Final Report

Development of Wind-Driven Rain Climatology and Coincidental Wind Speed Return Period Maps for Florida and Surrounding Coastal Areas

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Project Summary

1. Introduction

Rain water intrusion, in its various forms, persists as one of the most costly and prolific forms of damage to buildings in the United States. For exterior walls, rain water intrusion is closely related to the presence of wind to cause rain water impingement on walls. More importantly, the coincidental presence of wind also causes wind pressure differentials that force water behind claddings and into or through wall assemblies or components. This mechanism of rain water intrusion is prolific and is the cause of substantial economic impact, loss of building resiliency and useful life, and even has structural safety implications.

In this project, we have developed a wind-driven rain climatology and coincidental wind speed return period maps for Florida and surrounding coastal areas of the southeastern United States. The creation and accessibility of these products contributes to a better understanding of the risk associated with coincident wind/rain events. This report summarizes the results of this project, provides samples/descriptions of the new products now available online, and includes detailed methodology within the appendices.

2. Weather stations used in analysis

One-minute wind/precipitation data from 137 weather stations within Florida and nearby states in the southeastern United States were used in this project (Fig. 1). These data were obtained from the National Centers for Environmental Information (NCEI), and each station had at least 15 years of available data after quality-control methods were applied. The datasets for 3-second peak wind speed/direction (DSI-6405) and accumulated precipitation (DSI-6406) over each minute are available from as early as 2000.

Data could only be obtained for intervals when stations reported. Weather stations frequently lose power during extreme wind events such as hurricanes. Incorporating precipitation estimates from radars to fill data gaps and check the accuracy of the tipping bucket rain gauges in high winds would be desirable for a future study. Adopting this approach was beyond the scope of the current study.

Please see *Appendix A* for details regarding data acquisition, quality control, and station selection.

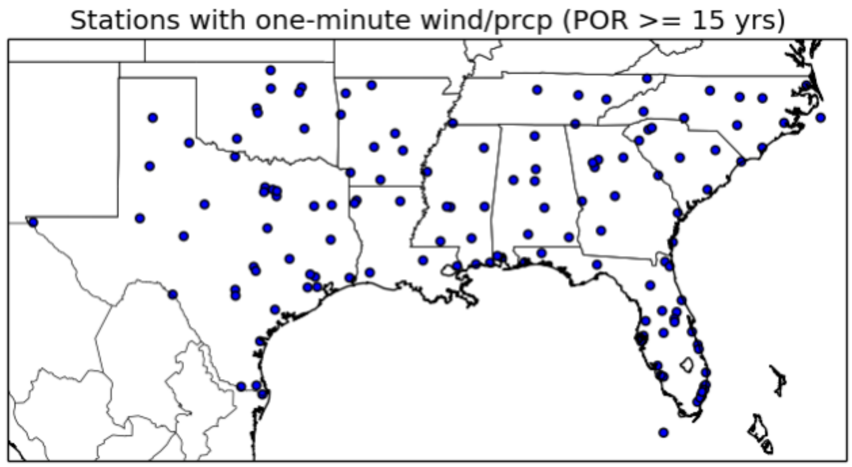

Figure 1. *Stations used in project analyses. These stations have at least 15 years of valid coincident wind/precipitation data after quality control.*

3. Siting information and wind adjustment factors

In contrast to the precipitation data, the wind speed data collected by the Automated Surface Observing System (ASOS) platform must be pre-processed to standardize the reported values to a common metadata format, i.e., gust duration, height, and terrain exposure condition. In the early 2000s, ASOS platforms operated cup anemometers that reported 5 s block average gusts. Between 2003-2009, the National Weather Service replaced the cup anemometers at most sites with ultrasonic anemometers that report 3 s moving average gusts. A cup anemometer behaves like a mechanical filter, i.e., it does not instantly respond to changes in wind speed like its ultrasonic counterpart (which has no moving parts). Thus, an appropriate adjustment had to be made to correct for the response characteristics. Further, the observation height of the anemometer varies from the 10 m standard height, and the surface roughness of the upwind fetch (terrain) vary significantly. Collectively, these variations can cause reported gust values to underreport surface wind field intensity by as much as 40%.

The method described in Masters et al. (2010) was applied to perform this conversion, using the equivalent of ASCE 7 basic wind speed conditions (10 m height, 3 s gust, open exposure conditions). Figure 2 shows the results of this conversion applied to data at a number of stations across Florida. The higher wind speeds associated with standardized data is typical of most stations across our region of study. Please see *Appendix B* for more discussion regarding wind adjustment factors and methodology.

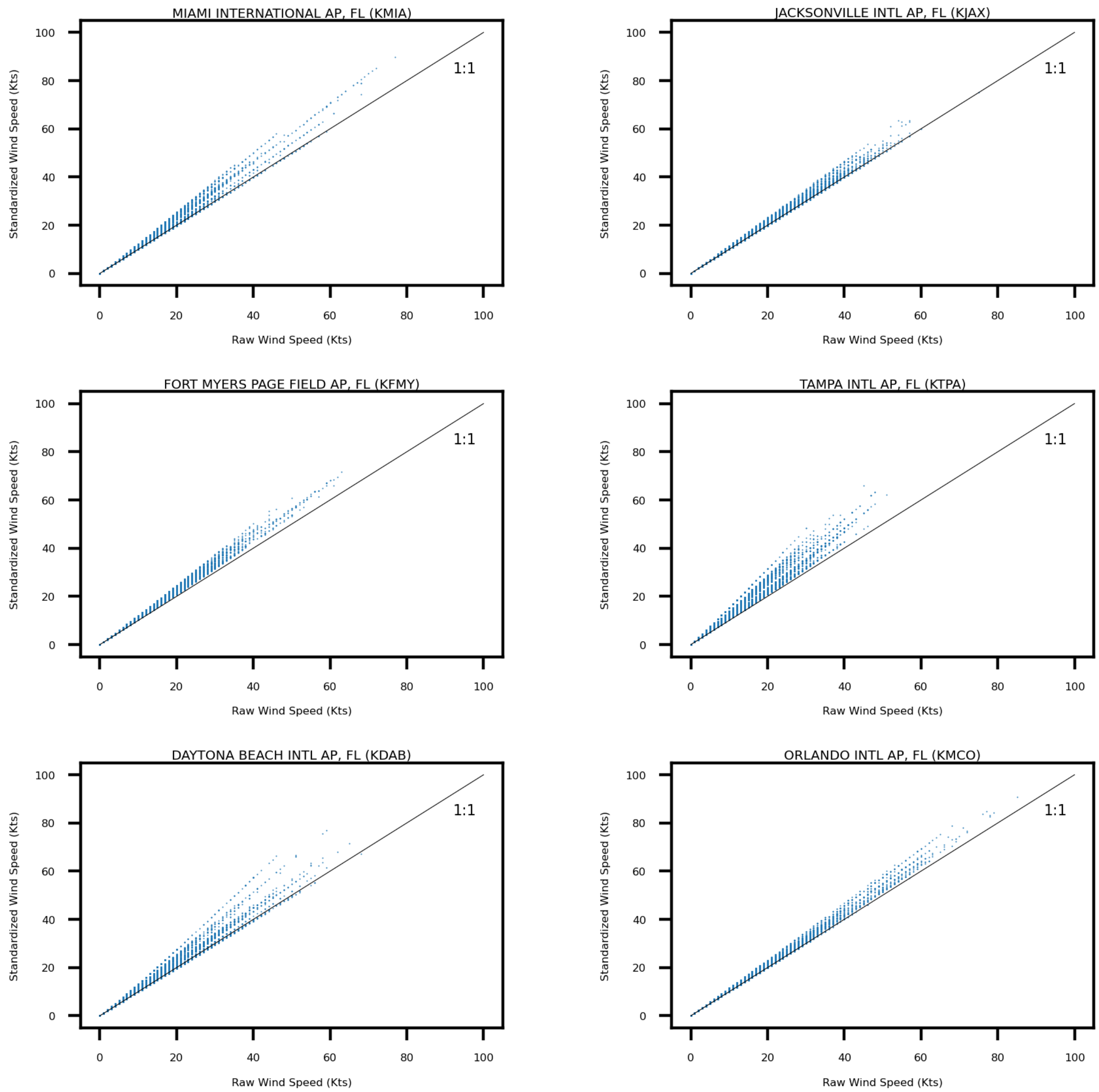

Figure 2. *Scatterplots of standardized and raw wind speeds coincident with rainfall at a number of stations across Florida. Each blue dot represents the raw peak wind speed (x) and its standardized value (y) for one minute of data. Standardized wind speeds represent raw data that is converted to ASCE 7 basic wind speed conditions (10 m height, 3 s gust, open exposure).*

4. Extreme value analysis

Extreme value analysis using coincident one-minute wind speed and precipitation data was performed for each of the 137 stations in our region of interest. Both standardized and raw wind speeds were used for separate analysis and comparison. From these analyses, the following products were created:

- Wind speed return period curves for coincident wind/rain events. Curves are created for 1, 5, 10, 25, 50, 100, and 500-year recurrence intervals, using standardized wind speed data.
- Maps of wind speed return levels associated with coincident rainfall intensities. These maps are generated for 1, 5, 10, 25, 50, 100, and 500-year wind speed recurrence intervals associated with rainfall intensity thresholds of 0.01, 0.05 and 0.10 in/min. These maps are generated using standardized wind speeds.
- Maps comparing the difference in wind speed return levels (standardized – raw wind speeds). These are constructed for the same recurrence intervals and rainfall intensity thresholds as the full standardized maps.

Below are samples and descriptions of each product.

a. Wind speed return period curves for coincident wind/rainfall events

Figure 3 provides samples of wind speed return period curves for a number of stations across Florida. Return periods of 25 years or less are represented by solid lines, while return periods greater than 25 years are represented by dashed lines. This distinction is made due to the amount of one-minute data available (~ 20 years). We feel that the amount of data available in this analysis supports the calculation of shorter recurrence intervals. Longer recurrence intervals (>25 years) are provided as estimates from our analysis. These curves can be interpreted as follows: at any given point on the curve for return period *X*, we expect the location to experience a weather event every *X* years (on average) that includes coincident wind speed and rainfall intensity magnitudes that meet or exceed the values represented by the given point.

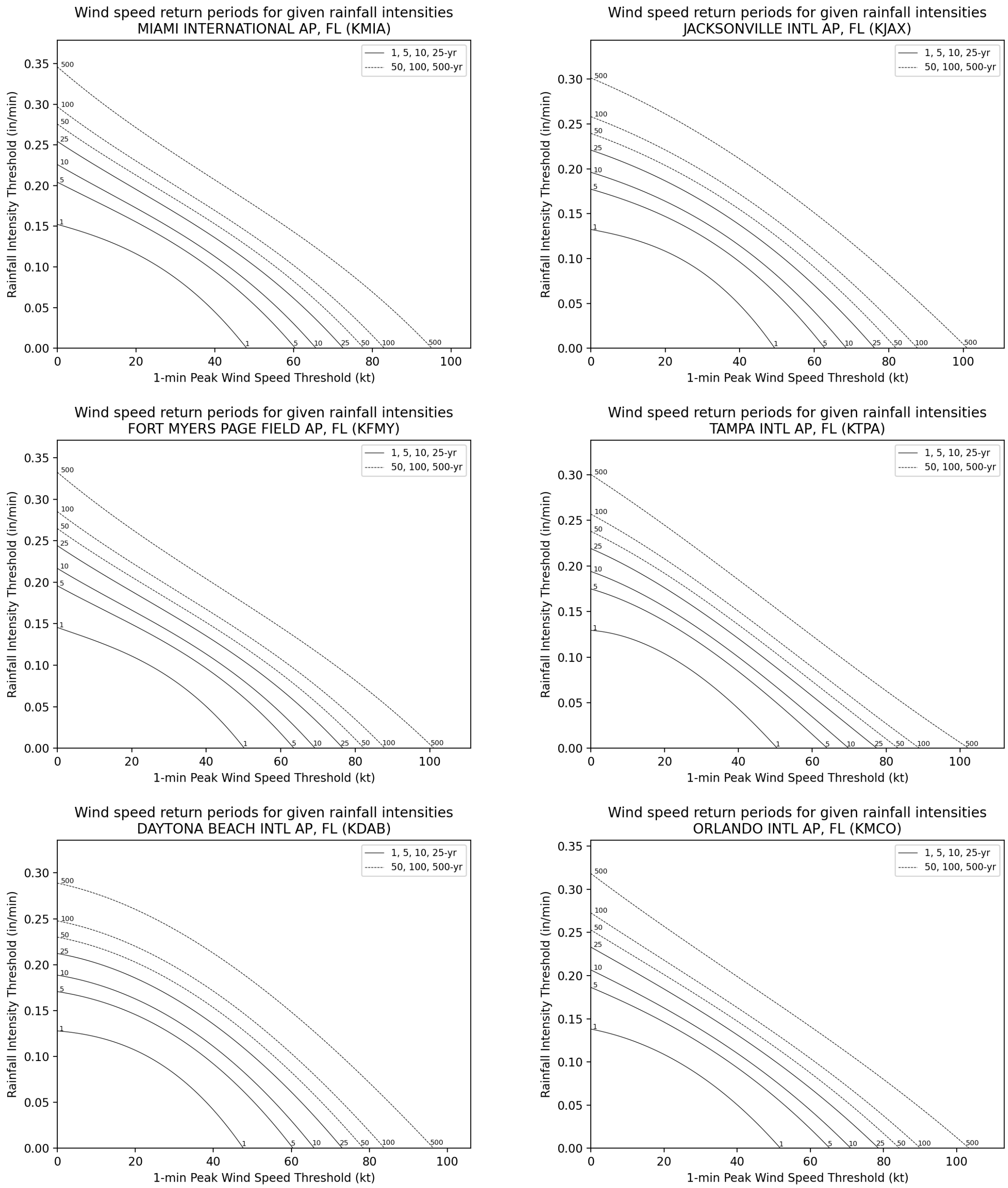

Figure 3. *Wind speed return period curves for coincident wind/rainfall events at a number of stations around Florida. Solid lines represent shorter return periods (1, 5, 10, 25-year) and dashed lines represent longer return periods (50, 100, 500-year). These curves are developed using standardized wind speeds.*

b. Maps of wind speed return levels for coincident wind/rainfall events

Figure 4 provides samples of standardized wind speed return level maps for our region of interest. These maps are constructed using linear spatial interpolation of results from all 137 stations included in the analysis. The northern and western edges of some states in our region have missing data because we only performed interpolation between stations, without any extrapolation.

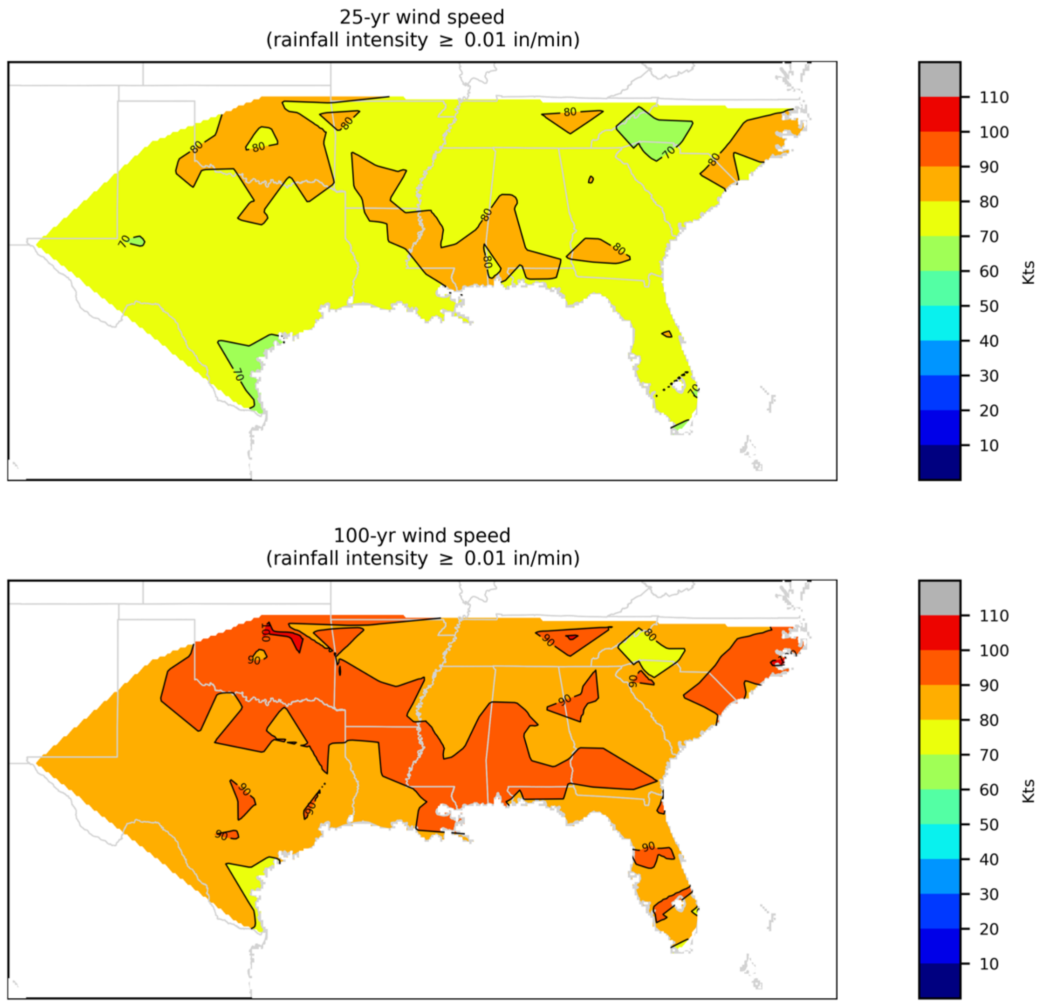

Figure 4. *Wind speed return levels for 25-year (top) and 100-year (bottom) return periods when rainfall intensities are greater than or equal to 0.01 in/min. These maps are developed using standardized wind speeds.*

c. Difference maps of wind speed return levels (Standardized – Raw)

Figure 5 provides samples showing the effect that using standardized wind speeds has on the extreme value analysis. Since wind speed adjustments are unique to each location based on conditions surrounding the weather station, no spatial interpolation is performed for these difference maps. When standardized wind speeds are used, the wind speed return levels are higher at most locations, with 10-20 knot increases occurring at many stations. This represents a percentage increase of greater than 10% over most of the region, and at some locations the increase approaches 40%.

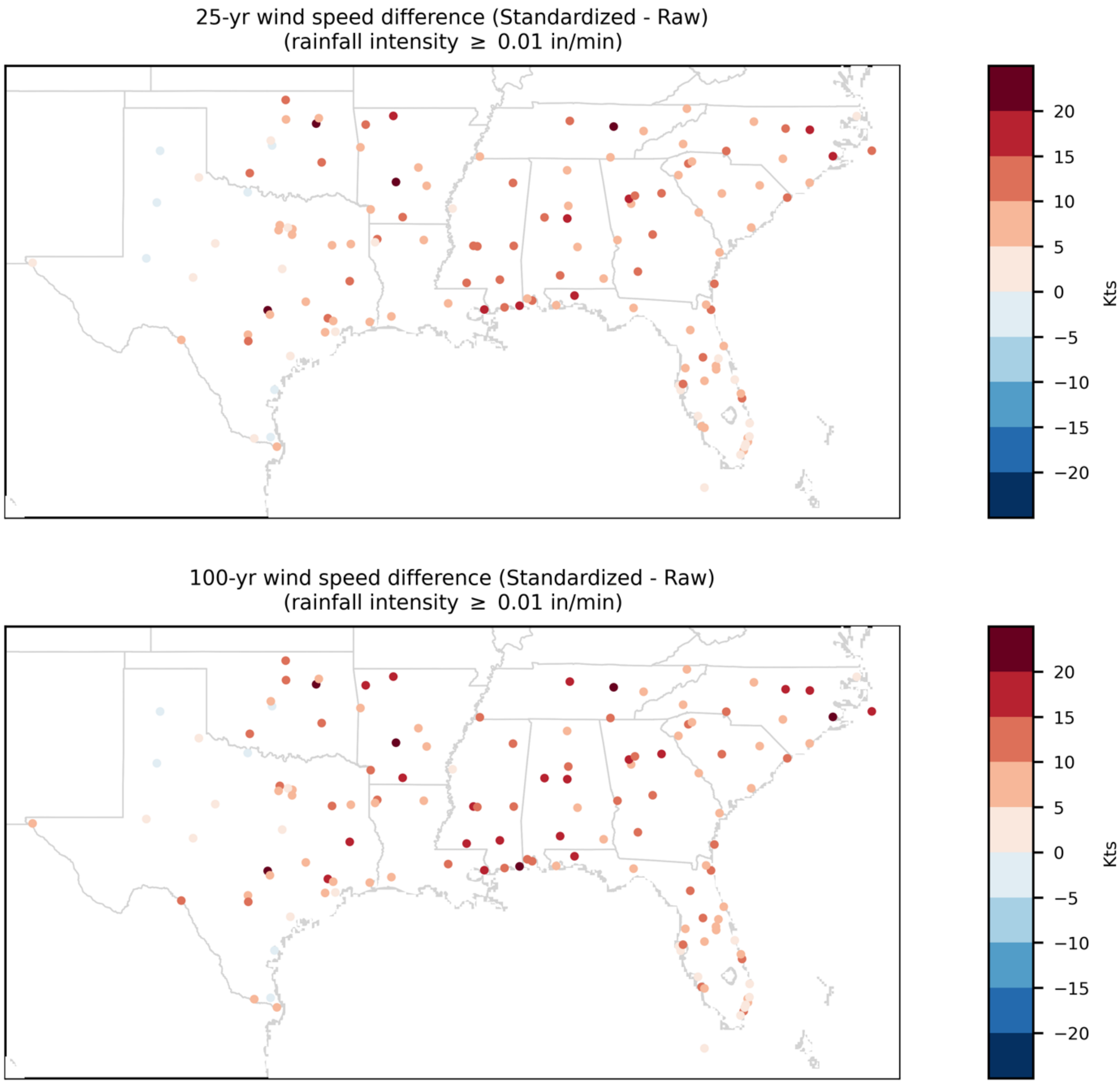

Figure 5. *Difference maps of wind speed return levels (Standardized – Raw) for coincident wind/rainfall events. Return levels are given for 25-year (top) and 100-year (bottom) return periods.*

Please see *Appendix C* for detailed methodology and discussion of extreme value analysis in this project using one-minute data. See also *Appendix D* for a discussion regarding the implications of using hourly weather reports for wind-driven rain analysis.

5. Product access

Products from this project reside in the following GitHub repository:

https://github.com/nrcc-cornell/wind-driven-rain

There you will find products including:

- Station inventory
- Standardized and raw wind speed return period curves for each station
- Tables of return period curve function coefficients (1, 5, 10, 25, 50, 100, 500-yr)
- Regional contour maps of standardized and raw wind speed return levels coincident with 0.01, 0.05 and 0.10 in/min rainfall intensities
- Regional station maps of wind speed return level differences (standardized – raw)
- This report

6. References

ASCE 7-22, 2022. Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers, Reston, Virginia.

Cai, Y. and D. Hames (2011). Minimum Sample Size Determination for Generalized Extreme Value Distribution. Communications in Statistics—Simulation and Computation. 40. 87-98. 10.1080/03610918.2010.530368.

Masters, F.J., P.J. Vickery, P. Bacon, and E.N. Rappaport, 2010: Toward objective, standardized intensity estimates from surface wind speed observations. Bulletin of the American Meteorological Society, 91, 1665-1682.

Appendix A: Weather data acquisition and quality control

Data acquisition

One-minute wind/precipitation data were obtained for 243 weather stations within Florida and other coastal and nearby states in the southeastern United States (Fig. A-1) from the National Centers for Environmental Information (NCEI, https://www.ncei.noaa.gov/pub/data/asos-onemin/). Datasets for 3-second peak wind speed/direction (DSI-6405) and accumulated precipitation (DSI-6406) over each minute are available from as early as 2000.

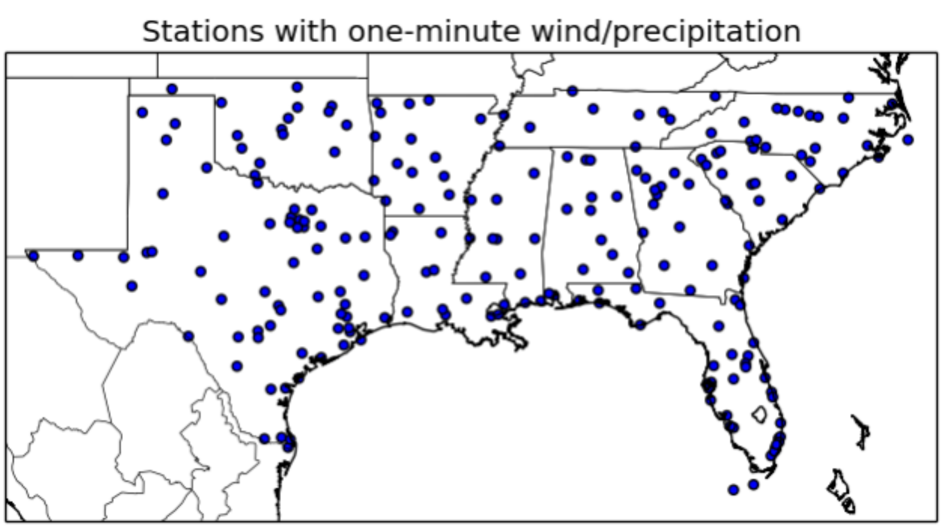

Figure A-1. *Region of interest and weather station locations with one-minute wind/precipitation data available.*

These one-minute data are originally in plain text format, contain gaps in files for missing data, and have changes or errors in column formatting throughout the periods of record. All of these dataset characteristics make scientific analysis on these data extremely difficult. Instead of working with the data in its original format, the text files were converted to HDF5 format and gaps in data were filled with missing data identifiers. Errors in text file formatting were also identified during this process, and associated data were set to missing. These changes in data formats allows for more efficient and reliable data access during subsequent analyses.

Aside from the Automated Surface Observing System (ASOS) processing algorithms, the one-minute data do not undergo further quality control before being archived at NCEI. Therefore, it was necessary to assess the quality of one-minute data, and remove errors when appropriate. Some quality control methods rely on comparison of questionable values to other datasets when identifying erroneous data. The following data were acquired and used for this purpose during automated QC methods:

- ASOS hourly reports (available from ACIS)
- Radar-guided daily precipitation (available from ACIS)

When manual QC methods were necessary, the following data assisted our assessment:

- Historical METARs from https://mesonet.agron.iastate.edu/request/download.phtml;
- Adjacent one-minute data from NCEI DSI-6405/6406 (+/- 5 minutes before and after data in question).

One-minute wind QC methodology

The following automated checks were performed and data replaced with missing identifiers if:

- values were physically impossible (e.g. direction not in 0-360, negative wind speeds);
- one-minute peak wind speeds exceed max gust for the day by more than 5 knots;
- one-minute peak wind speeds exceed 30 kts, but max daily gusts are not reported for that day (derived from hourly reports). This represents an inconsistency between the one-minute data and the higher-quality hourly reports.

Following the above automated checks, all remaining one-minute peak wind speeds that exceed 80 kts were verified manually. Consistency of weather conditions during adjacent minutes were used during this verification process. Sometimes erroneous data that made it through automated checks are found here – for instance, when both one-minute and hourly reports contain the same error.

One-minute precipitation QC methodology

The quality of one-minute precipitation data was also assessed, and errors removed. Automated checks assisted in finding errors and replacing them with missing identifiers if:

- values were physically impossible (negative precipitation amounts)
- one-minute values exceed observed (radar-guided) daily precipitation by more than 0.05 inches.

After the automated checks, all remaining one-minute precipitation amounts that exceed 0.30 inches were verified manually. Like the wind speed checks, weather conditions during adjacent minutes were used for verification of these extreme values. These manual checks are required, for example, on days when observed precipitation grids are not available for one reason or another.

Weather stations available for analysis

After applying the quality control methods to the one-minute data, there was a better understanding of the amount of useable data at each station. The valid periods of record ranged from a couple of years, to over 20 years (Fig. A-2). Stations with over 15 years of coincident wind/precipitation data were retained and used in the extreme value analyses of this project.

There were 137 stations that were retained from this procedure, with good spatial coverage across the region of interest (Fig. A-3).

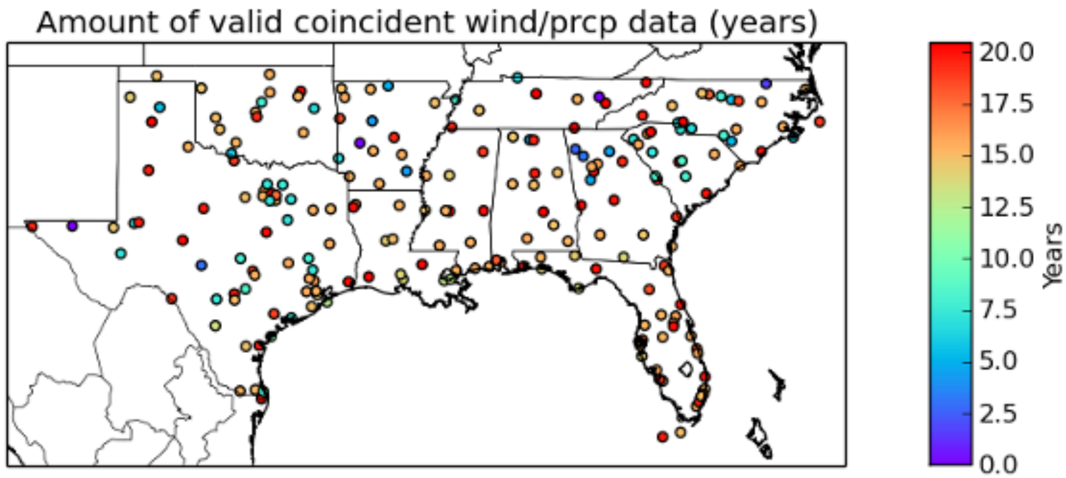

Figure A-2. *Amount of valid coincident wind/precipitation data after QC of one-minute data.*

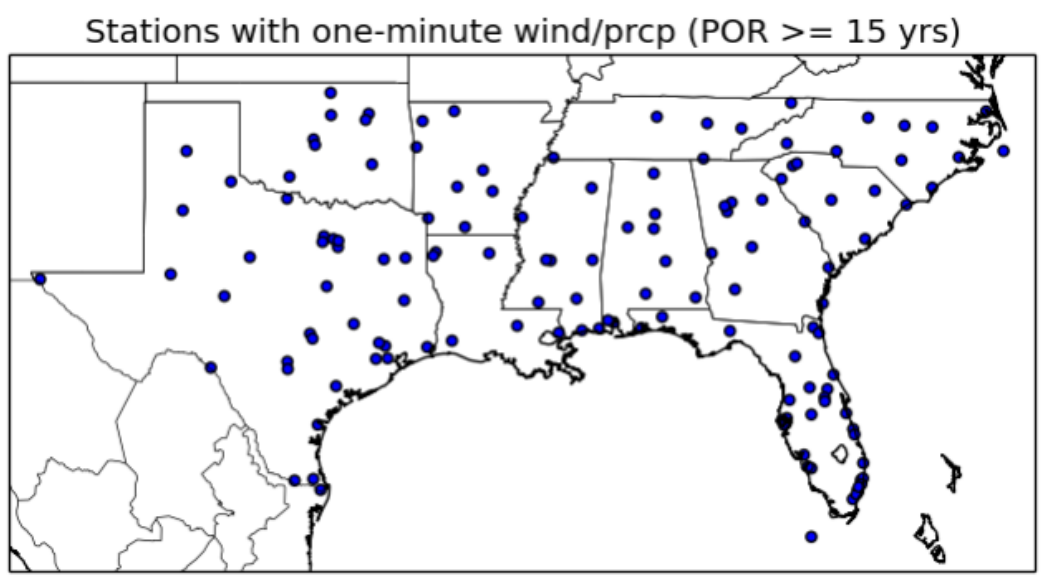

Figure A-3. *Stations retained for use in project analyses. These stations have at least 15 years of valid coincident wind/precipitation data after quality control.*

Appendix B: Standardizing one-minute wind speed data

The method described in Masters et al. (2010) was applied to convert raw wind speeds observed at each station to ASCE 7 basic wind speed conditions (10 m height, 3 s gust, open exposure conditions). Given the duration of the study (up to 20 years), year-specific conversion factors were developed for 16 wind directions to account for the era of the anemometer, terrestrial growth (e.g., tree canopy growth), new construction (e.g., new terminals or densification of building stock outside the airport), and other changes to the upwind fetch that can modify the surface roughness.

Effects of anemometer changes

Between 2003-2009, the National Weather Service replaced the Belfort cup anemometers at most sites with Vaisala ultrasonic anemometers that report 3 s moving average gusts. At most stations, this created a step change in gust factors across the anemometer transition. Due to this step change, the gust factors in each anemometer era were analyzed separately.

Gust factor smoothing methods and missing gust factor estimation

A gust factor is defined as the ratio between the peak wind gust for a specific duration to the mean wind speed for a period of time. The first step in standardizing wind speeds at a station is calculating the year-specific gust factors for each 16-point wind direction from the one-minute observed data. At least 30 wind observations were required to calculate a gust factor, otherwise this factor was not directly calculated for the year/wind direction with sparse data. Additionally, annual gust factors calculated for anemometer transition years were not used in our analyses. These requirements created some gaps of missing gust factor data that needed to be estimated so that wind speed standardization could proceed for all data. The following procedure allowed us to smooth out some variability in the gust factor data and provided a method to estimate missing gust factors.

For each wind direction and anemometer era, smoothing of annual gust factors proceeded as follows:

- If the number of years with valid gust factors was less than 10, a mean value was calculated and used for wind conversion during that period.
- If the number of years with valid gust factors was greater than or equal to 10, linear regression was performed on the time series of annual gust factors.

Most often, the Belfort era was shorter than 10 years, and annual gust factors were calculated and used for days during that period. The Vaisala era was often greater than 10 years, and trends in annual gust factors were assessed via linear regression. An exception to this was if there were a number of years without gust factors calculated due to a low number of wind observations.

Slopes of the linear regression fit to annual gust factors were calculated for all wind directions-anemometer eras for which data series length was sufficient. The following actions were taken depending on slope magnitude/significance:

- If $|slope| < 0.03$/decade: a mean gust factor was calculated and used.
- If $|slope| \geq 0.03$/decade: significance of slope from zero was assessed (95%, two-tailed). Linear regression equations with significant slopes were used to determine appropriate gust factors for use in wind conversion on specific dates. If slopes were not deemed significant, mean gust factors were used instead.

The above smoothing process allowed for appropriate gust factors to be determined by "days since 2000-01-01", chosen since our one-minute dataset began in 2000. The procedure smoothed out some variability in the data and allowed us to estimate gust factors for periods that contained missing gust factor data. Figure B-1 shows the results of this procedure performed for all 16-point directions at a sample station. Step changes due to anemometer transitions, mean gust factor calculations and trend assessments are all apparent in this example. Significant positive gust factor trends (indicated by green panels in Figure B-1) were confirmed by satellite imagery to be associated with terrestrial growth in those directions.

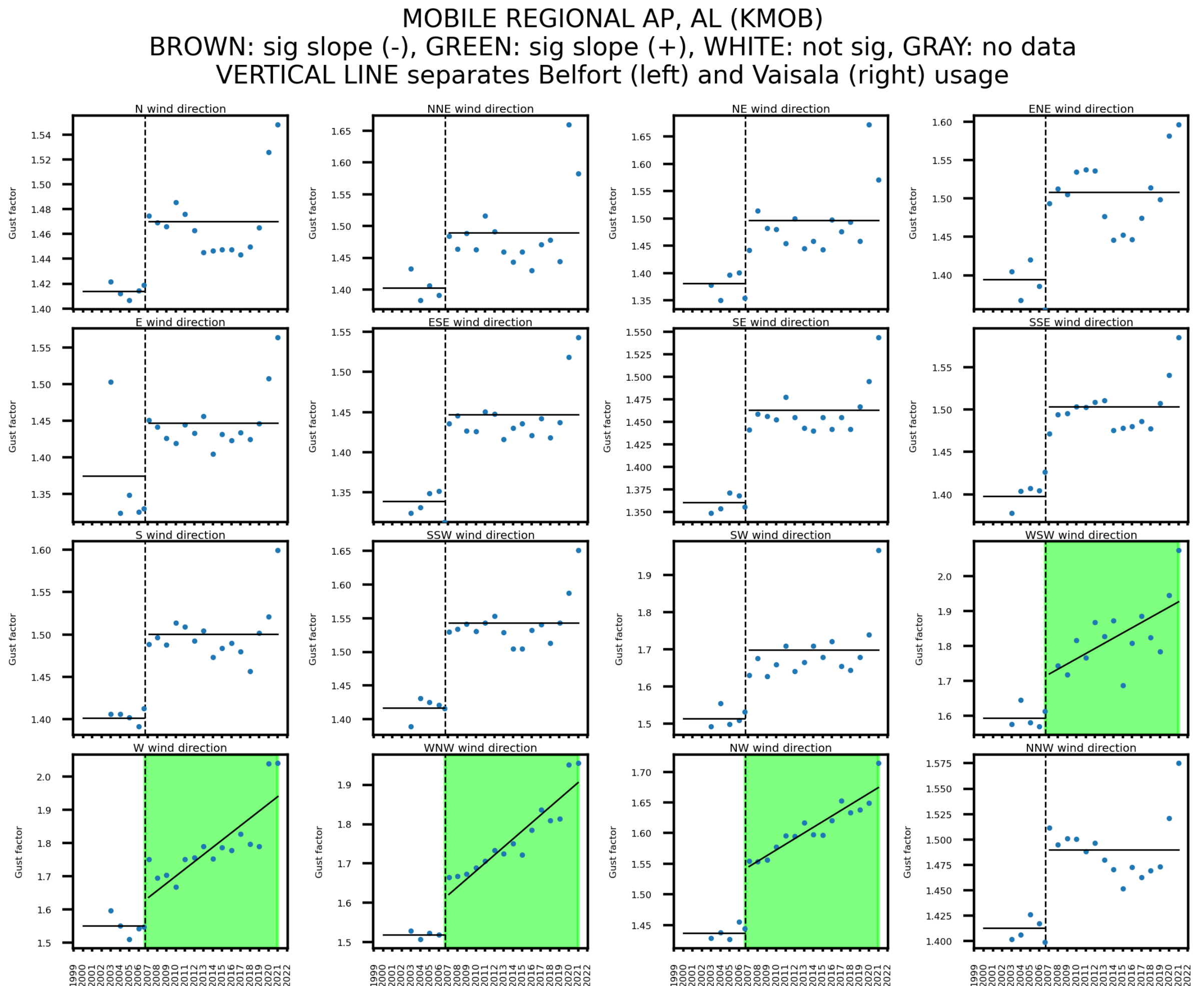

Figure B-1. *Gust factor analysis for each 16-point wind direction at Mobile Regional AP, AL. Annual gust factors (blue dots), mean gust factor calculations (horizontal lines), significant trend lines/shading, and anemometer changes (vertical lines) are all indicated.*

Most stations within our region of interest (86%) have significant gust factor trends associated with at least one direction. As noted earlier, these trends can be an artifact of many things. Increasing gust factors can be primarily associated with terrestrial growth or new construction. Decreasing gust factors, occurring less frequently, can sometimes be explained by terrestrial thinning or deconstruction.

It should also be noted that even greater detail can be undertaken when calculating and analyzing gust factors. For instance, seasonality in gust factor values can exist based on vegetation density during summer (thick) or winter (thin). Our calculation of annual mean gust factors averages over those differences. Also, building construction (or other factors) can introduce a step change rather than gradual transitions like terrestrial growth. Other than step changes due to anemometer transitions, these types of changes were not assessed. For example, multiple wind directions for the station highlighted in Figure B-1 appear to have a possible step change late in the period of record, but our methodology does not indicate this.

Applying wind speed multipliers to perform standardization

A wind speed multiplier must be determined each minute that can be used to convert raw wind speed to standardized conditions (10 m height, 3 s gust, open exposure). Determining this multiplier is dependent on the following data (see Masters et al., 2010 for details):

- Gust Factor, determined from date and time-dependent functions from previous section,
- Peak Wind Speed, reported each minute from observations,
- Height of anemometer in operation on given date,
- Type of anemometer in operation on given date

Each minute, the wind speed multiplier (wsm) is simply applied to the reported peak wind speed (U_r) to calculate a standardized wind speed value (U_s):

$$U_s = U_r * wsm$$

These standardized wind speeds are used when performing subsequent extreme value analysis.

Appendix C: Methods to construct wind speed return period curves and maps

Calculation of wind speed return periods

The process of calculating wind speed return periods conditional on rainfall intensities begins with grouping the one-minute data into bins based on observed rainfall amount exceeding a given threshold. For instance, the first bin includes all minutes that observe precipitation amounts greater than or equal to 0.01 inch. The second bin includes all minutes that observe precipitation amounts greater than or equal to 0.02 inch. Multiple sets of data continue to be constructed based on incrementally higher thresholds until the maximum observed one-minute precipitation amount is reached (i.e. if the maximum one-minute precipitation is 0.23 inches, this would results in 23 separate sets of minutes to be analyzed for this station).

Then within each of these bins, the maximum wind speed is identified and retained. Data within an 8-day window centered on this observation are eliminated. The highest wind speed in the remaining data series is retained and data within an 8-day window centered on this value omitted. This process repeats until all available observations are either retained or excluded. The resulting data series contains the highest wind speeds within independent 8-day windows over the period of record at the station associated with precipitation equal to or exceeding a given amount. Although all wind events within a particular precipitation bin are independent (i.e. are separated by at least 4-days), there is no requirement of independence between events in different precipitation bins. Thus, it is possible that the same wind speed observation is included in multiple cumulative bins and separate bins could include wind speeds separated by less than 4-days.

The set of wind speeds within each cumulative bin is then fit with a Gumbel distribution (chosen after comparison with Weibull and Frechet distributions), as long as the size of the set was greater than 100 events. This minimum sample size was chosen after applying the methods of Cai and Hames (2011) on our set of wind speed data, where we found that a sample size of 100 was sufficient, but a sample size of 50 was too small. Cai and Hames (2011) found results similar to ours when determining that the minimum sample size necessary to calculate return periods from a series of maximum annual wind speed data in Iceland was greater than 70. With these findings and preliminary results, we decided to use the full set of wind speeds rather than a partial duration series constructed from only 15-20 years of data. This decision produces smoother and more reliable results across rainfall intensity thresholds.

The probability density function of the Gumbel distribution is given by two parameters, shape and scale such that

$$f(x) = \frac{1}{\beta} e^{\frac{x-\mu}{\beta}} e^{-e^{\frac{x-\mu}{\beta}}}$$

where μ is the location parameter and β is the scale parameter. For each station-bin combination the values of μ and β are fit to the data using L-moment algorithms available from https://pypi.org/project/lmoments3/. Once fit, the wind speeds corresponding to recurrence intervals of 1-, 5-, 10-, 25-, 50-, 100-, and 500-years were calculated using the *SciPy Stats gumbel_r.isf* algorithm.

Across the southeastern United States, the sets of wind speeds were of sufficient size to perform these calculations for rainfall intensity thresholds up to 0.12 in/min at some coastal locations. For some drier inland locations, the amount of data only supported these calculations up to 0.04 in/min.

Estimating wind speed return periods for high rainfall intensity

Wind speed return periods associated with higher rainfall intensity thresholds could not be calculated directly due to the small number of very intense rainfall events. Instead, we chose to calculate rainfall intensity return periods associated with low wind speed thresholds for estimates of wind speed return periods associated with these more extreme rainfall events.

Rainfall intensity return periods associated with coincident wind speeds greater than or equal to incremental thresholds were calculated using the same methodology as wind speed return periods. In this case, we now fit the Gumbel distribution to sets of independent rainfall intensity events associated with wind speed thresholds.

Figure C-1 shows some examples of both wind speed return periods (triangles) and rainfall intensity return periods (circles) combined on the same chart for a few stations. Each type of calculated return period has a similar type of interpretation: at a given point on the chart for return period X, we expect the location to experience a weather event every X years (on average) that includes coincident wind speed and rainfall intensity magnitudes that meet or exceed the values represented by the given point.

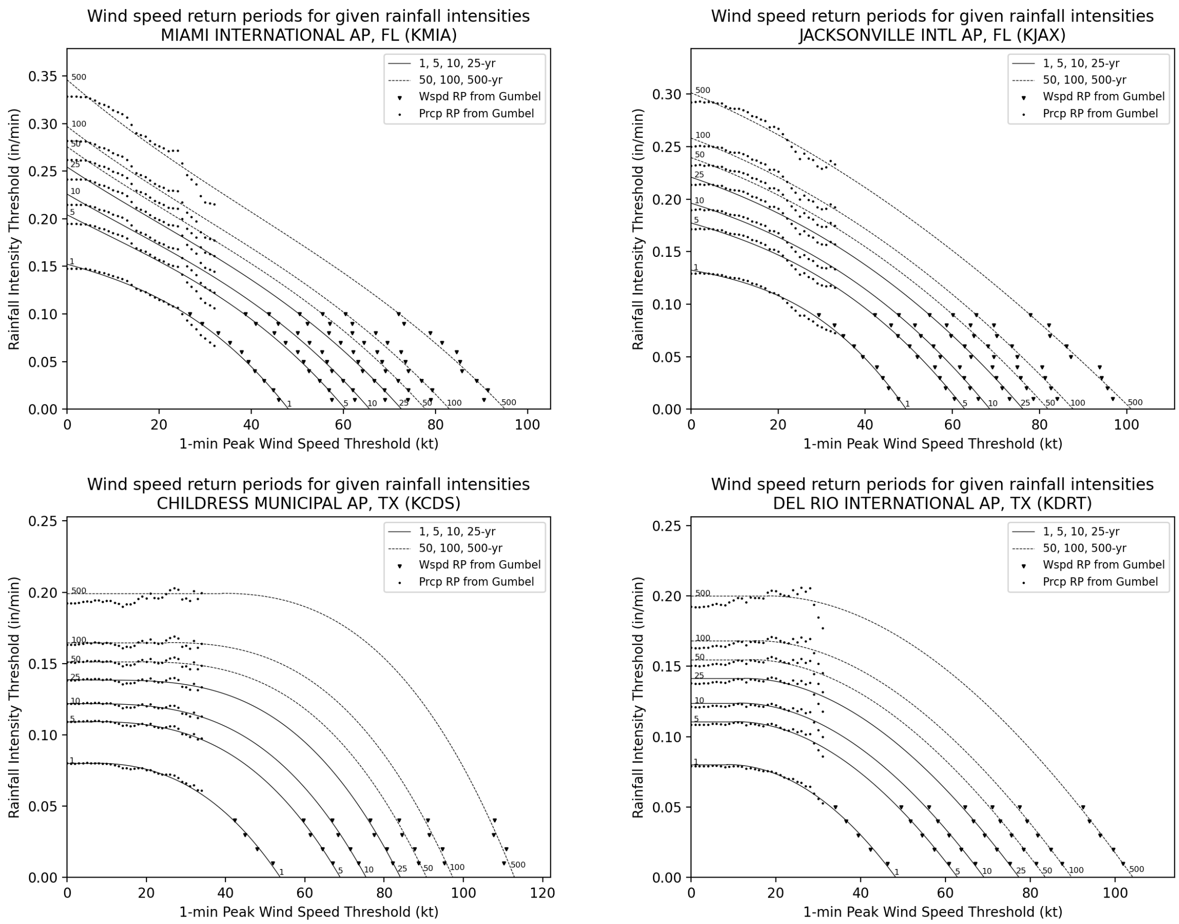

Figure C-1. *Calculated wind speed return period points (triangles) and rainfall intensity return period points (circles), with cubic functions fit to the combined set of points. Some functions fit to longer return periods (bottom stations) were modified slightly at low wind speed thresholds to satisfy monotonicity.*

Constructing return period curves

Since the different types of return periods (wind speed and rainfall intensity) in Fig C-1 can be interpreted in a similar way, we can use the rainfall intensity return period points on the charts as estimates for the wind speed return periods. This is also validated since each independently calculated set of return period points visually appear to "merge" to construct common lines for given return periods when sample sizes are sufficient. This serves as confirmation for our methods, and gives us confidence that a function can be fit to these points to represent common return periods across all wind speed and rainfall intensity thresholds. Fitting a function serves to smooth our results and allows for estimates of return periods in data-sparse areas of the chart.

Polynomials of different orders were fit to these points using NumPy's *polyfit* algorithm. The points were inversely weighted based on their density when fitting the polynomials. This resulted in wind speed return period points having a larger weight than the rainfall intensity return period points. After testing, cubic polynomials provided sufficient fit (R^2 typically 0.97-0.99), more detail than lower-order polynomials, yet fewer inflection points than higher-order polynomials that did not seem scientifically justified. For cases in which functions were not monotonic (sometimes longer return periods at ~ 20% of stations), the functions were modified slightly at low wind speed thresholds to satisfy this condition. The examples in Figure C-1 shows cubic functions fit to the calculated return period points, including some cases with functions modified to satisfy monotonicity. Final products include return period curves (without points) for 1, 5, 10, 25, 50, 100, and 500-year return periods calculated from standardized wind speeds at each station.

Constructing return period maps

Return period maps were constructed for all return periods (1, 5, 10, 25, 50, 100, 500-yr) and select rainfall intensity thresholds (0.01, 0.05, 0.10 in/min). For each station, the wind speed return level is first calculated from the cubic function that represents the return period of interest. The resulting set of wind speeds are then linearly interpolated to a grid with horizonal resolution of 0.1 degrees using SciPy's *interpolate.griddata* algorithm. Finally, this grid of values is mapped using the *contour* and *contourf* tools provided by Matplotlib and Basemap.

Final maps include wind speed return levels calculated from standardized wind speeds (10m, 3s, open terrain) and differences between wind speed return levels calculated from standardized and raw wind speeds.

Appendix D: Using hourly weather reports for wind-driven rain analysis

Reporting of summarized and instantaneous weather data each hour has been standard operating procedure at airports since mid-twentieth century. Potentially, these data provide a much longer period of record for WDR analysis than are available using one-minute data from the past two decades. Here we discuss the characteristics of hourly weather data, how they differ from the one-minute dataset used in this project, and the implications of using these data from coarser timescales when performing WDR analyses.

Hourly reports include the following information relevant to wind-driven rain analyses:

- Accumulated precipitation over the previous hour, ending at the time of the report
- Instantaneous wind speed and direction
- Wind gust during the previous ten minutes prior to the report (if applicable)
- Peak wind speed/direction/time of occurrence during the previous hour (if applicable)

While instantaneous wind speed/direction is always provided by hourly reports, wind gust and peak wind information are only reported if certain criteria are met. Additionally, the availability and frequency of wind gust and peak wind within hourly reports have changed over the past 70 years (Fig. D-1).

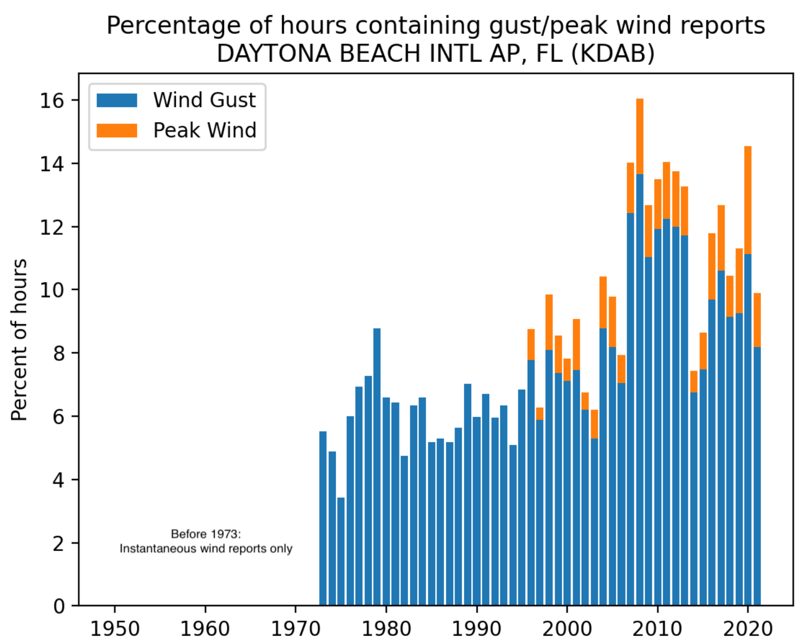

Figure D-1. *Percentage of hours with gust/peak wind reported at Daytona Beach Intl AP, FL, 1950-2021.*

The implementation of automated instrumentation over recent decades has contributed to these changes and has also allowed for archival of weather measurements at the one-minute timescale that we use in this project. The one-minute data includes accumulated precipitation over each minute, along with the peak wind speed/direction that has occurred each minute.

Using one-minute data for WDR analyses, we are better able to constrain data used in analyses to include only short durations of coincident wind and rainfall. Figure D-2 demonstrates this, where we can extract and use data from minutes with measurable rainfall, as indicated by green bars, and exclude minutes with drier (non-measurable rainfall) conditions. However, as weather measurements are summarized over increasingly longer periods of time, the ability to assess simultaneous wind/rainfall occurrences decreases. For instance, the 04:53 EST hourly report corresponding with this hour reported 0.05 inches of accumulated rainfall, and a peak wind of 27 knots. While consistent with the one-minute data, the hourly summary reduces our ability to determine coincidence of measurements. Wind speeds during all minutes (both 'wet' and 'dry' periods) are used to construct summaries in hourly reports, and the influences from dry periods cannot be excluded from such summaries.

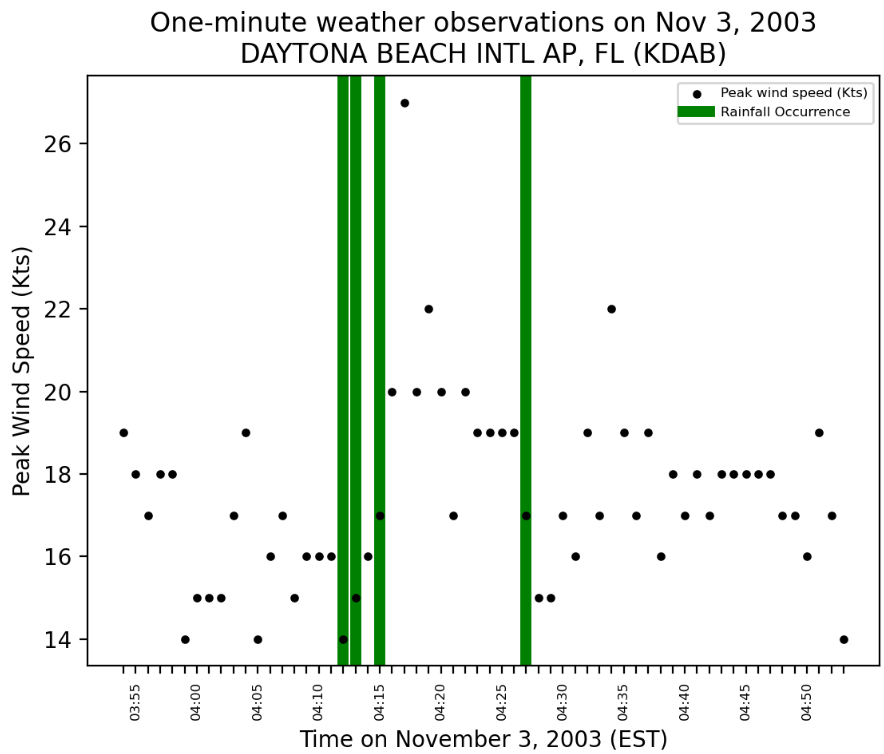

Figure D-2. *One-minute time series of measurable rainfall occurrence (green shading) and peak wind speed on November 3, 2003 from 03:54 – 04:53 am EST at Daytona Beach Intl AP, FL.*

Since hourly reports often do not include the maximum wind speed observed during the hour (unless certain criteria are met), frequency distribution of maximum reported wind speeds include a mix of instantaneous (at reporting time), gust, and peak wind speeds. Due to the changes in wind reporting over the years (Fig. D-1), the frequency distributions of maximum hourly wind speed can have very different characteristics depending on the period of analysis (Fig. D-3b,c,d). Calculating return periods from such distributions would require different methodology than we currently employ with one-minute data, which has consistently available peak wind speed measurements that produce well-distributed frequency shifted towards higher wind speeds (Fig. D-3a). A possible alternative method would be to use only the partial duration series (PDS) of wind speed events for extreme value analysis. PDS histograms are similar for hourly data constructed from one-minute data or from hourly reports over recent decades (Fig. D-4a,d). Likewise, there is more consistency between PDS histograms constructed from hourly reports for different periods of record, however there is still a shift in the PDS distribution due to the changes in wind reporting methods throughout the years (Fig. D-4b,c,d).

In this project, testing the use of wind speed PDS from only 15-20 years of data produced widely varying and inconsistent results for the available rainfall intensity thresholds at a station. For each rainfall intensity tested, a new conditional wind speed dataset was constructed and used to calculate the wind speed PDS. Construction of consistent and reliable wind speed return periods did not occur with a PDS containing only 15-20 events. These results are consistent with the findings of Cai and Hames (2011), who found that at least 70 years of wind speed data were necessary to calculate reliable return periods from the maximum annual wind speed series in Iceland. As a result, we chose to use frequency distributions of all data and not just the PDS, to increase sample size, consistency, and reliability of wind speed return period calculations conditional on numerous rainfall intensities.

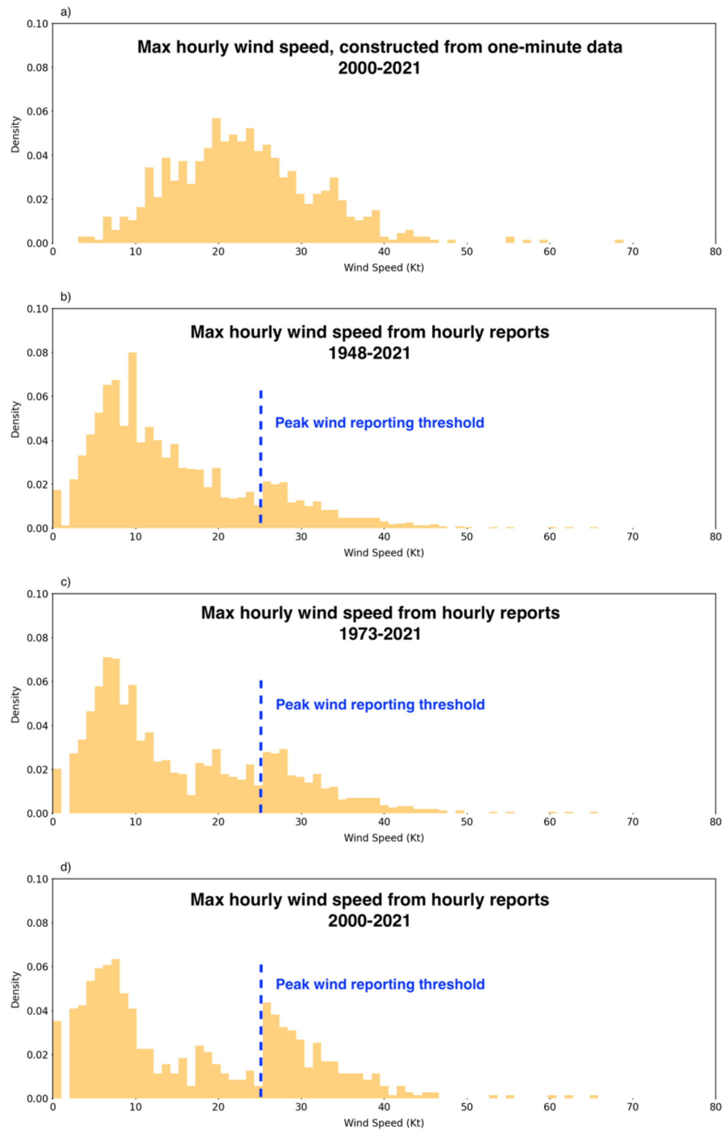

Figure D-3. *Frequency of maximum hourly wind speed associated with all hours reporting greater than or equal to 0.10 inches of rainfall at Daytona Beach Intl AP, FL. Separate histograms are presented for a) hourly summaries using one-minute peak winds (2000-2021), b) hourly reports for the full period-of-record (1948-2021), c) hourly reports after the start of wind gust reporting (1973-2021), and d) hourly reports after the start of peak wind reporting (2000-2021).*

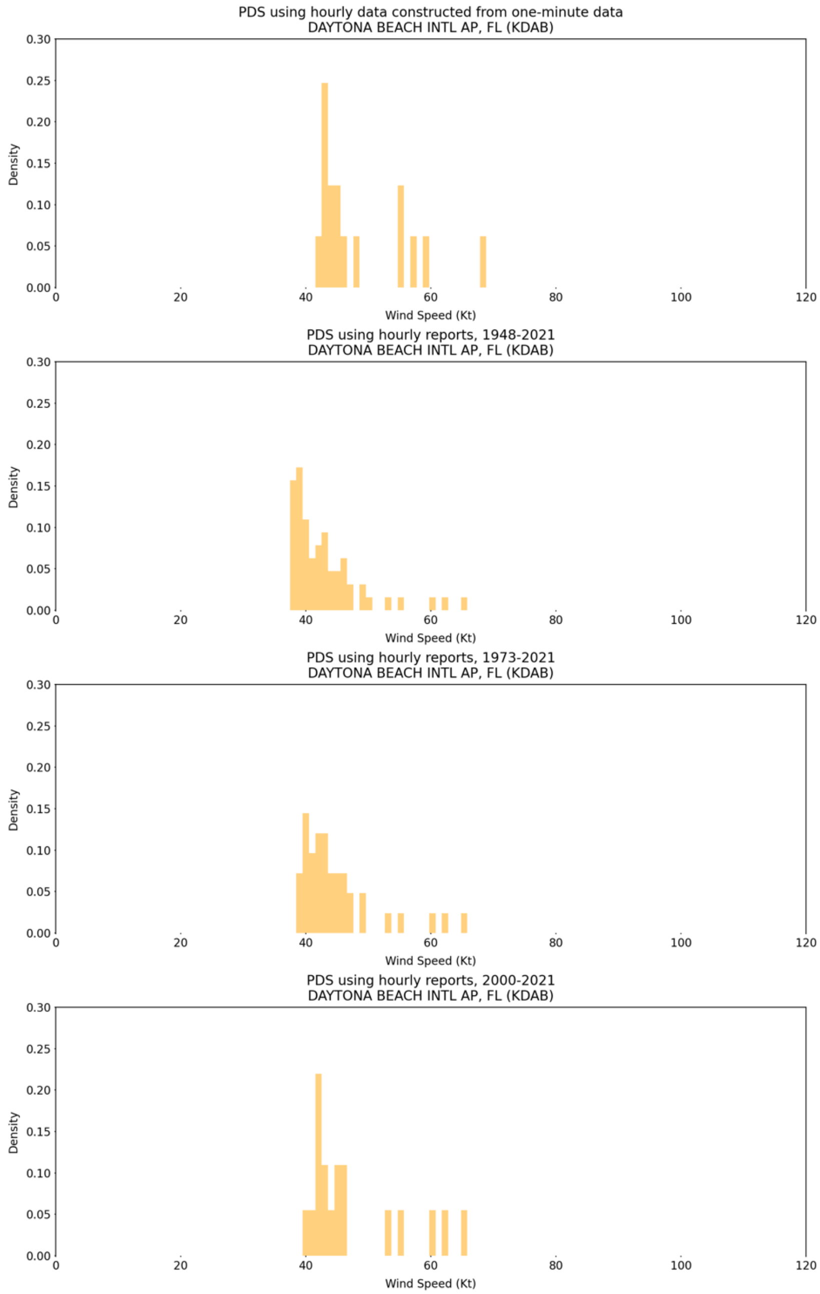

Figure D-4. *Maximum hourly wind speed partial duration series (PDS) constructed from hours reporting greater than or equal to 0.10 inches of rainfall at Daytona Beach Intl AP, FL. Separate histograms are presented for a) hourly summaries using one-minute peak winds (2000-2021), b) hourly reports for the full period-of-record (1948-2021), c) hourly reports after the start of wind gust reporting (1973-2021), and d) hourly reports after the start of peak wind reporting (2000-2021).*

Overall, using hourly weather reports is not ideal for wind-driven rain analyses, based on the following hourly data characteristics:

1) Unable to determine rainfall intensity over short periods from hourly accumulated rainfall.

2) Maximum wind speed is not always reported for the hour (criteria must be met).
3) Unable to eliminate the influence of wind speed during ‘dry’ periods during the hour.
4) Unable to determine if reported rainfall and wind speeds during the hour are coincident.
5) Changes in wind speed reporting over the period of record.
6) Maximum wind speed frequency distributions sometimes multi-modal due to 5). Alternative statistical methods from those used for one-minute data analysis must be explored. Using PDS from hourly data with long period of record (> 70 years) is possible, but these data would include long periods (20-30 years) of only instantaneous wind reports, and not maximum wind speeds occurring during the hours.

The use of available one-minute weather data serves to avoid these listed issues, but continues to have the disadvantage of shorter periods of record.