Relationship between Weather Parameters and Transmission System Resilience

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***Abstract*—This paper provides results of assessment of the Bulk Power System (BPS) resilience against diverse types of extreme weather observed in Florida. For four Florida locations with high population density we analyze detailed weather data and their relationship to frequency of forced transmission outages and transmission unavailability, quantify adverse impacts of different weather parameters to the grid and rank the parameters by these impacts. Finally, we derive functional relationships that characterize the resilience of transmission system against high winds, wind gusts, excessive hourly and accumulated precipitation.**

***Keywords*—North American Electric Reliability Corporation (NERC), Weather and transmission outages, Wind resilience, Precipitation resilience**

I. INTRODUCTION

Extreme weather is recognized as a top risk to power system reliability and resilience. This risk has been analyzed in multiple publications (e.g. [1]-[7]). Along with diverse types of extreme weather events (hurricanes, tornadoes, wildfires etc.) [3]-[6], many authors study more granular weather and outage data to evaluate impact of different meteorological covariates to reliability and performance of power systems to respond to questions such as "is temperature in area X associated with more transmission outages and if so, at what temperature range?"; "what is a relationship between wind gusts and distribution system outages in area Y?"; "is an investment in protection of power system against lightning pays off in terms of reduction of customer outages?" etc. For example, transmission outages caused by lightning were analyzed in [7], and by wet snow and wind in [8]. Papers [9]-[11] quantified wind impact to distribution outages, and a correlation between customer outages and cold weather variables was estimated in [12].

This study builds on resilience analysis against hurricanes for Florida transmission system [13] by focusing on granular weather and outage data. We consider weather variables as covariates for forced outage frequency and unavailability of overhead transmission lines. These covariates include numerical (wind speed, dry bulb temperature, hourly precipitation, wind gust, altimeter pressure etc.) as well as categorical (wind direction, weather condition, storm type etc.) variables. In Section III we determine and quantify the relationship between the covariates and outage frequency/percent of unavailability in the area, and rank the covariates by their impact to grid reliability and resilience. It comes as no surprise that the most impactful meteorological covariates describe wind and precipitation: two attributes associated with hurricanes which cause largest outage events on Florida transmission system. In Section IV we derive a functional relationship between each of the covariates and metrics for transmission resilience, and find critical levels of the covariates with statistically significant changes in the metrics. These types of results can be derived for any region with the available data, and they can guide the industry investment strategy and prioritization of grid hardening efforts.

II. DATA AND DEFINITIONS

We selected four weather stations in Florida, at the International airports in Ft. Myers, West Palm Beach, Miami and Orlando, which all have hourly weather data. Given the proximity to major cities, performance of transmission grid near each weather station affects large populations, and this makes these locations good choices for the study.

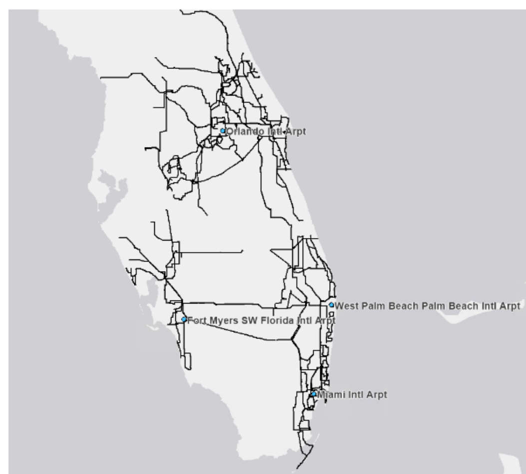

Fig. 1. Transmission lines with any portion within 50 miles of weather stations in Ft. Myers, West Palm Beach, Miami and Orlando.

For this study we used outage data collected by NERC in its Transmission Availability Data System (TADS) for transmission elements with voltages above 100 kV. For each weather station, we created a time series that links hourly weather data from Velocity Suite (VS) for the years 2015-2022 and TADS forced outages in vicinity of the station. These outages occurred on transmission lines in a radius of 50 miles around the weather station (Fig. 1).

Due to a lack of geolocation information in TADS and different naming conventions in TADS and VS, transmission inventories from these sources are not matched perfectly. In the study we use only those ac circuits from TADS that are confidently determined as having at least a part of the circuit inside the 50-mile radius from the station; we chose the radius as a minimum distance with a number of overhead lines sufficient for reliable statistical inference. For Miami, Orlando, West Palm Beach, and Ft Myers there are respectively 69, 37, 116, and 32 overhead ac circuits that comprise a transmission sub-system analyzed for a given location.

From TADS, we populate the time series with forced outage data, i.e., data for both automatic and operational outages. Automatic outages are those that result from an automatic trip of a switch and can be either momentary or sustained. Operational outages are those that result from the manual operation of a switch. For each selected transmission line, the number of outage-starts, ends, outage cause and duration within the hour are tracked for both types of outages. Also calculated from all lines at a given location are the hourly forced outage frequency per line, and the hourly unavailability percentage of overhead circuits.

For hourly weather variables from VS we have dry bulb temperature, dew point, humidity, wind speed (miles per hour or mph), wind direction, wind gust, precipitation, altimeter pressure inches of mercury, hourly and daily weather conditions. Based on hourly precipitation, rolling 24-hour total precipitation is calculated. Lightning data with adequate granularity are unavailable, but their inclusion in future studies would be crucial because Florida is one of the states with the highest lightning strike density and the best lightning protection (p. 83 [14]).

III. Weather Covariates and Ranking

For each location, a table with descriptive statistics for numerical weather covariates is provided. Next, for these covariates Pearson's and Spearman's correlations were tested to detect linear or monotonic relationship, respectively, between a covariate and the forced outage frequency at each location.

To analyze categorical covariates, we applied one-way ANOVA with Duncan's grouping to test for significant differences in forced outage frequency between different levels of the covariate (e.g. for different wind directions, storm types etc.). Finally, to compare and rank all covariates (numerical and categorical) with respect to the explanatory power (Pearson's coefficient R^2) for the forced outage frequency, we repeated a one-way ANOVA for all numerical covariates as well, testing for significant differences in outage frequency between ten bins defined as follows: bin 1 is the set of hourly observations between a minimum value of the covariate and its 10th percentile, bin 2 is the set of hourly observations between 10th and 20th percentile etc. All statistical tests use significance level 0.05.

The analyses described above were repeated for all the covariates and the overhead ac circuit unavailability percentage. Note that the relationship between a weather covariate and outage frequency is typically weaker than a relationship between the same weather covariate and circuit unavailability. It can be explained by the fact that the hourly outage frequency is much sparser dataset than the hourly unavailability: a given outage contributes to only one hourly outage frequency value (for the hour it started) and contributes to all hourly unavailability values for as long as it lasted.

A. Fort Myers

Table I shows the descriptive statistics for numerical weather variables recorded at Ft. Myers weather station.

TABLE I. Descriptive Statistics for Weather Variables at Ft Myers Weather Station

Weather Variable	N	Mean	Std Dev	Minimum	Median	Maximum
24 hour precipitation (inches)	70010	0.15	0.46	0	0	9.82
Altimeter Pressure (inches of Mercury	69921	30.04	0.11	27.99	30.04	30.55
Dew Point Temperature - Fahrenheit	70010	65.74	9.66	9	69	80.1
Hourly Precipitation (inches)	43418	0.01	0.08	0	0	2.83
Relative Humidity Percent	70010	75.12	16.88	13	79	100
Temperature (Dry Bulb) - Fahrenheit	70010	75.03	9.53	33.10	76	98.1
Wind Gust mph	5646	25.24	6.76	16.11	24.17	110.47
Wind Speed mph	69751	7.34	4.97	0	6.90	71.35

In Table II the explanatory power (R^2) is listed for all covariates that statistically significantly impact outage frequency or unavailability.

TABLE II. Weather Covariates for Forced Outage Frequency and AC Circuit Unavailability near Ft Myers

Weather Covariates at Ft. Myers	Pearson's Coeff R^2	
	Outage Frequency	Circuit Unavailability
24 hour precipitation rolling sum	0.19%	1.15%
Altimeter Pressure inches of Mercury	0.07%	1.43%
Dew Point Temperature - Fahrenheit	NA	0.30%
Hourly Precipitation (inches)	0.46%	0.13%
Relative Humidity Percent	0.08%	0.10%
Temperature (Dry Bulb) - Fahrenheit	0.05%	0.12%
Weather condition Day	NA	1.57%
Wind direction	NA	0.29%
Wind Gust mph	0.88%	2.38%
Wind Speed mph	0.06%	0.25%

Table II informs that the most impactful covariate for both outage frequency and unavailability is wind gust (highlighted in yellow). As we show below, statistically significant relationships in Table II are not linear and often not monotonic; still, not surprisingly, the highest outage frequency and unavailability are expected at largest wind gusts, highest precipitation levels and wind speeds. Inversely, the highest outage frequency and unavailability are observed at lowest level of altimeter pressure which is recorded during hurricanes. Coincidentally, the dry bulb temperature bins with significantly higher outage frequency correspond to middle temperature range (from 76°F to 78°F) typical during hurricanes and storms in this area that can be very disruptive for transmission system.

For hours with reported wind direction, the East direction is the most prevalent, and the highest outage frequency and the highest unavailability are observed during West-Southwest wind direction. The most frequently reported daily weather condition is Rain Mist. There is no significant differences in outage frequency for all reported weather conditions; however, circuit unavailability is statistically significantly higher for days with Rain Fog, Thunderstorm in vicinity, Rain, and Mist.

B. Miami

Table III shows the descriptive statistics for numerical weather variables recorded at Miami weather station.

TABLE III. DESCRIPTIVE STATISTICS FOR WEATHER VARIABLES AT MIAMI WEATHER STATION

Variable	N	Mean	Std Dev	Minimum	Median	Maximum
24 Hour precipitation (inches)	70011	0.19	0.52	0	0	7.77
Altimeter Pressure (inches of Mercury)	69991	30.04	0.10	29.21	30.04	30.51
Dew Point Temperature - Fahrenheit	70011	68.14	8.29	18	71	83
Hourly Precipitation (inches)	70011	0.01	0.07	0	0	3.33
Relative Humidity Percent	70011	72.54	13.37	18	74	100
Temperature (Dry Bulb) - Fahrenheit	70011	78.22	7.39	39.9	79	98.1
Wind Gust mph	10834	23.76	5.00	16.11	23.02	84.01
Wind Speed mph	69979	8.33	5.14	0	8.1	56.4

In Table IV the explanatory power (R^2) is listed for all weather covariates that statistically significantly impact outage frequency or unavailability.

TABLE IV. WEATHER COVARIATES FOR FORCED OUTAGE FREQUENCY AND AC CIRCUIT UNAVAILABILITY NEAR MIAMI

Weather Covariates at Miami	Pearson's Coeff R^2	
	Outage Frequency	Circuit Unavailability
24 hour precipitation rolling sum	0.062%	0.44%
Altimeter Pressure inches of Mercury	0.057%	0.67%
Dew Point Temperature - Fahrenheit	0.03%	0.28%
Hourly Precipitation (inches)	0.18%	0.60%
Relative Humidity Percent	NA	0.03%
Temperature (Dry Bulb) - Fahrenheit	NA	0.20%
Weather condition Day	0.24%	0.79%
Wind direction	0.04%	0.19%
Wind Gust mph	0.71%	1.54%
Wind Speed mph	0.06%	0.21%

Table IV shows that the most impactful numerical covariate for outage frequency and unavailability is wind gust (and a categorical Daily weather condition is the second most impactful for unavailability). The highest outage frequency and unavailability are expected at strongest wind gusts, highest precipitation levels and wind speeds, and at lowest altimeter pressure. Dry bulb temperature does not significantly impact outage frequency, but it is a significant monotonically increasing relationship with unavailability: the largest average circuit unavailability of 0.08 percent is observed for hours with dry bulb temp between 87°F and 98.1°F.

For hours with reported wind direction, the East direction is the most prevalent, and the highest outage frequency is observed during South-Southwest wind, and the highest unavailability is observed during Variable or No wind. The most frequently reported daily weather condition is Thunderstorm Fog. There is no significant differences in outage frequency for all reported weather conditions, and the circuit unavailability is statistically significantly highest for days with Thunderstorm in vicinity.

C. Orlando

Table V shows the descriptive statistics for numerical weather variables recorded at Orlando weather station.

TABLE V. DESCRIPTIVE STATISTICS FOR WEATHER VARIABLES AT ORLANDO WEATHER STATION

Variable	N	Mean	Std Dev	Minimum	Median	Maximum
24 Hour precipitation (inches)	69979	0.14	0.45	0	0	12.56
Altimeter Pressure (inches of Mercury)	70003	30.06	0.12	28.97	30.06	30.6
Dew Point Temperature - Fahrenheit	70003	63.88	11.11	10	66.9	82
Hourly Precipitation (inches)	70003	0.01	0.06	0	0	3.1
Relative Humidity Percent	70003	74.30	18.25	9	78	100
Temperature (Dry Bulb) - Fahrenheit	70003	73.58	10.52	27	75	99
Wind Gust mph	4940	26.33	6.77	16.1	25.3	90.9
Wind Speed mph	69984	8.02	5.06	0	8.1	55.2

In Table VI the explanatory power (R^2) is listed for all weather covariates that statistically significantly impact outage frequency or unavailability.

TABLE VI. WEATHER COVARIATES FOR FORCED OUTAGE FREQUENCY AND AC CIRCUIT UNAVAILABILITY NEAR ORLANDO

Weather Covariates at Orlando	Pearson's Coeff R^2	
	Outage Frequency	Circuit Unavailability
24 hour precipitation rolling sum	0.14%	0.30%
Altimeter Pressure inches of Mercury	0.028%	0.23%
Dew Point Temperature - Fahrenheit	NA	0.45%
Hourly Precipitation (inches)	0.23%	0.03%
Relative Humidity Percent	NA	NA
Temperature (Dry Bulb) - Fahrenheit	0.026%	0.22%
Weather condition Day	0.11%	1.18%
Wind direction	NA	0.11%
Wind Gust mph	0.78%	2.59%
Wind Speed mph	NA	0.06%

Table VI shows that the most impactful covariate for both outage frequency and circuit unavailability is wind gust. Not surprisingly, the highest outage frequency and unavailability are expected at largest wind gusts, highest hourly and accumulated precipitation levels. Inversely, the highest outage frequency and unavailability are observed at lowest level of altimeter pressure which is recorded during hurricanes. Temperature (both dew point and dry bulb) does not seem directly affect outages. Coincidentally, both dry bulb and dew point temperature bins with significantly higher unavailability correspond to the temperature range typical during hurricanes and storms in this area.

For hours with reported wind direction, the East direction is the most prevalent. Wind direction is statistically significant for unavailability, which is the highest during West-Northwest wind direction. The most frequently reported daily weather condition is Fog. Highest outage frequency and unavailability are observed for Rain Mist.

D. West Palm Beach

Descriptive statistics for numerical weather covariates at West Palm Beach weather station are shown in Table VII.

TABLE VII. DESCRIPTIVE STATISTICS FOR WEATHER VARIABLES AT WEST PALM BEACH WEATHER STATION

Variable	N	Mean	Std Dev	Minimum	Median	Maximum
24 Hour precipitation (inches)	69981	0.16	0.44	0	0	6.72
Altimeter Pressure (inches of Mercury)	69981	30.05	0.11	29.26	30.05	30.53
Dew Point Temperature - Fahrenheit	70005	67.08	8.71	11	70	82
Hourly Precipitation (inches)	43243	0.01	0.07	0	0	3.31
Relative Humidity Percent	70005	72.61	13.67	15	73	100
Temperature (Dry Bulb) - Fahrenheit	70005	77.11	8.08	37	78.1	95
Wind Gust mph	8052	26.75	5.79	16.11	26.47	96.67
Wind Speed mph	69978	9.98	5.67	0.0	10.36	65.59

In Table VI the explanatory power (R^2) is listed for all weather covariates with statistically significant relationship with outage frequency or unavailability.

TABLE VIII. WEATHER COVARIATES FOR FORCED OUTAGE FREQUENCY AND AC CIRCUIT UNAVAILABILITY NEAR WEST PALM BEACH

Weather Covariates at West Palm Beach	Pearson's Coeff R^2	
	Outage Frequency	Circuit Unavailability
24 hour precipitation rolling sum	0.14%	0.75%
Altimeter Pressure inches of Mercury	0.062%	0.58%
Dew Point Temperature - Fahrenheit	0.04%	0.237%
Hourly Precipitation (inches)	0.27%	0.25%
Relative Humidity Percent	0.07%	0.09%
Temperature (Dry Bulb) - Fahrenheit	NA	0.15%
Weather condition Day	0.42%	0.51%
Wind direction	NA	0.244%
Wind Gust mph	1.16%	1.84%
Wind Speed mph	0.060%	0.16%

Table VIII informs that the most impactful covariate for both outage frequency and circuit unavailability is wind gust. The highest outage frequency and unavailability are expected at largest wind gusts and wind speed, and highest accumulated precipitation.

For hours with reported wind direction, the East direction is the most prevalent. Wind direction is statistically significant for unavailability, which is the highest during South-southwest winds. The most frequently reported daily weather condition is Thunderstorm. Highest outage frequency and unavailability are observed for Rain Thunderstorm, and Rain Mist.

E. General Observations

Tables IX and X summarize results of the analyses of Section III by listing statistically significant weather covariates for forced outage frequency and circuit unavailability, respectively, for each location in decreasing order of the explanatory power (adjusted R^2 for ANOVA).

TABLE IX. STATISTICALLY SIGNIFICANT WEATHER COVARIATES FOR FORCED OUTAGE FREQUENCY

Stastistically significant Weather Covariates for Forced outage frequency of overhead ac circuits			
Ft Myers	Miami	Orlando	West Palm Beach
Wind Gust	Wind Gust	Wind Gust	Wind Gust
Hourly Precipitation	Weather condition Day	Hourly Precipitation	Weather condition Day
24 hour precipitation	Hourly Precipitation	24 hour precipitation	Hourly Precipitation
Relative Humidity	Wind Speed	Weather condition Day	24 hour precipitation
Altimeter Pressure	24 hour precipitation	Altimeter Pressure	Relative Humidity
Wind Speed	Altimeter Pressure	Temperature (Dry Bulb)	Altimeter Pressure
Temperature (Dry Bulb)	Wind direction		Wind Speed
	Dew Point Temperature		Dew Point Temperature

TABLE X. STATISTICALLY SIGNIFICANT WEATHER COVARIATES FOR OVERHEAD AC CIRCUIT UNAVAILABILITY

Stastistically significant Weather Covariates for Unavailability of overhead ac circuits			
Ft Myers	Miami	Orlando	West Palm Beach
Wind Gust	Wind Gust	Wind Gust	Wind Gust
Weather condition Day	Weather condition Day	Weather condition Day	24 hour precipitation
Altimeter Pressure	Altimeter Pressure	Dew Point Temperature	Altimeter Pressure
24 hour precipitation	Hourly Precipitation	24 hour precipitation	Weather condition Day
Dew Point Temperature	24 hour precipitation	Altimeter Pressure	Hourly Precipitation
Wind direction	Dew Point Temperature	Temperature (Dry Bulb)	Wind direction
Wind Speed	Wind Speed	Wind direction	Dew Point Temperature
Hourly Precipitation	Temperature (Dry Bulb)	Wind Speed	Wind Speed
Temperature (Dry Bulb)	Wind direction	Hourly Precipitation	Temperature (Dry Bulb)
Relative Humidity	Relative Humidity		Relative Humidity

The analyses in Section III confirm that the highest outage frequency and unavailability are often observed at the levels of weather covariates typical during hurricanes, which is the most disruptive and damaging type of extreme weather for Florida's power grid—but these levels can be observed without hurricanes as well. Another critical point to remember is the fact that a causal relationship cannot be derived exclusively from the above results—it would be known from physics, engineering, as well as industry practices under various weather conditions. For example, strong wind and high precipitation can arguably cause transmission outages and contribute to their longer durations, while atmospheric pressure and temperature are not causal covariates and, even when for this Florida study they are statistically significant, they are coincidental and highly correlated with tropical storms and hurricanes.

IV. ANALYSIS OF RESILIENCE AGAINST WIND AND PRECIPITATION

The two outage statistics we selected, the hourly forced outage frequency and the hourly ac circuit unavailability, allow us to quantify and track important attributes of a resilient power system: the hourly outage frequency gauges the system ability to withstand extreme conditions, and the hourly unavailability measures the system ability to reduce impact and recover from the extreme conditions. Connecting these resilience statistics with the most statistically significant weather covariates provides essential information about grid resilience. In this section we include scatterplots, fitted curves, and derive equations connecting the expected outage metrics with wind gust and 24-hour accumulated precipitation. To create the scatterplots we used the mean values for the bins defined for ANOVA and Duncan's grouping in III(A-D). For many statistically significant covariates, the scatter plot is well approximated by a parabolic curve.

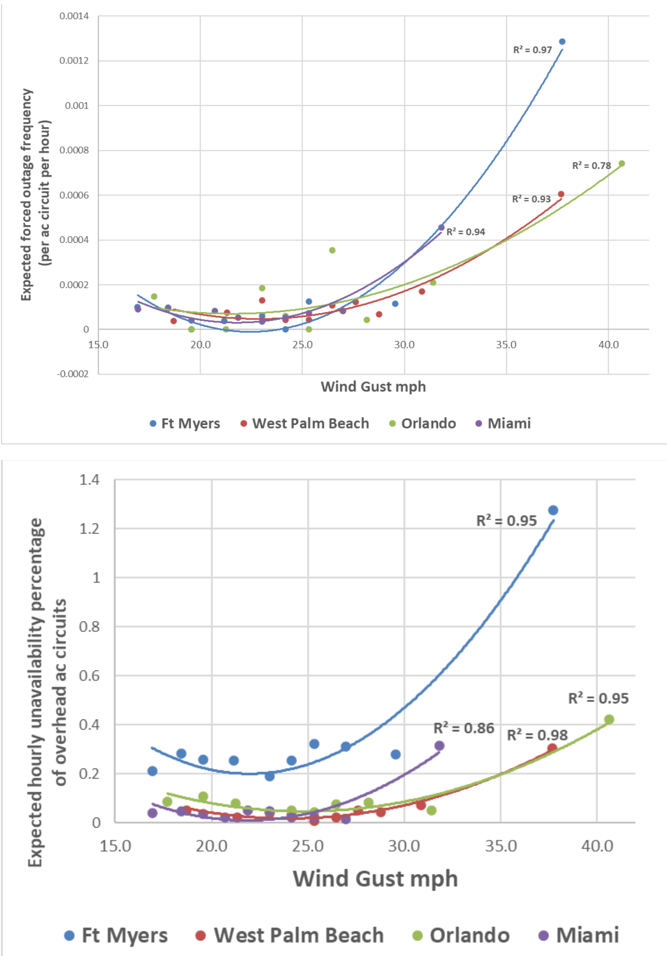

Fig. 2. Expected hourly Forced outage frequency and Expected hourly unavailability of overhead ac circuits versus Wind gust.

Fig. 2 shows fitted quadratic functions connecting wind gust with outage frequency (top) and with unavailability (bottom) for the four weather stations; here R^2 indicates a goodness of fit.

The expected forced outage frequency $EFOFreq(WG)$ and the expected percent of unavailability $EPUnav(WG)$at a wind gust WG (mph) can be calculated by (1)-(4) and (5)-(8), respectively. The WG values for a weather station must be inside the hourly wind gust range observed at this station as shown in Tables I, III, V, and VII.

$$EFOFreq(WG)_{FM} = 10^{-7} * (54 * WG^2 - 2424WG + 27098) \quad (1)$$

$$EFOFreq(WG)_{WPB} = 10^{-7} * (24WG^2 - 1118WG + 13263) \quad (2)$$

$$EFOFreq(WG)_{Or} = 10^{-7} * (18WG^2 - 781WG + 9107) \quad (3)$$

$$EFOFreq(WG)_{Miami} = 10^{-7} * (40WG^2 - 1746WG + 19333) \quad (4)$$

$$EPUnav(WG)_{FM} = 10^{-4} * (42WG^2 - 1831WG + 22099) \quad (5)$$

$$EPUnav(WG)_{WPB} = 10^{-4} * (15WG^2 - 716WG + 8769) \quad (6)$$

$$EPUnav(WG)_{Or} = 10^{-4} * (14WG^2 - 717WG + 9352) \quad (7)$$

$$EPUnav(WG)_{Miami} = 10^{-4} * (28WG^2 - 1215WG + 13348) \quad (8)$$

At lower levels of wind gusts, the expected outage frequencies in the four areas are similar and stable, significantly increasing for bin 10 with the largest wind gusts; the outage frequency at Ft. Myers increases most dramatically. The unavailability curve for Ft. Myers is consistently above the curves for other locations. Similarly to the outage frequency, at lower levels of wind gust the expected unavailability in the four areas is stable, significantly increasing for bin ten with the largest wind gusts. We confirm these observations with Duncan's grouping test for ANOVA [15], which statistically compares unavailability percentage at various levels (bins) of wind gust, and show results in Fig.3. For each location, the average unavailability percentages of bins are listed in decreasing order. A bar connects bins with non-significant difference in unavailability. Therefore, for all locations the unavailability for a respective bin 10 is statistically significantly greater than for all other bins, and bins 1-9 have statistically similar unavailability. The same results hold true for the forced outage frequency at different levels of wind gusts.

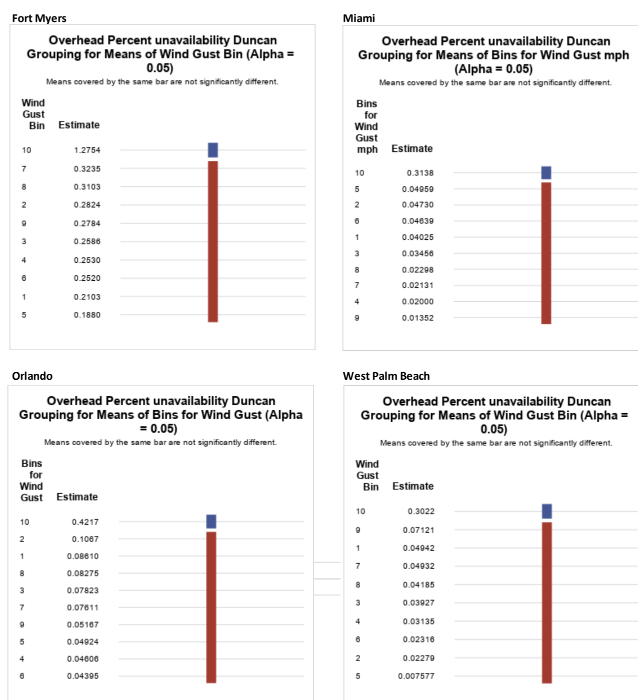

Fig. 3. Duncan grouping for unavailability percentage of overhead ac circuits by Wind gust level.

Analogous results are derived for wind speed except its relationship with outage frequency in Orlando which is not statistically significant. (We omit the graphs and equations for curves due to the space limitations). These results imply that the transmission grid in Florida typically is not impacted by wind gusts below 30 mph and wind speed below 15 mph (the minimum of lower bounds for bin ten over the four datasets). Next, a graph in Fig. 4 shows fitted quadratic functions connecting 24-hour cumulative precipitation with outage frequency (top) and with unavailability (bottom) for the four weather stations; here R^2 indicates a goodness of fit.

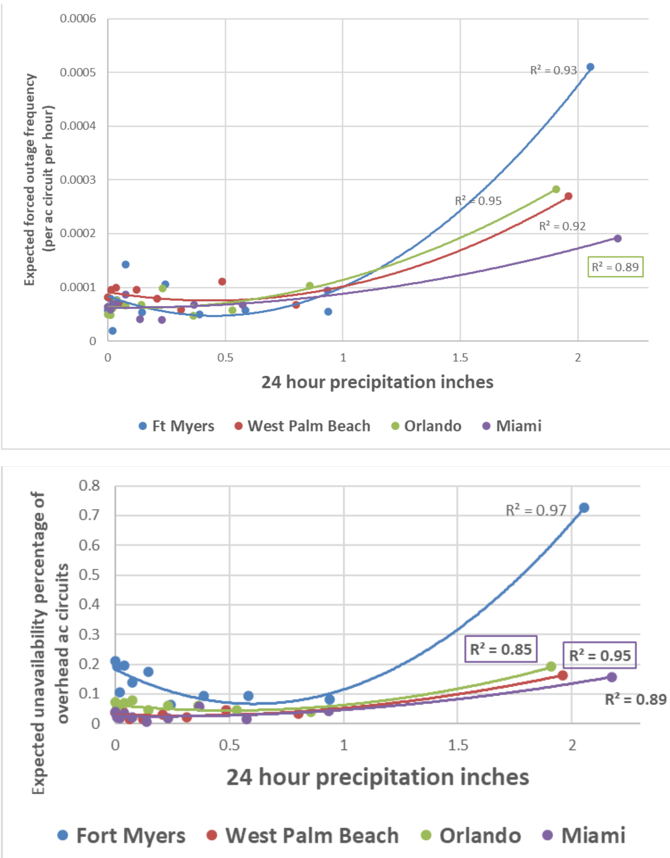

Fig. 4. Expected hourly Forced outage frequency (top) and Expected hourly unavailability of overhead ac circuits (bottom) versus 24-hour precipitation.

The expected forced outage frequency $EFOFreq(Prec)$ and the expected percent of unavailability $EPUnav(Prec)$ at a 24-hour accumulated precipitation level (inches) can be calculated by (9)-(12) and (13)-(16), respectively. The precipitation values for a weather station must be inside the range of the 24-hour accumulated precipitation recorded at this station as shown in Tables I, III, V, and VII.

$$EFOFreq(Prec)_{FM} = 10^{-5} * (18 * (Prec)^2 - 16 * (Prec) + 8) \quad (9)$$

$$EFOFreq(Prec)_{WPB} = 10^{-5} * (8 * (Prec)^2 - 7 * (Prec) + 9) \quad (10)$$

$$EFOFreq(Prec)_{Or} = 10^{-5} * (14 * (Prec)^2 - 11 * (Prec) + 6) \quad (11)$$

$$EFOFreq(Prec)_{Miami} = 10^{-6} * (29 * (Prec)^2 - 4 * (Prec) + 62) \quad (12)$$

$$EPUnav(Prec)_{FM} = 10^{-4} * (3153(Prec)^2 - 3833(Prec) + 1832) \quad (13)$$

$$EPUnav(Prec)_{WPB} = 10^{-4} * (479(Prec)^2 - 263(Prec) + 307) \quad (14)$$

$$EPUnav(Prec)_{Or} = 10^{-4} * (727(Prec)^2 - 726(Prec) + 627) \quad (15)$$

$$EPUnav(Prec)_{Miami} = 10^{-4} * (340(Prec)^2 + 10(Prec) + 257) \quad (16)$$

At lower levels (up to 1.1 inch) of cumulative precipitation the expected outage frequencies in the four areas are similar and stable, significantly increasing for the bin with the largest precipitation; the outage frequency at Ft. Myers increases most dramatically. The unavailability curve for Ft. Myers is above the curves for other locations. Similarly to the outage frequency, at lower levels of precipitation the expected unavailability in the four areas is stable, significantly increasing for the bin with the largest precipitation. These observations are confirmed by results of Duncan's grouping test for ANOVA, which statistically compares outage frequency and unavailability percentage at various levels (bins) of cumulative precipitation. Similarly to wind speed and wind gust, the hours with largest precipitation on average have statistically significantly greater outage frequency and unavailability percentage. These results imply that overhead ac circuits in Florida (which comprise about 96% of the Florida inventory of transmission lines) typically are not impacted by precipitation below the 24-hour cumulative level of 1.1 inches. For hourly precipitation, only at Orlando location the greater outage frequency and unavailability are associated with higher precipitation values. In the other locations the greater outage frequency and unavailability occur at average hourly precipitation (below 0.1 inches). It is expected that the precipitation impact to underground cables to be much more significant since high precipitation can cause flooding; however, we exclude cables from the study due to a small sample size at each location which makes the statistical approach unreliable.

V. Conclusions and Discussion

The study found that in Florida wind gust and precipitation are most significant numerical weather covariates for forced outages of the overhead transmission lines. These weather parameters are typically associated with hurricanes and tropical storms but their extreme values are observed not only during these extreme weather events. Comparing significance of hourly precipitation and 24-hour accumulated precipitation to forced outages, we conclude that the hourly precipitation is more impactful to the outage starts and the accumulated precipitation to the ac circuit unavailability. In resilience terms it means that instantaneous precipitation is more impactful during the outage/degradation phase of a transmission resilience event and accumulated precipitation during the restoration phase.

The forced outages in West Palm Beach—Miami area have no significant relationship with temperature while in another two locations a slight increase in outage frequency and unavailability is observed at the middle temperature range typical for tropical storms and hurricanes (70-75°F for Orlando and 76-78°F for Ft. Myers). The rather weak relationship between temperature and forced transmission outages reflects unique Florida temperature profile with neither freezing days nor heat above 100°F recorded over the eight years (see Tables I, III, V, VII). In other regions that may be affected by extreme cold or extreme heat, temperature is expected to be one of the most significant covariates for transmission outages. Overall, the results summarized in Tables II, IV, VI, and VII are in accord with findings technical report [Fig. 1 in 16] that list wind, temperature, and precipitation as primary weather variables affecting transmission and distribution (with their impact dependent on asset type, location, and climate zone).

We also found that daily weather condition and wind direction are statistically significant categorical weather covariates; the system reliability and resilience are tested during weather conditions associated with increased precipitation level such as rain, thunderstorm, mist, fog.

The functional relationships discovered between levels of significant numerical covariates and the expected outage frequency and unavailability enable risk assessment and can assist in prioritization of hardening efforts by the industry. Interestingly, neither significant relationship is linear with majority being well-approximated by second-order (parabolic) curves. Typically, we see stable outage rates and unavailability percentages for multiple levels of a weather covariate (wind gust, 24-hour accumulated precipitation, wind speed etc.) contrasting with a prominent increase in outages at the weather covariate values where the system resilience is tested. Often, these increases are statistically significant compared with stable levels of outage frequency and unavailability. The outage frequencies for the stable levels are similar between the four location; however, unavailability at Fort Myers is consistently greater than at the other locations. Currently, we do not have lightning data mapped to the time series, but future iterations will seek to add this as across North America lightning strikes are a cause of many outages.

The approach developed here is general and can be applied to any location. From here we aim to take the methodology to areas outside of the gulf to assess different climate profiles to see how the relative importance of covariates changes. With additional weather data this method can be extended to study wildfire risk in the West, ice storms in the Midwest, snow storms/polar vortexes in the Northeast etc. It is likely that results derived for Florida transmission system would be quite different for other regions, but wind gusts and other extremes brought by hurricanes can occur as other storms such as thunderstorms or blizzards. Additionally, tracking resilience over time will be invaluable for assessing the impact of grid hardening efforts and give companies insight as to which type of hardening may be more effective for a given area.

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