Gust Factors: Meteorologically Stratified Climatology, Data Artifacts, and Utility in Forecasting Peak Gusts

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ABSTRACT

Gust factors in Milwaukee, Wisconsin, are investigated using Automated Surface Observing System (ASOS) wind measurements from 2007 to 2014. Wind and gust observations reported in the standard hourly ASOS dataset are shown to contain substantial bias caused by sampling and reporting protocols that restrict the reporting of gusts to arbitrarily defined “gusty” periods occurring during small subsets of each hour. The hourly ASOS gust reports are found to be inadequate for describing the gust characteristics of the site and ill suited for the study of gust factors. A gust-factor climatology was established for Milwaukee using the higher-resolution, 1-min version of the ASOS dataset. The mean gust factor is 1.74. Stratified climatologies demonstrate that Milwaukee gust factors vary substantially with meteorological factors, with wind speed and wind direction exerting the strongest controls. A variety of modified gust-factor models were evaluated in which the peak wind gust is estimated by multiplying a gust factor by the observed, rather than forecast, wind speed. Errors thus obtained are entirely attributable to utility of the gust factor in forecasting peak gusts, having eliminated any error associated with the wind speed forecast. Results show that gust-factor models demonstrate skill in estimating peak gusts and improve with the use of meteorologically stratified gust factors.

1. Introduction

Wind gusts, sudden brief increases in wind speed (Huschke 1959), are accompanied by pressure and force fluctuations that are relevant to a diverse range of applications including wind energy; aviation; timber damage assessment; design codes for buildings, bridges, and electrical transmission lines; and resuspension models for deposited radioactive particles (Manasseh and Middleton 1999; Jung et al. 2016; Paulsen and Schroeder 2005; Giess et al. 1997; Pryor et al. 2014; Greenway 1979; Suomi et al. 2013; Wong and Miller 2010). Meteorological factors such as stability and turbulence exert strong influences, but gusts and wind speed are also controlled by nonatmospheric parameters that are termed metadata (Powell et al. 1996). Chief among these are averaging period and sampling duration, although instrument response characteristics, measurement height, and the height and spatial density of upwind terrain elements are also important (Jung and Schindler 2016; Mitsuta and Tsukamoto 1989; Carter 1974; Wichers Schreur and Geertsema 2008; Greenway

1979; Harper et al. 2010; Masters et al. 2010; Pryor et al. 2014; Suomi et al. 2016; Van der Hoven 1957).

The World Meteorological Organization (WMO) has provided recommendations for the precise definitions and measurement protocols of both wind gust and wind speed (Beljaars 1987). Worldwide consensus is lacking, however, and not all governmental agencies have adopted these guidelines. The WMO standard for estimating the wind speed is the 10-min average (Harper et al. 2010), yet the wind speed reported by the U.S. Automated Surface Observing System (ASOS) is a 2-min average (NOAA 1998). Wind gusts have been formally defined as “the wind speed deviation from the mean which, on average, is exceeded once during the reference period” (Kristensen et al. 1991). The WMO recommends defining a gust as the maximum 3-s average during a 10-min sampling period (Suomi et al. 2015), but reporting requirements exist in some regions but not in others (Harper et al. 2010). The ASOS gust-reporting criteria, for example, include the requirement that gusts must exceed lulls by at least 10 kt ($1 \text{ kt} = 0.51 \text{ m s}^{-1}$) (<http://w1.weather.gov/glossary/index.php?word=gust>; <http://w1.weather.gov/glossary/index.php?word=wind+gust>).

The gust factor (GF) is the ratio of the wind gust to the wind speed. When averaged over extended time periods,

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it becomes a climatological measure of gustiness (Sherlock 1952). Gust factors figure prominently in wind conversion, the practice of converting between wind speeds averaged over different time periods (Harper et al. 2010), often for the purpose of standardizing or comparing wind impacts. Wind conversion is commonly used in applications relating to the intensity of tropical cyclones, structural engineering, and wind energy (Masters et al. 2010; Greenway 1979; Suomi et al. 2013). In the literature on tropical cyclones, the GF is defined as a theoretical conversion between a wind speed estimate and the expected highest gust of a given duration within a stated observation period (Harper et al. 2010). Other applications of wind conversion include exposure, a practice in which measured surface winds are corrected for the influence of flow obstacles (Powell et al. 2004). The determination of extreme winds, often defined as the maximum 10-min-averaged wind with a return period of 50 yr (Lombardo et al. 2009; Larsén et al. 2012), is another application of wind conversion that is used by structural designers to estimate maximum wind loads.

Wind gust and wind speed metadata are clearly specified for certain wind-conversion applications. Conversion factors (i.e., gust factors) recommended for tropical-cyclone conditions assume gust durations of 3, 60, 120, 180, or 600 s and (mean) wind averaging periods of 60, 120, 180, 600, or 3600 s (Harper et al. 2010). For exposure estimation, Masters et al. (2010) standardized gust duration and wind averaging period at 3 s and 1 h, respectively. Corresponding values of 10 min and 1 h are used for structural-design considerations (Soe and Thant 2014), whereas ASOS gusts are the highest 3-s wind measured during a 10-min period.

Issues around sampling duration and averaging period notwithstanding, forecasting peak gusts remains difficult given the small spatial and temporal scales at which they occur (Mitsuta and Tsukamoto 1989). Although a variety of approaches have been developed, often on the basis of postprocessing of numerical weather prediction (NWP) model products (Suomi et al. 2013), no common parameterization exists to simulate wind gusts in NWP or regional climate models (Goyette et al. 2003). Parameterization methods include physical models that are based on downmixing of winds using model-generated soundings (Hart and Forbes 1999; Green and Poremba 2012), turbulence parameterizations (Panofsky and Dutton 1984; Schulz 2008; Wichers Schreur and Geertsema 2008; Brasseur 2001), and statistical methods involving model output statistics (Rudack 2006) and probability density functions (Friederichs et al. 2009).

The GF model is a simple statistical technique in which a known gust factor is multiplied by a forecast

wind speed to yield a predicted peak wind gust. Comparisons among gust-modeling techniques, while scarce, suggest that the performance of GF models is comparable to that of other modeling approaches (Brasseur 2001; Goyette et al. 2003).

In addition to sampling and averaging protocols, gust factors are sensitive to meteorological and environmental factors including wind speed, stability, and upstream surface roughness (Davis and Newstein 1968; Carter 1974; Ágústsson and Ólafsson 2004; Shellard 1965; Harper et al. 2010; Masters et al. 2010; Suomi et al. 2013; Paulsen and Schroeder 2005). Typical values range from 1.3 over open water to 2.3 in the middle of large cities (Wieringa 1973; Harper et al. 2010; Pryor et al. 2014). Some studies have found tropical values to be generally larger than extratropical values (Choi and Hidayat 2002; Orwig and Schroeder 2007; Paulsen and Schroeder 2005). The GF models are in operational use by federal weather forecasting agencies in several countries, including the United States, United Kingdom, and Denmark (Cook et al. 2008; Kramer and Alsheimer 2013; Blaes et al. 2014; Woetmann Nielsen and Petersen 2001). It does not appear, however, that these operational GF models exploit the known sensitivities of the GF to changing meteorological conditions.

The two principal research questions addressed in this paper are whether the ASOS dataset is suitable for determining GF climatologies and whether the known sensitivities of the GF to meteorological variables can be exploited to improve GF model performance. To address these questions, we establish a GF climatology for Milwaukee, Wisconsin, and assess the GF-model performance at that location. We examine the sensitivity of GFs to several meteorological variables, and, unlike in previous studies, we harness these sensitivities by developing and evaluating meteorologically stratified GF models. Another novelty of this work is the adoption of a GF-model evaluation procedure in which gust forecasts are evaluated independent of the errors associated with wind speed forecasts. In addition, by including a limited analysis of GFs at another mid-latitude site, we offer evidence that our method for developing and evaluating GF models can be used generally.

2. Data and methods

a. Meteorological data

ASOS wind speed, wind gust, wind direction, and cloud observations were obtained from the U.S. National Centers for Environmental Information (formerly National Climatic Data Center) for the period from January 2000 to December 2014 at Milwaukee (station

FIG. 1. Aerial view of the KMKE ASOS station, located at General Mitchell International Airport in Milwaukee.

identifier KMKE). Located at General Mitchell International Airport (42.955°N , 87.904°W ; 204 m MSL), KMKE is situated approximately 10 km south of downtown Milwaukee and 5 km west of Lake Michigan (Fig. 1). The ASOS observations are available hourly (NOAA 1998) and also with 1-min resolution at selected sites, including KMKE. In this study, both the standard hourly (denoted ASOS_h) observations and the higher-resolution, 1-min observations (denoted ASOS_m) were used so as to examine the sensitivity of the GF to the observations from which they are derived.

Wind measurements at KMKE were made atop a 10-m tower. On 14 September 2006, the previously used Belfort Instrument Co. model 2000 cup and vane anemometer that reported 5-s-duration gusts was changed

to a Vaisala, Inc., model 425 sonic anemometer reporting 3-s gusts (<http://www.ncdc.noaa.gov/homr>). Previous studies have shown that 3-s gusts may be up to 5% larger than 5-s gusts (Lombardo et al. 2009; Suomi et al. 2015). This specific change in instrumentation has been shown to cause abrupt increases of 7% in gust factors (Masters et al. 2010). For these reasons, we restricted our analysis to the 2007–14 period.

In addition, ASOS_m and ASOS_h wind observations for 2014 were obtained for the ASOS station located in Atlanta, Georgia (33.630°N , 84.442°W ; 308 m MSL). Portions of the analyses conducted for Milwaukee were also performed for the shorter Atlanta dataset to demonstrate the applicability of the GF-model results to other locations.

TABLE 1. Details of the ASOS wind and gust datasets.

Dataset	Abbreviation	Obs period	No. of hourly obs	No. of matching hourly obs ^a
ASOS hourly	ASOS _h	Jan 2007–Dec 2014	9154	8495
ASOS 1 min	ASOS _m	Jan 2007–Dec 2014	61 978	8495

^a Hours for which wind and gust observations were reported in both the ASOS_h and ASOS_m datasets.

1) ONE-MINUTE (ASOS_m) OBSERVATIONS

The ASOS_m wind and gust observations are the average and highest, respectively, 3-s wind observed each minute (NOAA 1998). After applying quality-control procedures to remove erroneous data, 61 978 h of wind and gust observations were available for analysis, accounting for 88% of all hours during the 2007–14 study period (Table 1). [In the 2014 Atlanta ASOS_m dataset, 8142 h (92.9%) were available for analysis.]

2) ONE-HOUR (ASOS_h) OBSERVATIONS

The hourly wind speed reported in the ASOS_h dataset, hereinafter called the reported wind, is defined as the 2-min average of the 3-s wind measured during minutes 51 and 52 of the hour. The ASOS_h reported wind thus excludes observations made during 58 min (97%) of each hour. The ASOS_h gust observation, hereinafter called the reported gust, is defined as the highest 3-s average wind recorded during the 10-min period from minutes 43 to 52 of each hour. The reported gust thus excludes observations made during 50 min (83%) of each hour. Reported gusts must satisfy three criteria corresponding to minutes 43–52 of the hour: 1) the reported wind must be greater than 2 kt, 2) the difference between the reported gust and the reported wind must be ≥ 3 kt, and 3) the reported gust must exceed the minimum 3-s wind speed by at least 10 kt (NOAA 1998).

The ASOS_h sampling protocols and reporting criteria create three important differences between gusts reported in the ASOS_m and ASOS_h datasets:

- 1) Gusts less than 14 kt (7.2 m s^{-1}) are never reported in the hourly ASOS_h dataset.
- 2) The availability of ASOS_h gusts is limited by the reporting criteria. During the 2007–14 study period in Milwaukee, gusts were reported during 9154 h, only 13.1% of all possible hours (Table 1). (In the 2014 Atlanta ASOS_h dataset, the corresponding percentage was 12.6%.)
- 3) For any given hour, ASOS_h reported gusts are never larger than ASOS_m gusts. In section 3a, we show that the ASOS_h reported gusts are usually less than ASOS_m gusts as a result of the differences in observation periods (10 and 60 min for ASOS_h and ASOS_m gusts, respectively).

b. Methods

1) DETERMINING GUST FACTORS

Gust factors were determined using both the ASOS_m and ASOS_h observations. For the ASOS_h observations, calculating the GF (GF_h) is straightforward, because each hourly report, if the reporting criteria are met, contains only one wind observation and one gust observation:

$$\text{GF}_h = \frac{\text{reported gust}}{\text{reported wind}}. \quad (1)$$

The ASOS_m observations offer the opportunity to create a GF for each minute, but we calculate one GF per hour to allow for a more direct comparison with the GF_h. We define a mean wind as the average of all sixty 1-min wind speed observations in the hour, and we define a peak gust as the highest 1-min gust observation in the hour (i.e., the highest 3-s wind speed during the entire hour). The GF from ASOS_m (GF_m) is thus

$$\text{GF}_m = \frac{\text{peak gust}}{\text{mean wind}}. \quad (2)$$

The necessity of using the higher-resolution ASOS_m dataset in GF research has been noted before (e.g., Powell et al. 2004; Masters et al. 2010). Nevertheless, the ASOS_h dataset or its equivalent has been used in many GF studies (e.g., Brasseur 2001; Friederichs et al. 2009; Ágústsson and Ólafsson 2004; Green and Poremba 2012; Rudack 2006).

The effects of the ASOS_h sampling protocol on the determination of GFs are illustrated in Fig. 2, which shows ASOS_m and ASOS_h wind and gust observations for one sample hour in Milwaukee. In this example, the ASOS_m peak gust (the highest wind speed observed during the entire hour) is 53 kt (27.3 m s^{-1}), whereas the ASOS_h reported gust (the highest wind speed measured during the 10-min period between minutes 43 and 52) is 41 kt (21.1 m s^{-1}). (Note that the knot is the native unit of the ASOS wind instrumentation.) In a similar way, the ASOS_m mean wind (the average of all wind speed observations during the hour) is 27 kt (13.9 m s^{-1}), whereas the ASOS_h reported wind (the average wind speed during the 2-min period between minutes 51 and 52)

FIG. 2. One-minute $ASOS_m$ wind (green) and gust (blue) observations for one sample hour in Milwaukee, illustrating the effects of ASOS reporting practices on gusts and gust factors. The $ASOS_m$ GF [$GF_m = (\text{peak gust})/(\text{mean wind}) = 1.96$] incorporates observations during the entire hour, whereas the $ASOS_h$ GF [$GF_h = (\text{reported gust})/(\text{reported wind}) = 1.86$] is derived from observations during a 10-min period (purple shading), ignoring the majority of the hour's measurements.

is 22 kt (11.3 m s^{-1}). The resulting GF using $ASOS_m$ data is $GF_m = 1.96$, whereas that using $ASOS_h$ data is $GF_h = 1.86$.

The differences in the periods for $ASOS_m$ and $ASOS_h$ wind and gust observations could thus result in sizeable differences between the GF_m and the GF_h . Gust-factor differences of the magnitude shown in Fig. 2 (0.10) are not negligible, given the range of typical values reported by Wieringa (1973). In section 3b, we present evidence that such differences are often exceeded in both the Milwaukee and Atlanta datasets.

As previously noted by Paulsen and Schroeder (2005) and Masters et al. (2010) in the context of tropical-cyclone winds, the use of $ASOS_h$ data to determine GFs at a particular location may yield unrepresentative results, because this dataset reports only a small fraction of the wind observations made during each hour: $n = 9154$ in the study presented here, as compared with $n = 61\,978$ for the corresponding $ASOS_m$ observations. In section 3a, we show that the $ASOS_h$ reporting criteria create an

additional bias by including only stronger wind events. Because no standard protocol exists for the wind and gust averaging times used in the computation of gust factors (Davis and Newstein 1968; Harper et al. 2010), a key aspect of this work is to elucidate the influence of the $ASOS_h$ reporting criteria and sampling periods on GFs and their subsequent climatologies.

2) METEOROLOGICALLY STRATIFIED GUST FACTORS

In addition to elucidating the differences between the GF_m and the GF_h , we create a GF climatology by stratifying the GFs according to wind speed, wind direction, season, month, time of day, and atmospheric stability. This stratification is motivated by a desire to better understand the meteorological controls on GFs, which in turn could prove useful in forecasting wind gusts. The stratification is applied only to GF_m , because the $ASOS_m$ dataset has the capability to better capture the character of wind gusts, as compared with the $ASOS_h$ dataset, for

which sampling protocols and reporting criteria create evident biases.

The GF_m GFs were stratified into 5-kt (2.6 m s^{-1}) bins for wind speed and 30° bins for wind direction. Gust-factor stratification by atmospheric stability was accomplished using the Pasquill (1961) stability classification scheme, which considers surface-based observations of cloud cover, insolation (incoming solar radiation), and wind speed. Following Luna and Church (1972), insolation was determined via a combination of cloud cover and solar angle. Sounding data were not used because of the absence of a collocated radiosonde station in Milwaukee, as well as the insufficiency of twice-daily radiosonde measurements in adequately describing diurnal cycles of stability.

3) GUST-FACTOR MODELS

The GF model

$$\text{gust}_{\text{fcst}} = \text{GF} \times \text{wspd}_{\text{fcst}} \quad (3)$$

is a simple means of forecasting the peak gust ($\text{gust}_{\text{fcst}}$) given a known GF and a forecast wind speed $\text{wspd}_{\text{fcst}}$, the latter often obtained from NWP models. Any error in the gust forecast thus includes a contribution from the error associated with the wind speed forecast. In this study, we replace $\text{wspd}_{\text{fcst}}$ with a wind speed observation corresponding to the forecast hour. This equates to making a perfect wind speed “forecast,” eliminating any errors associated with $\text{wspd}_{\text{fcst}}$. With this strategy, the skill of the GF model in Eq. (3) is solely due to the representativeness of the GF that is used.

Wind gust forecasts were evaluated for all hours in the 2007–14 period for which wind and gust observations were available. Forecast performance was also evaluated for “gusty” subsets of the overall period, during which observed gusts exceeded 25 kt (12.9 m s^{-1}).

Several variants of the GF in Eq. (3) were used. Mean-GF models used the average GF_m and GF_h corresponding to the entire study period. These values are reported in section 3b. Stratified models incorporated GF_m stratified by wind speed [5-kt (2.6 m s^{-1}) bins], wind direction (30° bins), stability (Pasquill category), time of day, and season. A doubly stratified GF model was also tested, using GF_m stratified by a combination of wind speed and wind direction. All GF models were compared with the no-skill models of “persistence” ($\text{gust}_{\text{fcst}} = \text{gust}$ observation from previous hour) and “climatology” ($\text{gust}_{\text{fcst}} = \text{average gust}$ for a particular season and time of day).

Verification metrics of bias ($\text{gust}_{\text{fcst}} - \text{observed gust}$) and absolute error ($|\text{bias}|$) were used for all models. Mean- and stratified- GF_m models were verified against the ASOS_m peak-gust observations, and the mean- GF_h

model was verified against the ASOS_h reported gust observations. The GF_h model was also verified against the ASOS_m peak-gust observations to illustrate the consequences of both formulating and evaluating GF models using observations corresponding to only small subsets of each hour. Absolute-error distributions for selected pairs of models were compared via the sign test (Mendenhall et al. 1990) and were considered to be statistically significant when the null hypothesis (of no difference) was rejected at the 99% confidence level.

3. Results and discussion

a. Wind and gust climatology

The gust factor as defined in Eqs. (1) and (2) is the ratio of an observed wind gust to an observed wind speed. Both numerator and denominator are sensitive to the sampling periods and reporting criteria that are associated with the datasets from which they are derived. Therefore, before presenting the GF climatology, we first examine these sensitivities.

The sensitivity of wind speed observations to the gust-reporting criteria is shown in Fig. 3a. The gust-reporting criteria (ASOS_h dataset only) severely reduce the number of observations and strongly bias the distribution toward higher wind speeds. Climatological GFs determined using the ASOS_h dataset would therefore be expected to be smaller than those determined with ASOS_m data, because the wind speeds (the GF denominator) are larger.

Distributions of ASOS_m mean wind (60-min average) and ASOS_h reported wind (2-min average) during hours for which a gust is reported in both datasets—thereby removing the bias due to gust-reporting criteria—are remarkably similar (Fig. 3b). This is not surprising, given the known gap in the wind speed energy spectrum occurring between periods of a few minutes and a few hours (Van der Hoven 1957), although subsequent analyses suggest that the spectral gap may be only a factor of 2 lower than the higher-frequency peak (Jensen 1999).

As expected, ASOS_h gust observations are also highly sensitive to the reporting criteria, as shown in Fig. 3c. Recall from section 2a(2) that ASOS_h gusts are reported only when they exceed the ASOS_h reported wind, as well as lulls, by specified amounts. Like the case for wind speed, the reporting criteria severely reduce the number of ASOS_h reported gusts and bias the observations toward higher values. The lack of such criteria for the ASOS_m peak gusts explains the occasional presence of very weak “gusts” [i.e., $<5 \text{ kt}$ (2.6 m s^{-1})]. Unlike the wind speed observations, however, gust observations from the two datasets exhibit an important sensitivity to

FIG. 3. Wind and gust observations during 2007–14 in Milwaukee, illustrating sensitivity to data artifacts. (a) Distributions of ASOS_m mean wind (red) and ASOS_h reported wind (blue), illustrating sensitivity to ASOS_h gust-reporting criteria. (b) Distributions of ASOS_m mean wind (red) and ASOS_h reported wind (blue), but with only hours for which gusts are reported in both datasets included. (c) Distributions of ASOS_m peak gusts (red) and ASOS_h reported gusts (blue), illustrating sensitivity to ASOS_h gust-reporting criteria. (d) Distributions of ASOS_m peak gust (red) and ASOS_h reported gust (blue), but with only hours for which gusts are reported in both datasets included, illustrating sensitivity to ASOS_h sampling period.

sampling periods (Fig. 3d). During hours for which both are reported, the ASOS_m peak gust is always greater than or equal to the ASOS_h reported gust. Although more than half of the differences (ASOS_m peak gust minus ASOS_h reported gust) are under 5 kt (2.6 m s^{-1}) when ASOS_h gusts are reported, the differences become larger with increasing gustiness (Fig. 4), because the hourly ASOS_h gusts sample only 10 min of each hour. Differences of 5 and 10 kt (2.6 and 5.1 m s^{-1}) or larger

were found in 11.8% and 0.8% of observations, respectively.

The data artifacts resulting from reporting criteria and sampling periods thus render the ASOS_h wind and gust data ill suited for the determination of GFs, which are intended to be representative measures of local climatological gustiness (Sherlock 1952). The ASOS_m observations, which better capture the character of wind gusts, are a much more appropriate means of determining GFs.

FIG. 4. Difference in gust observations ($ASOS_m$ peak gust minus $ASOS_h$ reported gust) as a function of $ASOS_m$ peak gust during 2007–14 in Milwaukee during hours for which a gust is reported in both datasets ($n = 8495$). Each circle represents multiple points, because gusts from both datasets are reported in integer units. The curve (right scale) shows the frequency distribution of the strength of $ASOS_m$ peak gusts for hours in which gust differences are <5 kt (2.6 $m\ s^{-1}$).

(Refer to the [appendix](#) for additional evidence of the biases contained in the $ASOS_h$ dataset.)

b. Gust-factor climatology

The mean GF_m for Milwaukee is 1.74, as based on the full set of 1-min $ASOS_m$ data during 2007–14 ($n = 61\,978$). The corresponding mean GF_h , as based on the full set of hourly $ASOS_h$ data during the same period ($n = 91\,54$), is 1.58. Similar values for extratropical locations were reported by [Paulsen and Schroeder \(2005\)](#) and [Cook \(1986\)](#).

The mean GF_h is 9.2% smaller than the mean GF_m , confirming the expected low bias associated with the $ASOS_h$ gust-reporting criteria and sampling protocols. [In Atlanta, the mean GF_h (1.65; $n = 1106$) is 13.6% smaller than the mean GF_m (1.91; $n = 8142$).] When we eliminate the $ASOS_h$ reporting bias by considering only hours for which gusts are reported in both datasets ($n = 8495$), the mean difference $GF_m - GF_h$ is 0.15 ([Fig. 5](#)). This difference again emphasizes the pervasive impact of the sampling period on the determination of GFs: even without the low bias due to the $ASOS_h$ gust-reporting criteria, sampling gusts during only 10 min of each hour causes a low bias of 9% in GFs calculated using this dataset. Having demonstrated that GFs that are based on $ASOS_h$ data suffer from artifacts due to sampling and reporting protocols, the remaining climatology of gust factors stratified by wind speed and other variables will be

restricted to the GF_m gust factors, which are based on $ASOS_m$ data.

Gust factors are known to be sensitive to surface roughness ([Powell et al. 2004](#); [Pryor et al. 2014](#); [Suomi et al. 2013](#)), although [Harper et al. \(2010\)](#) point out that GFs determined for sites located on hills or slopes may not be representative of their true gust climates because of changing wind direction and/or the lack of an extended constant roughness fetch for many kilometers. [Masters et al. \(2010\)](#) provided a database of directionally stratified GFs and surface-roughness values for hurricane-prone regions in the eastern United States, but because their focus was on tropical-storm conditions their method excluded conditions with mean winds under $5\ m\ s^{-1}$ ($9.7\ kt$) and nonneutral stability—roughly one-third of their dataset.

In this study, wind direction was used as a proxy for surface roughness because the measurement site is surrounded by highly heterogeneous terrain ([Fig. 1](#)). Wind directions from south-southeast to north and from north-northeast to southeast have large fetches over land and water, respectively. Wind direction had a sizeable impact on the GF_m ([Fig. 6](#)). When one considers all wind speeds together, mean GF_m values of 1.6–1.7 occurred with winds with a long fetch over Lake Michigan (60° – 150°) whereas larger values up to 1.8 were associated with inland winds (240° – 30°). Other studies have similarly reported higher GFs in association with larger surface roughness ([Wieringa 1973](#);

FIG. 5. Distribution of differences (kt) between $ASOS_m$ and $ASOS_h$ gust factors ($GF_m - GF_h$) during 2007–14 in Milwaukee, illustrating sensitivity to sampling period. Only hours for which gusts are reported in both datasets are included.

Harper et al. 2010; Masters et al. 2010; Paulsen and Schroeder 2005; Powell et al. 2004).

Wind speed also exerts an important influence on GFs. Milwaukee GFs decrease with increasing wind speed (Fig. 6)—a finding that is consistent with previous studies (Davis and Newstein 1968; Carter 1974; Mitsuta and Tsukamoto 1989; Ágústsson and Ólafsson 2004; Paulsen and Schroeder 2005; Pryor et al. 2014). When one considers all wind directions together, the mean GF_m decreases from 1.91 to 1.64 when the wind speeds increase from the 0–5-kt ($0–2.6 \text{ m s}^{-1}$) range to ≥ 15 kt (7.7 m s^{-1}). This GF sensitivity of 0.27 to differing wind speeds is meaningful, because it represents 27% of the range of typical values reported by Wieringa (1973).

The variability in the GF_m is largest when wind speeds are under 5 kt (2.6 m s^{-1}), with standard deviations of ~ 0.4 regardless of wind direction (Fig. 6). This variability decreases as wind speeds increase, with standard deviations dropping to ~ 0.15 for winds in the 10–15-kt ($5.1–7.7 \text{ m s}^{-1}$) range. In Milwaukee, GF_m variability is more sensitive to wind speed than to wind direction, though this result may depend somewhat on the definition of the wind speed ranges and the wind direction sectors utilized.

Previous studies have reported a relationship between GF and stability in which the GF decreases as the atmosphere becomes more stable (Carter 1974; Kramer and Alsheimer 2013; Davis and Newstein 1968; Ágústsson and Ólafsson 2004). In Milwaukee, we find

FIG. 6. $ASOS_m$ GF_m (bars; left scale) stratified by wind speed and direction over 2007–14. Error bars indicate ± 1 standard deviation. The number of observations (circles; right scale) is shown for each wind direction sector.

FIG. 7. The GF_m s (bars) and wind speed (circles) stratified by hour on the basis of Milwaukee ASOS_m data for 2007–14.

that the GF_m indeed decreases from 2.0 for “extremely unstable” conditions (Pasquill category A) to 1.68 for “neutral” conditions (category D), in agreement with the aforementioned previous studies. As stability increases further from the neutral (D) to the “stable” (F) categories, the GF_m does not continue to decrease but rather increases to 1.84.

The stability-stratified GF results may be understood by considering the role of wind speed in determining stability categories (Pasquill 1961). During the daytime, an increase in categorical stability from unstable (A) to neutral (D) is associated with an increase in wind speed. At night, the opposite is true: a stability increase from neutral (D) to stable (F) is accompanied by a decrease in wind speed. The strong sensitivity of GF to wind speed that was noted earlier (Fig. 6) thus appears to partially mask the sensitivity of GF to stability.

A site-specific wind direction effect may also contribute to the lack of a monotonic dependence of GF on stability because in Milwaukee advection from the direction of Lake Michigan typically brings unstable air in the winter and stable air in the summer. In addition, the Pasquill classification scheme may not provide an adequate representation of atmospheric stability over the neutral-to-stable range (Luna and Church 1972).

In addition to being influenced by wind speed, wind direction, and stability, the GF_m exhibited moderate variation when stratified by hour of day (Fig. 7). The GF_m was lowest during the afternoon and highest around sunrise. This is consistent with the inverse relationship between GF_m and wind speed (Fig. 6), because wind speed (also shown in Fig. 7) peaks during the afternoon and reaches a minimum just before sunrise.

c. Performance of the gust-factor model

In this study, we replace $wspd_{fcst}$ in the GF model of Eq. (3) with the observed wind speed during the forecast hour. Any error in $gust_{fcst}$ is therefore attributable to the representativeness of the GF in forecasting peak gusts (i.e., in the GF model itself). Our model performance results thus represent a “best case scenario,” because operational GF models will suffer from imperfect wind speed forecasts.

Results of GF-model performance for the full 2007–14 period are shown in Table 2. Verification metrics were determined for all models: mean (nonstratified) and stratified GF_m and GF_h , persistence, and climatology. The type of observation used for verification is also listed in Table 2 (ASOS_m peak gust or ASOS_h reported gust). The mean absolute error (MAE) ranges from 1.20 to 4.82 kt (0.62–2.48 ms^{-1}) over all models. The mean bias is small, between -0.12 and 0.62 kt (between -0.06 and 0.32 ms^{-1}), for all models except the GF_h model verified against the ASOS_m peak gust. The mean bias for this model is -1.67 kt (-0.86 ms^{-1}), reflecting the fact that the ASOS_h reported gusts can never be larger than the ASOS_m peak gusts.

The GF-model results are meaningful in a variety of contexts. Most important, as noted above, is that they represent an upper bound on the performance expected of an operational GF model. A sense of the additional error arising from imperfect wind speed forecasts may be obtained by sampling wind speed forecast errors from distributions reported in recent studies (Traiteur et al. 2012; Zamo et al. 2016; Cheng et al. 2017). Accordingly, wind speed forecast errors sampled from a distribution

TABLE 2. Results for GF-model performance for Milwaukee for 2007–14. Results are sorted by ascending mean absolute error. Climatology values are provided in the appendix. Sigma indicates the standard deviation.

Model	Stratification	<i>n</i>	Verification	Bias (kt)		Absolute error (kt)	
				Mean	σ	Mean	σ
GF _m	Wind speed; wind direction	59 329	ASOS _m peak gust	0.09 (0.05 m s ⁻¹)	1.69 (0.87 m s ⁻¹)	1.20 (0.62 m s ⁻¹)	1.19 (0.61 m s ⁻¹)
GF _m	Wind speed	59 329	ASOS _m peak gust	0.09 (0.05 m s ⁻¹)	1.81 (0.93 m s ⁻¹)	1.30 (0.67 m s ⁻¹)	1.26 (0.65 m s ⁻¹)
GF _m	Wind direction	59 329	ASOS _m peak gust	0.37 (0.19 m s ⁻¹)	1.79 (0.92 m s ⁻¹)	1.33 (0.68 m s ⁻¹)	1.25 (0.64 m s ⁻¹)
GF _m	Hour/season	59 329	ASOS _m peak gust	0.31 (0.16 m s ⁻¹)	1.87 (0.96 m s ⁻¹)	1.40 (0.72 m s ⁻¹)	1.34 (0.69 m s ⁻¹)
Mean GF _m (=1.74)	None	59 329	ASOS _m peak gust	0.39 (0.20 m s ⁻¹)	1.90 (0.98 m s ⁻¹)	1.40 (0.72 m s ⁻¹)	1.34 (0.69 m s ⁻¹)
Persistence _m (no skill)	—	59 329	ASOS _m peak gust	0.02 (0.01 m s ⁻¹)	2.91 (1.50 m s ⁻¹)	2.03 (1.08 m s ⁻¹)	2.09 (1.08 m s ⁻¹)
Mean GF _h (=1.58)	None	6048	ASOS _h reported gust	0.62 (0.32 m s ⁻¹)	3.03 (1.56 m s ⁻¹)	2.49 (1.28 m s ⁻¹)	1.84 (0.95 m s ⁻¹)
Mean GF _h (=1.58)	None	5525	ASOS _m peak gust	-1.67 (-0.86 m s ⁻¹)	3.57 (1.84 m s ⁻¹)	3.05 (1.57 m s ⁻¹)	2.49 (1.28 m s ⁻¹)
Climatology _m (no skill)	Hour/season	59 329	ASOS _m peak gust	-0.12 (-0.06 m s ⁻¹)	6.02 (3.10 m s ⁻¹)	4.82 (2.48 m s ⁻¹)	3.61 (1.86 m s ⁻¹)

with MAE, mean bias, and standard deviation of 2.92 kt (1.5 m s⁻¹), 0.0 kt (0.0 m s⁻¹), and 2.33 kt (1.2 m s⁻¹), respectively, when added to $wspd_{fcst}$ in Eq. (3) would increase the MAE of a GF model by 2.16 kt (1.11 m s⁻¹). This mean wind forecast error component is larger than the MAEs of most GF models shown in Table 2.

Although the MAE is fairly small—less than 3 kt (1.54 m s⁻¹) for nearly all GF models, there are many cases for which errors are much larger. The MAE for the mean GF_m model is 1.40 kt (0.72 m s⁻¹), for example, but there are 1112 h during 2007–14 (1.9% of all hours analyzed) for which the absolute error exceeds 5 kt (2.6 m s⁻¹). These are typically hours for which particularly small or large GFs are observed (i.e., GF < 1.5 or GF > 2.0). Moreover, large differences in model performance are evident at times. For example, there are 202 h (3.7% of matched cases) when the difference in the absolute errors between the mean GF_m and mean GF_h models exceeds 5 kt (2.6 m s⁻¹) and 25 h (0.45%) when the difference exceeds 8 kt (4.1 m s⁻¹). These hours are typically characterized by large differences between ASOS_m and ASOS_h winds or gusts.

Even small performance differences among GF models may have both physical relevance and operational significance, because errors in gust forecasts may also include errors in wind speed estimation. In wind-energy applications, for example, an important factor in selecting a location for turbine placement is the wind-energy density, which is a measure of the total amount of power in a moving air mass and is proportional to the third power of the wind speed (Johnson and Erhardt 2016). Another example is building construction, in which wind loads on crane operations and partially completed structures may cause damage at speeds well below the design wind speed for the completed structure (Houghton 1985).

A further comparison of the mean GF_m and mean GF_h models lends insight into the impact of the restricted ASOS_h observation periods on GF model performance. The mean GF_m model exhibits an MAE of 1.40 kt (0.72 m s⁻¹) (Table 2). The mean GF_h model, which is based on GFs derived from the ASOS_h dataset with its 2 min h⁻¹ wind observing period and 10-min observing period for gusts, exhibits a larger MAE of 2.49 kt (1.28 m s⁻¹) when verified against ASOS_h reported gusts. The difference in the error distributions of these two models is statistically significant, providing evidence that GF models derived from the ASOS_m dataset perform better than models that are based on ASOS_h data. [In Atlanta, the mean GF_m model similarly outperformed the mean GF_h model, with MAEs of 1.97 kt (1.01 m s⁻¹) and 3.27 kt (1.68 m s⁻¹), respectively.] Moreover, the performance of the GF_h

TABLE 3. As in Table 2, but during hours for which gusts of 25 kt or greater were observed. Results are sorted by ascending mean absolute error.

Model	Stratification	n	Verification	Bias (kt)		Absolute error (kt)	
				Mean	σ	Mean	σ
GF _m	Wind speed; wind direction	4682	ASOS _m peak gust	-0.95 (-0.49 m s ⁻¹)	2.88 (1.48 m s ⁻¹)	1.92 (0.99 m s ⁻¹)	2.34 (1.20 m s ⁻¹)
GF _m	Wind direction	4682	ASOS _m peak gust	0.46 (0.24 m s ⁻¹)	3.16 (1.63 m s ⁻¹)	2.24 (1.15 m s ⁻¹)	2.28 (1.17 m s ⁻¹)
GF _m	Wind speed	4682	ASOS _m peak gust	-1.17 (-0.60 m s ⁻¹)	3.06 (1.57 m s ⁻¹)	2.25 (1.16 m s ⁻¹)	2.38 (1.22 m s ⁻¹)
GF _m	Hour/season	4682	ASOS _m peak gust	-0.01 (-0.01 m s ⁻¹)	3.30 (1.70 m s ⁻¹)	2.30 (1.18 m s ⁻¹)	2.36 (1.21 m s ⁻¹)
Climatology _m (no skill)	Hour/season	4682	ASOS _m peak gust	0.11 (0.06 m s ⁻¹)	2.93 (1.51 m s ⁻¹)	2.33 (1.20 m s ⁻¹)	1.78 (0.92 m s ⁻¹)
Mean GF _m (=1.74)	None	4682	ASOS _m peak gust	0.34 (0.17 m s ⁻¹)	3.32 (1.71 m s ⁻¹)	2.35 (1.21 m s ⁻¹)	2.36 (1.21 m s ⁻¹)
Mean GF _h (=1.58)	None	1759	ASOS _h reported gust	0.67 (0.34 m s ⁻¹)	3.60 (1.85 m s ⁻¹)	2.97 (1.53 m s ⁻¹)	2.13 (1.10 m s ⁻¹)
Persistence _m (no skill)	—	4682	ASOS _m peak gust	-1.49 (-0.77 m s ⁻¹)	4.17 (2.15 m s ⁻¹)	2.97 (1.53 m s ⁻¹)	3.28 (1.69 m s ⁻¹)
Mean GF _h (=1.58)	None	2766	ASOS _m peak gust	-2.07 (-1.06 m s ⁻¹)	4.00 (2.06 m s ⁻¹)	3.51 (1.81 m s ⁻¹)	2.82 (1.45 m s ⁻¹)

model is misleading. When verified against ASOS_m peak gusts, which describe the peak gust during the entire hour, the MAE increases by 22% to 3.05 kt (1.57 m s⁻¹).

The mean GF_h model thus suffers from an ill-posed formulation in which 1) GF_h derived from wind and gust observations sampled during very small subsets of each hour is considered to be representative of the overall climatological gustiness, 2) these GF_hs are used in Eq. (3) to predict the maximum gust that will occur during the entire forecast hour, and 3) with the ASOS_h dataset, verification of gust_{fcst} is only possible during the 10-min “reported gust” measurement period.

The GF_m model demonstrates skill in forecasting peak gusts: the mean GF_m model outperforms the no-skill persistence_m and climatology_m models (Table 2). The differences in error distributions between the mean GF_m and both no-skill models are statistically significant. The seasonal/hourly peak gust climatology composing the climatology_m model is shown in the appendix.

The GF_m-model performance exhibits statistically significant improvement when the gust factors used in Eq. (3) are stratified by meteorological variables, hour, and season (Table 2). Stratification by wind speed offers the largest improvement, followed by wind direction and hour/season. The best model performance occurs when the GF_m is doubly stratified by wind speed and direction. This improvement is expected, given the observed sensitivity of GFs to wind speed, surface roughness, and wind direction (Wieringa 1973; Powell et al. 2004; Harper et al. 2010; Masters et al. 2010; Pryor et al. 2014).

The GF models were also applied to a restricted evaluation period limited to hours for which gusts of 25 kt (12.9 m s⁻¹) or greater were observed (Table 3). During these gusty periods, the MAEs are larger and more variable, with mean bias ranging from -2.1 kt (-1 m s⁻¹) to 0.7 kt (0.4 m s⁻¹). The principal characteristics of the GF_m-model performance that were found with the unrestricted evaluation period (Table 2) were again found to be statistically significant: it is superior to the mean GF_h model; it demonstrates skill by outperforming persistence_m; its performance improves when stratified by wind speed, wind direction, and hour/season; and the best performance is achieved with a double stratification by both wind speed and wind direction. Not surprising, the climatology_m model exhibits a smaller MAE when the observation period is restricted to gusty conditions, because the associated climatology (not shown) has the same restriction.

4. Summary and conclusions

A climatology of gust factors was determined for Milwaukee using ASOS wind measurements from 2007

FIG. A1. Gust climatology for Milwaukee that is based on the (top) 1-min ASOS_m and (bottom) hourly ASOS_h datasets for 2007–14. Mean values are shown that are based on approximately 650 ASOS_m peak-gust and 95 ASOS_h reported gust observations during each hour and season. Standard deviations ranged from 5 to 7 kt (2.6–3.6 m s^{−1}) for ASOS_m peak gusts and from 2 to 5 kt (1.0–2.6 m s^{−1}) for ASOS_h reported gusts.

to 2014. Gust measurements are highly sensitive to the reporting criteria associated with the hourly ASOS_h dataset, which restrict the reporting of gusts to arbitrarily defined gusty periods occurring between minutes 43 and 52 of each hour. The reporting criteria produce the following artifacts in ASOS_h gust observations: 1) Gusts are infrequently reported in the ASOS_h hourly dataset; in Milwaukee, gusts were included in only 13% of all possible hours. 2) ASOS_h gusts are strongly biased toward higher wind speeds; gust climatologies determined using this dataset would therefore be positively skewed. The 10-min observation interval provides an additional bias in ASOS_h reported gusts, because the maximum gust during the hour normally occurs outside this interval. Even when the reporting criteria are met, therefore, the ASOS_h reported gusts underrepresent the actual peak gust. Gust factors determined from ASOS_h data are similarly affected. In Milwaukee, GFs determined using ASOS_h data are 9% smaller than those determined

from the higher-resolution ASOS_m dataset and do not provide a representative measure of climatological gustiness.

Using the higher-resolution, 1-min ASOS_m dataset, a climatology of GFs was established for Milwaukee with the following principal characteristics:

- 1) The mean GF is 1.74.
- 2) GFs are sensitive to wind speed, ranging from 1.91 to 1.64 during weak and strong winds, respectively.
- 3) GFs are sensitive to wind direction, used in this study as a proxy for surface roughness. GFs of 1.6–1.7 were associated with winds with a long fetch over Lake Michigan, whereas values up to 1.8 occurred with inland winds.
- 4) GFs exhibit moderate diurnal variability, likely associated with changes in wind speed.

A variety of GF models were also evaluated for Milwaukee. In such models, the peak gust is normally estimated by multiplying a GF by a wind speed forecast.

In this study, however, we replace the wind speed forecast with the observed wind speed during the forecast hour. When verified against observed peak gusts, the forecast errors are therefore entirely attributable to the GF model itself (i.e., to the representativeness of the GF in forecasting peak gusts). Forecast errors thus obtained are small, but model results are meaningful in a relative sense, providing insight on how to best maximize the performance of GF models.

The GF model evaluation for Milwaukee revealed the following:

- 1) Models using GFs derived from 1-min ASOS_m data perform better than those using hourly ASOS_h data.
- 2) GF models demonstrate skill in forecasting peak gusts, as compared with the no-skill models of climatology and persistence.
- 3) Model performance improves when GFs are stratified by wind speed, wind direction, hour, and season.
- 4) Double stratification by both wind speed and wind direction provides the best performance.
- 5) During particularly gusty conditions, the best performance occurs when GFs are doubly stratified by both wind speed and wind direction.

Our analysis suggests that GF models are a viable means of forecasting peak wind gusts. A limited analysis of similar wind and gust data for Atlanta suggests that the method may be generally applicable at other midlatitude locations. The GFs used in such models should be derived from wind and gust measurements that are free of data artifacts such as those present in the hourly ASOS_h dataset. Stratifying the GFs by controlling variables such as wind speed and direction offers a means of maximizing the performance of gust-factor models.

APPENDIX

Gust Climatology for Milwaukee

The 1-min ASOS_m peak gust climatology for Milwaukee, stratified by hour and season, is presented in Fig. A1. Early morning minima and afternoon maxima occur throughout the year, with the largest diurnal variation occurring during summer. Gusts are strongest during winter and spring and weakest during summer. Also shown is the corresponding climatology of hourly ASOS_h reported gusts, which exhibits little diurnal variability and larger, seasonally dependent mean values ranging from 19 to 23 kt (9.8–11.8 m s⁻¹). This difference in climatologies again reveals the large biases introduced by the ASOS_h sampling periods and reporting criteria on gust measurements.

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