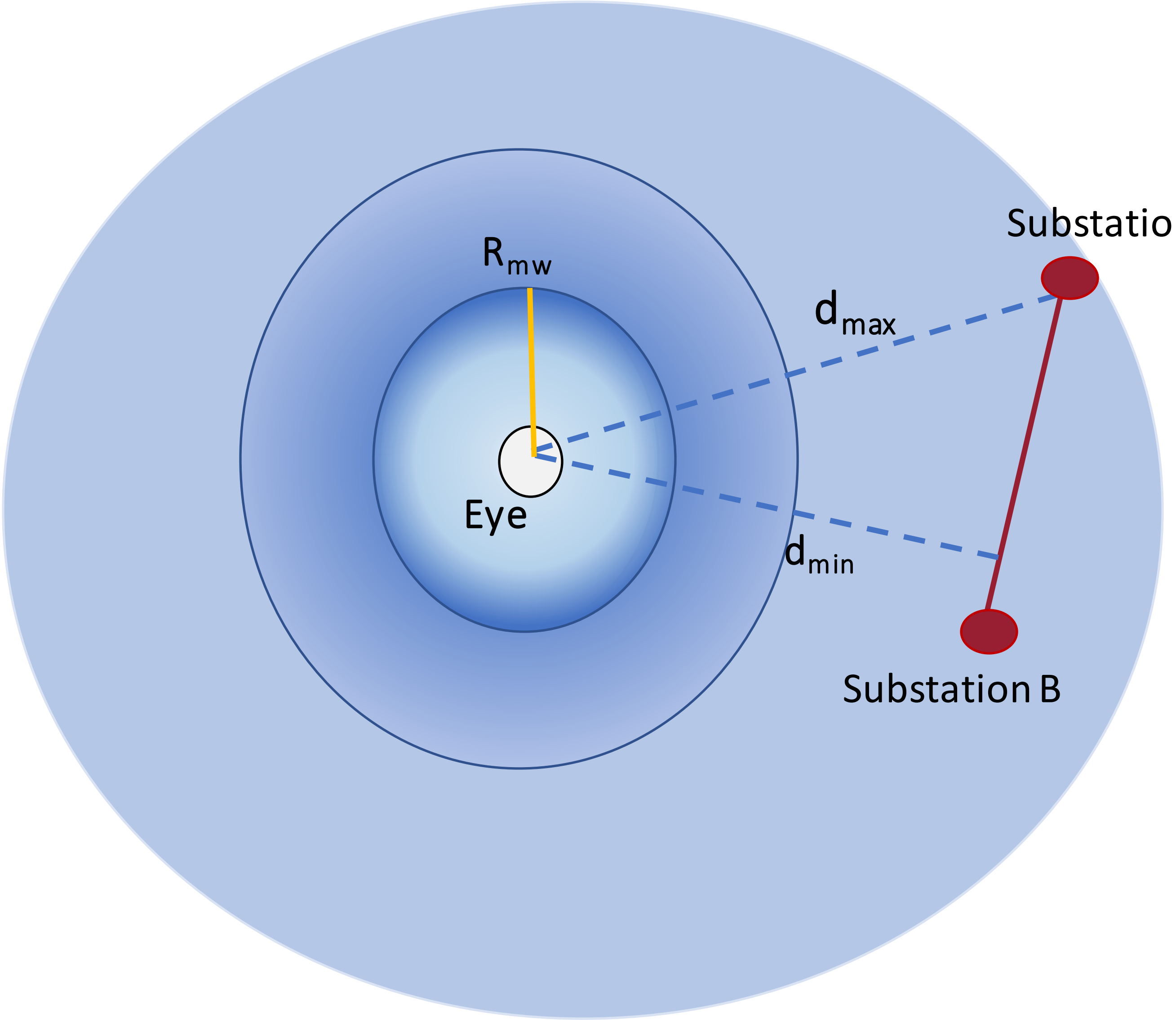
Impact Matrix Illustration



$$him_{j,h} = \begin{cases} w_{m_h} & d_{min}(j,h) \le r_{mw_h} \le d_{max}(j,h) \\ max\begin{pmatrix} w_{d_h}(d_{min}(j,h,)|m_h) \\ w_{d_h}(d_{max}(j,h,)|m_h) \end{pmatrix} & otherwise \end{cases}$$

[4]

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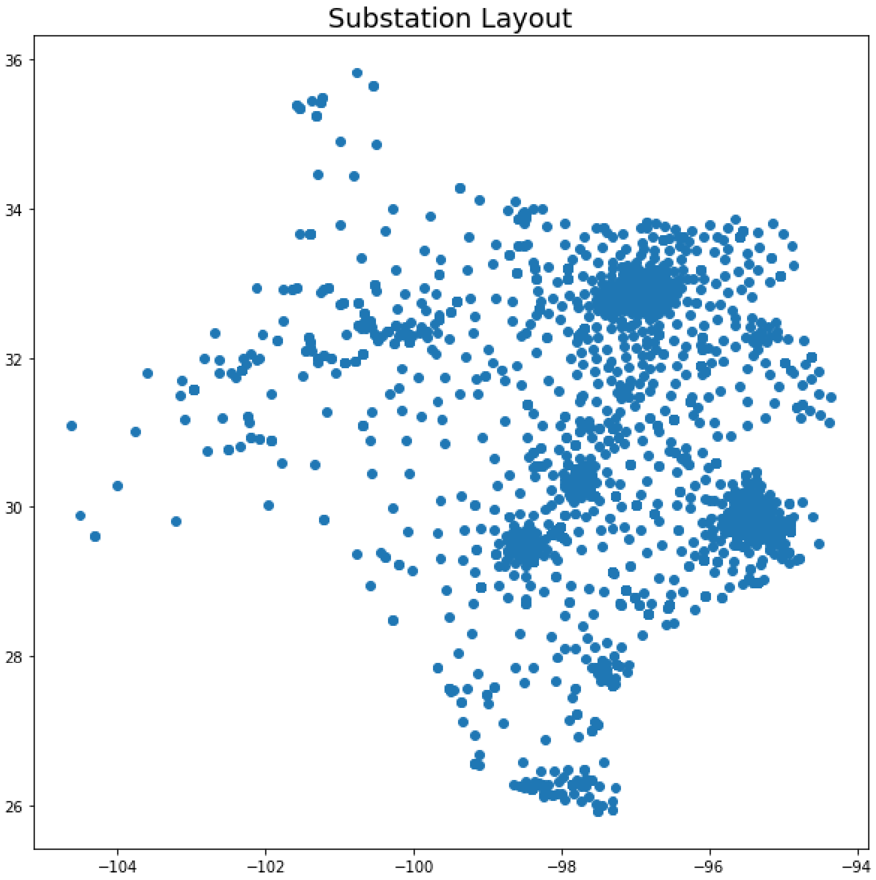
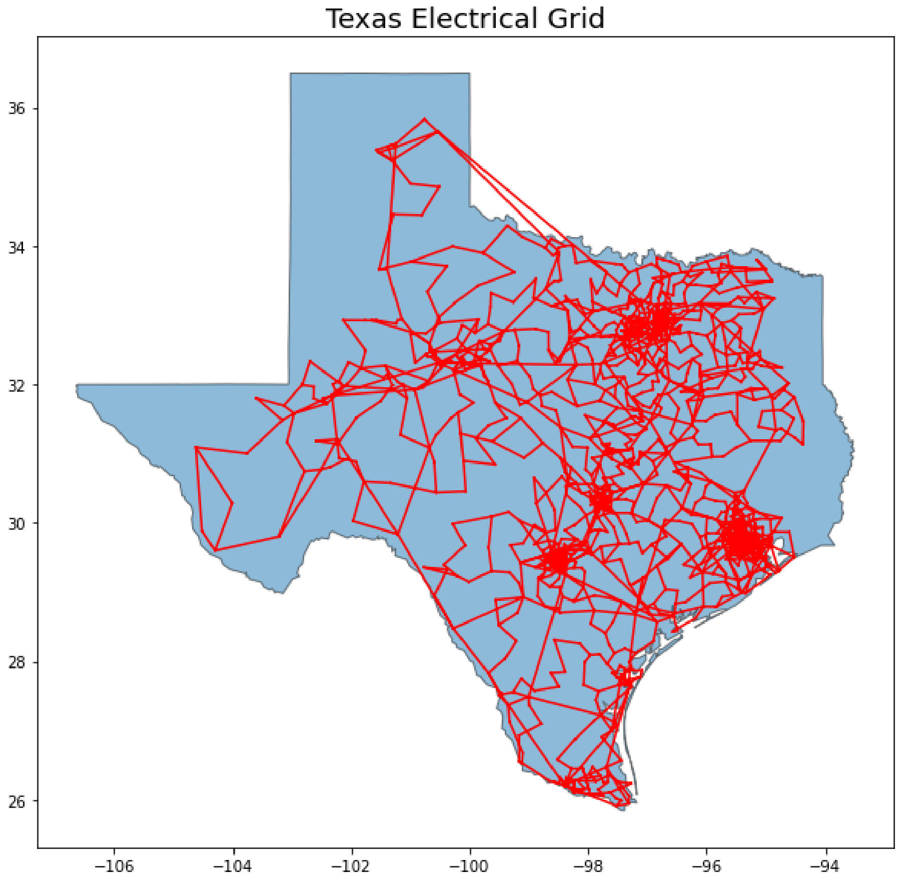
Power Distribution Model: Texas Electrical Grid

- Substations represented as Coordinate points
- Transmission lines are assumed to be straight-line connections
- **If a single point on a transmission line is affected, the entirety of a line is treated as such**





[2] A.B. Birchfield, T. Xu, K.M. Gegner, K.S. Shetye, and T.J. Overbye, "Grid Structural Characteristics as Validation Criteria for Synthetic Networks," IEEE Transactions on Power Systems, vol. 32, no. 4, pp. 3258-3265, July 2017.

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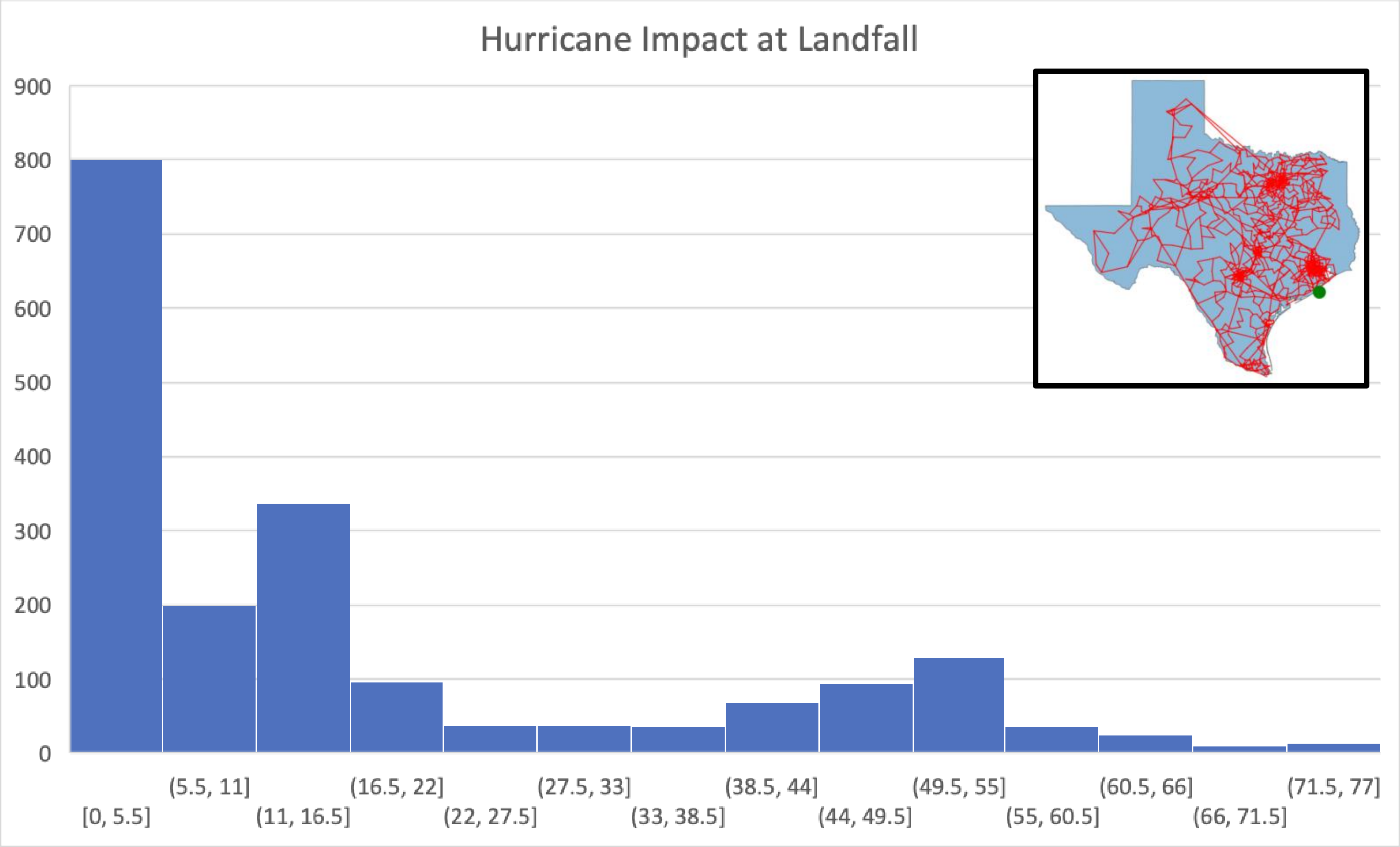
Single Timestep Initial Impact assessment

- Assuming the landfall at (-95.2, 28.9) Hurricane Impact Matrix can be applied
- Transmission lines are separated into bins based on w_m (maximum windspeed)
- Future analysis is done on each transmission line



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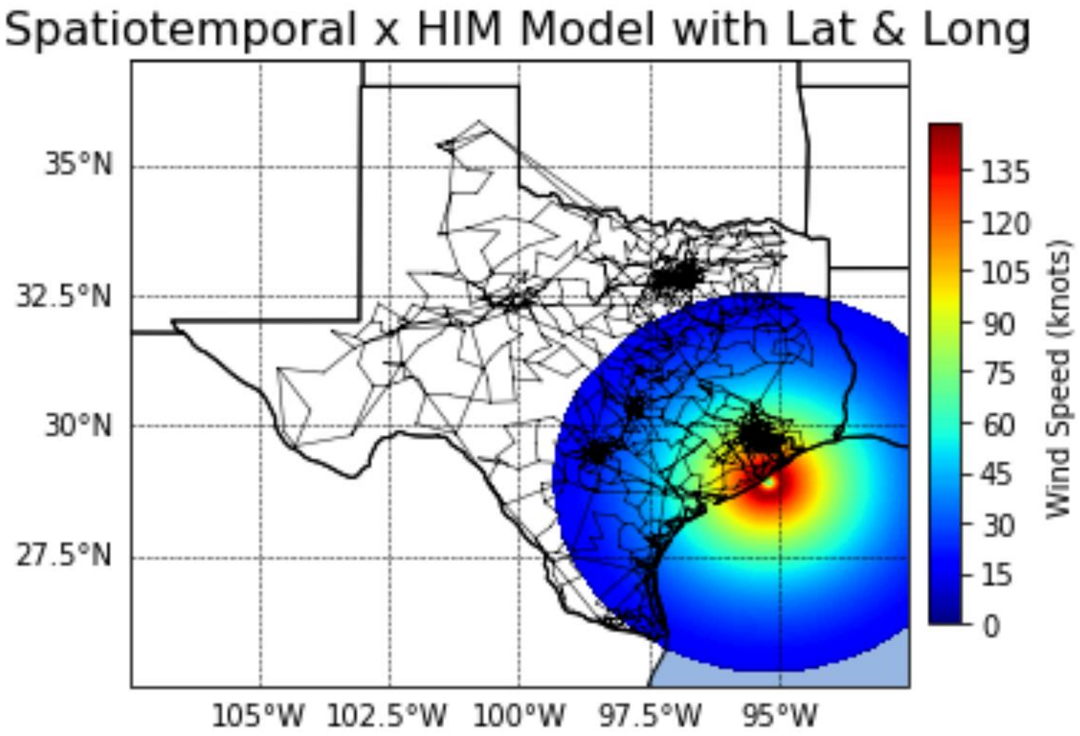
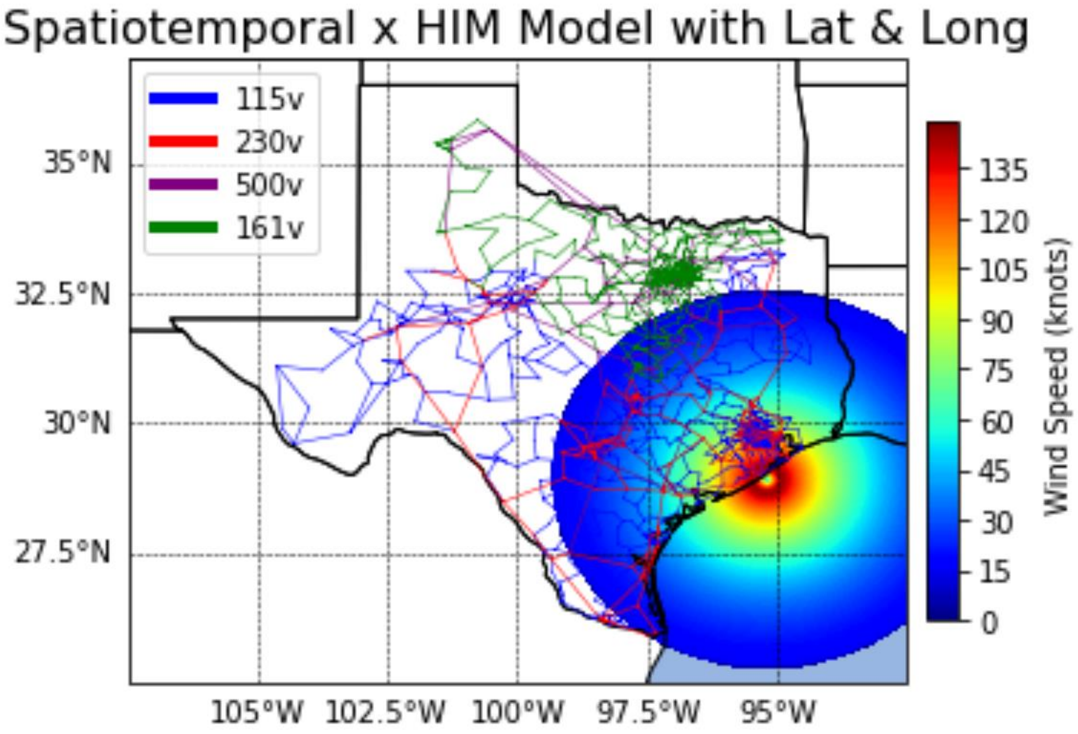
Power Distribution Model w/ Spatiotemporal Windstorm Model





(Right image includes voltage levels)

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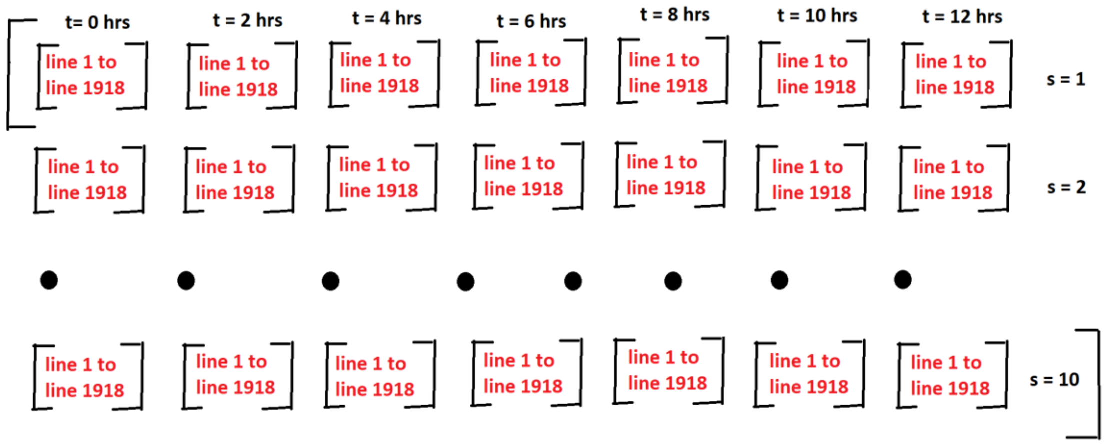
Outage Probability

- The hurricane impact matrix creates a multidimensional array in the format to the right for each line
  - An array is generated for each track (3 tracks)
- A KDE of windspeeds for each transmission line (total of 10*7 = 70 pts) and an expected value is generated from the KDE **(g)**
  - 70x1918 array is shortened to a 1x1918 array
- Outage probability is calculated according to formulas proposed in [4] **(h)**



(g) $$\hat{w}_j = \sum_{p=1}^{Np} Pr_p * \hat{w}_{j,p} = \sum_{p=1}^{Np} Pr_p \int_0^{\infty} u * f_{j,p}(u)du$$

(h) $$\Pr\{out_j\} = \begin{cases} 0 & \hat{w}_j \le w_1 \\ \dfrac{\hat{w}_j - w_1}{w_2 - w_1} & w_1 \le \hat{w}_j \le w_2 \\ 1 & \hat{w}_j \ge w_2 \end{cases}$$ [4]

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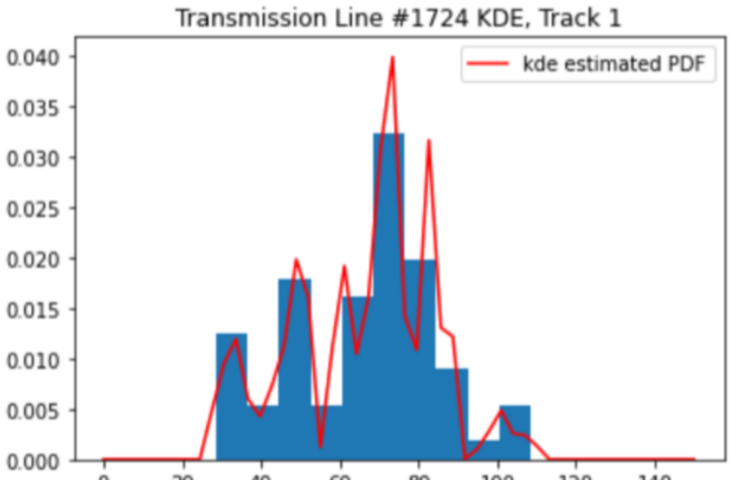
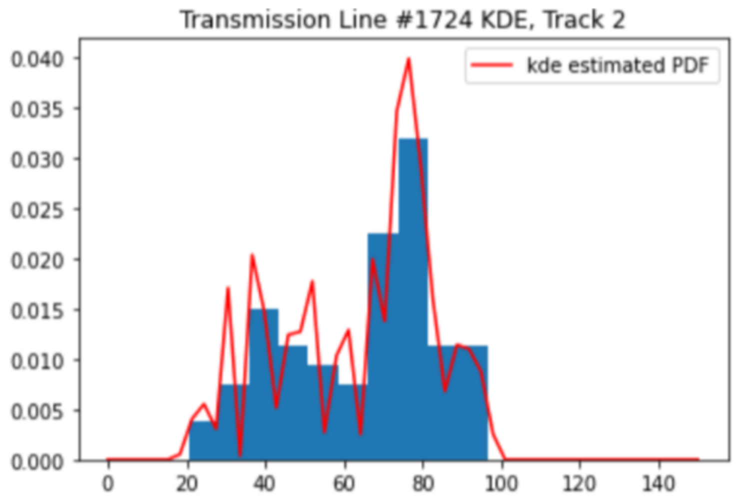
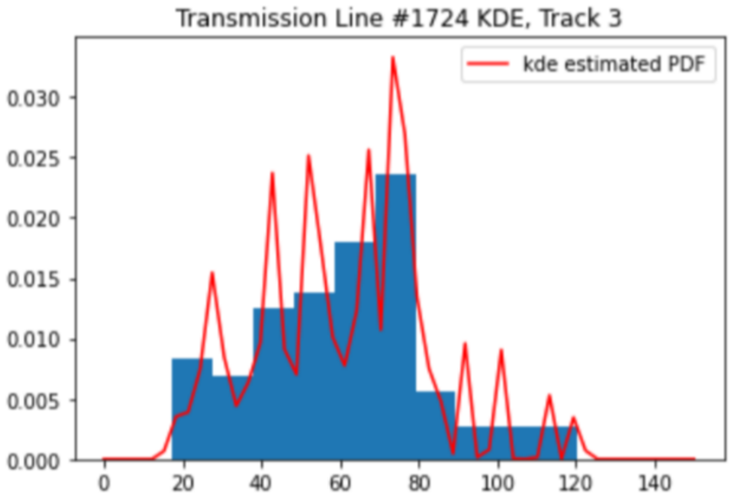
Example of PDF for a Transmission Line



66.10619755742802



64.25538204656044



61.22215669711142

- Example of PDF for transmission line #1724 for 3 different tracks, along with its expected wind speed value.

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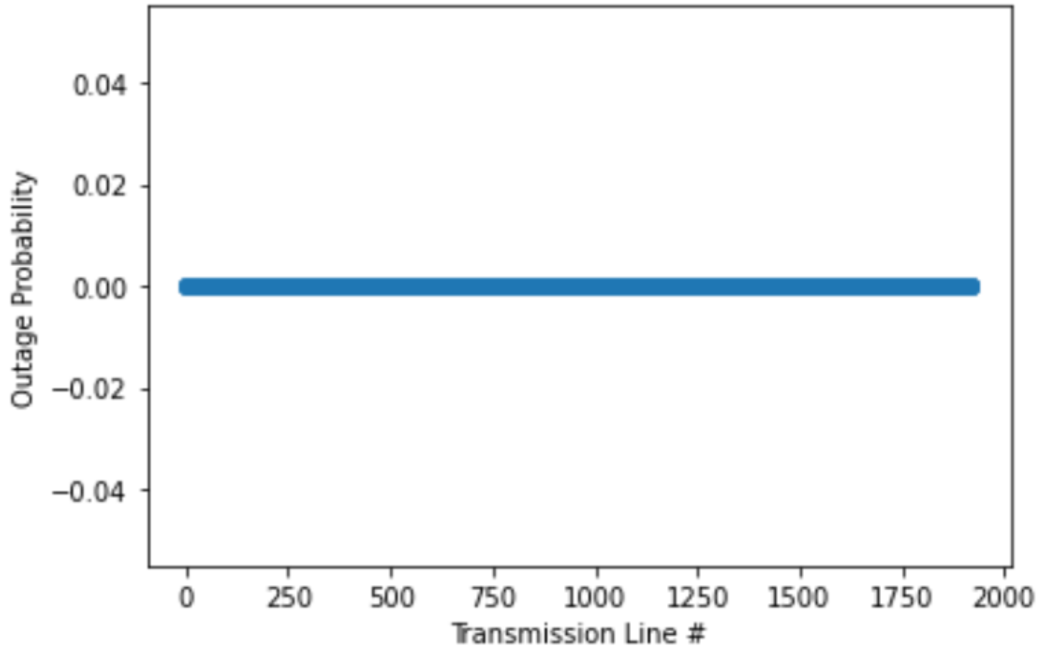
Results: Outage Probability – Case 1



- **Case 1:** Assumed the constant wind speeds which led to line outage were w1 = 110 mph and w2 = 155 mph. Calculated expected wind speed value from PDF. This case was modeled from the paper.

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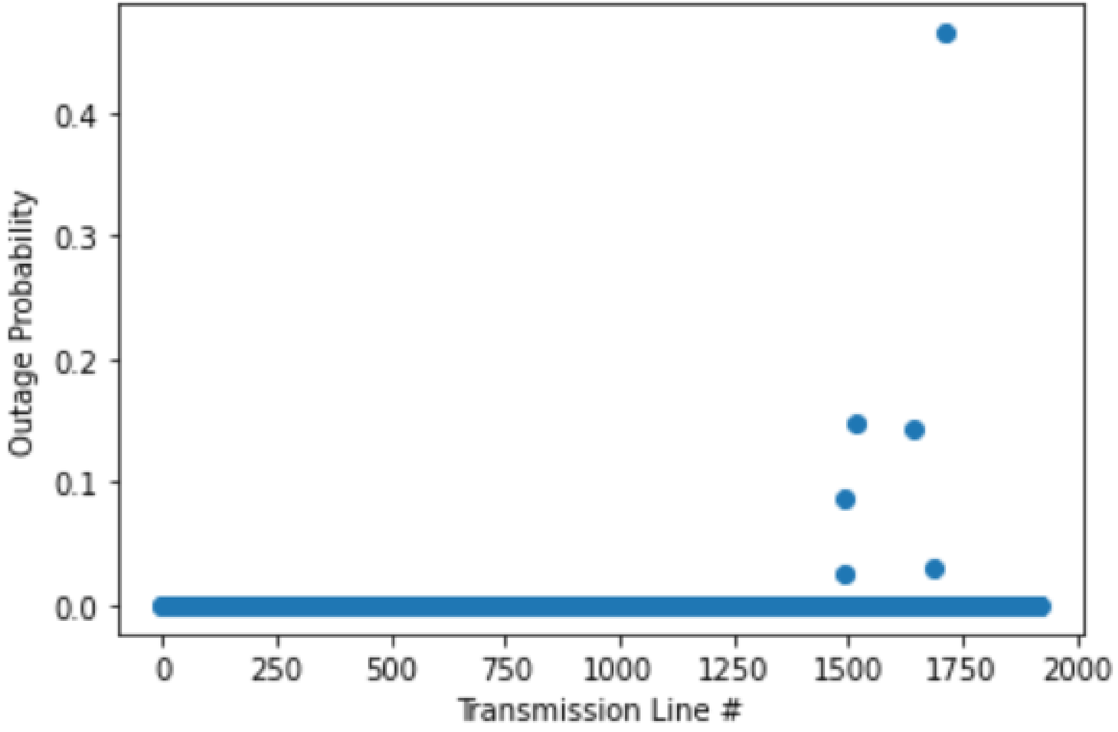
Results: Outage Probability – Case 2



- **Case 2:** Assumed the constant wind speeds which led to line outage were w1 = 110 mph and w2 = 155 mph. Instead of calculating expected wind speed value from PDF, calculated a random sample from the PDF.

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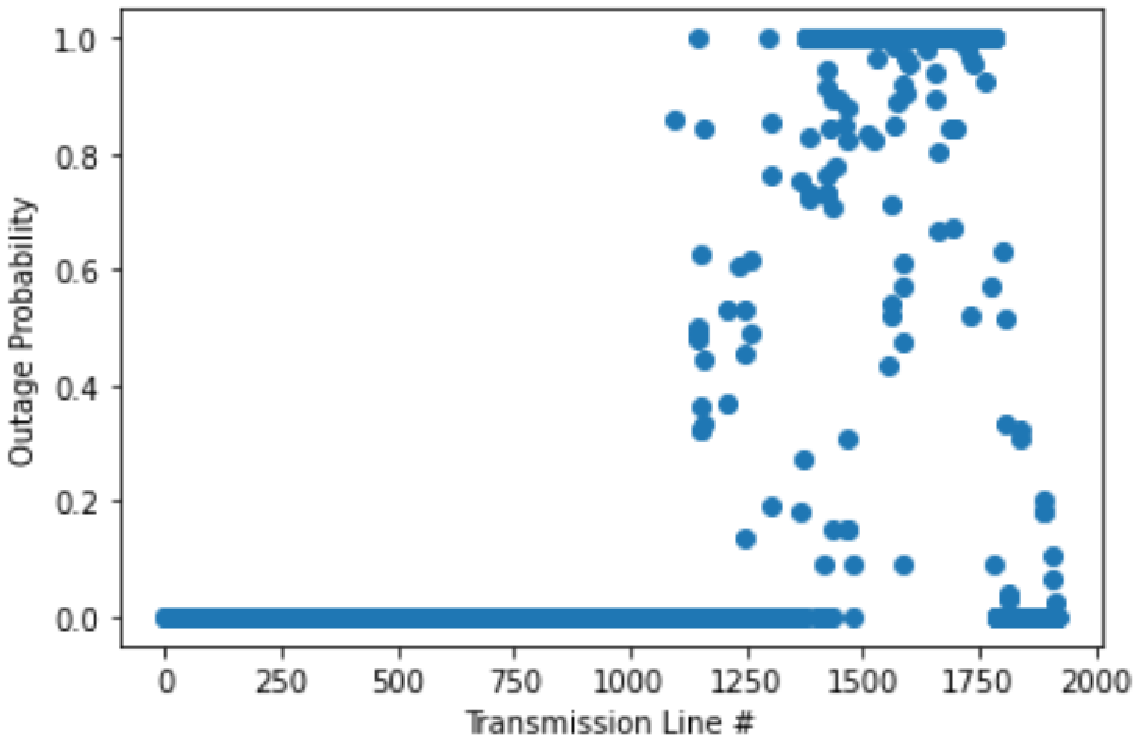
Results: Outage Probability – Case 3



- **Case 3:** Assumed the constant wind speeds which led to line outage were w1 = 50 mph and w2 = 70 mph

Analysis of Results

- Obviously, this might seem a bit suspicious

- The algorithm conflates different timesteps (e.g. the values of t=12 when the hurricane is basically harmless get averaged into the windspeed affecting a transmission line, which lowers the value substantially)

    - This reason is supported by the graphs above

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