Sub-Regional Variability in Wind Turbine Blade Leading-Edge Erosion Potential

F Letson¹, R J Barthelme² and S C Pryor¹

¹Department of Earth & Atmospheric Sciences, Cornell University, Ithaca, NY 14853, USA
²Sibley School of Mechanical & Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA
E-mail: fl368@cornell.edu, sp2279@cornell.edu

Abstract. Leading Edge Erosion (LEE) of wind turbine blades leads to significant degradation of aerodynamic performance. Previous research has suggested kinetic energy transferred to the rotating blades from hydrometeor impacts is an important source of LEE. The Southern Great Plains (SGP) of the United States has substantial wind energy development and experiences a high frequency of heavy rain and hail that contribute to atypically high LEE potential. The current study quantifies the degree to which the drivers of LEE exhibit sub-regional variability across a 500,000 km² area of the SGP. The analysis uses five years of data from nine RADAR stations to characterize the precipitation climate and wind speeds from ERA5. The results illustrate strong spatial gradients in all three atmospheric drivers of LEE: (i) Frequency of power producing wind speeds. (ii) Occurrence of intense precipitation. (iii) Occurrence of hail and maximum hail size. For example, annual precipitation varies by a factor of 10 across Texas and the prevalence of hail events ranges from hundreds of 5-minute events per year to nearly zero. Northwestern Texas has high wind turbine installed capacity and high joint probability of hail and/or heavy precipitation and power-producing wind speeds.

1 Introduction
Leading Edge Erosion (LEE) of wind turbine blades leads to significant degradation of aerodynamic performance, energy losses [1], and potentially costly repair and replacement [2]. Previous research has shown that kinetic energy transferred to the rotating blades from hydrometeor impacts is an important source of material stress and LEE [3-6]. Wind turbine blades are constructed of composite materials, with coatings to protect the structure from environmental stresses [7]. These coatings are subject to material fatigue from kinetic energy transferred by hydrometeor impacts. The amount of kinetic energy transferred is a function of; the closing velocity (terminal fall velocity of hydrometeors, wind speed and rotational speed of the blade) and hydrometeor size and phase. The accumulated energy transfer is determined by the marginal and joint probability distributions of extreme precipitation and wind speed. In some environments hail (and to a lesser extent large rain drops) dominate the total annual accumulated kinetic energy transfer. As much as 300 J of energy may be transferred by impacts from hailstones with diameters in excess of 20 mm [8]. Such impacts may be sufficient to exceed the threshold energy (72 - 140 J [9]) required to damage blade coatings in a single event [4]. The implication is that areas with a high prevalence of deep convection and hail (such as the US Southern Great Plains; SGP) [10] may exhibit atypically high risk of LEE [11]. The deep convection responsible for extreme (heavy) rainfall and hail production is both highly episodic and manifest at micro-α to meso- scale (0.1 to 100 km). Thus LEE may also exhibit substantial sub-regional variability.
The current study assesses the frequency and severity of rain, hail and concurrent wind speeds (i.e., the atmospheric drivers of LEE) as well as their spatial variability across an area of the SGP with frequent deep convection and substantial wind energy development (~500,000 km²; Figure 1). Using publicly available dual polarization Doppler RADAR data, and output from a high-resolution reanalysis product, the joint statistics of wind, rain and hail are used to compute kinetic energy of hydrometeor impacts and thus develop an erosion climatology.

2 Data and Methods

The key innovation of this research is that we are seeking to integrate data from multiple RADAR with the reanalysis-derived wind speeds close to wind turbine hub-heights to generate a spatially consistent, gridded description of the drivers LEE potential at the regional scale. The analysis methodology employs precipitation data from nine RADAR stations in Texas and Oklahoma over a five-year period (2014-2018; Figure 1). As in our previous research [4], precipitation rate and hail occurrence are determined from RADAR data products.

Wind speeds are a key driver of LEE potential, as they determine blade tip speeds, which dominate the closing velocity of the blade with hydrometeors. Tip speeds increase with blade length and the rotor speed and thus are maximum at rated wind speeds and above [4]. Doppler RADAR systems deployed in the National Weather Service network are not primarily designed to accurately capture low to moderate wind speeds. Thus, hourly wind speeds at 100-m a.g.l. (i.e., near WT hub-heights) \( (U) \) at a spatial resolution of 30 km by 30 km are drawn from ERA5 reanalysis [12]. ERA5 outperforms previous reanalysis data sets for wind energy applications and has a higher spatiotemporal resolution than both ERA-interim and MERRA-2 [13, 14], making it more appropriate for use in the current research.

Precipitation (rain and hail) are characterized by observations from nine dual-polarization S-band RADAR (data available from https://www.ncdc.noaa.gov/data-access/radar-data). Hail and rainfall are characterized by two RADAR data products (each with a spatial resolution of 1° azimuth by 1 km):
(1) Precipitation rate (N1P) in mm hr$^{-1}$ derived directly from RADAR reflectivity which is strongly linked to hydrometeor size and concentration [15]. Precipitation rates are reported approximately every five minutes depending on precipitation conditions. Highest rainfall rates are associated with larger rain droplet diameters [16].

(2) Hail reports (NHI). The presence and characteristics of hailfall are determined using the Hail Detection Algorithm, which operates based on reflectivity, aspect ratio of hydrometeors (determined by the dual-polarization system), vertically-integrated liquid water content, and altitude of the melting layer [17, 18]. Hail reports are issued every 5 minutes when there are hail producing storms within the RADAR observation radius. Those reports include storm cell location, probability of hail, and maximum estimated hail size (MESH which is the 75th percentile hail stone diameter, $D_{75}$).

Output from ERA5 is hourly at the top of the hour and represents a single model integration time step of approximately 15 minutes. Thus RADAR-based hail and rainfall rates are sampled for the time period closest to the beginning of each hour. Additionally, the RADAR data are resampled in space to the 30 km by 30 km spatial resolution used in ERA5 (Figure 2). Thus, the spatial mean of the five-minute output of the mean rainfall rate ($RR$) from the RADAR in each ERA5 grid cell is taken as representative for each hour. Hail is characterized hourly for each grid cell by the total number of 5-minute hail reports and the maximum $D_{75}$ recorded during the hour. Annual total precipitation amounts and rates, hail reports, wind speeds and their joint statistics are reported below.

Since previous research suggests the total kinetic energy transferred to the WT blades from hydrometeor impacts is dominated by hail [4], herein we focus on kinetic energy transferred to the WT blades from hail impacts. The impact energies are calculated as follows [4]: For $D_{75}$ up to 50 mm, a single-parameter exponential distribution is used to describe the size distribution of hail [19], and the total kinetic energy of impacts expected per m$^2$ of blade leading edge is calculated by
summing the kinetic energy contribution for all hailstone sizes (up to the limit of twice the $D_{75}$ value). Periods of $D_{75} > 50$ mm are not modelled, as the form of the single-parameter hailstone size distribution is empirically derived using only hail events with smaller $D_{75}$. Kinetic energies are calculated using hydrometeor mass (based on radius and a density of 900 kg m$^{-3}$), and a vector sum of wind speed, terminal velocity and blade tip velocity ($f(U)$). Blade tip speeds are used because the tip is the area which experiences the most impact energy and thus highest erosion potential. Tip speeds are estimated based on the design characteristics of the NREL 5 MW turbine, which has a cut-in wind speed of 4 ms$^{-1}$ and a tip speed of 80 ms$^{-1}$ at its rated winds speed of 12 ms$^{-1}$ [20, 21].

3 Results and discussion

Long-term mean wind speeds vary across the study domain and indicate excellent wind resource (annual mean wind speeds at 100 m a.g.l. > 7 ms$^{-1}$; Figure 3a) in the areas in the north-west of the domain where there is most wind energy installed capacity (Figure 1). The south and east of the domain show annual mean wind speeds at 100 m a.g.l. below 5 ms$^{-1}$ (Figure 3a). Wind speeds at or above rated (12 ms$^{-1}$) occur with a frequency of between 8 and 12 % in the northwest (Figure 3b). If precipitation falls during these periods the high tip speeds mean potential erosion will be at a maximum.

Figure 3. (a) Annual mean wind speed at 100-m from ERA5 (2014-2018) and (b) fraction of hours with U>12 ms$^{-1}$.

Annual rainfall totals vary between 300 and 1000 mm and are positively correlated in space with highest mean wind speeds and highest frequency of 100-m a.g.l. wind speeds close to the rated speed of the NREL 5 MW turbine (Figure 4a). Heavy rains (defined here as $RR > 5$ mm hr$^{-1}$) occur between 0.02% and 1% of the time across the domain. The cells with the most frequent heavy rain are in areas of wind energy development and overlap with the areas of highest total precipitation (Figure 4a&b). Since dust and insects can accumulate on blade leading edges between rains, and also cause aerodynamic losses [22], the mean time between significant rains ($RR > 5$ mm hr$^{-1}$), is also of interest to aerodynamic losses. These dry periods have an average duration from 100 to 1000 hours in the northwest of the domain where wind turbines are prevalent, and the mean is frequently > 1000 hours in drier areas of the domain, such as the south (Figure 4c).
Figure 4. RADAR-based (a) mean annual precipitation total (mm) (b) fraction of hours with RR > 5 mm hr\(^{-1}\) (c) mean number of hours between heavy rains (RR > 5 mm hr\(^{-1}\)).

Each 30 km × 30 km grid cell in the domain contains 50 to 500 5-minute hail reports per year with the cells in the northwest of the domain being more hail prone than others (Figure 5a). When only severe hail events (with \(D_{75} > 25\) mm) are considered, the peak cells contain ~75 5-minute events per year, and their locations overlap with the cells with largest total number of hail reports. Hail events are also highly seasonal. The total number of hail reports within a stations 230-km radius varies from near zero during winter months, to 20,000 to 25,000 during summer (Figure 6), when deep convection is more common.

Figure 5. – RADAR-based estimates of (a) Annual mean number of hail events and (b) Number of annual hail reports with \(D_{75} > 25\) mm.
Since the two dominant atmospheric drivers of LEE are wind speed (rotor rotational speed) and hydrometeor terminal fall velocity and mass [4], the joint statistics of precipitation and wind speed are critical to understanding the frequency of potentially erosive events. Joint histograms of wind speed with each precipitation parameter (total hail reports, \( D_{75} \) and \( RR \)) based on data from all grid cells are shown in Figure 7. Wind speeds from ERA5 clearly conform to a Weibull distribution (Figure 7), and most frequently fall in the wind speed range for which WT rotor speed is variable for the NREL 5MW, and indeed for most wind turbines (4-12 ms\(^{-1}\)). Accurate wind speeds in this range are especially relevant to estimates of LEE potential. Once \( U > 12 \) ms\(^{-1}\), blade rotational velocities are constant (up to cut-out), and at their maximum. Heavy precipitation events for wind speeds in this range are uncommon but critical to LEE, since these periods contain both a larger total mass of rain and a much larger number of large raindrops [16].

Frequencies shown in Figure 7 describe the total number of ERA5 grid cells in all hours that occupy a certain class of \((RR, U)\), and are thus referred to as cell-hours. For large numbers of cell-hours per year, wind speeds from ERA5 indicate a typical wind turbine would be at rated speed during both heavy precipitation (i.e. \( RR > 20 \) mm hr\(^{-1}\)) and/or there was hail (including times when \( D_{75} > 80 \) mm) (Figure 7b,c). Since these joint histograms represent the domain totals, and the northwestern area of the domain (with the greatest wind energy development), has a more frequent occurrence of high winds, heavy rain and severe hail than other areas of the domain (Figures 3, 4 and 5), it is nearly certain that severe joint events are more likely at wind farm locations than Figure 7 would indicate.

As described above, hail may be a particularly important driver of WT LEE. In the current study, LEE potential from hail occurs primarily at \( D_{75} > 25 \) mm and \( U > 10 \) ms\(^{-1}\) (Figure 8). The decrease in impact energy for \( D_{75} > 38 \) mm is likely an artifact of extending the empirical hailstone size distribution to hailstone sizes which are rarely observed, and which were outside the range used in its development [19]. Kinetic energies shown in Figure 8 are a worst-case scenario for a wind turbine within any given ERA5 grid cell, as the geographic size of any hail-producing storm cell will likely be smaller (~ 10 km in diameter) than the ERA grid spacing [23, 24], and the time scale for serve hail is < one hour [25]. Nevertheless, wind-hail events of this severity occur in the domain during ~4300 cell-hours per year, or a mean of 6 hours in each cell (Figure 7b).
Figure 7. Joint histograms of wind speed at 100-m a.g.l. and precipitation sampled at hourly time steps across all cells in the domain (each N is one cell-hour) (a) number of hail reports vs wind speed (b) maximum D_{75} vs wind speed (c) RR vs wind speed. Note that the color scale is logarithmic.

Figure 8. Leading edge erosion potential, characterized by 5-minute total kinetic energy of impact (J) per unit area of the rotor tip as a function of wind speed (U) and hail size (D_{75}).
4 Concluding remarks

Characterizing the spatial and temporal scales over which the marginal and joint probability distributions of the atmospheric drivers of wind turbine blade leading edge erosion potential vary is important for designing any future geospatial description of wind turbine LEE risk. Here we present data sets appropriate to describe that variability and apply them for a region centered on the Southern Great Plains (SGP). Understanding this variability and the atmospheric context for LEE helps to assign uncertainties in the risk projections and identify the potential for that risk to change under global climate evolution.

The current study shows that the drivers of LEE: wind rain and hail, vary substantially at sub-regional scales (hundreds of km). Over the SGP, areas which experience frequent heavy rain and hail are also those with the best wind resource and the greatest degree of wind development. Thus, the LEE potential over most of the regions with highest installed capacity exceeds the regional mean. There is considerable spatial variability in hail frequency across the study domain. The KMAF RADAR in west-central Texas exhibits considerably higher values than the two southernmost RADAR (Figure 5 and 6). This is consistent with our a priori postulate that LEE potential varies markedly over the SGP. Heavy rainfall and hail occur frequently during power-producing wind speeds (Figure 7). Hail frequency and thus LEE potential also exhibit temporal variability (e.g. at seasonal and interannual timescales, Figure 6).

It is important to note that individual precipitation events, especially hail, may have smaller spatiotemporal extent than can be characterized using disjunct hourly measurements and a spatial discretization of 30 km. Future studies of the geospatial variability in LEE climate, especially in regions where much of the heavy precipitation is driven by deep convection, should be of sufficient resolution to capture this spatial variability in order to avoid underestimation of LEE at wind farm sites. Such research would benefit from use of on-site measurements of precipitation properties and hub-height wind speeds.

Ultimately, long-term goal of this research is to inform wind farm developers and owner/operators about the potential for LEE and inform their decisions regarding various strategies for erosion mitigation, such as application of erosion-resistant coatings [6] or rotor speed curtailment during highly-erosive atmospheric conditions [3]. The relative efficiency of these two strategies critically relies on the frequency with which curtailment would be required and thus the degree to which the erosion potential is concentrated on a few events. For the SGP it appears that curtailment may indeed be variable given that hail dominates kinetic energy transfer and is highly episodic.

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