Gust Factors and Turbulence Intensities for the Tropical Cyclone Environment

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ABSTRACT

Gust factors are used to convert peak wind speeds averaged over a relatively short period (e.g., 3 s) to mean wind speeds averaged over a relatively long reference period (e.g., 1 h) or vice versa. Such conversions are needed for engineering, climatological, or forecasting purposes. In this paper, gust factors in tropical cyclone (TC) winds are estimated from Florida Coastal Monitoring Program (FCMP) observations of near-surface TC wind speeds representative of flow over the sea surface and over open flat terrain in coastal areas. Comparisons are made with gust factors in extratropical winds over open flat terrain that are available in the literature. According to the results of the study, for gust durations of less than 20 s, the Durst model underestimates, and the Krayer–Marshall model overestimates, gust factors of TC winds over surfaces with roughness specified in the American Society of Civil Engineers (ASCE) 7 Standard Commentary as typical of open terrain. Consideration should be given to these findings when updating the gust factors provided in the ASCE 7 Standard Commentary. The study also compares gust factors in TC winds obtained from FCMP data with gust factors in extratropical winds obtained from near-surface wind data collected at eight Automated Surface Observing System (ASOS) stations and concludes that, depending upon terrain roughness, gust factors in TC winds can be higher by about 10%–15% than gust factors in extratropical winds. The study also presents FCMP-based estimates of turbulence intensities and their variability and shows that turbulence intensities in TC winds increase as the terrain roughness increases. The longitudinal turbulence intensity can vary from storm to storm and can exceed its typical value by as much as 20%. It is recommended that future TC wind measurement campaigns obtain temperature data usable for stratification estimation purposes, as well as information on waves and storm surge upwind of the anemometer towers.

1. Introduction

The gust factor (GF) is defined as the ratio of the peak wind speed averaged over a short period to the mean wind speed averaged over a relatively long reference period. The GF is used to convert peak wind speeds averaged over a short period (e.g., 3 s) to mean wind speeds averaged over a relatively long reference period (e.g., 1 h) or vice versa. Such conversions are needed in engineering applications (e.g., for converting reference speeds used in the definition of pressure coefficients) or in climatology and forecasting (e.g., for converting peak wind speeds into sustained wind speeds or 10-min speeds).

A number of studies on gust factors have been reported in the literature. Based on wind measurements at Cardington, England, Durst (1960) derived a statistical relationship between maximum wind speeds averaged over various periods and the corresponding hourly mean wind speeds, for sites with open terrain exposure and flat topography. Based on the Digital Anemograph Logging Equipment (DALE) wind data from the Met Office, Ashcroft (1994) found values of gust factors in fair agreement with those obtained by Durst (1960). Using the statistical method described by Durst (1960), Krayer and Marshall (1992) compared gust factors derived from tropical cyclone (TC) wind records with those derived by Durst from extratropical wind records. They found that the ratio of the 2-s peak wind speed (i.e., peak wind speed averaged over 2 s) to the 10-min mean speed was on average about 1.55, as compared to the corresponding Durst value of 1.40, and that more than 80% of the observed gust factors were higher for TC winds than for extratropical winds. Differences between results obtained for weak and strong TC winds were not significant. Using wind data collected from both landfalling TCs and extratropical storms, Paulsen...
and Schroeder (2005) found that for terrains with the same roughness, mean gust factors for TC winds were higher than those for extratropical winds. Similar results had been presented by Schroeder and Smith (2003). However, according to Vickery and Skerlj (2005), gust factors in TC winds do not differ appreciably from those associated with extratropical winds [i.e., the conclusions reached by Krayer and Marshall (1992) are not valid]. Similarly, according to Sparks and Huang (2001), who used Automated Surface Observing System (ASOS) and Coastal Marine Automated Network (C-MAN) data, gust factors for inland stations in TC conditions are essentially the same as those in extratropical storms. The literature review indicates that to date no definitive conclusion has been reached regarding the relative magnitude of gust factors for TC and extratropical winds. Additional research is therefore necessary in support of climatological applications and future design provisions in codes and standards. This paper presents the results of such research.

The Florida Coastal Monitoring Program (FCMP), focused on investigating near-surface TC wind behavior and resulting wind loads on low-rise structures, has acquired near-surface wind measurements during TC passages. This study uses selected FCMP data to estimate gust factors and to compare them with those obtained by Durst (1960) and Krayer and Marshall (1992). The estimates are affected by small errors due to the anemometer response characteristics, which are such that high-frequency components of the turbulence are filtered out. These errors are estimated in the appendix to this paper. In addition, the study presents results of the effect of observational height, wind speed, and surface roughness length on the magnitude of the gust factor. The study also presents FCMP-based estimates of turbulence intensities and their variability.

The paper is organized as follows: section 2 describes methods for gust factor and turbulence intensity estimation. The estimation of the gust factor requires the estimation of the normalized standard deviation and of a peak factor, while the estimation of the turbulence intensity is based on the normalized standard deviation estimate for very small time averaging periods. Section 3 describes the TC wind speed measurements and wind speed characteristics. Section 4 focuses on the estimation of surface roughness lengths. Sections 5 and 6 describe the estimation of normalized standard deviations and turbulence intensities and of peak factors, respectively, and include comparisons with results available in the literature. Section 7 is devoted to the estimation of the gust factors and their variability, and to comparisons with available results. Section 8 presents the conclusions of this work.

2. Methods for gust factor and turbulence intensity estimation

Consider a record of length $T$ and, within that record, all the successive intervals of length $t$ such that $t < T$. Let $u_{\text{max}}(T, t)$ denote the largest of the mean wind speeds averaged over the intervals of length $t$, and let $U$ denote the mean wind speed averaged over the time period $T$ (see section 3). The gust factor for the record of length $T$ and the time intervals of length $t$ is defined as

$$GF(T, t) = \frac{u_{\text{max}}(T, t)}{U(T)}. \quad (1)$$

Wind engineers commonly use 2 or 3 s for $t$, and 10 min or 1 h for $T$. The current American Society of Civil Engineers (ASCE) 7 Standard (ASCE 2006) wind speed map uses wind speeds expressed in terms of the 3-s gust at 10-m height in open country terrain.

For a sample of a statistically stationary discrete stochastic process $x_i (i = 1, 2, \ldots, n)$, it is possible to define the sample mean $\bar{x}$, the sample normalized standard deviation (i.e., the ratio of the standard deviation and the mean, also referred to as the coefficient of variation) $SD_x$, and the sample peak $\text{max}(x_i)$. The following expression defines the peak factor $g$ of the process:

$$\text{max}(x_i) - \bar{x} = g \bar{x} SD_x.$$

Dividing the above expression by $\bar{x}$ yields

$$\frac{\text{max}(x_i)}{\bar{x}} - 1 = g SD_x \quad \text{or} \quad \text{max}(x_i) = \bar{x} + g SD_x.$$ \hspace{1cm} (2)

In the particular case of a wind speed record, the ratio on the left-hand side of this expression is defined as the gust factor, which can be similarly written in the form (Durst 1960; Wieringa 1973)

$$GF(T, t) = 1 + g(T, t) SD_u(T, t), \quad (3)$$

where $g(T, t)$ is the peak factor, and $SD_u$ is the normalized standard deviation, defined as

$$SD_u(T, t) = \frac{\sqrt{\sum_{i=1}^{N} u_{i}^2(t) / (N - 1)}}{U(T)}. \quad (4)$$

Where $u_i(t) (i = 1, 2, \ldots, N)$ are departures of the $N$ individual means over time $t$ from the mean wind speed $U(T)$ over a given observation period $T$, and $N = T / t$. For a segment with length $T$ of a stationary random signal, the peak factor is a measure of the difference between the largest of the $N$ individual means over time
t and the entire segment’s mean over time T. For short gust durations t, SD_u(T,t) is approximately equal to the turbulence intensity TI_u, that is,

$$T I_u = \sigma_u / U,$$

where \( \sigma_u \) is the standard deviation of the longitudinal wind velocity component. Equation (2) yields

$$g(T, t) = [G F(T, t) - 1] / S D_u(T, t).$$

Given the gust factor GF(T, t) and the normalized standard deviation SD_u(T, t), Eq. (5) defines the peak factor g(T, t). For the particular case of very small t, the peak factor is discussed by Mitsuta and Tsukamoto (1989).

Equation (3) with t = 0.2 s and T = 5 min was used by Schroeder and Smith (2003) for estimating TI_u. Furthermore, by replacing \( u' \) with \( v' \) and \( w' \) (the lateral and vertical wind fluctuation components) in SD_u(T, t), Eq. (4) can be used to evaluate the lateral turbulence intensity (TI_v) and vertical turbulence intensity (TI_w), respectively. The gust factor based on a set of records, each of which has length T, is defined as the mean of the respective gust factors GF(T, t). For that set of records a standard deviation (sd) may be calculated that reflects the variability of the gust factors based on the individual records of the set.

3. TC wind data measurements

This study uses surface wind data with 10-Hz resolution collected in real time during hurricane passages. Gill 200-27005 three-dimensional propeller anemometers at 5 and 10 m were used in conjunction with an R.M. Young vane wind monitor (05103V) at 10 m, which determined the direction of the mean wind speed. Dynamic characteristics of the anemometer’s four-blade polypropylene helicoid propellers include a 2.7-m 63% recovery distance constant and a damped natural wavelength of 7.4 m. Data collected were processed in real time by an orthogonalization routine to extract the \( u, v, \) and \( w \) components (Masters 2004). The anemometers were calibrated to follow the cosine law within 3% over the \( \pm 30^\circ \) range. In addition to the wind anemometry, the FCMP data acquisition system measures temperature, pressure, and humidity at the 3-m level (Masters 2004).

This study uses wind data collected during four hurricane passages, namely Hurricanes Gordon (2000), Isidore (2002), Lili (2002), and Ivan (2004). Five selected FCMP observation sites were located in coastal areas, as shown in Figs. 1 and 2. For each hurricane, FCMP tower names, locations, coordinates, position description, governing surface roughness estimated in section 4, recording times, and hourly and peak gust wind speeds are listed in Table 1. The FCMP tower locations and hurricane tracks are shown in Fig. 2.

Wind data collected from the five selected FCMP towers, denoted as Isidore, Gordon, Ivan-1, Ivan-2, and Lili, were preprocessed and only datasets satisfying quality-control requirements were used for this study. Data preprocessing and data quality control included 1) separate analysis of hourly record segments with overlapping 15-min segments; 2) decomposition of the records into longitudinal, lateral, and vertical components; 3) application of a 10 m s

3\(^{-1}\) mean wind speed minimum threshold at 10 m, assumed to correspond to neutral stability conditions; 4) removal of segments with direction shifts larger than 20° to avoid records in which wind speeds may correspond to more than one terrain exposure (Masters 2004); and 5) evaluation of the hourly segments for statistical stationarity by using the reverse arrangement test. Reverse arrangement tests were performed at the level of significance \( \alpha = 0.025 \) to identify candidates for elimination (Bendat and Piersol 2000). Since temperature data were collected only at 3-m elevation and no eddy heat flux data were available, assumption 3) was made on the basis of preliminary estimates (see, e.g., Simiu 1982) according to which, for the wind speeds listed in Table 1, deviations from the logarithmic profile would typically not exceed one or at most a few percentage points, depending on wind speed. For this reason, other researchers including Krayer and Marshall (1992) and Vickery and Skerlj (2005) also assumed neutral stability for wind speeds comparable to those considered in this paper. The comparisons between gust factors estimated in this study and those estimated by other researchers are therefore valid, despite the errors, which are believed to be small and inherent in the respective estimates. Nevertheless, in the authors’ opinion, future measurements should include temperature and eddy flux measurements, allowing a clear determination of actual stability conditions.

The wind direction was conventionally measured clockwise from the north as shown in Fig. 1. The mean wind speed increased with height for all four storms. Mean wind direction time histories are similar at the two different observation heights (5 and 10 m) for each of the five tower observations. Time histories of records selected for analysis are shown in Fig. 3. It is emphasized that, while the entire time histories shown in Fig. 3 are nonstationary, each of the 1-h segments selected for analysis satisfied the stationarity requirement.

4. Estimation of surface roughness lengths

If the upwind surface roughness changes at a fetch distance x upwind from the location of interest, an inner
Fig. 1. FCMP tower sites selected for analysis.
boundary layer (IBL) of height $d(x)$ develops above the surface for $x > 0$. The layer above the IBL is called the outer boundary layer (OBL). In the OBL, that is, at elevations $z(x) > d(x)$, the airflow is governed by the surface roughness upstream of the terrain roughness change, and the mean wind profile can be described by the logarithmic law in which the upstream surface roughness length is used (Bradley 1968). The mean wind

Table 1. FCMP tower names and locations, wind direction, recording times, wind speeds, and surface roughness.

<table>
<thead>
<tr>
<th>Hurricane name</th>
<th>Isidore</th>
<th>Gordon</th>
<th>Ivan-1</th>
<th>Ivan-2</th>
<th>Lili</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCMP tower names</td>
<td>T2</td>
<td>T3</td>
<td>T1</td>
<td>T2</td>
<td>T3</td>
</tr>
<tr>
<td>Coordinates (N,W)</td>
<td>(30°21'08&quot;, 87°10'25&quot;)</td>
<td>(28°03'41&quot;, 82°49'44&quot;)</td>
<td>(30°28'45.4&quot;, 87°11'12.8&quot;)</td>
<td>(30°28'21.0&quot;, 87°52'30.0&quot;)</td>
<td>(29°54'50&quot;, 91°45'35&quot;)</td>
</tr>
<tr>
<td>Descriptions</td>
<td>Gulf Breeze, FL; north of the sea coastline</td>
<td>Honeymoon Island, FL; northeast of the sea shoreline</td>
<td>Pensacola Regional Airport, FL</td>
<td>Fairhope, AL; north of the Fairhope Municipal Airport</td>
<td>Lydia, LA; flat open land with very few obstacles</td>
</tr>
<tr>
<td>Measurement period</td>
<td>2044 UTC 26 Sep–1136 UTC 26 Sep</td>
<td>1730 UTC 17 Sep–1250 UTC 17 Sep</td>
<td>2026 UTC 14 Sep–1800 UTC 14 Sep</td>
<td>0053–1505 UTC 16 Sep</td>
<td>0415 UTC 3 Oct–1802 UTC 4 Oct</td>
</tr>
<tr>
<td>Wind direction$^a$</td>
<td>(130°, 200°) CW$^b$</td>
<td>(180°, 290°) CW$^b$</td>
<td>(135°, 240°) CW$^b$</td>
<td>(50°, 300°) CW$^b$</td>
<td>(145°, 230°) CW$^b$</td>
</tr>
<tr>
<td>No. of hourly segments$^c$</td>
<td>34</td>
<td>18</td>
<td>37</td>
<td>41</td>
<td>27</td>
</tr>
<tr>
<td>Hourly wind speed (m s$^{-1}$)</td>
<td>12.1</td>
<td>14.7</td>
<td>11.1</td>
<td>15.8</td>
<td>11.5</td>
</tr>
<tr>
<td>Max</td>
<td>17.6</td>
<td>18.5</td>
<td>29.9</td>
<td>24.3</td>
<td>22.5</td>
</tr>
<tr>
<td>Mean</td>
<td>14.0</td>
<td>17.2</td>
<td>19.6</td>
<td>18.8</td>
<td>15.0</td>
</tr>
<tr>
<td>Std dev</td>
<td>1.69</td>
<td>0.7</td>
<td>5.3</td>
<td>2.5</td>
<td>3.4</td>
</tr>
<tr>
<td>3-s gust (m s$^{-1}$)</td>
<td>27.1</td>
<td>29.8</td>
<td>47.5</td>
<td>39.9</td>
<td>35.8</td>
</tr>
<tr>
<td>Surface roughness length (m)</td>
<td>0.0011</td>
<td>0.0002</td>
<td>0.0080</td>
<td>0.0116</td>
<td>0.0082</td>
</tr>
<tr>
<td>Max</td>
<td>0.0060</td>
<td>0.0014</td>
<td>0.0551</td>
<td>0.0497</td>
<td>0.0589</td>
</tr>
<tr>
<td>Mean</td>
<td>0.0027</td>
<td>0.0007</td>
<td>0.0222</td>
<td>0.0257</td>
<td>0.0248</td>
</tr>
<tr>
<td>Std dev</td>
<td>0.0013</td>
<td>0.0004</td>
<td>0.0121</td>
<td>0.0091</td>
<td>0.0147</td>
</tr>
<tr>
<td>Governing surface roughness</td>
<td>Sea surface</td>
<td>Sea surface</td>
<td>Open terrain</td>
<td>Open terrain</td>
<td>Open terrain</td>
</tr>
</tbody>
</table>

$^a$ Wind direction is measured clockwise from the north as shown in Fig. 1.
$^b$ CW: clockwise; (e.g., wind direction during Isidore T2 varies clockwise from 130° to 200°).
$^c$ Number of hourly segments (i.e., records of 1-h length) satisfying data quality-control requirements.
FIG. 3. Time histories of wind speed records at 10-m observation height selected for analysis.
speed within the lower part of the IBL, whose approximate height is \( \delta_{eq}(x) \approx x/100 \) (Simiu and Scanlan 1996, p. 71), can be described by the logarithmic law with the surface roughness length prevailing downwind of the roughness change. The upper part of the IBL consists of a transition zone in which the flow properties are intermediate between those prevailing in the OBL and the lower part of the IBL.

For Isidore and Gordon, wind passed from the sea to land. The maximum distance from the tower to the location of the terrain roughness change is \( x \approx 80 \) m for Isidore, and \( x \approx 180 \) m for Gordon (Fig. 1). The height of the IBL is approximately

\[
\delta(x) \approx 0.28z_{0r} \left( \frac{x}{z_{0r}} \right)^{0.8},
\]

where \( z_{0r} \) is the roughness length for the rougher surface (Wood 1982), assumed to be 0.03 m for open terrain. For Isidore, Eq. (6) yields \( \delta(x) \approx 4.6 \) m, that is, the anemometers are within the outer layer both at 5- and 10-m elevation, and the flow past both anemometers is governed by the sea surface roughness. For Gordon \( \delta(x) \approx 8.8 \) m, meaning that the 5-m elevation anemometer is within the transition zone of the IBL, whereas the 10-m anemometer may be assumed to be within the OBL, that is, the flow measured by the 10-m anemometer may be assumed to be governed by the sea surface roughness.

For Ivan-1, Ivan-2, and Lili, the homogeneous terrain has fetch larger than 1 km upwind of the location of interest, so \( \delta_{eq}(x) > 1000 \text{ m}/100 = 10 \) m, and the wind speeds at 5- and 10-m height may be assumed to be described by the logarithmic law with open terrain roughness length.

The flow features are influenced by the terrain roughness. Given the values of the longitudinal turbulence intensity \( (TI_u) \) at measurement height \( z \), the logarithmic law in neutral conditions can be used to estimate the surface roughness length \( z_0 \) as follows (Wieringa 1993):

\[
z_0 = \exp(\ln z - \sqrt{\beta} \cdot \kappa/TI_u),
\]

where \( \sqrt{\beta} = \sigma_u/u_* \) is the ratio of the standard deviation \( (\sigma_u) \) of the longitudinal wind component to the friction velocity \( (u_*) \) [Eq. (A2) can be used for the calculation of \( u_* \); \( \kappa \approx 0.4 \) is the von Kármán constant.

According to Lumley and Panofsky (1964), for a fully developed neutrally stratified flow within the surface layer, \( \sqrt{\beta} \) is a constant that can be assumed to be largely independent of the underlying terrain roughness. According to Deaves (1981), \( \sqrt{\beta} \approx 2.79 \) appears to describe adequately fully developed extratropical equilibrium flows over open terrain. The mean values of \( \sqrt{\beta} \) are 3.28 and 3.10 over water for Isidore and Gordon, respectively, and 3.38, 2.85, and 2.72 over open terrain for Ivan-1, Ivan-2, and Lili, respectively. Thus, values of \( \sqrt{\beta} \) obtained by the FCMP wind measurements can be higher than those proposed by Deaves (1981). In one of the three open terrain records, \( \sqrt{\beta} \) exceeds the typical value proposed by Deaves (1981) by about 20%. This variability is not surprising, and reflects the fact that, unlike certain fundamental universal constants (e.g., von Kármán’s constant), \( \sqrt{\beta} \) may well be a parameter whose values differ within limits from storm to storm.

In structural engineering applications, the variabilities inherent in this and other micrometeorological, climatological, aerodynamics, and mechanical parameters are recognized, and taken into account within a structural reliability framework. It is therefore appropriate to extract from measurements not only typical values of such parameters, but also information on their variability.

Based on near-surface wind measurements from the FCMP towers under strong wind conditions, the surface roughness lengths around the tower site were estimated by using Eq. (7). For sea surface (Isidore and Gordon), the surface roughness lengths vary from 0.0002 to 0.0060 m; for open terrain (Ivan-1, Ivan-2, and Lili), the surface roughness lengths vary from 0.0080 to 0.0589 m. Estimated mean surface roughness lengths around the tower sites are shown in Table 1. It is seen in Table 1 that the surface roughness is greater for Isidore than for Gordon. This may be due to differences between the wind and wave directions. Information on wave directions was not obtained for this study. To the extent that the requisite information might be available and could be obtained in the future, research aimed at understanding the reason for the higher surface roughness in the case of Isidore would be warranted. In view of the possible influence of wave direction on roughness length estimates, it is desirable that wave direction information be recorded in future hurricane wind measurement programs. The estimates of surface roughness lengths are used in sections 5-7.

### 5. Estimation of normalized standard deviation and turbulence intensity

Normalized standard deviations \( SD_u \) [Eq. (3)] are affected by surface roughness. Estimates of surface roughness lengths in section 4 were used to stratify the estimates of \( SD_u \) at 10-m height into four roughness regimes (RR), 0.0002 m \( \leq z_0 < 0.001 \) m (named RR1),
0.001 m \leq z_0 < 0.007 m \text{ (named RR2)}, \ 0.007 m \leq z_0 < 0.03 \text{ m (named RR3)}, \text{ and } 0.03 m \leq z_0 < 0.06 \text{ m (named RR4)}, \text{ which were also used for comparisons of peak factors in section 6 and gust factors in section 7. RR1 generally corresponds to marine exposure, RR2 to a mixture of marine and land, and RR3–RR4 to open land exposure [the ASCE Standard 7–05 (ASCE 2006) defines open terrain as having roughness lengths of about 0.01–0.15 m, with typical values of about 0.02 m]. Note that for the stations considered by Vickery and Skerlj (2005), locations having estimated roughness lengths between 0.02 and 0.07 m are treated as representative of open country terrain.}

Figure 4a presents estimated values of $SD_u$ at 10-m elevation for terrains with various surface roughness lengths. Results show that higher values of $SD_u$ correspond to rougher terrains.

Estimated values of $SD_u$ become fairly stable for gust durations $t$ less than approximately 1 s for each roughness regime, as shown in Fig. 4a. The estimated values decrease monotonically as $t$ increases, that is, the longer the averaging times $t$, the smaller are the departures $u'(t)$ from the respective means [see definitions following Eq. (3)]. For $t = 3600$ s the departure $u'(t)$ from the mean $U(t)$ vanishes, so $SD_u = 0$, as in Fig. 4a. In addition, the estimates of $SD_u$ were found to decrease as the observational height increases for gust durations $t < 10$ s, as shown in Fig. 4b. This is due predominantly to the increase of the mean speed $U(T)$ with height and the fact that fluctuations about the mean are almost constant with height for sufficiently small $t$. However, for large values of $t$ the values of $SD_u$ become increasingly smaller at both 10 and 5 m, while the number $N$ of

**Fig. 4.** (a) Estimated normalized standard deviation at 10-m observation height for various surface roughness lengths. (b) Ratios of the normalized standard deviations at 10-m observation height to those at 5 m [$SD_{u,10m}(1 \ h, t)/SD_{u,5m}(1 \ h, t)$] for various surface roughness lengths.
segments of duration $t$ decreases. For these two reasons the errors in the estimation of the ratios shown in Fig. 4b become increasingly large for larger $t$. Note that the records for Gordon were not considered in Fig. 4b, since for the 5-m elevation the anemometers were in the internal boundary layer’s transition zone, as indicated in section 4.

To compare observed values of $\text{SD}_u$ based on hourly mean wind speeds at 10-m elevation with those obtained by Durst (1960) and Krayer and Marshall (1992), the estimates of $\text{SD}_u$ over surface roughness regimes of 0.007–0.03 m (RR3) and 0.03–0.06 m (RR4) are plotted in Fig. 5. For RR3, estimated values of $\text{SD}_u$ are larger than those proposed by Durst for gust durations less than 3 s and are lower for gust durations larger than 3 s, as shown in Fig. 5. For RR4 the crossover value is about 35 s. Values of $\text{SD}_u$ obtained by Krayer and Marshall are larger than those obtained from the FCMP wind measurements.

As mentioned earlier, $\text{SD}_u(T,t)$ can be used to estimate the turbulence intensity for short gust durations $t$ and mean wind speeds over the observation period $T$. Equation (3) with $T = 60$ min and $t = 0.1$ s (corresponding to the sampling frequency of 10 Hz) was used for estimating the longitudinal, lateral, and vertical turbulence intensities ($\text{TL}_u$, $\text{TL}_v$, and $\text{TL}_w$). The turbulence intensity based on a set of hourly records is defined as the mean of the respective turbulence intensities. The estimates of the turbulence intensity and the turbulence intensity ratios at 10-m elevation are summarized in Table 2.

Turbulence intensities $\text{TL}_u$, $\text{TL}_v$, and $\text{TL}_w$ increase as the surface roughness increases. Estimates of $\text{TL}_u$ over sea (11.3% and 13.4%) are lower than those over flat open land (17.8% and 20.4%). The vertical turbulence intensity $\text{TL}_w$ has a similar pattern, and varies from 3.9% and 4.7% for sea surface to 7.1% and 8.5% for flat open land exposure. As noted earlier, it is the authors’ opinion that such variabilities are to be expected in TC flows.

The results show that $\text{TL}_u > \text{TL}_v > \text{TL}_w$ for each roughness regime. The mean ratios between the lateral and longitudinal turbulence intensities ($\text{TL}_v/\text{TL}_u$) vary from 0.73 to 0.89; the mean ratios between the vertical and longitudinal turbulence intensities ($\text{TL}_w/\text{TL}_u$) vary from 0.34 to 0.42, as shown in Table 2.

In estimating the vertical wind speed component the precision with which the towers are leveled in the field should be taken into account. For the FCMP towers, information on leveling precision was not available to the authors. The results concerning vertical turbulence components presented in this section should therefore be qualified accordingly. Leveling precision, if inadequate, can influence estimates of vertical turbulence, and should be recorded in future measurements.

### 6. Peak factor estimation and comparisons

Peak factors $g$ based on hourly mean wind speeds at 10-m height were estimated using Eq. (5) and plotted as functions of the gust duration for various surface roughness regimes in Fig. 6. The peak factors $g$ at different gust durations and surface roughness regimes are summarized in Table 3.
roughness regimes, as shown in Fig. 6. Estimated values of $g$ for TC winds over sea (Isidore and Gordon) are lower than those over flat land (Ivan-1, Ivan-2, and Lili) for gust durations less than 100 s, as shown in Fig. 6. Estimated values of the coefficient of variation (CV; defined as the ratio of the standard deviation to the mean) of the peak factor for 3-s gust duration are 0.104 and 0.110 for TC winds over sea and over open land, respectively.

For 10-m elevation, a comparison of observed values of $g(T = 3600 \text{ s})$ over surface roughness regimes of 0.007–0.03 m (RR3) and 0.03–0.06 m (RR4) with those obtained by other researchers is shown in Fig. 7. The results show that observed $g$ values are larger than those obtained by Durst (1960) and assumed by Krayer and Marshall (1992). The differences increase as the gust duration increases.

7. Gust factor estimation, comparisons, and variability

In this section, estimated TC gust factors for 5- and 10-m heights are evaluated with respect to varying roughness lengths. This section compares gust factors for TC and extratropical winds, as well as gust factors based on FCMP data with those obtained by other investigators.

a. Gust factor dependence on surface roughness length and observational height

For each record, the gust factor was estimated using Eq. (1). The gust factor based on a set of records, each of which has length $T$, is defined as the mean of the respective gust factors $GF(T, t)$. The estimated gust factors based on hourly mean wind speeds ($T = 1 \text{ h}$) at 10-m elevation are plotted in Fig. 8 for both sea surface
and open land. Gust factors are heavily dependent on terrain conditions. Higher values of the gust factor correspond to the rougher surface terrains, as shown in Fig. 8. Estimated values of gust factors over land ($0.007 \leq z_0 < 0.06$ m) are significantly higher than those over sea surface ($0.0002 \leq z_0 < 0.007$ m). For example, mean values of 3-s gust factors are 1.31, 1.41, 1.59, and 1.69 for roughness regimes RR1, RR2, RR3, and RR4, respectively. The dependence of the estimates of gust factors on surface roughness conditions is in agreement with the results of Ashcroft (1994) for extratropical winds and Schroeder and Smith (2003) for TC winds.

For the observational heights of 5 and 10 m, TC gust factors were estimated and plotted in Fig. 9. Results show that the values of gust factor decrease with increasing observation height. For example, for roughness regime $0.007 \leq z_0 < 0.03$ m, the 3-s gust factors are 1.64 and 1.59 for 5- and 10-m levels, respectively. Note also that the reduction of the gust factors as the height increases becomes smaller or vanishes for longer averaging times.

b. Gust factors for various TCs and mean wind speed regimes

Gust factors were estimated for each of the five FCMP tower sites. Figure 10 presents the resulting gust factor curves at 10-m elevation for different TC winds. Estimated values of gust factors obtained from Ivan-1, Ivan-2, and Lili (i.e., over open terrain) are significantly higher than those obtained from Isidore and Gordon (i.e., over sea surface). This is consistent with the observation that gust factors increase with upstream surface roughness. For winds over open land the estimated gust factors for Ivan-1, Ivan-2, and Lili are comparable, except for some slightly lower values resulting from Lili, as shown in Fig. 10.

For winds over sea surface (Isidore and Gordon), the estimated values of gust factors for Isidore are higher than those from Gordon. This can be attributed to a comparatively rougher surface for Isidore, since the estimated mean surface roughness length of 0.0027 m for Isidore is larger than the value 0.0007 m for Gordon (Table 1).

To investigate the effects of wind speed on the variation of gust factors of TC winds at 10-m elevation, the estimated gust factors were separated into four mean hourly wind speed regimes, $10 \leq U < 15$ m s$^{-1}$, $15 \leq U < 20$ m s$^{-1}$, $20 \leq U < 25$ m s$^{-1}$, and $25 \leq U < 30$ m s$^{-1}$. Figure 11 presents estimated values of gust factors at 10-m elevation for two mean hourly wind speed regimes for sea surface and four mean hourly wind speed regimes for open terrain. The estimated gust factors are comparable over different mean wind speed regimes, except that values of gust factors for $25 \leq U < 30$ m s$^{-1}$ are slightly lower than those obtained from other wind speed regimes for open terrain, as shown in Fig. 11b. For winds over sea surface (Isidore and Gordon) and over open land (Ivan-1, Ivan-2, and Lili), the estimated means and standard deviations of the gust factors corresponding to various mean hourly wind speed regimes are shown in Table 3.

The standard deviations reflect the variability of the gust factors based on the individual records of a set. Estimated values of CV of gust factors for wind over sea surface ranged from 0.026 to 0.048. The CV of gust factors for wind over open terrain ranged from 0.024 to 0.106.

**Fig. 8.** Gust factors at 10-m observation height for terrains with various surface roughness lengths.
c. Comparison of gust factors for TC and extratropical winds

This section includes estimates of gust factors in extratropical winds obtained from near-surface wind data collected by eight ASOS stations in 2004, as shown in Table 4, and compares them with gust factors associated with TC winds. This section also compares 5-s gust factors based on mean hourly extratropical wind speeds (Table 5) with results obtained from FCMP observations. The authors chose ASOS sites that appear to provide a reasonable sample, and the selection criteria excluded sites where mixed extratropical and tropical storms would occur. A threshold of 10 m s⁻¹ for hourly mean wind speed was employed for data quality control. There was no definitive way of estimating the roughness lengths, so the authors assumed a conventional open exposure value of 0.03 m for the roughness of the ASOS sites. Thunderstorm events were automatically removed, since for thunderstorms the peak gust factors (as defined in the paper and elsewhere) would have very large values—outliers—on account of the low mean hourly speeds. The ASOS reporting procedure provides 5-s peak gusts for every 1-min interval of the record; the mean hourly speed is the arithmetic mean of the 60 successive averages listed for each hour. A detailed explanation of ASOS 1-min near-surface wind data is included in DSI-6405 (NCDC 2006). Estimated 5-s gust factors based on mean hourly extratropical wind speeds vary from 1.40 to 1.50, as shown in Table 5. The 5-s gust factors obtained from FCMP TC winds are 1.54 and 1.64 for roughness regimes of 0.007 m ≤ z₀ < 0.03 m and 0.03 m ≤ z₀ < 0.06 m, respectively. Thus, for the 5-s gust factors, the estimated values associated with TC winds are higher than those associated with extratropical winds. For example, the gust factor in TC winds can be more than 10% higher than the gust factor associated with extratropical winds for the roughness regime of 0.007 m ≤ z₀ < 0.03 m, and more than 17% higher for the roughness regime of 0.03 m ≤ z₀ < 0.06 m.

From the results presented in Tables 5 and 6, the values of CV of gust factors can be evaluated. Estimated values of CV of 5-s gust factors for extratropical winds ranged from 0.067 to 0.108, showing low variability of gust factors analyzed using different segments. Estimated values of CV of 3-s gust factors for TC winds are 0.031, 0.035, 0.038, and 0.077, for roughness regimes RR1, RR2, RR3, and RR4, respectively. Estimated values of CV of 5-s gust factors for TC winds are 0.023, 0.029, 0.039, and 0.067, for roughness regimes RR1, RR2, RR3, and RR4, respectively. In view of the low CV values for TC winds, it can be stated that the mean value estimated for each roughness regime can be considered a useful measure of the gust factor for that regime. It is also noted that, both for 3- and 5-s gust factors, the estimated values of the CV increased with increasing terrain roughness, reflecting higher variability of the gust factors as the terrain roughness increases.

Figure 12 shows the histograms of 5-s gust factors for extratropical winds from two ASOS stations and for FCMP TC winds over the roughness regimes of...
FIG. 10. Gust factors at 10-m observation height for five TC records.

FIG. 11. Variation of gust factors with wind speed at 10-m observation height: (a) sea surface and (b) open terrain.
0.007 m \leq z_0 < 0.03 m and 0.03 m \leq z_0 < 0.06 m. The histograms of gust factors of extratropical winds from stations KCPR and KBIL are roughly similar, as shown in Fig. 12; both are clearly skewed. The mean values of 5-s gust factor are 1.40 and 1.42 for KCPR and KBIL, respectively. The mean values of 5-s gust factor are 1.54 and 1.64 for FCMP TC winds over the roughness regimes of 0.007 m \leq z_0 < 0.03 m and 0.03 m \leq z_0 < 0.06 m, respectively. For 0.007 m \leq z_0 < 0.03 m (RR3) the histogram is symmetrical, whereas for 0.03 m \leq z_0 < 0.06 m (RR4) the estimated skewness of the histogram is

\[ s = \frac{\sum_{i=1}^{23} (x_i - \mu)^3}{23 \sigma^3} \approx 0.75, \] (8)

where \( \mu \) and \( \sigma \) are, respectively, the sample mean and standard deviation, and the sample size is 23. The skewness may be due to the relatively small size of the sample, rather than being a reflection of population skewness. To check this assumption, 100 samples of size 23 were generated from a standard Gaussian distribution. Their skewness coefficients are plotted in Fig. 13, and indicate that under the assumption that the population is Gaussian the probability that a sample of size 23 from that population has a histogram with an absolute value of the skewness of about 0.75 is about 15%.

d. Comparison of estimated gust factors with results obtained by other investigators

1) OPEN TERRAIN WITH ROUGHNESS 0.007 M \leq z_0 < 0.03 M (REGIME RR3), 10-M ELEVATION

The estimated gust factor curve based on the in situ TC wind measurement data obtained from FCMP closely matches the Durst curve for gust durations larger than 20 s, but its ordinates are higher than those of the Durst curve for gust durations of less than 20 s, as shown in Fig. 14 and Table 7. The estimated values of the gust factor from the FCMP wind measurements are lower than those obtained by Krayer and Marshall (1992), as shown in Fig. 14. The 3-s gust factors based on hourly mean wind speed are 1.52, 1.59, and 1.66 for Durst (1960), FCMP TC winds, and Krayer and Marshall (1992), respectively (Table 7). The analysis by Masters (2004) of FCMP data obtained in nine tropical cyclones for terrain exposure with 0.02–0.04-m roughness length led to similar conclusions.

Table 3. Estimated means and std dev of gust factors at 10-m height for various mean hourly wind speed regimes. Gust factor estimated as a mean of the gust factors calculated for each of a set of wind speed records. The standard deviation reflects the variability of the gust factors based on the individual records.

<table>
<thead>
<tr>
<th>z (m)</th>
<th>Regime</th>
<th>Std dev</th>
<th>Mean</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007</td>
<td>5-s</td>
<td>0.062</td>
<td>1.465</td>
<td>1.436</td>
<td>1.418</td>
<td>1.382</td>
<td>1.335</td>
<td>1.291</td>
<td>1.256</td>
<td>1.202</td>
<td></td>
</tr>
<tr>
<td>0.03</td>
<td>5-s</td>
<td>0.063</td>
<td>1.444</td>
<td>1.418</td>
<td>1.400</td>
<td>1.370</td>
<td>1.326</td>
<td>1.271</td>
<td>1.244</td>
<td>1.200</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>5-s</td>
<td>0.181</td>
<td>1.708</td>
<td>1.667</td>
<td>1.633</td>
<td>1.584</td>
<td>1.509</td>
<td>1.425</td>
<td>1.392</td>
<td>1.324</td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>5-s</td>
<td>0.067</td>
<td>1.690</td>
<td>1.644</td>
<td>1.611</td>
<td>1.564</td>
<td>1.487</td>
<td>1.398</td>
<td>1.354</td>
<td>1.274</td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>5-s</td>
<td>0.058</td>
<td>1.687</td>
<td>1.644</td>
<td>1.618</td>
<td>1.572</td>
<td>1.494</td>
<td>1.395</td>
<td>1.356</td>
<td>1.256</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>5-s</td>
<td>0.070</td>
<td>1.642</td>
<td>1.603</td>
<td>1.581</td>
<td>1.529</td>
<td>1.467</td>
<td>1.369</td>
<td>1.322</td>
<td>1.215</td>
<td></td>
</tr>
</tbody>
</table>

* Number of 1-h-long segments for each wind regime.

Table 4. ASOS stations selected for analysis. Location indicator is assigned by the International Civil Aviation Organization (ICAO).

<table>
<thead>
<tr>
<th>No.</th>
<th>Station name</th>
<th>Location indicator</th>
<th>Station position</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natrona County International Airport</td>
<td>KCPR</td>
<td>42°53′51″N, 106°28′23″W</td>
<td>WY</td>
</tr>
<tr>
<td>2</td>
<td>Sheridan County Airport</td>
<td>KSHR</td>
<td>44°46′10″N, 106°58′08″W</td>
<td>WY</td>
</tr>
<tr>
<td>3</td>
<td>Billings Logan International Airport</td>
<td>KBIL</td>
<td>45°48′25″N, 108°32′32″W</td>
<td>MT</td>
</tr>
<tr>
<td>4</td>
<td>Great Falls International Airport</td>
<td>KGTF</td>
<td>47°28′24″N, 111°22′56″W</td>
<td>MT</td>
</tr>
<tr>
<td>5</td>
<td>Austin Straubel International Airport</td>
<td>KGRB</td>
<td>44°28′46″N, 088°08′12″W</td>
<td>WI</td>
</tr>
<tr>
<td>6</td>
<td>La Crosse Municipal Airport</td>
<td>KLSE</td>
<td>43°52′46″N, 091°15′24″W</td>
<td>WI</td>
</tr>
<tr>
<td>7</td>
<td>Bishop Airport</td>
<td>KBIH</td>
<td>37°22′16″N, 118°21′29″W</td>
<td>CA</td>
</tr>
<tr>
<td>8</td>
<td>Ely Airport</td>
<td>KELY</td>
<td>39°17′42″N, 114°50′43″W</td>
<td>NV</td>
</tr>
</tbody>
</table>
Table 5. The 5-s gust factors for extratropical winds from ASOS at 10-m elevation. Gust factor based on a set of records is defined as the mean of the respective gust factors. The standard deviation reflects the variability of the gust factors based on the individual records.

<table>
<thead>
<tr>
<th>ASOS stations</th>
<th>KCPR</th>
<th>KSHR</th>
<th>KBIL</th>
<th>KGTF</th>
<th>KGRB</th>
<th>KLSE</th>
<th>KBIH</th>
<th>KELY</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of segments</td>
<td>4969</td>
<td>1119</td>
<td>2008</td>
<td>3247</td>
<td>393</td>
<td>504</td>
<td>734</td>
<td>794</td>
</tr>
<tr>
<td>Gust factor</td>
<td>1.40</td>
<td>1.48</td>
<td>1.42</td>
<td>1.41</td>
<td>1.49</td>
<td>1.50</td>
<td>1.48</td>
<td>1.50</td>
</tr>
<tr>
<td>Std dev</td>
<td>0.10</td>
<td>0.16</td>
<td>0.12</td>
<td>0.11</td>
<td>0.10</td>
<td>0.11</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

2) Open terrain with roughness 0.03 m ≤ \( z_0 < 0.06 \) m (Regime RR4), 10-m ELEVATION

The ordinates of the estimated gust factor curve based on the in situ TC wind data obtained from FCMP are higher than those of the Durst curve, as shown in Fig. 14 and Table 7. The estimated values of the gust factor from the FCMP wind measurements are comparable to (i.e., only marginally higher than) those obtained by Krayer and Marshall (1992) for gust durations of less than 4 s, as shown in Fig. 14. The 3-s gust factors based on hourly mean wind speeds are 1.52, 1.69, and 1.66 for Durst (1960), FCMP TC winds, and Krayer and Marshall (1992), respectively.

The above results suggest that an upward adjustment of the Durst curve may be needed for evaluating the gust factors associated with TC winds over open terrain. For 0.007 m ≤ \( z_0 < 0.03 \) m, the degree of upward adjustment is lower than proposed by Krayer and Marshall (1992) (Fig. 14; Table 7): for peak 3-s gusts, the upward adjustment would be about 5%. However, for 0.03 m ≤ \( z_0 < 0.06 \) m the upward adjustment would be about 11%.

The measurement system mechanically filters the amplitudes of short wavelength gusts due to the response characteristics of the wind anemometer (Schroeder and Smith 2003). For this reason, the actual gust factor ordinates are slightly higher than those estimated from FCMP measurements. In view of the type of anemometry available at the time at which the data analyzed by Durst were recorded, this is assumed to be the case for the gust factors proposed by Durst as well. As shown in the appendix, for very short averaging times (e.g., \( t < 0.2 \) s), the gust factors estimated from FCMP records are lower than the actual gust factors by about 2% for flow over water and 4% for flow over open terrain. For longer averaging times these percentages decrease. These results reinforce the conclusion that the TC gust factors for periods of about 3 s should be larger than their counterparts for extratropical winds as proposed by Durst.

8. Conclusions

Using the near-surface wind measurements collected by FCMP towers (Isidore, Gordon, Ivan-1, Ivan-2, and Lili) during hurricane passages, this study presents estimates of gust factors, and of turbulence statistics, for TC winds over coastal areas. The conclusions are listed below:

1) For 10-m elevation over open exposure terrain, and for 0.007 m ≤ \( z_0 < 0.03 \), the Durst (1960) model yields gust factors lower than those based on the FCMP data for gust durations less than 20 s, and closely matches those based on the FCMP data for gust durations larger than 20 s; for 0.03 m ≤ \( z_0 < 0.06 \) m, the Durst model yields gust factors lower than those based on the FCMP data for all gust durations.

2) For 10-m elevation over open exposure terrain, and for 0.007 m ≤ \( z_0 < 0.03 \) m, the FCMP data yield gust factors lower than those based on the Krayer and Marshall (1992) model for gust durations lower than about 500 s; for 0.03 m ≤ \( z_0 < 0.06 \) m, the FCMP data yield gust factors that do not differ significantly from those based on the Krayer and Marshall (1992) model for gust durations of 3 s to about 400 s.

3) Estimated values of 5-s gust factor associated with TC winds based on FCMP data are higher than those associated with nonhurricane winds obtained from eight ASOS stations; for winds over roughness regimes of 0.007 m ≤ \( z_0 < 0.03 \) m and 0.03 m ≤ \( z_0 < 0.06 \) m, TC gust factors can be more than 10% and 17% higher, respectively, than the extratropical wind gust factors.

4) The dependence of the estimates of gust factors on upstream surface roughness conditions is in agreement with the results of Ashcroft (1994) and Schroeder and Smith (2003). Values of gust factors of TC winds at 5-m elevation were larger than those at 10-m elevation.

Table 6. Gust factors for TC winds from FCMP at 10-m elevation for RR1 (0.0002 m ≤ \( z_0 < 0.001 \) m), RR2 (0.001 m ≤ \( z_0 < 0.007 \) m), RR3 (0.007 m ≤ \( z_0 < 0.03 \) m), and RR4 (0.03 m ≤ \( z_0 < 0.06 \) m). Gust factor based on a set of records is defined as the mean of the respective gust factors. The standard deviation reflects the variability of the gust factors based on the individual records.

<table>
<thead>
<tr>
<th>Roughness regime</th>
<th>RR1</th>
<th>RR2</th>
<th>RR3</th>
<th>RR4</th>
<th>RR1</th>
<th>RR2</th>
<th>RR3</th>
<th>RR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gust factor</td>
<td>1.31</td>
<td>1.41</td>
<td>1.59</td>
<td>1.69</td>
<td>1.29</td>
<td>1.37</td>
<td>1.54</td>
<td>1.64</td>
</tr>
<tr>
<td>Std dev</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.13</td>
<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>No. of segments</td>
<td>18</td>
<td>34</td>
<td>82</td>
<td>23</td>
<td>18</td>
<td>34</td>
<td>82</td>
<td>23</td>
</tr>
</tbody>
</table>
FIG. 12. Histograms of 5-s gust factors based on hourly wind speeds at 10-m observation height.
The stationarity of the hourly record segments analyzed in this study was checked by the reverse arrangements test at the level of significance $\alpha = 0.025$. It has been assumed throughout the paper that the flow stratification is neutral. Owing to the absence of measurements of eddy heat flux and of temperatures for at least two elevations, this assumption could not be verified by using actual data. Preliminary estimates for typical flows available in the literature suggest that the results of this study are not affected significantly by the assumption of neutral stratification of the flows. Other researchers, including Kray and Marshall (1992) and Vickery and Skerlj (2005), also assumed neutral stability for wind speeds comparable to those considered in this paper. Thus comparisons with results of other researchers are not affected significantly by errors inherent in the neutral stratification assumption. However, it is the authors’ opinion that measurements needed to estimate the stratification of TC flows should be obtained in the future so that the influence of stability on TC gust factors can be studied in detail. In addition, we note that, while information on the extent to which storm surge and wave patterns may have changed the coastal interface and affected the ocean surface roughness was not available for this work, such information should be recorded in future measurement campaigns.

Acknowledgments. The authors are grateful to the Florida Coastal Monitoring Program (FCMP) for providing hurricane wind measurements for this study; Dr. Forrest James Masters, for providing information on the FCMP anemometer system and introducing Bo Yu to boundary layer meteorology science during the preliminary stages of his Ph.D. work; Dr. Emil Simiu for useful exchanges; and the reviewers for their constructive and helpful comments.

APPENDIX

Corrections to Gust Factor Estimates

Owing to their response characteristics, the Young anemometers filter out short wavelength gusts (Schroeder and Smith 2003). Ordinates of spectra $S_u$ estimated from

![Figure 13: Skewness coefficient for 100 samples of size 23 generated from a Gaussian distribution.](http://journals.ametsoc.org/jamc/article-pdf/48/3/534/3552024/2008jamc1906_1.pdf)

**FIG. 13.** Skewness coefficient for 100 samples of size 23 generated from a Gaussian distribution.

<table>
<thead>
<tr>
<th>$T$(s)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durst (1960)</td>
<td>1.56</td>
<td>1.54</td>
<td>1.52</td>
<td>1.48</td>
<td>1.43</td>
<td>1.37</td>
<td>1.32</td>
<td>1.25</td>
</tr>
<tr>
<td>Krayer and Marshall (1992)</td>
<td>1.73</td>
<td>1.69</td>
<td>1.66</td>
<td>1.62</td>
<td>1.55</td>
<td>1.47</td>
<td>1.42</td>
<td>1.32</td>
</tr>
<tr>
<td>FCMP: RR3</td>
<td>1.66</td>
<td>1.62</td>
<td>1.59</td>
<td>1.54</td>
<td>1.47</td>
<td>1.38</td>
<td>1.33</td>
<td>1.26</td>
</tr>
<tr>
<td>FCMP: RR4</td>
<td>1.79</td>
<td>1.73</td>
<td>1.69</td>
<td>1.64</td>
<td>1.57</td>
<td>1.47</td>
<td>1.43</td>
<td>1.35</td>
</tr>
</tbody>
</table>

TABLE 7. Comparison of gust factors based on Durst, Krayer and Marshall, and FCMP TC winds at 10-m elevation. RR3: (0.007–0.03 m); RR4: (0.03–0.06 m).
FCMP records are therefore lower at reduced frequencies \( f = nz/U \), larger by about 0.2 than their Kaimal spectra \( S^K_u \) counterparts, which represent approximately spectra based on Kolmogorov theory validated by careful measurements (Busch et al. 1968, p. 580; Teunissen 1970, p. 27; Simiu and Scanlan 1996, section 2.3.3). For this reason, the actual turbulence intensity and gust factors are higher than their FMCP-based counterparts by amounts estimated in this appendix.

The ratio of the corrected estimate of the longitudinal turbulence intensity to the estimated turbulence intensity based on FCMP records is

\[
\gamma_{TI} = \frac{\left( \int_0^\infty S^L_u \frac{dn}{u^2_z} + \int_m^{n_1} \frac{S^K_u}{u^2_z} \frac{dn}{m} \right) \sqrt{\int_0^\infty S^L_u \frac{dn}{u^2_z}}}{\sqrt{\int_0^\infty S^K_u \frac{dn}{u^2_z}}},
\]

(A1)

where \( n \) is the frequency (Hz), \( U \) is the mean wind speed (m s\(^{-1}\)), and \( z \) is the height above ground (m), and where it is assumed that \( n_1 = 0.2U/z \). The friction velocity \( u_* \) is defined as

\[
u_* = (\overline{u^'w^2} + \overline{v^'w^2})^{1/4},
\]

(A2)

where \( u^' \), \( v^' \), and \( w^' \) are the longitudinal, lateral, and vertical wind fluctuation components, respectively. The expression for \( S^K_u \) is (Kaimal et al. 1972)

\[
\frac{nS^K_u(n)}{u^2_z} = \frac{105f}{(1 + 33f)^{\frac{5}{3}}}.
\]

(A3)

Given the values of turbulence intensity \( TI^F \) estimated from the FCMP records, the corrected turbulence intensity \( TI^A \) is

\[
TI^A = TI^F \gamma_{TI}.
\]

(A4)

The peak factors \( K^A \) can be estimated by the expression

\[
K^A = [2 \ln (\nu^A T)]^{1/2} + 0.577/[2 \ln (\nu^A T)]^{1/2}
\]

(A5)

(see, e.g., Simiu and Scanlan 1996, 639–640). The mean upcrossing rate \( \nu^A \) has the expression

\[
\nu^A = \left( \frac{\left( \int_0^\infty n^2 S^A_u \frac{dn}{n^2} \right)^{1/2}}{\left( \int_0^\infty S^A_u \frac{dn}{n^2} \right)^{1/2}} \right)
\]

(A6a)

\[
\nu^A = \left( \frac{\left( \int_0^\infty n^2 S^A_u \frac{dn}{n^2} \right)^{1/2}}{\left( \int_0^\infty S^A_u \frac{dn}{n^2} \right)^{1/2}} \right)^{1/2},
\]

(A6b)

where \( T \) is the observation period in seconds (in this case 3600 s).

Peak factors \( K^F \) based on FCMP records can be estimated by

\[
K^F = [2 \ln (\nu^F T)]^{1/2} + 0.577/[2 \ln (\nu^F T)]^{1/2}
\]

(A7)

We can now write the ratio, for short averaging times (say 0.2 s), of the corrected estimate of the gust factor to the estimated value based on FCMP records:

\[
\nu^F = \left( \int_0^\infty n^2 S^F_u \frac{dn}{n^2} \right)^{1/2}
\]

(A8)


\[ \gamma_{GF} = \frac{GF^A}{GF^F} = \left(1 + \frac{\bar{K}^A T^A}{\bar{K}^F T^F}\right) / \left(1 + \frac{\bar{K}^A}{\bar{K}^F T^F}\right). \]  

(A9)

Estimates of surface roughness lengths in section 4 were used to stratify the computational results into four roughness regimes (RR), 0.0002 m ≤ \( z_0 \) < 0.001 m (named RR1), 0.001 m ≤ \( z_0 \) < 0.007 m (named RR2), 0.007 m ≤ \( z_0 \) < 0.03 m (named RR3), and 0.03 m ≤ \( z_0 \) < 0.06 m (named RR4).

The peak factor and turbulence intensity, for \( t = 0.1 \) s and \( T = 3600 \) s, are shown in Table A1 for both the FCMP and the corrected case. Also shown in Table A1 are the respective gust factors. It is seen that the corrected gust factors are about 2% and 4% higher than those obtained from the FCMP wind measurements for sea surface and open land, respectively. Since the contribution of the high-frequency fluctuations to the gust factor decreases as the averaging time for the gust factor increases, it is concluded that the gust factors estimated from FCMP data in the body of the paper are lower than the actual gust factors by less than about 2% for flow over water and 4% for flow over open terrain.

### REFERENCES


