Meteorologically Stratified Gust Factors for Forecasting Peak Wind Gusts across the United States

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ABSTRACT: Wind gusts are common to everyday life and affect a wide range of interests including wind energy, structural design, forestry, and fire danger. Strong gusts are a common environmental hazard that can damage buildings, bridges, aircraft, and trains, and interrupt electric power distribution, air traffic, waterways transport, and port operations. Despite representing the component of wind most likely to be associated with serious and costly hazards, reliable forecasts of peak wind gusts have remained elusive. A project at the University of Wisconsin–Milwaukee is addressing the need for improved peak gust forecasts with the development of the meteorologically stratified gust factor (MSGF) model. The MSGF model combines gust factors (the ratio of peak wind gust to average wind speed) with wind speed and direction forecasts to predict hourly peak wind gusts. The MSGF method thus represents a simple, viable option for the operational prediction of peak wind gusts. Here we describe the results of a project designed to provide the site-specific gust factors necessary for operational use of the MSGF model at a large number of locations across the United States. Gust web diagrams depicting the wind speed– and wind direction–stratified gust factors, as well as peak gust climatologies, are presented for all sites analyzed.

KEYWORDS: Atmosphere; Forecasting; Forecasting techniques; Wind effects

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Wind gusts are complex, small-scale weather phenomena that occur when high momentum air is brought to the surface. Due to their small spatiotemporal scale, however, neither gusts nor the relevant physical parameters associated with accompanying turbulent structures can be routinely measured via standard meteorological observing networks.

Gusts are common to everyday life and affect a wide range of interests including wind energy, structural design, forestry, and fire danger. Strong gusts are a common environmental hazard that can damage buildings, bridges, aircraft, and trains, and interrupt electric power distribution, air traffic, waterways transport, and port operations (Changnon 2009; Thalla and Stiros 2018; Jung and Schindler 2019; Teoh et al. 2019; Su et al. 2021). The risk of windstorm-related economic losses is of great interest to the insurance industry and local governments. Moreover, models of economic losses from wind damage are based on gust speeds, particularly for winter storms (Welker et al. 2016) and forest damage (Valta et al. 2019).

Despite representing the component of wind most likely to be associated with serious and costly hazards, reliable forecasts of peak wind gusts have remained elusive. Existing methods, recently summarized by Sheridan (2018), include physically based models involving postprocessing of numerical weather prediction output variables in light of physical reasoning concerning boundary layer turbulence, and statistical, data-driven methods employing extreme value statistics or empirical approaches. Unfortunately, the development and verification of gust forecast models is hindered by sampling and reporting protocols associated with both operational and archived wind observations (Harris and Kahl 2017).

A project at the University of Wisconsin–Milwaukee is addressing the need for improved peak gust forecasts with the development of the meteorologically stratified gust factor (MSGF) model. The MSGF model combines site-specific gust factors (the climatological ratio of peak wind gust to average wind speed) with wind speed and direction forecasts to predict peak wind gusts. A methodology for constructing the site-specific gust factors was presented by Harris and Kahl (2017). Gust factors, doubly stratified by wind speed and direction, were shown to provide the greatest utility in forecasting peak gusts. Peak gust forecasts are easily prepared by multiplying the gust factor by a wind speed forecast. When coupled with model output statistics (MOS) wind guidance and evaluated at 15 sites across the United States, the MSGF model showed skill in predicting peak gusts out to 72 h (Kahl 2020). The MSGF method thus represents a simple, viable option for the operational prediction of peak wind gusts.

Operational use of the MSGF model requires the construction of site-specific gust factors, a time- and data-intensive process requiring the acquisition, quality control, assembly, and processing of voluminous 1-min wind and gust observations. One-minute-resolution data must be used in order to avoid the sampling and reporting artifacts present in hourly data archives (Harris and Kahl 2017). These artifacts arise from operational protocols that restrict “hourly” wind reporting to wind speed and direction measured during only 2 min of each hour. Peak gust values, included only when reporting criteria are satisfied (NOAA 1998), correspond to measurements during only 10 min of each hour (Harris and Kahl 2017). At each site included in the Kahl (2020) MSGF model evaluation study, over 4,000,000 1-min observations were needed to construct archives of approximately 64,000 hourly gust factors over the 2010–17 period analyzed, with all minutes of each hour represented. Construction of these local, meteorologically stratified gust factors thus represents an obstacle to the adoption of the MSGF model by operational meteorologists.

Here we present the results of a project designed to provide the gust factors necessary for operational use of the MSGF model at a large number of locations across the United States. We also demonstrate how the gust factors, which on their own reveal interesting features of local gust climatologies, can be quickly combined with MOS or other wind forecast models to produce peak gust forecasts. All relevant data, including gust factors, local peak gust climatologies, and geospatial analyses of gust features, are available online at tinyurl.com/MSGFs.

Site locations

Using the procedures described by Kahl (2020), 1-min wind and gust measurements at 178 Automated Surface Observing System (ASOS) sites during 2010–17 were acquired, quality controlled, and assembled into archives of hourly wind speed, wind direction, and peak wind gust. Sites were chosen based on considerations of data quality and completeness, as well as a desire for broad geographical coverage. Where possible, locations with larger populations were emphasized. The hourly values represent average wind speed and direction, and peak gust measured *over the entire hour*, free of restrictive ASOS protocols (Harris and Kahl 2017).

At the 178 sites analyzed (Fig. 1) hourly wind speed, wind direction, and peak gust were thus determined for 81.3%–96.6% of the 70,128 possible reporting hours during the 8-yr period at each location. Individual years, months, and hours were well represented at all sites. Site details are provided online at tinyurl.com/MSGFs.

Maps of 95th and 99th percentiles of peak gusts throughout all months of the year are shown in Fig. 1. Great Plains sites tend to experience the highest peak gusts, although locally gusty areas are also noted at other locations including some Great Lakes and East Coast sites. Seasonal maps (Fig. 2) are largely consistent with previous gust climatologies (e.g., Letson et al. 2018; Gilliland et al. 2019), reflecting the seasonality of gust-producing weather phenomena including cyclogenesis and deep convection.

Gust webs

Hourly gust factors were determined for all sites and stratified by wind speed (0–5-, 5–10-, 10–15-, and >15-kt bins; $1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$) and wind direction (30° bins) combinations. “Meteorologically stratified” refers to this stratification.

The gust factors are presented as “gust web” diagrams that display mean values and occurrence frequencies for the 48 wind speed and direction stratifications. The gust webs, specific to each location, provide the means to forecast peak gusts using the MSGF model. Example gust webs for Waukegan, Illinois (KUGN) and Rapid City, South Dakota (KRAP) are shown in Fig. 3. At Waukegan, for example, a forecaster with MOS¹ guidance indicating ENE winds at 17 kt would multiply the forecast wind speed by the gust factor of 1.63 to obtain a peak wind gust forecast of 28 kt (Harris and Kahl 2017).

In addition to providing the gust factors necessary to utilize the MSGF model, the gust webs also reveal interesting details

Fig. 1. The (top) 95th and (bottom) 99th percentiles of peak gusts (kts) observed during 2010–17 during all months of the year. Circles represent locations for which meteorologically stratified gust factors and associated analyses are available. Site details and additional maps are provided at tinyurl.com/MSGFs.

¹ Application of the gust factor model requires wind speed and direction forecasts. MOS guidance is a common postprocessing product provided by many numerical weather prediction systems (e.g., Struzewska et al. 2016); however, any type of wind speed and direction forecast may be used with the MSGF model.

Fig. 2. The 99th percentiles of peak gusts (kts) observed during 2010–17 during meteorological seasons of (top left) winter, (top right) spring, (bottom left) summer, and (bottom right) autumn. Site details are provided at tinyurl.com/MSGFs.

of the local wind and gust climatologies. This is illustrated in Fig. 3, where the two examples shown present very different gust characteristics. At Rapid City (KRAP) the strongest winds (>15 kt) occur most frequently in the NW and NNW sectors, with gust factors of around 1.5. Strong winds from the WNW and WSW sectors are less frequent but gustier, with gust factors of around 1.7. At Waukegan (KUGN), located on the western shore of Lake Michigan, the directional dependence of gustiness is much more pronounced. Gust factors associated with strong winds (>15 kt) range from 1.61 to 2.31. This directional variability in gust factors is due in large part to site-specific heterogeneity in surface roughness (Suomi et al. 2013).

The directional dependence of gustiness may be quantified using a directional ratio (DR) statistic. We define the DR, which considers only winds ≥ 10 kt (the outer two rings of the gust web diagrams) as

$$DR = \frac{GF_{\max}}{GF_{\min}},$$

where $GF_{\max}$ and $GF_{\min}$ are the largest and smallest gust factors, respectively, among all 30° wind sectors. The DR values at most sites analyzed range from 1.0 to 1.2 (Fig. 4), indicating modest directional dependence of mean peak gust magnitude. At a few sites, however,

pronounced DR values as large as 1.5 are observed. Waukegan (KUGN) is one such site, with a DR of 1.44.

Sites such as Waukegan exemplify the utility of the MSGF model in forecasting peak wind gusts at coastal or mountain/valley locations with highly directionally dependent scenarios. For example, an operational meteorologist equipped with MOS guidance for Waukegan indicating winds of 17 kt would combine that guidance with the KUGN gust web (Fig. 3) to prepare a peak gust forecast. If the expected wind direction is WSW (GF = 2.31) the peak gust forecast is 39 kt. If the guidance indicates a wind direction of SSW (GF = 1.61), the peak gust forecast would be 27 kt.

Local peak gust climatologies

Peak gust climatologies for the same 2010–17 analysis period, stratified by hour and season, were also prepared for each of the 178 sites analyzed and are readily available on the website (tinyurl.com/MSGFs). Like the gust webs, these hourly and seasonal analyses reveal interesting characteristics of the local gust climates and can provide forecasters with situational awareness concerning gusts. Examples for Fresno, California (KFAT), and Portland, Oregon (KTTD), are shown in Fig. 5. These climatologies reveal that summer is the gustiest season in Fresno, with average peak gusts reaching nearly 15 kt. Peak gusts tend to be weakest during winter. In Portland, on the other hand, peak gusts tend to be strongest in winter and weakest in summer. Curiously, the diurnal variation in mean peak gusts is nearly absent during winter at Portland, although standard deviations (not shown) are largest during this season.

Conclusions

Here we present the results of a project designed to provide the gust factors necessary for operational use of the meteorologically stratified gust factor (MSGF) model at a large number

Fig. 3. Gust webs showing meteorologically stratified gust factors at (top) Waukegan, Illinois (KUGN) and (bottom) Rapid City, South Dakota (KRAP). The concentric rings represent mean wind speed ranges of 0–5 (center), 5–10, 10–15, and >15 kt (outermost). The radial lines represent the boundaries of 30° wind sectors, clockwise from north as per meteorological convention. The symbols represent the occurrence frequencies of mean wind speed and direction combinations. Similar gust factors at many additional sites are provided at tinyurl.com/MSGFs.

of locations across the United States. Using this model, peak gust forecasts are easily prepared by multiplying a site-specific gust factor by a wind speed forecast. Determination of these gust factors is a significant undertaking, requiring multiyear analyses of millions of 1-min wind observations at each site in order to avoid the sampling and reporting artifacts present in hourly data archives. In addition to their operational significance, these data have the potential to expand our understanding of peak gusts and our ability to predict them.

The MSGF model has been shown to be skillful in predicting peak gusts out to 72 h (Kahl 2020) and is thus a viable option for the operational prediction of peak wind gusts, particularly at locations with strongly directionally dependent gust scenarios. Gust factors and peak gust climatologies for all sites analyzed, provided at tinyurl.com/MSGFs, allow the

Fig. 4. Directional ratio (DR), which quantifies the directionality of gustiness (see text for details), considering measurements during all months. Seasonal DR maps are available at tinyurl.com/MSGFs.

Fig. 5. Peak gust climatology for (top) Fresno, California (KFAT), and (bottom) Portland, Oregon (KTTD), stratified by hour and meteorological season.

MSGF model to be applied at 178 locations across the United States. Application of the model at other locations is also possible but would require the preparation of gust factors utilizing the procedures outlined by Kahl (2020). Future work will address MSGF model performance during specific types of gust-producing weather phenomena.

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