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ANALYSIS OF SPATIALLY-VARYING WIND CHARACTERISTICS FOR DISTRIBUTED SYSTEMS

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ABSTRACT

Design wind speeds for various return periods are provided in most national design codes throughout the world (e.g., NBCC 2010, ASCE 7-10). The design wind speeds are often based on an extreme value analysis of historical data obtained from a number of meteorological stations distributed over the region of interest. However, only the extreme wind speed magnitude is typically available to the designer, which does not provide information on the directional characteristics or underlying probability distribution of the wind. These parameters of the local wind characteristics may be useful for designers of directionally-sensitive structures or for higher-order reliability-based design. This paper describes an analysis of wind records obtained from discrete meteorological stations and the methods used to develop estimates of wind speed and directionality. The trends in wind speed and direction for a set of stations are also discussed. Following this, statistical wind parameters (including wind speed and direction) can be extracted for a number of locations within the study area. These values can be subsequently used to assess the reliability of one or more point structures, or a distributed system. The results are compared with those based on a traditional Gumbel (Type I) extreme value analysis for the same set of station data.

Keywords: Wind speed, wind load, wind directionality, distributed systems, reliability-based design

1. INTRODUCTION

The design wind speed is the cornerstone of any code or standard describing wind loading of structures. In any design procedure, this wind speed is combined with an array of various other constants and factors describing the structure in question (i.e., geometric and dynamic properties), the approaching flow of the wind (i.e., speed and turbulence along height or length), and the importance of the structure. For a wind loading code specific to a country or region, the design wind speed will often vary across the geographic region of interest, with structures in different regions being designed for different speeds. The design wind speeds may be expressed as discrete points (e.g. NBCC 2010) or as maps showing contour plots (e.g., ASCE/SEI 7-10), and are often available for various return periods.
The development of such maps often relies on the statistical analysis of carefully vetted and standardized sets of wind data obtained at meteorological stations, often over time periods ranging from 20 to 50 years. The format and measurement frequency of anemometer records differs among countries, and the quality of the data may vary depending on the meteorological station. Differences between historical wind data in Canada and the United States is discussed by Mara and Lombardo (2013).

The design wind speeds that are presented in codes and standards are typically not associated with wind direction. The design wind speed would generally be combined with a conservative wind loading direction for the structure (e.g., enveloped pressure coefficients from wind tunnel tests), which would define the design loads. This value may then be reduced to recognize the probability associated with the design wind approaching from the direction resulting in the greatest response. Reductions such as these (i.e., K_d in ASCE 7-10) typically varies from 0.8 to 0.9, depending on the structure. However, reductions accounting for directionality of design winds are not used for all structures, with an example being typical design procedures for transmission lines (e.g., ASCE Manual No. 74 (ASCE 2010b)). Transmission lines are relatively directionally-sensitive compared to buildings or other structures; the design condition tends to be that where wind approaches at directions normal (or slightly skewed in some cases) to the conductors, and this load decreases significantly for other orientations. In this light, the directional characteristics of the wind may be of interest to the designer when approaching either serviceability or design loads. The underlying joint probability of wind speed and direction would also be an important component if carrying out a higher-order reliability analysis of the structure or system.

This paper compares different methods for estimating wind speed and direction for different points along a distributed system, based on a spatial area defined by a set of meteorological stations. Analyses of the extremes and parent data from each station are considered, and each set of data are interpolated in two ways: i) based on the estimated wind speed, and; ii) based on the statistical parameters. The following sections provide background on the historical wind data used in this study, and the probabilistic theory used for the statistical analysis of the wind data at each station.

1.1 Wind Data

The wind data for the current study was obtained from the Integrated Surface Hourly (ISH) database, which is maintained by the National Climatic Data Center (NCDC) at the National Oceanic and Atmospheric Administration (NOAA). This database is public domain and can be accessed at ftp://ftp.ncdc.noaa.gov/pub/data/noaa/ . The ISH database catalogs a variety of land-surface meteorological data for approximately 20 000 stations around the world and contains a large number of variables recorded at hourly intervals.

Wind speeds specified in codes and standards are commonly referenced by a height, exposure category, and averaging time. For example, the NBCC specifies a mean hourly reference wind velocity pressure at a height of 10m in open country terrain. However, the wind speeds observed at anemometers may often be affected by upstream terrain conditions, adjacent buildings, or may be recorded at heights other than 10m. In each of these cases, the wind records need to be standardized to a basic condition for processing and comparison to code specific values. For the stations considered in the current work, the wind records were standardized to a height of 10m based on the power law, and the upstream terrain was considered at 20° intervals to correct to a standard open terrain (i.e., z_o = 0.03m). This procedure is based on ESDU (ESDU 2005), which uses the Harris and Deaves boundary layer model (e.g., Harris and Deaves 1981) for incorporating numerous transitions of terrain roughness and fetch length. Comparisons between standardized and original anemometer data are further discussed by Mara et al. (2013). Additional meteorological observations (i.e, present weather observation, atmospheric pressure, temperature) during recorded high winds speeds were also considered in the quality assurance of the data (e.g., Mara and Gatey 2013).

As a result of the above procedures, the dataset at each station was taken as representative of the mean hourly wind speeds at 10m height in open country terrain. Further details on the stations used in the current paper are provided in Section 2.

1.2 Extreme Value Analysis

In extreme value theory, the linear-stability postulate results in three types of extreme value probability distributions (e.g., Castillo 1988). The extreme value Type I distribution, commonly referred to as the Gumbel distribution, is often used to model the annual maxima of environmental phenomena such as extreme wind speed or precipitation events.

The cumulative distribution function of the Gumbel model is taken as

[1] $$F(x) = \exp(-\exp(-(v-\mu)/\alpha))$$

where $F(x)$ denotes the cumulative distribution function, *v* denotes the value of the random variable *V*, and μ and α are the location parameter (mode) and scale parameter (dispersion), respectively. The reduced extreme variate, *Z*, is then expressed as

[2] $$Z = (V-\mu)/\alpha$$

The mean and standard deviation of V, μ_v and σ_v, respectively, are then expressed as

$$[3]\quad \mu_v = \mu + \alpha\gamma \quad \text{and} \quad \sigma_v = \alpha\pi / \sqrt{6}$$

in which γ is the Euler constant (0.5772). The T-year return period value of V, v_t, can then be estimated by

$$[4]\quad v_t = \mu + \alpha z_t$$

in which $z_t = -\ln(-\ln(1-1/T)$.

The coefficient of variation (COV), which describes the variability in the annual maxima, can also be calculated from these parameters. The mean and COV values are of use if a higher-order reliability-based study is undertaken for a distributed system, for which statistical parameters are of interest. As the scope of the current paper is limited to the estimation of extreme wind speeds for spatial areas, only the Gumbel location and scale parameters are considered in the spatial interpolation, while Eq. [4] is used to estimate the extreme wind speeds from the interpolated parameters μ and α. In the current work, all fitting of the annual maxima was carried out based on the Method of Moments.

1.3 Parent Distribution

The joint probability distribution of wind speed and direction at a particular station can be developed from a long record of historical data (typically greater than 20 years). The probability distribution can be obtained at different return periods of interest (e.g., weekly, monthly, annual), which can show how the directionality of winds for a station may change with strength of wind speed. The probability of the wind speed, V, exceeding some value V_i, within a given azimuth sector of $(\alpha_i \pm \Delta\alpha/2)$, $(\alpha_{i,\min})$ and $(\alpha_{i,\max})$, can be written as

$$[5]\quad P(V > V_i, \alpha_{i,\min} < \alpha_i < \alpha_{i,\max}) = P(\alpha_{i,\min} < \alpha_i < \alpha_{i,\max}) \times P(V > V_i \mid \alpha_{i,\min} < \alpha_i < \alpha_{i,\max})$$

The histogram of the wind speed and direction are often fit to probability distributions for convenience in estimating wind speeds at various levels of exceedance (i.e., return periods). A commonly used distribution for this is the Weibull distribution, which for wind from any sector α can be expressed as

$$[6]\quad P(>V, \alpha) = a(\alpha)\exp\left(-(V_i / c(\alpha)\right)^{k(\alpha)}$$

in which $a(\alpha)$ is the relative frequency of occurrence in sector α, $c(\alpha)$ is a scale parameter for sector α, and $k(\alpha)$ is a scale parameter for sector α. This probability distribution can readily be assessed based on a given number of sectors for a meteorological station, and used to estimate the wind speed and direction at various return periods of interest for the location.

More recently, a bi-modal Weibull distribution has been used to develop the probability distributions, based on observations of poor fits in the tail related to the parameters in Eq. [6] (Xu et al. 2008). This distribution results in two weighted sets of Weibull scale and shape parameters, which can be useful when multiple weather phenomena are observed in the wind speed statistics. The probability distribution function for any wind sector α can be expressed as

$$[7]\quad P(>V) = a\left(w_1 \left(\frac{k_1}{c_1}\right)\left(\frac{V}{c_1}\right)^{(k_1-1)} \exp\left(\frac{-V}{c_1}\right)^{k_1} + (1-w_1)\left(\frac{k_2}{c_2}\right)\left(\frac{V}{c_2}\right)^{(k_2-1)} \exp\left(\frac{V}{c_2}\right)^{k_2} \right)$$

where a, c_1, k_1, w_1, c_2, and k_2 can be calculated for each wind sector, and thus become functions of α. Note that $\sum_{\alpha_{0\deg}}^{\alpha_{360\deg}} a(\alpha_i) = 1$.

2. WIND STATION SET AND SPATIAL AREA

As a component of hazard assessment for a transmission line, approximately 20 North American meteorological stations across the area of interest were identified and analyzed; a subset of 7 of these stations are presented and used for discussion. For presentation in this paper, the latitude and longitude coordinates of the original stations have been shifted; however their relative locations are maintained. The station numbers, coordinates, and length of historical record are shown in Table 1.

The extent of the spatial area considered in the study is shown in Figure 1. This spatial area is approximately 250 km in the north-south direction (shown as latitude) and 350 km in the east-west direction (shown as longitude). Also shown are the meteorological station reference numbers and the hypothetical route of a transmission line. While any number of intermediate points could be considered for interpolation, three arbitrary points (referred to as tower checkpoints) will be used to demonstrate the methods for this paper. The arbitrary tower checkpoints represent the start of the transmission line (Start Tower), the midpoint of the transmission line (Mid Tower), and the endpoint of the transmission line (End Tower). Note that the transmission line is roughly characterized by two span orientations: Span 1 routed along 147°/327° and Span 2 routed along 105°/285°.

Table 1: Station reference numbers and years of data for each station.

Station	Latitude	Longitude	Years	No. Annual Max.
1	37.753	-49.934	1993 - 2012	20
2	37.065	-49.183	1973 - 2012	40
3	35.925	-49.811	1973 - 2012	40
4	37.566	-46.403	1973 - 2012	40
5	36.217	-46.484	1984 - 2013	30
6	35.405	-47.131	1973 - 2012	40
7	35.844	-45.194	1973 - 2012	40

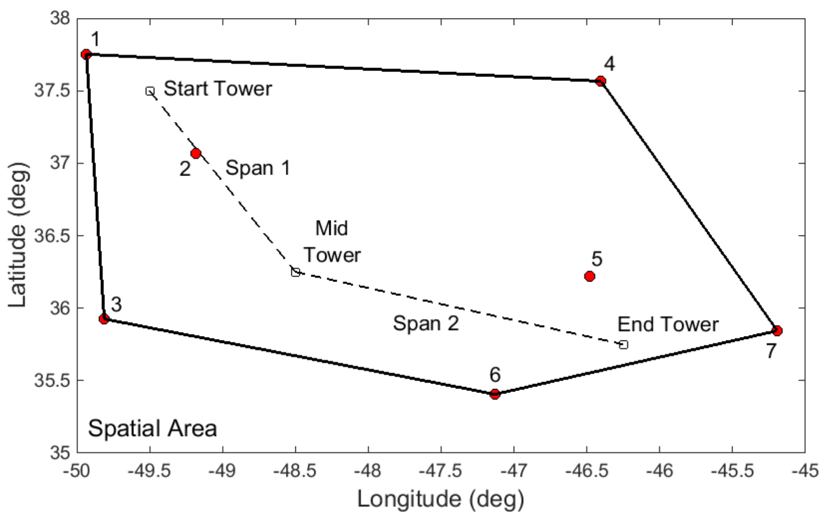


Figure 1. Plot of spatial area indicating meteorological stations, hypothetical transmission line route, and tower checkpoints.

An analysis of the extreme and parent probability distributions, based on the Gumbel and bi-modal Weibull, respectively, were performed on the standardized wind data for each station listed in Table 1. In the following sections, methods for the interpolation of wind speed and direction at the tower checkpoints are described and the results are compared.

3. EXTREME VALUE ANALYSIS OF STATION SET

The extreme value analysis of each station yielded the statistical parameters μ and α for the data at each station, as well as the estimated wind speed a given return period, $V_{RP,e}$. In the following sections, the extreme wind speeds for the tower checkpoints are estimated based on i) interpolation of the station parameters μ and α, and; ii) direct interpolation of the estimated wind speeds at each station, $V_{RP,e}$.

3.1 Interpolation of $V_{RP,e}$

The annual maxima for each station were analyzed and fit to a Gumbel distribution using the Method of Moments. Wind speeds for 10-year, 50-year, and 100-year return periods were calculated, although additional return periods could be calculated based the fits at each station. For each return period, the estimated extreme wind speed, $V_{RP,e}$, was mapped to the location of the station. Based on a cubic interpolation between the stations, contour plots were developed for the estimated wind speed at each return period. This interpolation method implies that all stations receive equal weighting, and the surface is constrained to passing through each station. Additional interpolation methods are available for the interpolation of data such as these, with varying advantages and disadvantages, but are beyond the scope of this paper. Discussion on available interpolation techniques are presented by Hong et al. (2014) and Hong and Ye (2014). An example contour plot for the estimated 50-year extreme wind speed across the spatial area is shown in Figure 2. The estimated wind speeds for each return period at each tower checkpoint are listed in Table 2; these appear under the heading 'From Interpolation of $V_{RP,e}$'.

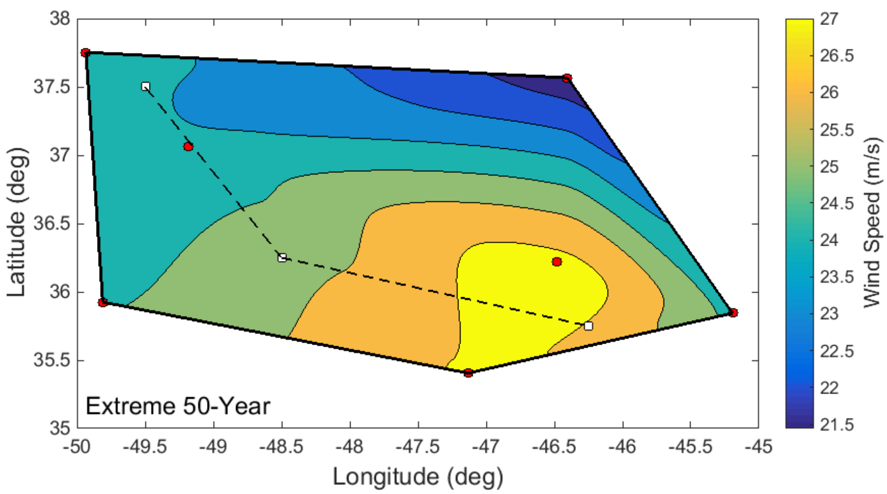
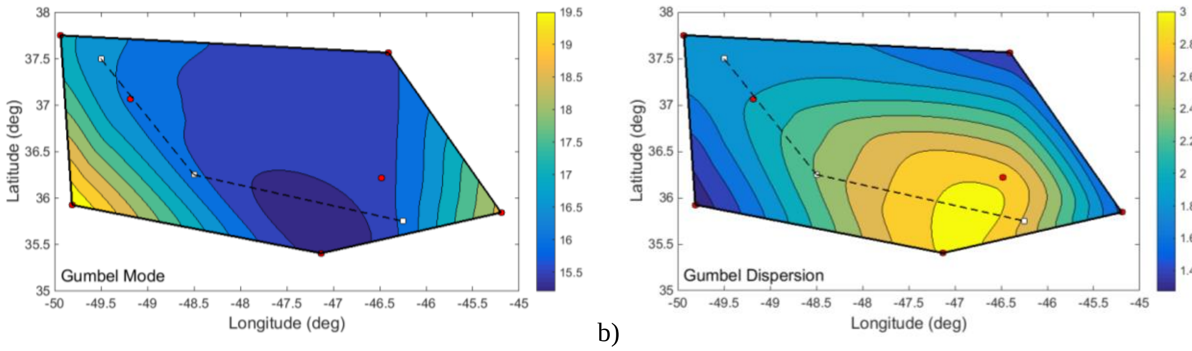


Figure 2: Contour plot showing spatial variation of estimated 50-year wind speed (m/s).

3.2 Interpolation of Extreme Value Parameters

The Gumbel mode and dispersion parameters (μ and α) were calculated for each station based on the fit to the Gumbel distribution described in Section 1.2. For comparison to the interpolation of the extreme wind speeds, the mode and dispersion were mapped to the coordinates of each station, and the same method was used for interpolation at other points in the spatial area. Example contour plots of the mode and dispersion parameters across the spatial area are shown in Figure 3. Thus, for each tower checkpoint, a new extreme value distribution was defined by the interpolated parameters; these were used to estimate the extreme wind speeds at each tower checkpoint. The estimated wind speeds for each return period at each tower checkpoint are listed in Table 2; these appear under the heading 'From Interpolated Parameters'.



a) b)

Figure 3: Contour plots showing spatial variation of Gumbel parameters a) mode (μ), and b) dispersion (α).

As can be observed in Table 2, there is very little difference in the estimated wind speed at each tower checkpoint between the two methods used (i.e., From interpolation of the estimated speeds, From interpolation of the Gumbel parameters). While this is consistent for the particular station set presented here, the inclusion of a larger number of stations or a larger spatial area may introduce differences.

Table 2: Estimated wind speeds (m/s) from Extreme Value Distribution based on each interpolation method.

	Estimated Wind Speed (m/s) from Extreme Value Distribution					
	From Interpolated Parameters			From Interpolation of $V_{RP,e}$		
Return Period	Start	Mid	End	Start	Mid	End
1 Year	16.7	16.2	16.1	16.7	16.2	16.1
10 Year	21.0	21.6	22.4	21.0	21.6	22.3
50 Year	24.2	25.6	26.9	24.2	25.6	26.9
100 Year	25.6	27.3	28.9	25.5	27.3	28.9

4. PARENT ANALYSIS OF STATION SET

The parent analysis of each station yielded a set of bi-modal parameters for each wind direction (i.e., a, c_1, k_1, w_1, c_2, and k_2), as well as the estimated wind speed at a given return period, $V_{RP,p}$. In the following sections, the wind speeds for the tower checkpoints are estimated based on: i) interpolation of the station parameters, and; ii) interpolation of the estimated wind speeds at each station from the parent distribution, $V_{RP,p}$.

4.1 Interpolation of $V_{RP,p}$

The hourly wind speed data for each station were analyzed and fit to a bi-modal Weibull distribution. Wind speeds for 1-week, 1-month, 1-year, 10-year, 50-year, and 100-year were calculated, although additional return periods could be calculated based on the fits at each station. For each return period, the estimated parent wind speed, $V_{RP,p}$, was mapped to the location of the station, and these were interpolated for the tower checkpoints using a similar technique to that for the extreme wind speeds described in Section 3.1. An example contour plot for the estimated 1-year wind speed across the spatial area is shown in Figure 4. The estimated wind speeds for each return period at each tower checkpoint are listed in Table 3; these appear under the heading 'From Interpolation of $V_{RP,p}$'.

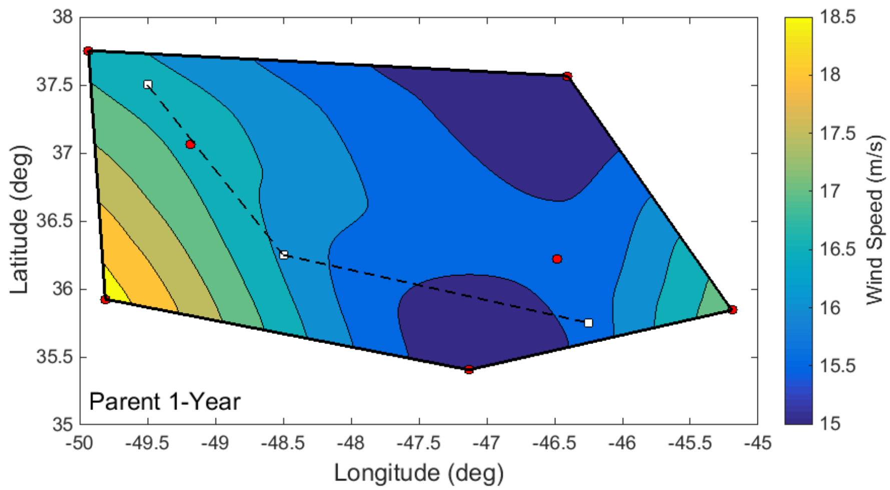
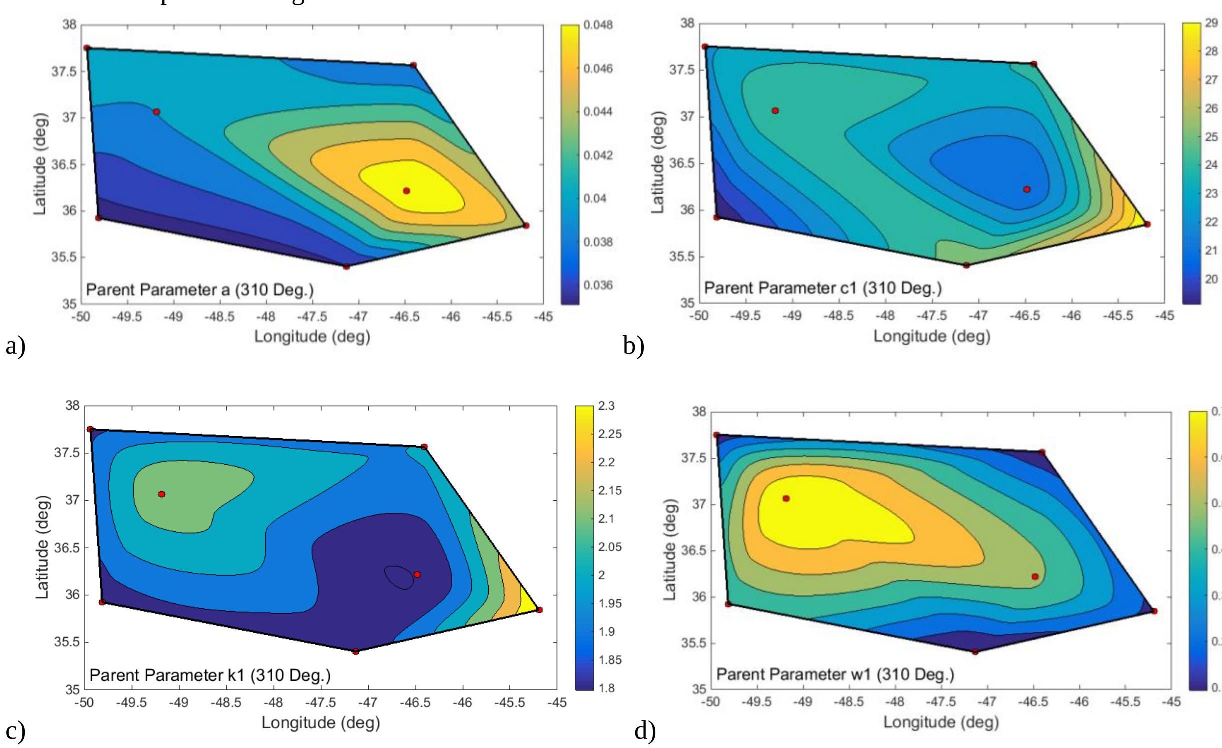
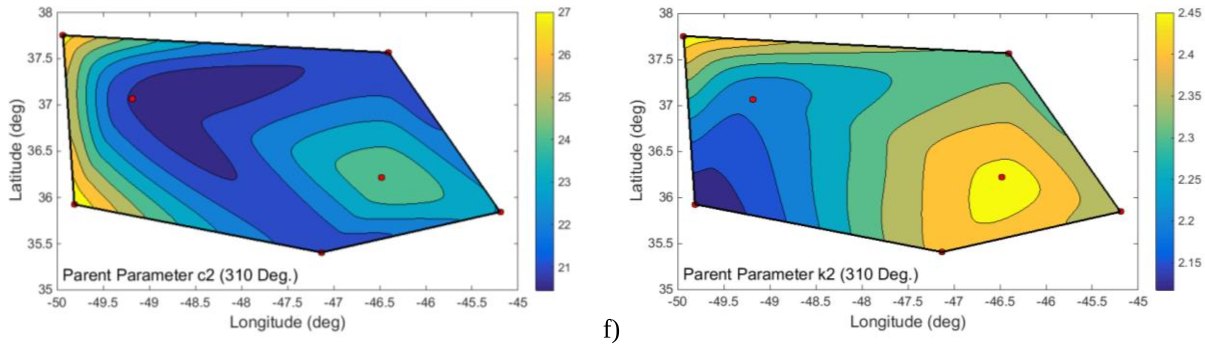


Figure 4: Contour plot showing spatial variation of estimated 1-year wind speed (m/s).

4.2 Interpolation of Parent Parameters

The joint probability parent distribution parameters, in this case the six parameters describing conditional bi-modal Weibull distribution (a, c_1, k_1, w_1, c_2, and k_2), were assembled for each wind direction. These parameters were then interpolated for each wind direction at each of the tower checkpoint locations along the hypothetical transmission line. A set of example contour plots for the bi-modal Weibull parameters corresponding to wind direction 310° are shown across the spatial area in Figure 5. At each tower checkpoint, a location-specific description of wind speed and direction was obtained, providing a description of the dominant wind directions at various return periods along the transmission line.





e) f)

Figure 5: Contour plots showing spatial variation of Parent Parameters (bi-modal Weibull).

The estimated wind speeds obtained at each tower checkpoint through the interpolation of the parent parameters are listed in Table 3; these appear under the heading ‘From Interpolated Parameters’. It is shown that although ‘bullseye’ characteristics are observed in the spatial variation of some of the parent parameters (i.e., wind direction 310° in Figure 5), when the full range of azimuths are combined for each tower checkpoint the resulting wind speeds closely match those interpolated directly from the estimated parent wind speed. This observation is similar to that made between the interpolation of the extreme Gumbel parameters and the estimated extreme wind speed. Note that return periods greater than 1 year are shaded in Table 3 as estimates from extreme value distributions are more commonly used at these return periods.

Table 3. Estimated wind speeds (m/s) from Parent Distribution based on each interpolation method.

	Estimated Wind Speed (m/s) from Parent Distribution					
	From Interpolated Parameters			From Interpolation of $V_{RP,p}$		
Return Period	Start	Mid	End	Start	Mid	End
Week	10.3	10.4	9.8	10.7	10.3	9.9
Month	12.9	12.9	12.1	13.3	12.8	12.2
1 Year	16.6	16.6	15.9	16.7	16.4	15.7
10 Year	19.5	19.4	19.2	19.4	19.6	19.1
50 Year	21.4	21.2	21.2	21.2	21.6	21.3
100 Year	22.2	21.9	22.1	22.0	22.5	22.2

5. DISCUSSION

Wind loading codes do not typically provide corresponding directionality information with design wind speeds. However, there is often a reduction factor available to account for the probability that the design wind speed may not align with the structural direction resulting in the greatest loads; this is often in the range of 0.8 – 0.9, depending on the structure. However, some structures, such as transmission lines, are quite directionally-sensitive when considering wind loading. This is due to the fact that the conductor wires often account for the majority of the load, and only accumulate load in the transverse direction (i.e., wind component perpendicular to the wires). Currently, no reduction in wind loading due to directionality is recommended in most design codes (e.g., ASCE Manual No. 74 (ASCE 2010)). This may be related to the fact that lower load factors may be used for these types of structures than those for occupied buildings.

However, the dominant wind directions expected for transmission line route may be of interest to designers. Based on the analysis in Section 4, the relative importance of wind directions (as related to a wind speed at a particular return period) can be calculated. Relative importance plots of the wind directions associated with a 50-year return period are shown for each of the tower checkpoints in Figure 6. The route directions of the hypothetical transmission line are superimposed on the plots, showing that the expected wind characteristics at each tower checkpoint are fairly directional. It is also shown that the probability of a 50-year wind intersecting the transmission line route at

90° (i.e., full loading of the conductor wires) is lower for Span 1 (Start Tower to Mid Tower) than for Span 2 (Mid Tower to End Tower). While any sort of reduction in design wind load would have to be carefully considered along with the load factor in use for a particular distributed system, this information would also be useful for integrating the variability of local wind conditions with a capacity model (e.g., Mara and Hong 2013) for the purposes of a higher-order reliability analysis of a point structure or system. The probability distributions developed at any number of tower checkpoints along the length of the route could serves as the loading input into such an analysis.

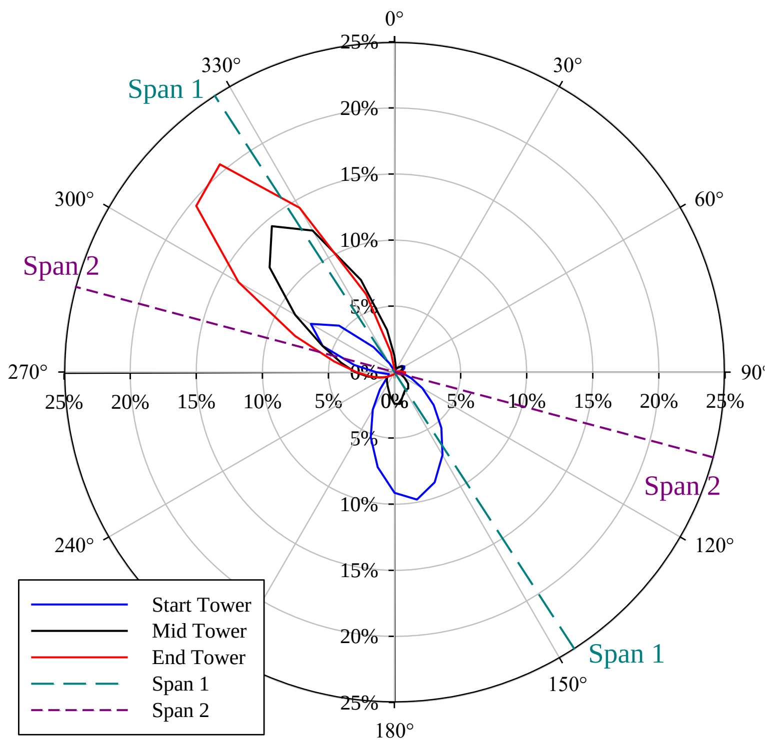


Figure 6: Relative importance plot for 50-year winds for winds at different points along transmission line.

While the hypothetical transmission line used in this paper only had a single change in path, the approach may be extended to more complex paths (i.e., avoiding an obstacle), with an number of tower checkpoints along the line. An example of a transmission line with a more complex path is shown in Figure 7. As it could be assumed that each line starts and ends in similar locations, the analyses along each route option could also be compared and considered in the selection of the final transmission line. Aspects such as separation distance and importance of redundancy should also be considered when performing route comparisons such as this, but are beyond the scope of this paper.

6. CONCLUSIONS

Probability distributions describing the wind speed and direction at various points along a distributed system (i.e., hypothetical transmission line route) were interpolated based on a set of standardized historical wind data for a number of stations across a defined spatial area. The wind speeds were estimated based on both an extreme value distribution (Type I) and the parent distribution (bi-modal Weibull). For each distribution, interpolation was carried out for the estimated wind speeds as well as the underlying statistical parameters. These values were compared, and the two interpolation methods yielded similar results. The estimated wind speeds from the extreme value analysis were greater in magnitude, as would be expected, compared to those from the parent distribution. While extreme value analysis has historically been used to set a magnitude for design wind speeds, information from the parent distribution can be used to identify dominant wind directions for a given area or estimates of wind speeds for lower return periods. This information may be useful to designers if considering directionally-sensitive structures, higher-order reliability assessment, or response to wind under serviceability conditions.

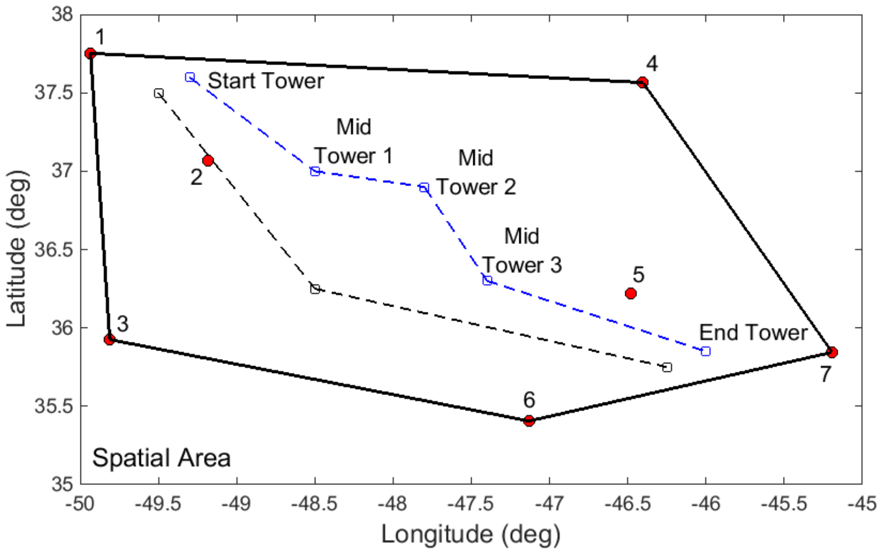


Figure 7: Example plot of more complicated transmission line path to traverse an obstacle.

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