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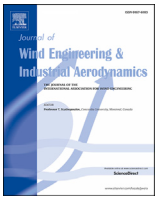

Observed gust wind speeds in the coterminous United States, and their relationship to local and regional drivers

F. Letson [a,*], S.C. Pryor [a,*], R.J. Barthelmie [b], W. Hu [a]

[a] Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, United States
[b] Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, United States

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ABSTRACT

Given the importance of wind gusts to structural design and the economic and ecological impacts of extreme winds, there is a need for better understanding of the spatial variability of wind gusts. Sonic anemometer wind measurements at 10-m a.g.l. from 801 US National Weather Service Automated Surface Observation System sites are used to characterize gust climates across the coterminous United States. These data indicate substantial regional and sub-regional variability across a range of gust metrics. For example, the locally-determined 95th percentile gust values exceed 16.46 ms^{-1} at most sites throughout the central plains, but are below 14.40 ms^{-1} throughout almost all of the southeastern stations. When site-specific gust metrics are conditionally sampled by the likelihood of deep convection and frequency of extra-tropical cyclones, the results indicate that gust factors tend to be lower in regions with higher convective potential, and higher in areas with a higher frequency of extra-tropical cyclones. Conversely, 1 and 10-year return period gusts are higher in the region with high convective potential, but do not exhibit consistently higher values in regions with a high frequency of extra-tropical cyclones. Terrain complexity and higher surface roughness are also found to increase gust factors but not absolute gust magnitudes.

1. Introduction and motivation

Near-surface intense sustained and gust wind speeds are caused by high momentum air being brought towards the surface (due to vertical wind shear (non-convective) or buoyancy (convective) effects). The driving phenomena associated with high-magnitude wind events (including extreme near-surface wind gusts) span many scales and include; intense extra-tropical cyclones (and frontal activity therein) (Changnon, 2011), boundary-layer turbulence (generated by shear due to rough/inhomogeneous terrain/land cover) (Sheridan, 2011), deep convection (Choi and Hidayat, 2002; Orwig and Schroeder, 2007), and topographic-flow interactions (Changnon, 2011) including mountain waves and wake phenomena (Clark and Farley, 1984).

Intense and extreme wind gusts may represent a hazard to aviation (Young and Kristensen, 1992), can cause damage to forests (Meyers et al., 2003) and lead to failures of the electricity distribution network (particularly when coupled to ice accumulation) (Sinh et al., 2016). Extreme wind events (including gusts) are also a leading cause of property damage (Della-Marta et al., 2010). In the period from 1952 to 2006 there were an average of 3.1 wind events in the United States each year with damage exceeding 25 million dollars. The average total cost of these wind events was 354 million dollars per year (Changnon, 2009). Intense winter winds in the Northern Hemisphere have exhibited an increase in severity since 1950, and the physical mechanism behind this increase, particularly with regard to modification of extra-tropical cyclones (a major driver of winter winds) is poorly understood (Ma and Chang, 2017; Vose et al., 2014).

The force exerted by wind on an object is proportional to the square of wind speed, thus correctly identifying the peak wind speeds to which a structure will be subjected is critical to the design of buildings, bridges (ASCE, 1998) and wind turbines (IEC, 2005; Suomi et al., 2013). Underestimates of extreme gusts could lead to structural failures, while overestimates may result in costly over-design.

Design standards typically call for the calculation of an extreme sustained or gust wind speed with a specific return period (1 and 50 years in the case of the wind turbine design standards (IEC, 2005)). Estimation of these extreme events (i.e. the magnitude of wind speed or gust expected to be met or exceeded once during the specified time interval) (Gomes and Vickery, 1978) is frequently undertaken by fitting an extreme value distribution to monthly or annual maxima from site-specific

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* Corresponding authors.
E-mail addresses: fl368@cornell.edu (F. Letson), sp2279@cornell.edu (S.C. Pryor).

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measurements or model output (Staid et al., 2015), or by referring to a reference map (such as the ASCE 7 gust map (Peterka and Shahid, 1998), available at http://windspeed.atcouncil.org/). Among other causes, estimation of long-return period extreme values through distribution fitting has increased uncertainty when:

(i) Applied to short observational records. Some past analyses have sought to minimize the impact of short observational data records by aggregation of data from multiple sites into regional 'superstations' (e.g. the peak gust map associated with the American Society of Civil Engineers (ASCE) standards for buildings and structures (ASCE, 1998; Vickery et al., 2009)). This technique reduces statistical uncertainty, due to the long synthetic record length available at each superstation, but also has the effect of smoothing out local variations in the wind climate (Simiu et al., 2003).

and/or

(ii) The measurement records inaccurately represent gust magnitudes. A key limitation of past analyses in the coterminous US (CONUS) was reliance on measurement records from cup anemometers. The slow (dynamic) response of a cup (or propeller) anemometer to a wind speed change can lead to an underestimate of the peak gust (Beljaars, 1987). A cup anemometer can only measure 71% of the magnitude of fluctuating eddies with a length scale of $2\pi\lambda_d$ and less for smaller eddies (Brock and Richardson, 2001). A short distance constant (where the distance constant (λ_d) is the distance the wind travels before the anemometer reaches 63.2% of a step change in wind speed) can be achieved by having low inertia which is usually accomplished by reducing the distance between the cups and the rotating shaft (Emeis, 2010). Nevertheless, measurement bias will remain. Conversely, a sonic anemometer measures the travel time of an acoustic signal over a fixed path between a pair of transducers oriented into different directions to measure the three components of wind velocity (and virtual temperature) at high frequency (10–50 Hz, Kochendorfer et al. (2012)) and high fidelity (Coquilla et al., 2010), thus permitting detailed description of gusts. The ability of sonic anemometers to accurately measure changes in wind direction and gusts, the resistance to mechanical failures and the availability of heated models to prevent icing, spurred the US National Weather Service (NWS) to change all Automated Surface Observation Systems (ASOS) to ice-free, 2-D sonic anemometers during the early 2000's.

and/or

(iii) When the wind climate at the site in question includes extreme wind speeds resulting from more than one driving mechanism. This is referred to as a 'mixed climate'. In this case, the distribution of extremes may converge slowly, or not converge to a distribution which actually represents the wind climate at the site (Cook et al., 2003; Gomes and Vickery, 1978). The approach being taken by the National Institute for Standards and Technology (NIST) treats thunderstorm winds separately from non-thunderstorm winds and fits extreme-value distributions to each. When tested using wind speed observations from three ASOS stations near New York City, thunderstorm winds were found to dominate when predicting peak gusts with very long return periods (50–500 years and greater). When compared to this method of thunderstorm separation, fitting a single, Gumbel type distribution to the mixed set of thunderstorm and non-thunderstorm extremes (the method used in the current analysis) was found to be unconservative, but only marginally so (Lombardo et al., 2009). NIST is also in the process of producing a map of non-tornadic extreme winds with return periods of 10–100,000 years using ASOS data largely from before the sonic anemometer deployment and application of local, linear regression (Pintar et al., 2015).

While some of these challenges are difficult to completely overcome, modernization of the NWS ASOS network (Fig. 1) to include sonic anemometers provides an opportunity to investigate gust climate in CONUS with relatively high fidelity and spatial resolution and to explore regional variability in the mechanisms responsible for wind gusts. Here we use these data to characterize variations in wind gusts and gust factors across CONUS, and relate them to the local and regional climate and landscape (see Fig. 1). In section 2 we briefly summarize the gust climatology derived based on these data and in section 3 we describe the variation of gust statistics conditionally sampled by descriptors of regional and local drivers of the wind climate. We conclude in section 4 by contextualizing our results and discussing some of the research caveats and limitations.

2. Gust conditions across CONUS

2.1. Data and methods

Site-specific wind conditions are characterized herein using wind speed measurements at 10-m (at 651 stations) or 8 m (at the remaining 189 station) above ground level (a.g.l.) from the 5-minute ASOS data set (NOAA, 2016) in which sustained wind speeds ($\overline{U}$) and gusts (*gust*) are recorded with a resolution of 1 knot (0.514 ms^{-1}) are rounded *up* to the nearest knot (data available at; ftp://ftp.ncdc.noaa.gov/pub/data/asos-fivemin/; m). Gust events in the ASOS database are 3-second maxima, reported in each 5-minute period when the gust criteria are met. The ASOS algorithm calculates a 2-minute average of 3-second averages every minute. A gust is reported when the 3-second maximum wind speed exceeds the current 2-minute average by 3 knots or more, exceeds the minimum 3-second average in the last 10 min by at least 10 knots and the current 2-minute average wind speed is at least 3 knots (see ASOS User's Guide (Nadolski, 1998; NOAA, 2004)). ASOS stations examined herein record wind gust events for between 0.6% and 41% of 5 min periods with a median reporting rate for gusts of 13%.

The ASOS records used herein are subject to QA/QC prior to being placed in the data archive, but were subjected to three additional quality assurance tests before being used in the current study. These tests are designed to remove erroneously high gust events which may be reported

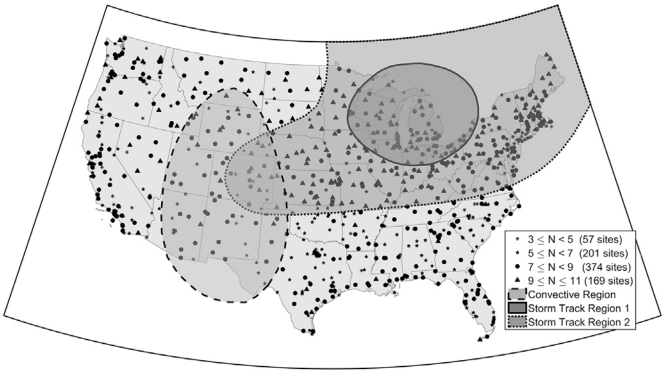

Fig. 1. ASOS site locations and regions used in the analyses. The symbol for each site indicates the number of years of sonic anemometer data (post sonic deployment through 2015) available at that site, N. The shaded states represent areas of high extra-tropical cyclone frequency. Storm track region 1, with the largest cyclone frequency, is the darkest gray. Storm track region 2 is shown in medium-gray. Storm track region 3 (the remainder of CONUS, excluding Storm Track Regions 1 & 2) is the region with the smallest likelihood of extra-tropical cyclones and is shown in the lightest gray (Bengtsson et al., 2006; Eichler and Higgins, 2006). The black, dashed oval outlines the region where deep convection is expected to be a major cause of wind gusts (Aires et al., 2014; Tawfik et al., 2015).