FORECASTERS’ FORUM

Maximum Wind Gusts Associated with Human-Reported Nonconvective Wind Events and a Comparison to Current Warning Issuance Criteria

PAUL W. MILLER

Department of Geography, The University of Georgia, Athens, Georgia

ALAN W. BLACK

IIHR–Hydroscience and Engineering, The University of Iowa, Iowa City, Iowa

CASTLE A. WILLIAMS AND JOHN A. KNOX

Department of Geography, The University of Georgia, Athens, Georgia

(Manuscript received 3 September 2015, in final form 31 December 2015)

ABSTRACT

Nonconvective high winds are a deceptively hazardous meteorological phenomenon. Though the National Weather Service (NWS) possesses an array of products designed to alert the public to nonconvective wind potential, documentation justifying the choice of issuance thresholds is scarce. Measured wind speeds from the Global Historical Climatology Network (GHCN)-Daily dataset associated with human-reported nonconvective wind events from Storm Data are examined in order to assess the suitability of the current gust criteria for the NWS wind advisory and high wind warning. Nearly 92% (45%) of the nonconvective wind events considered from Storm Data were accompanied by peak gusts beneath the high wind warning (wind advisory) threshold of 58 mi h\(^{-1}\) (25.9 m s\(^{-1}\)) [46 mi h\(^{-1}\) (20.6 m s\(^{-1}\))], and greater than 74% (28%) of all fatal and injury-causing events were associated with peak gusts below these same product gust criteria. NWS wind products were disproportionately issued in areas of complex terrain where wind climatologies include a greater frequency of high wind warning threshold-level gusts, irrespective of observed impacts. For many areas of the eastern United States, a 58 mi h\(^{-1}\) (25.9 m s\(^{-1}\)) gust of convective, tropical, or nonconvective origin falls within the top 0.5% of all observed daily maximum wind gusts, nearly eliminating the possibility of a nonconvective gust meeting the issuance criterion.

1. Introduction

Hazardous high winds can be generated by a number of meteorological mechanisms including thunderstorms and tropical cyclones. However, the steep gradients of surface atmospheric pressure responsible for windstorms can also be generated by extratropical cyclones and even terrain differences [e.g., downslope and gap winds; Knox et al. (2011)]. In these instances, winds are termed nonconvective and may occur without the presence of clouds or precipitation. Nonconvective winds tend to occur across larger spatial and temporal scales and produce a more homogeneous wind field as compared to winds associated with thunderstorms or tornadoes (Lacke et al. 2007; Ashley and Black 2008; Pryor et al. 2014).

The National Weather Service (NWS) possesses an array of products designed to communicate the risk of hazardous nonconvective winds to the public. Such products include the somewhat familiar “wind advisory” and “high wind warning,” as well as a multitude of marine/coastal wind products (e.g., lake wind advisory, small craft advisory for winds, brisk wind advisory, gale warning, storm warning, hurricane force wind warning) and an additional suite of products tailored for specific circumstances in which wind is one of several criteria (e.g., dust storm warning, blizzard warning, etc.). The issuance criteria for wind advisories and high wind

Corresponding author address: Paul Miller, Dept. of Geography, The University of Georgia, Rm. 204, 210 Field St., Athens, GA 30602. E-mail: paul.miller@uga.edu

DOI: 10.1175/WAF-D-15-0112.1

© 2016 American Meteorological Society
Table 1. Issuance criteria for NWS wind advisories and high wind warnings [mi h⁻¹ (m s⁻¹)] (National Weather Service 2015a).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wind advisory</th>
<th>High wind warning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained</td>
<td>25–39 (11.2–17.4)</td>
<td>≥40 (17.9)</td>
</tr>
<tr>
<td>Gust</td>
<td>46–57 (20.6–25.5)</td>
<td>≥58 (26.0)</td>
</tr>
</tbody>
</table>

Warnings can be achieved by either sustained winds or wind gusts (Table 1).

Though the justification for the wind speed thresholds used to define a wind advisory and high wind warning is unknown, other details of the products’ histories are more certain. As part of the NWS modernization during the early 1990s, the agency significantly restructured the format (S. Nelson, NWS Peachtree City, 2015, personal communication) and variety (National Weather Service 2015b) of the weather products that it issued. This expansion led to the development of the “nonprecipitation” weather products, including the wind products mentioned above (National Weather Service 2015b). Following an exhaustive review of sources documenting the modernization, including an exchange with the NWS director who oversaw the modernization program (J. Friday, NWS, 2015, personal communication), an explanation for the wind speed criteria could not be discovered.

In the absence of clear documentation, the issuance criteria’s origins can only be speculated upon. The thresholds may possibly be based upon wind speeds believed to affect the 1950s aviation industry, or the wind force category of the Beaufort scale associated with tree failure. For example, the high wind warning gust threshold of 58 mi h⁻¹ (25.9 m s⁻¹) is identical to the NWS threshold used to define severe wind gusts from thunderstorms. According to Galway (1989), this selection was influenced by the U.S. Air Force’s use of 58 mi h⁻¹ (25.9 m s⁻¹) as the lower limit of their severe thunderstorm wind gust definition. The 58 mi h⁻¹ (25.9 m s⁻¹) threshold may simply have been carried over from thunderstorm to nonconvective wind products within the NWS.

However, the application of aviation thresholds to the warning criteria for nonconvective wind products may not be appropriate. In the United States, nonconvective winds kill an average of 24 people annually (Ashley and Black 2008), but Black and Ashley (2010) found no deaths from nonconvective wind-related aviation crashes from 1977 to 2007. As such, any nonconvective wind product threshold should originate in observed impacts among the general population. Since these wind speed thresholds determine whether the NWS alerts the public of dangerous weather conditions via a wind advisory or high wind warning, it is important that the thresholds actually capture the wind speeds that lead to losses. The goal of this research is to identify the wind speeds that result in nonconvective losses, and assess the suitability of wind advisory and high wind warning gust thresholds. It is hoped that this research will initiate a discussion about the suitability of the current NWS wind advisory and high wind warning criteria, ultimately serving to improve their utility and reduce nonconvective wind losses.

2. Data

Two datasets were used extensively in this analysis, performed using data from the period 1996–2013 for the continental United States. The first dataset, the Storm Events Database (National Centers for Environmental Information 2015), contains the records used to create the official Storm Data publication, which is our second dataset. The Storm Events Database and Storm Data are maintained by the National Centers for Environmental Information (NCEI) and catalog the occurrence of severe, hazardous, or unusual weather of many types across the United States. The Storm Data publication compiles nonconvective wind events beginning in 1959, but records have only been digitized within the Storm Events Database for the period from 1996 to the present. Commonly used in severe weather research, Storm Data and the Storm Events Database are the most comprehensive datasets for hail, thunderstorm wind, and tornadoes, although they have also been applied to other weather hazards such as fatal lightning strikes (López et al. 1995; Ashley and Gilson 2009), blizzard climatologies (Schwartz and Schmidlin 2002), and nonconvective wind fatalities (Ashley and Black 2008), among others. Storm Data and the Storm Events Database contain measured and estimated reports from a number of sources [e.g., Automated Surface Observing System (ASOS) data, trained spotters, the general public, or social media]. However, researchers have criticized both sources for documented errors in the times and locations given for severe weather events (e.g., Witt et al. 1998a,b; Williams et al. 1999; Trapp et al. 2006), as well as for the underreporting of fatalities (López et al. 1993; Black and Mote 2015).

Nonconvective winds can appear under a number of categories within a Storm Data publication (Ashley and Black 2008), especially prior to the 2005 issuance of NWS directives on Storm Data that standardized many meteorological event categories (National Oceanic and Atmospheric Administration 2007). However, nonconvective wind reports in the Storm Events Database for the 1996–2013 period have been standardized in accordance with these instructions,
eliminating the need for a subjective analysis to determine which events are nonconvective in nature, as in Ashley and Black (2008). Within the Storm Events Database, nonconvective wind events are categorized as either “high wind” or “strong wind,” and these events were extracted for our analysis. For the sake of consistency with other studies that use hazardous weather event data from Storm Data, we refer to the data extracted from the Storm Events Database as Storm Data hereafter.

Theoretically, the values within Storm Data’s magnitude field can be analyzed to discern the strength of the wind gusts that trigger significant wind events. However, the distribution of Storm Data wind magnitudes clearly indicates a systematic trend in the entry method that would bias any analysis (Fig. 1). The spikes in Fig. 1a at 45–47.4 mi h$^{-1}$ (20.1–21.2 m s$^{-1}$) and 57.5–59.9 mi h$^{-1}$ (25.7–26.8 m s$^{-1}$) correspond to the default minimum NWS gust thresholds for wind advisory and high wind warning criteria (Table 1), respectively. For this reason, daily wind observations were retrieved from NCEI’s Global Historical Climatology Network (GHCN)-Daily dataset (Menne et al. 2012b). GHCN stations that measure wind observations can provide the data in a variety of formats (Table 2). For this study, only the AWND, WSF1, WSF2, WSF5, WSFG, and WSFI measurements were considered (refer to Table 2 for an explanation of these acronyms). Data from GHCN stations is quality controlled by NCEI (Menne et al. 2012a) and can be considered more reliable than estimates based on human judgments despite their spatial displacement from where the report may have originated. Given the synoptic scale of these nonconvective wind events, nearby GHCN stations can

TABLE 2. Daily GHCN station wind products, their codes, explanations, and units.

<table>
<thead>
<tr>
<th>Measurement code</th>
<th>Explanation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWND</td>
<td>Avg daily wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
<tr>
<td>WDF1</td>
<td>Direction of fastest 1-min wind</td>
<td>°</td>
</tr>
<tr>
<td>WDF2</td>
<td>Direction of fastest 2-min wind</td>
<td>°</td>
</tr>
<tr>
<td>WDF5</td>
<td>Direction of fastest 5-s wind</td>
<td>°</td>
</tr>
<tr>
<td>WDFG</td>
<td>Direction of peak wind gust</td>
<td>°</td>
</tr>
<tr>
<td>WDFI</td>
<td>Direction of highest instantaneous wind</td>
<td>°</td>
</tr>
<tr>
<td>WDFM</td>
<td>Fastest mile wind direction</td>
<td>°</td>
</tr>
<tr>
<td>WDMV</td>
<td>24-h wind movement</td>
<td>km</td>
</tr>
<tr>
<td>WSF1</td>
<td>Fastest 1-min wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
<tr>
<td>WSF2</td>
<td>Fastest 2-min wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
<tr>
<td>WSF5</td>
<td>Fastest 5-s wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
<tr>
<td>WSFG</td>
<td>Peak gust wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
<tr>
<td>WSFI</td>
<td>Highest instantaneous wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
<tr>
<td>WSFM</td>
<td>Fastest mile wind speed</td>
<td>1/10 m s$^{-1}$</td>
</tr>
</tbody>
</table>

FIG. 1. Histograms of (a) Storm Data reported gusts for the 17,151 events that included a magnitude value and (b) GHCN-Daily peak gust measurements for the same events shown in (a).
offered a reasonable depiction of the intensity of an event. Comparing the histograms of GHCN maximum gusts versus Storm Data reported gusts shows that the GHCN observations create a smoother, fuller, and more symmetric histogram than do the Storm Data magnitudes (Fig. 1b). For this reason, Storm Data results are used only to provide the date and forecast zone for which a nonconvective wind event occurred, with the actual magnitude of the wind coming from the GHCN-Daily dataset.

3. Methods

GHCN wind measurements were paired to Storm Data events with which they coincided temporally and spatially. Each Storm Data event analyzed has information on the date, time, and NWS forecast zone where the high wind occurred. To successfully pair the greatest number of Storm Data events with GHCN gusts, the spatial details of each Storm Data entry were adjusted to reflect a current NWS forecast zone. If the NWS zone had changed during the period of record, other information in the Storm Data entry or narrative was used to determine the equivalent modern-day NWS zone. If multiple GHCN stations existed within the NWS zone, then the Storm Data event was assigned multiple daily wind observations.

There were also data consistency challenges when combining the GHCN wind observations and Storm Data. The time and date of high wind events in Storm Data were recorded in two distinct forms. The first, and most frequent, method treats Storm Data events as temporally continuous with a nonzero duration period (i.e., the begin time does not equal the end time). In these cases, all instances of high wind gusts or damage during the windy period had been aggregated together and given a single narrative and a single representative wind magnitude for the event, resulting in one Storm Data entry for the entire windy period.

The second, less frequent, method (consisting of approximately 6% of events) treats Storm Data events as discrete points in time (i.e., begin time equals end time). The same NWS zone could then appear multiple times within a windy period, with each entry in Storm Data representing an individual instance of a high wind gust in that zone and given its own reported magnitude specific to that instance. This method results in a single windy period having multiple entries in Storm Data, and creates problems for the statistical analysis because the wind observation from a nearby GHCN station would then be unequally represented within the dataset. Thus, any Storm Data events with their NWS zone appearing more than once within a windy period were aggregated into a single event. For each aggregated event, the maximum GHCN-Daily average wind and gust from that zone during the entire period were retained. These aggregated events were not given a “source” since the constituent reports during the windy period often originated from different sources.

After correcting for spatial and temporal issues between the datasets, all Storm Data events were joined to a wind-observing GHCN station within the affected zone, if one existed. GHCN peak gusts could be paired with 17151 Storm Data events. For each pair, the maximum daily wind measurement (i.e., WSF1, WSF2, WSF5, WSFG, and WSFI) recorded by any station within the Storm Data event zone at any time during any day either partially or entirely encompassed by the Storm Data event was extracted. This was driven by the GHCN-Daily archive structure that records only maximum wind gusts on a given day, with the time of the maximum gust rarely included. Thus, the maximum gust on days only partially included in a Storm Data event was assumed to have occurred during the event. Since Storm Data records periods of exceptional weather impact, it is very reasonable to assume that the peak gust for a given day contributed to the event being referenced in Storm Data.

As Fig. 1b indicates, most GHCN peak gust observations fell within reasonable expectations except for 49 gusts that exceeded 100 mi h$^{-1}$ ($44.7$ m s$^{-1}$). Though gusts greater than 100 mi h$^{-1}$ ($44.7$ m s$^{-1}$) are possible, especially given our focus of significant nonconvective high wind events, the integrity of the observations was nonetheless investigated. Upon manual inspection, 38 of these 49 events were recorded at the Mount Washington Observatory in New Hampshire (station ID USW00014755). These observations were judged not to be representative of the wind speeds regularly experienced by humans in the northern New Hampshire area, and all Mount Washington observations were discarded. The other 11 observations originated from 10 GHCN stations but were given no quality flags by NCEI; these observations were allowed to remain in the dataset.

The distribution of GHCN maximum daily gusts (Fig. 1b), though more realistic than the distribution of Storm Data magnitudes (Fig. 1a), displays two curious features. One spike is apparent near, but slightly less than, the wind advisory gust criterion and another is found within the bin exactly capturing the high wind warning gust threshold. This result is interpreted as an artifact of the warning issuance criteria. Even though Fig. 1b is composed of independently recorded GHCN wind observations, NWS employees ultimately choose
when to submit an event to Storm Data. Since many Storm Data entries reference an ASOS, an Automated Weather Observation System (AWOS), a mesonetwork, or an official NWS observation as the source of the report, it is believed that the spike at 57.5–59.9 mi h\(^{-1}\) (25.7–26.8 m s\(^{-1}\)) is a result of automated station observations (which are also recorded in the GHCN network) serving as the “source” for subsequent Storm Data reports. Given that the purpose of this study is to identify the wind speeds at which human activity is impacted, Storm Data reports arising simply from gusts exceeding NWS wind product criteria at these automated stations in the absence of human impact are undesired. Though it is possible that instrument-reported events could have been accompanied by human impacts, the lack of detail in Storm Data’s events descriptions make such a determination difficult. While fewer than half of Storm Data’s events contain an event description, descriptions are more often included for human-reported (45.9%) than for instrument-reported (36.4%) events. Additionally, 71.5% of human-reported events with a description contain words such as “tree(s),” “vehicle(s),” “thrown,” “blown,” “damage,” “power,” etc., whereas only 26.0% of event descriptions from automated stations contain such language. For automated station events, many descriptions simply state that the wind was detected by an instrument [i.e., “Wind gust of 52 knots (60 mph) was measured at ORF”].

Thus, Fig. 1b was reproduced with reports only from human sources.\(^1\) For clarity, these values were still retrieved from GHCN stations (which include ASOS stations), but only if Storm Data cited a human, not an ASOS, as the source of the report. By eliminating “reports” easily accessible to NWS employees through the Advanced Weather Interactive Processing System (AWIPS) display, the influence of policy-related thresholds is expected to be minimized. The large decrease in sample size resulting from the elimination of automated reports is not desirable; however, given the increased likelihood that these entries were prompted by genuine human impacts, this subset will be used throughout the remainder of the analysis.

To summarize, the final dataset consists of 4271 GHCN peak daily wind gusts associated with Storm Data reports that originated from a human source.

\(^1\)Human sources include categories such as trained spotter, law enforcement, emergency manager, public, fire department/rescue, utility company, etc.
Figure 2 provides a schematic of the workflow used to arrive at the final dataset. We now examine the results from this dataset.

4. GHCN peak gust results and discussion

a. Identification of hazardous nonconvective wind speeds

Before any comparisons to NWS thresholds can be made, it is important to thoroughly justify the GHCN peak gust results and relate them to previous research. Figure 3 depicts the distribution of GHCN peak gusts associated with human-reported nonconvective wind events. Without contributions from threshold-driven events, the frequency spike at 57.5–59.9 mi h\(^{-1}\) (25.7–26.8 m s\(^{-1}\)) vanishes, and a clear maximum is evident between 42.5 and 44.9 mi h\(^{-1}\) (19.0–20.1 m s\(^{-1}\)). This feature draws immediate attention as a possible meaningful human wind sensitivity threshold. At first glance, this spike seems to resemble the 58 mi h\(^{-1}\) (25.9 m s\(^{-1}\)) policy-driven relative maximum in Fig. 1b, but the spike from the low to mid-40 mi h\(^{-1}\) (17.9 m s\(^{-1}\)) range falls in a bin less than the 46 mi h\(^{-1}\) (20.6 m s\(^{-1}\)) gust criterion for wind advisories. Thus, it is not readily apparent how this range of gusts might be an artifact of NWS policy. Additionally, the maximum is not a simple reflection of the basic wind gust climatology (see section 4b). Without any justification for discrediting the 42.5–44.9 mi h\(^{-1}\) (19.0–20.1 m s\(^{-1}\)) feature, it is assumed that this represents a physically meaningful maximum of nonconvective wind impact.

The events used to create Fig. 3 can also be examined spatially by plotting them according to the NWS county warning area (CWA) in which they occurred. Figure 4 shows that the human-reported nonconvective wind events are concentrated in the northeastern United States. Meanwhile, the central United States is characterized by a much smaller

![Figure 3](image)

**Fig. 3.** GHCN gusts for the 4271 *Storm Data* events originating from human sources.

**Fig. 4.** Map of human-reported nonconvective wind events from *Storm Data* between 2006 and 2013, coincident with the wind product issuance maps in Fig. 7 and wind climatologies in Fig. 8. Points were randomly placed within the NWS CWA boundary of the WFO that filed the report. Humans report the greatest number of nonconvective wind impacts in forested regions east of the Mississippi River.
density of human reports. CWAs in mountainous regions of the western United States also represent relative maxima of human reports, but the area of contiguous, highly impacted CWAs is smaller than in the eastern United States.

In addition to spatial details, Storm Data also records any known injuries or fatalities. Figure 5 illustrates the distribution of peak wind gusts for nonconvective wind events with which Storm Data documented a direct fatality or injury. While it could be reasoned that wind speeds capable of killing or injuring humans must be substantially stronger than the maximum from the low to mid-40 mi h\(^{-1}\) (17.9 m s\(^{-1}\)) range in Fig. 3, this is not the case. Figure 5a depicts a relative maximum of fatal events between 30 and 34.9 mi h\(^{-1}\) (13.4–15.6 m s\(^{-1}\)), and Fig. 5b exhibits a secondary injury-causing event maximum in the 40–44.9 mi h\(^{-1}\) (17.9–20.1 m s\(^{-1}\)) range. Both the fatal and injury-causing distributions exhibit their absolute maxima in the 50–54.9 mi h\(^{-1}\) (22.3–24.6 m s\(^{-1}\)) bin. Though the distributions of directly fatal and injury-causing events might be marginally shifted toward stronger wind gusts from Fig. 3, it is apparent that significant bodily harm regularly results from nonconvective gust speeds that do not require the issuance of warnings. A theoretical justification for this finding and its precedent in previous research will be the topic of the following discussion.

**b. Physical reasoning for hazardous wind speed distribution**

It is important to theoretically explain the distribution observed in Fig. 3 so that it can be understood why such seemingly weak wind gusts result in frequently observed impacts. It is hypothesized that the range of gusts between 40 and 55 mi h\(^{-1}\) (17.9–24.6 m s\(^{-1}\)), where the frequency of Storm Data events is greatest, represents a middle ground between climatological frequency and the damaging force exerted by the wind. Since weaker wind gusts are more common climatologically (Fig. 6a), their greater frequency increases their likelihood of occasionally producing damage, even if minor. Meanwhile, the force generated by the wind against a surface can be proved proportional to the square of the wind speed based on Newtonian force balances. As the gust speed increases, the climatological frequency decreases [following a maximum between 15 and 20 mi h\(^{-1}\) (6.7–8.9 m s\(^{-1}\)); see Fig. 6a], but the force increases quadratically. Presumably, there is a range of gust speeds that represents the most problematic coincidence of frequency and force. We can show this idea with a simple formula:
Testing this basic conceptual model is straightforward. The entirety of the GHCN-Daily dataset can be used to represent the wind gust climatology curve while the gust’s force can be represented by a simple quadratic curve. Multiplying the two curves yields a hypothetical Storm Data frequency distribution. Figure 6a depicts the two factors in Eq. (1), the product curve, and the

\[ \text{Frequency}_{\text{Storm Data}} \propto \text{Frequency}_{\text{climatology}} \times \text{Force}_{\text{wind}} \]

(1)

Fig. 6. Illustrations of the hypothetical impact calculation for (a) GHCN maximum daily gusts and (b) GHCN daily average wind. From top to bottom, each panel depicts the frequency curve of the 18-yr GHCN wind climatology, the force function, the hypothetical impact distribution resulting from Eq. (1), and the observed distribution from Storm Data events. For simplicity, the y axes are labeled qualitatively since section 4b is only concerned with the shapes of the curves and their positions along the x axes.
observed Storm Data frequency curve for comparison. The width of the hypothesized distribution corresponds well to the observed Storm Data frequency curve. However, the shapes of the distributions are not particularly similar, and the hypothetical distribution is shifted roughly 10 mi h⁻¹ (4.5 m s⁻¹) toward weaker wind speeds.

Another consideration not yet addressed is that nonconvective wind events are usually accompanied by prolonged periods of sustained winds in addition to gusts. If the sustained winds primed the environment for impact and the gusts are simply “the straw that broke the camel’s back,” then Fig. 3 might also be partially reflective of the daily average winds accompanying the gusts. Thus, the same procedure described above was repeated for the GHCN-Daily average wind between 0 and 40 mi h⁻¹ (0–17.9 m s⁻¹; Fig. 6b). (Of the 4271 Storm Data events that were paired with GHCN gusts, 4212 also recorded the average wind.) The shape and width of the average wind hypothetical distribution and Storm Data event distribution are almost identical. However, although the bulk of the distributions align much more closely, the hypothetical curve is still shifted toward slightly weaker wind speeds than the observed distribution. The conceptual model was also computed on a regional scale, and approximately the same offset was observed in all regions.

c. Performance of the conceptual model and its precedent in previous research

Several possibilities could account for the disagreement between the hypothesized distributions and the Storm Data observed distributions. For instance, the Storm Data event distribution is composed of GHCN maximum daily gusts, and it cannot be known whether the maximum gust prompted the Storm Data report. Also, as referenced above, the combination of the sustained winds and wind gusts may be more significant than the gusts alone. This possibility is supported by the closer model alignment using the daily average wind distributions rather than the maximum gust distributions. Finally, Eq. (1) is an intuitive, first-order explanation for nonconvective wind impact, and ignores key considerations like mitigation and adaptive measures by both human and natural systems. For instance, structural engineers design buildings to withstand the force exerted by climatologically frequent wind speeds without suffering damage. In natural systems, trees demonstrate a multitude of mechanisms for surviving substantial wind loads [for a thorough discussion refer to Read and Stokes (2006)], but when exposed to winds outside of their common climatological range, catastrophic damage can occur (Bailey et al. 1997, p. 269). Therefore, human and natural mitigation measures might shift the observed impact curve toward stronger wind speeds compared to the hypothetical curve.

The results shown here are supported by previous research. Several forestry studies have observed winds below 40 mi h⁻¹ (17.9 m s⁻¹) to cause windthrow (the breaking or uprooting of trees by the wind) of healthy trees (Oliver and Mayhead 1974; Francis and Gillespie 1993; Gardiner et al. 2000; Peltola 2006). Oliver and Mayhead (1974) found that during windstorms, windthrow occurred at speeds well below what was calculated for tree failure based on winching studies performed in the same forest. Anecdotally, a catastrophic April 2014 windthrow event in Athens, Georgia, described by a local arborist as a “once in a lifetime” occurrence (J. Ritzler, New Urban Forestry, Athens, Georgia, 2015, personal communication) resulted from maximum gusts of 44 mi h⁻¹ (19.7 m s⁻¹) accompanied by sustained winds greater than 30 mi h⁻¹ (13.4 m s⁻¹) for a period of several hours.

Several explanations for tree failure at these wind speeds can be postulated. One is that the vibrations of a tree exposed to unusually strong sustained winds for an extended period of time can loosen the soil around the root system leading to failure at weaker-than-expected wind speeds (Oliver and Mayhead 1974). This also supports why the distribution of the hypothetical nonconvective wind impact more closely resembles the observed wind impact when considering GHCN average daily wind. In addition, the 2014 Athens event occurred at the beginning of the spring “greening” period when the leaf area of, and consequently the wind loading experienced by, the region’s trees was rapidly increasing. A period of rain earlier that morning also served to moisten and loosen area soils. Circumstantial factors such as these may be influential in facilitating tree failure at weaker-than-expected wind speeds.

5. Comparison to current NWS product criteria

As described in the introduction, the lack of wind product threshold documentation raises concerns over the NWS requirements for the products’ issuance. Most troubling is that the majority of deadly, injury-causing, and human-reported events occur with peak gusts below the current high wind warning gust criterion (Table 3). Greater than one-quarter of all directly fatal and
directly injury-causing nonconvective wind events (within the 4271 human source events considered here) occurred below the wind advisory gust threshold, and greater than 74% occurred below the high wind warning gust criteria (Table 3).

An archive of NWS wind advisories and high wind warnings obtained from the Iowa Mesonet data portal (https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml) was used to create maps of wind product issuance across the continental United States between 2006 and 2013 (Fig. 7). While NWS directives allow for individual Weather Forecast Offices (WFOs) to adjust thresholds based on local climatology, Fig. 7 demonstrates that wind product issuance is still driven largely by regional wind climatologies. Areas of complex terrain in the western United States receive the majority of high wind warnings issued by the NWS, and some WFOs in the Rocky Mountains region choose not to issue wind advisories. In contrast, many WFOs in the eastern United States commonly issue wind advisories, but did not issue a high wind warning, and many others issued only one or two during this 7-yr period. Though these CWAs suffer losses from nonconvective wind events (Fig. 4), the current NWS high wind warning definition fails to capture the wind speeds that generate damage in these areas. Ideally, the dots in Fig. 4 and the dark gray/black regions in Fig. 7 would be spatially coincident, meaning that the most wind products were issued in the areas that experienced the most nonconvective high wind losses; however, this is not the case. The spatial displacement of the areas of frequent high wind warning issuance from the areas of nonconvective wind impact suggests that the current warning criteria prohibits high wind warning issuance in areas of frequent human impact.

Although the current gust criteria can be perceived to be reasonable values, they are actually climatologically exceptional events. Figure 8 shows a spatial depiction of the climatological percentiles of both the wind advisory (Fig. 8a) and high wind warning gust criteria (Fig. 8b). Since the purpose of Fig. 8 is to contextualize the absolute climatological frequency of the wind gusts used to issue these products, no effort was made to filter out gusts associated with convective or tropical systems. In the high elevations of the western United States, the wind advisory gust criterion is as common as the 89th percentile. These mountainous regions with more frequent strong gusts correspond well to the wind product issuance maxima depicted in Fig. 7. However, for much of the eastern United States a 46 mi h\(^{-1}\) (20.6 m s\(^{-1}\)) gust falls within the upper 2% of all gusts observed in the CWAs (including convective and tropical winds). Meanwhile, the majority of percentiles for the high wind warning gust criterion exceed the rarest 1% of all gusts. Thirteen CWAs witnessed 58 mi h\(^{-1}\) (25.9 m s\(^{-1}\)) gusts or stronger once every \(>2.5\) yr while two CWAs (Charleston, South Carolina, and Jackson, Kentucky) observed these gusts only once every \(>5\) yr (including convective and tropical). It is clear that the high wind warning threshold represents a climatologically extreme event for most CWAs in the eastern United States. Additionally, when this threshold is met, it is not necessarily even as a result of nonconvective winds. The true climatological frequency for nonconvective winds of this magnitude is assumed to be more infrequent than indicated in Fig. 8.

With their current gust definitions, wind advisories and high wind warnings fail to encompass a significant number of events associated with nonconvective wind damage. Figure 8 demonstrates that regional wind climatologies vary significantly within the United States, and should be incorporated to at least some degree in the development of nonconvective wind product gust thresholds. The circumstantial factors (e.g., soil moisture and tree leaf area) discussed in section 4c also deserve further consideration in the establishment of revised issuance criteria. However, if a standard national threshold is desired, more empirically justifiable gust criteria might be 35 and 47 mi h\(^{-1}\) (15.6 and 21.0 m s\(^{-1}\)) for the wind advisory and high wind warning, respectively. These thresholds would capture the majority of the nonconvective wind events while still occurring infrequently enough to avoid overissuance (Table 4).

However, modifying the wind advisory and high wind warning issuance criteria could potentially affect the way in which the general public perceives these alerts. In decreasing the threshold, the number of wind products issued annually would increase, possibly influencing the public’s decision to take appropriate protective measures. Prior to understanding the consequences of
threshold modification, we must first understand how the public currently perceives these products as a whole. A forthcoming study by Williams et al. (2016, manuscript submitted to Wea. Forecasting) reveals that weather-salient participants generally associated substantially weaker wind speeds with both a wind advisory (28 mi h\(^{-1}\)) and a high wind warning (38 mi h\(^{-1}\)) compared to their local WFO’s thresholds. Based on these results, the public could find a reduced threshold more reasonable.

An increase in product issuance would potentially be accompanied by an increase in the false alarm ratio...
FIG. 8. Map of the climatological percentile of the gust criterion for (a) wind advisories and (b) high wind warnings by NWS CWAs. Percentiles were derived using GHCN-Daily wind gusts for the same 8-yr period for which the wind products in Fig. 7 were available. Ideally, the areas of concentrated black dots in Fig. 4 and the regions of dark gray/black in Figs. 7 and 8 would be relatively coincident, indicating that warnings were issued most frequently in areas where wind impacts were experienced most frequently.
(FAR) associated with wind products. This leads to the question, Will an increase in nonconvective wind product FAR affect the behaviors and intentions of the public to take protective actions for wind events? The distinction between the actual calculated FAR and an individual's perceived FAR (the frequency at which an individual perceives a false alarm to occur in their local area) is critical to answering this question. Previous research has revealed that, compared to the actual FAR produced by the NWS, the perceived FAR is underestimated by the average respondent (Ripberger et al. 2015). Similarly, Trainor et al. (2015) concluded that the perceived FAR is not influenced by the actual FAR. However, the relationship between the actual FAR and an individual’s likelihood of taking protection action is still unclear (Dow and Cutter 1998; Benight et al. 2004; LeClerc and Joslyn 2015; Ripberger et al. 2015; Trainor et al. 2015). While the most recent literature suggests that increasing the actual FAR negatively impacts an individual’s likelihood of taking protective action, this research has been largely limited to convective hazards. Since it is unclear how well these results translate to nonconvective wind events, it is difficult to fully anticipate the societal response to reducing the wind product issuance thresholds. Though recent work has sought to compute actual nonconvective wind product FARs (Layer and Colle 2015), future research should attempt to determine how the perceived FAR is evaluated for high wind events. This would help determine the circumstances, if any, when a wind event would be labeled as a “false alarm” by the general public and how such a perception would impact their likelihood of taking protective action in the future.

### 6. Conclusions

The societal impacts of nonconvective high winds in the United States are infrequently acknowledged in the American research literature or media outlets. While the NWS does issue several products designed to communicate the potential for dangerous nonconvective winds to the public, such as wind advisories and high wind warnings, the origin/justification for the issuance criteria is unclear. In this study, Storm Data was used to identify the times and locations of significant nonconvective wind events from 1996 to 2013. Daily maximum wind gusts and daily average wind speeds from GHCN stations were then paired with Storm Data reports based on the spatial and temporal characteristics of the nonconvective wind event. The synoptic scale and relatively large spatial autocorrelation of nonconvective wind fields (compared to convective winds) permits this substitution with reasonable confidence. Additionally, Storm Data events were narrowed to include only those events whose reports originated from human sources in an attempt to limit the artificial, policy-driven reporting pattern resulting from the NWS definition for “high winds.”

Nearly 92% (45%) of all Storm Data nonconvective wind reports occurred with GHCN peak gusts weaker than the high wind warning (wind advisory) criteria. Unfortunately, statistics for events associated with injury and death are not reassuring; greater than 28% of all injury-causing and fatal events occur below the wind advisory threshold, and greater than 74% of all such events occur below the high wind warning threshold. In light of this analysis, it appears that revised gust criteria for NWS wind product issuance are needed. Though gust criteria recommendations of 35–46 mi h⁻¹ (15.6–20.6 m s⁻¹) for wind advisories and ≥47 mi h⁻¹ (21.0 m s⁻¹) for high wind warnings are suggested, communicating weather hazards to the public is an extremely complex process, and any amendments to advisory/warning criteria deserve additional research in the future. Specifically, an investigation of the circumstances surrounding the impact [e.g., overturned vehicles, fallen trees, etc., as in Ashley and Black (2008)] as a function of wind speed could help inform any nonconvective wind product revisions. Recommended avenues for future research also include the duration of sustained winds on resulting nonconvective wind damage, and how sustained winds should best be incorporated into any revised issuance criteria.

Though severe convective storms and tropical cyclones might generate more powerful winds, abundant research has focused on these systems, their impacts,
and on reducing losses from these hazards. Nonconvecative winds continue to result in damage to life and property, while receiving considerably less thought and attention. It is hoped that this research will be the first step to improving the warning process for nonconvective wind, and will lead to a reduction in the loss of life and property to these winds.

Acknowledgments. The authors thank Jared Rackley, Kelly Harris, Lynne Seymour, Lauren Anderson, John Ritzler, and two anonymous reviewers for their comments in the early stages of this manuscript’s composition. CAW acknowledges the support of a National Science Foundation Graduate Research Fellowship in the completion of this work (Grant DGE-1443117). Any opinions, findings, conclusions, or recommendations expressed in this manuscript are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES


