Measurements of Overwater Gust Factor From NDBC Buoys During Hurricanes

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Abstract

Simultaneous measurements of wind speed at 10 m ($U_{10}$), peak gust ($U_{gust}$), significant wave height and dominant wave period recorded by four NDBC buoys since 1985 for $U_{10}\ \$\ 20$ m/s during hurricanes have been analyzed. It is found that under the conditions of near-neutral stability and non-fully developed seas, the gust factor (i.e., $U_{gust} / U_{10}$) is 1.25 ± 0.05 and the ratio of friction velocity ($u_*$) to $U_{10}$ (i.e., $u_* / U_{10}$) is 0.05 ± 0.005. Since both coefficients of variation are within 10%, several applications for operational use in air-sea interaction are provided. In addition, the gust factor at 5 m above the sea surface is found to be 1.27 ± 0.04.

## 1. Introduction

In extreme wind analysis, according to Atkinson (1971), it is important to distinguish between the highest sustained wind speeds and the peak gusts. The sustained wind speed is the mean wind speed over some averaging period while the peak gust is the highest value recorded by the anemometer. The gust factor is the ratio of peak gust to sustained speed. Typically the gust factor can be 50% for inland stations and 20% for offshore (due to less friction).

The National Data Buoy Center (NDBC), an agency within the National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), has deployed several buoys in the Gulf of Mexico and Caribbean Sea with wind measurements at 10 m, $U_{10}$, along with wind gust measurement, $U_{gust}$. The averaging period for $U_{10}$ is 8 minutes and the period for gust is 5 seconds. For more details, see www.ndbc.noaa.gov.

Since 1985 in the Gulf of Mexico and 2005 in the Caribbean Sea, the NDBC has archived hourly records of $U_{10}$, $U_{gust}$, $H_s$ (significant wave height), and $T_p$ (dominant wave period) along with other parameters. It is the purpose of this report to evaluate the characteristics of overwater gust factor and their applications.

## 2. Measurements

In air-sea interaction, when $U_{10}\ \$\ 20$ m/s, saturation of breaking waves prevails (Amorocho and DeVries, 1980) , resulting in $u_* / U_{10} = 0.0504$ where $u_*$ is the friction velocity. According to Emanuel (2003), at the extreme wind speeds encountered in hurricanes, the sea surface becomes enveloped in spray and spume, to the extent that the transition between air and water begins to resemble an emulsion, with bubble-filled water gradually transitioning to spray-filled air. In short, the wind is dragging the foam and spray in addition to the physical sea surface. Because of these reasons, all data associated with $U_{10} \geq 20$ m/s are retained for this analysis. Table 1 summarizes the data sets used in this study. Note that 41% of the total samples were obtained in the year 2005 because of Hurricanes Katrina, Emily, and Wilma. It is interesting to note that the eastern Gulf of Mexico (represented by buoy 42003) is the much more frequent location for $U_{10} \geq 20$ m/s than the central (42001) and western (42002) Gulf. Table 1 shows that there are 191 hourly data (or samples) available for further analysis.

3. Analysis

In wind-wave interaction, one must first classify whether or not the seas are fully developed. According to Taylor and Yelland (2001), for deep water and fully developed seas,

$$H_s = 0.0248\, U_{10}^2 \tag{1}$$

and

$$T_p = 0.729\, U_{10} \tag{2a}$$

or

$$\frac{C_p}{U_{10}} = 1.14 \tag{2b}$$

where $C_p$ (= $gT_p / 2\pi$ in which g is the gravitational acceleration) is the phase speed at the peak of the wave spectrum. Eq. (2b) states that the waves are barely outrunning the 10 m wind and has been used as a criterion for fully developed seas (see Csanady, 1999, p. 65). Note that $C_p / U_{10}$ also represents the wave age.

According to Hsu (1974), the sea-surface roughness can be a function of wave steepness (or slope) ($H_s / L_p$) where $L_p = g\, T_p^2 / 2\pi$ is the wavelength. Therefore, for fully developed seas, according to Eqs. (1) and (2),

$$\frac{H_s}{L_p} = 0.0299 \tag{3}$$

Thus, in order to minimize the swell effect, we further retain the hourly records when $H_s / L_p \geq 0.0300$ which reflects the "pure" wind and wave interaction. This requirement reduces the 191 samples down to 136.

Another effect is the stability. In the atmospheric boundary layer the buoyancy length scale, L, also known as the Obukhov (or Monin-Obukhov) length, is a fundamental parameter that characterizes the "stability" of the surface layer (see, e.g., Hsu, 1988). L describes the relative importance between the buoyancy effect (or thermal turbulence) and the wind shear (or mechanical turbulence). According to Hsu and Blanchard (2004), L can be parameterized as follows:

For unstable conditions (i.e., when $T_{sea} > T_{air}$),

$$\frac{z}{L} = -\frac{1000\left(T_{sea} - T_{air}\right)\left(1 + \frac{0.07}{B}\right)}{\left(T_{air} + 273.2\right) U_z^2} \tag{4}$$

For stable conditions ($T_{air} > T_{sea}$),

$$\frac{z}{L} = \frac{620\left(T_{air} - T_{sea}\right)}{\left(T_{air} + 273.2\right) U_z^2} \tag{5}$$

According to Hsu (1998 and 1999),

$$B = 0.146\left(T_{sea} - T_{air}\right)^{0.49} \tag{6}$$

where z is the height normally set to 10 m, $T_{air}$ and $T_{sea}$ stand for the air and sea temperatures, respectively; $U_z$ is the wind speed at height z, and B is the Bowen ratio.

According to Smith (1980), neutral stability at the air-sea interface exists if $-0.1 < z / L < 0.05$. Because all data as retained satisfy this criterion, we say these 136 samples were in near-neutral stability at the air-sea interface (within 10 m above the sea surface).

According to Hsu (1988) and Taylor and Yelland (2001),

$$U_{10} = \frac{u_*}{\kappa} \ln \frac{Z}{Z_0} \tag{7}$$

$$Z_0 = 1200\, H_s \left(\frac{H_s}{L_p}\right)^{4.5} \tag{8}$$

where $\kappa$ (= 0.4) is the von Karman constant and $Z_0$ is the roughness parameter. With the simultaneous measurements of $U_{10}$, $U_{gust}$, $H_s$, and $T_p$, we can now compute $u_*$, which plays an important role in air-sea interaction.

## 4. Results

Our results are shown in Figs. 1 and 2 for the variations of $U_{gust}$ and $u_*$ against $U_{10}$, respectively. The coefficient of determination, $R^2$, is also included in each figure. Note that $R^2$ is the ratio of the explained variation to the total variation. Since in both figures, $R^2$ is high, the ratio of $U_{gust} / U_{10}$ and $u_* / U_{10}$ should be near constant. Hence, we apply the statistical mean and standard deviation of the data such that for $20 < U_{10} < 50$ m/s ($45 < U_{10} < 112$ mph)

$$G = 1.25 \pm 0.045 \tag{9}$$

and

$$\frac{u_*}{U_{10}} = 0.051 \pm 0.0046 \qquad \textbf{(10)}$$

Note that since the coefficients of variation (i.e., the ratio of standard deviation to the mean) for both Eqs. (9) and (10) are within 10%, which are also within the field accuracy of the wind measurements for both speed and gust (see NDBC's website), we can say that Eqs. (9) and (10) can be used operationally.

In order to compare the above grand means and the regression equations provided in Fig. 1 for G at 10 m and Fig. 3 for G at 5 m, Tables 2 and 3 are provided. It can be seen that the differences are very small. Therefore, we recommend use of the simpler mean values rather that the derived regressions.

From Eq. (10) we have

$$C_d = \left( \frac{u_*}{U_{10}} \right)^2 = 2.6 \ x \ 10^{-3} \qquad \textbf{(11)}$$

where $C_d$ is the drag coefficient. Since the ratio of $u_* / U_{10}$ provided by Amorocho and DeVries (1980) and Eq. (10) are nearly identical, we can say that under breaker saturation conditions, when $U_{10} \geq 20$ m/s, the drag coefficient is independent of $U_{10}$ as given in Eq. (11). This result is consistent with the theory of Emanuel (2003), GPS sonde data in various hurricanes (Powell et al., 2003), and the numerical modeling by Moon et al. (2004).

5. Applications

a. Power-law Wind Profile

In the atmospheric surface boundary layer which extends from the surface up to a few hundred feet, the wind speed generally increases with height. Operationally, the power-law wind profile is often used (e.g., Panofsky and Dutton, 1984)

$$V_2 = V_1 \left( \frac{Z_2}{Z_1} \right)^P \qquad \textbf{(12)}$$

and according to Hsu (1988),

$$P = \frac{u_*}{\kappa \, U_{10}} \qquad \textbf{(13)}$$

where $V_1$ is the reference (or known) wind speed (e.g., from a buoy) at the known height of $Z_1$ (e.g., 5 or 10 m), $V_2$ is the wind speed needed at the height of $Z_2$, and P is the exponent of this power-law profile. Now, substituting Eq. (10) into (13) and setting $\kappa = 0.4$, we get P = 0.128. Since NDBC has numerous buoys with $Z_1 = 5$ m rather than 10 m, we can now adjust those data to 10 m such that

$$V_{10m} = U_{5m}\left(\frac{10}{5}\right)^{0.128} = 1.09\,U_{5m} \tag{14}$$

Using Eq. (14), one can investigate the gust factor at 5 m above the sea surface. This is accomplished as follows: NDBC buoy 42040 was selected because it encountered Hurricanes Earl and Georges in September 1998, Ivan in September 2004 and Katrina in August 2005. Next we retain all $U_5 \geq 18$ m/s during these hurricanes and perform the same quality assurance steps for wave and stability effects as discussed previously. The result is shown in Fig. 3. With 56 samples retained for the final analysis, it is found that

$$U_{5\,gust} = 1.25\,U_5 + 0.40 \tag{15}$$

with $R^2 = 0.95$. Since $R^2$ is high, we obtain the mean and standard deviation for the gust factor at 5 m. The result is

$$G_5 = 1.27 \pm 0.040 \tag{16}$$

b. Relationship Between G and P

Analogous to the estimation of wind maximum, $U_{max}$ (see Panofsky and Dutton, 1984)

$$U_{\max} = U_{10} + 3\,\sigma_u \tag{17}$$

we postulate that

$$U_{gust} = U_{10} + A\,\sigma_u \tag{18}$$

where $\sigma_u$ is the standard deviation of the wind speed in the downwind direction. The coefficient A needs to be determined as follows: According to Panofsky and Dutton (1984, p. 377) under neutral conditions in the surface layer,

$$\sigma_u = 2.4\,u_* \tag{19}$$

Substituting Eq. (19) into (18), one gets

$$U_{gust} = U_{10} + 2.4\,A\,u_* \tag{20}$$

or

$$\frac{u_{gust}}{U_{10}} = G = 1 + 2.4\,A\,\frac{u_*}{U_{10}} \tag{21}$$

On the basis of Eqs. (9) and (10), A = 2.0. Substituting this value into Eq. (18) and from Arya (1988) that $P = \sigma_u / U_{10}$, one gets

$$\frac{U_{gust}}{U_{10}} = 1 + 2\,\frac{\sigma_u}{U_{10}} \tag{22}$$

Therefore,

$$G = 1 + 2P \qquad \textbf{(23)}$$

Eq. (23) was first proposed by Hsu (2003a) with only 21 samples during Hurricane Kate in 1985. Eq. (23) states that P can be determined directly from the gust factor measurements, which are available routinely.

### c. Sea-Surface Drift Velocity

From time to time, operational meteorologists may be asked to estimate the sea-surface drift velocity, i.e., the surface current induced by the wind. This can be accomplished as follows: According to Wu (1975) the magnitude of surface drift velocity in deep water is

$$u_{sea} = 0.55\, u_* \qquad \textbf{(24)}$$

Substituting Eq. (10) into (24), we have

$$u_{sea} = 0.028\, U_{10} \qquad \textbf{(25)}$$

so that under hurricane conditions the surface drift is also about 3% of the wind speed at 10 m, in good agreement with the general 3% rule used operationally (see, e.g., Bishop, 1984, and Hsu, 1988). Note that this 3% rule is for deep water before shoaling. During hurricanes, the shoaling depth (in meters) can be estimated as (1013 - $P_0$) where $P_0$ is the minimal sea-level pressure (in mb) associated with the storm (Hsu, in press).

## 6. Discussions

During hurricanes, the overwater gust factor at 5 and 10 m above the sea surface as measured by NDBC buoys were analyzed. Because the gust factor may vary with height, instrument type, exposure, and sampling period, the data sets used in this study are based on NDBC measurements. Non-NDBC measurements are beyond the scope of this report. For sampling periods which differ from those of the NDBC, see, e.g., Krayer and Marshall (1992). For gust factor at the shoreline environment, see Hsu (2003b). For gust factor variation from offshore to inland, see Powell (1982) and Hsu (2001 and 2003c).

## 7. Conclusions

Several conclusions can be drawn from this study: (a) during hurricanes, when the stability is near neutral and the seas are not fully developed, the gust factor is found to be

1.25 and 1.27 at 10 m and 5 m, respectively; (b) the friction velocity is approximately 5% of the wind speed at 10 m; (c) the exponent of the power-law wind profile (P) is 0.128; (d) the gust factor (G) and P are related linearly; and (e) the sea surface drift velocity ($u_{sea}$) is approximately 3% of $U_{10}$ in agreement with the general 3% rule for the deep water environment. Note that these results should be useful for marine meteorologists and engineers (e.g., during hurricanes, these inputs are needed for the estimation of wind loading and ocean currents on offshore structures and oil spills (see, e.g., Bishop, 1984, Hsu 2003a and in press)). Note also that the purpose of Figures 1 and 3 is to demonstrate the linearity between U and G. The intercepts should not be interpreted as the measurement error. Unless there is a perfect fit, the intercepts cannot be zero. However, in view of the high $R^2$ values, we provide the average and standard deviation for operational use.

Author

Dr. S. A. Hsu has been a Professor of Meteorology at Louisiana State University since 1969, after he earned his Ph.D. in Meteorology from the University of Texas at Austin. He is the author of Coastal Meteorology (Academic Press, 1988) and numerous papers on coastal and marine meteorology and air-sea interaction. Dr. Hsu is also an AMS Certified Consulting Meteorologist. Dr. Hsu can be contacted at the LSU Coastal Studies Institute, 308 Howe-Russell Geoscience Building, Baton Rouge, Louisiana, 70803-7527; email: sahsu@lsu.edu.

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Table 1.
Simultaneous measurements of $U_{10}$, $U_{gust}$, $H_s$, and $T_p$ during hurricanes in the central Gulf of Mexico (NDBC buoys 42001, 42002, and 42003) and in the northwestern Caribbean Sea (buoy 42056) (data sources: www.ndbc.noaa.gov and www.nhc.noaa.gov). The data sets are analyzed when $U_{10} \geq 20$ m/s (see text for explanation).

| Buoy | Year | Month | Day | Hours | Hurricane |
|---|---|---|---|---|---|
| 42001 | 1985 | 8 | 14 | 4 | Danny |
| | 1995 | 10 | 4 | 11 | Opal |
| | 2002 | 10 | 2 | 7 | Lili |
| | 2005 | 8 | 28/29 | 11 | Katrina |
| 42002 | 1985 | 10 | 28/29 | 13 | Juan |
| | 1989 | 10 | 15 | 3 | Jerry |
| 42003 | 1985 | 11 | 20/21 | 21 | Kate |
| | 1988 | 11 | 22 | 6 | Keith |
| | 1992 | 8 | 25 | 8 | Andrew |
| | 1995 | 10 | 4 | 4 | Opal |
| | 1998 | 9 | 26/27 | 11 | Georges |
| | 2000 | 9 | 16/17 | 3 | Gordon |
| | 2004 | 9 | 14/15 | 21 | Ivan |
| | 2005 | 8 | 27/28 | 12 | Katrina |
| 42056 | 2005 | 7 | 17/18 | 9 | Emily |
| | 2005 | 10 | 21/22 | 47 | Wilma |
| Total hours (samples) = | | | | 191 | |

Table 2.

A comparison of G from Eq. (9) and the regression equation from Fig. 1 (where G = 1.32 - 1.76 / $U_{10}$).

| $U_{10\ m}$ | Eq. (9) | From Fig. 1 |
|---|---|---|
| 20 | 1.25 | 1.23 |
| 30 | 1.25 | 1.26 |
| 40 | 1.25 | 1.28 |
| 50 | 1.25 | 1.28 |
| Mean | 1.25 | 1.26 |

Table 3.

A comparison of G from Eq. (16) and the regression equation from Fig. 3 (where G = 1.25 + 0.40 / $U_5$).

| $U_{5\ m}$ | Eq. (16) | From Fig. 3 |
|---|---|---|
| 20 | 1.27 | 1.27 |
| 30 | 1.27 | 1.26 |
| 40 | 1.27 | 1.26 |
| 50 | 1.27 | 1.26 |
| Mean | 1.27 | 1.26 |

Figure 1. Variations of $U_{gust}$ versus $U_{10}$ under hurricane conditions.

Figure 2. Variations of $u_*$ versus $U_{10}$ under hurricane conditions.

Figure 3. Variations of $U_{gust}$ versus $U_5$ under hurricane condition as measured by NDBC buoy 42040. Note that the wind peak gust was measured at 5 m above the sea surface.

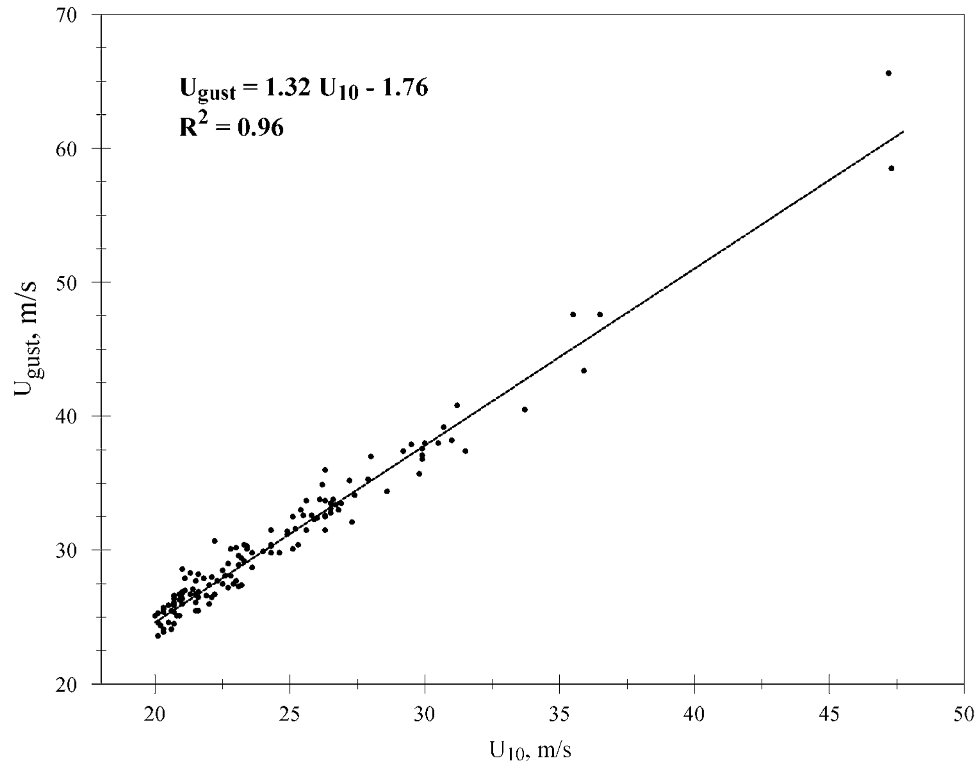



**Figure 1**

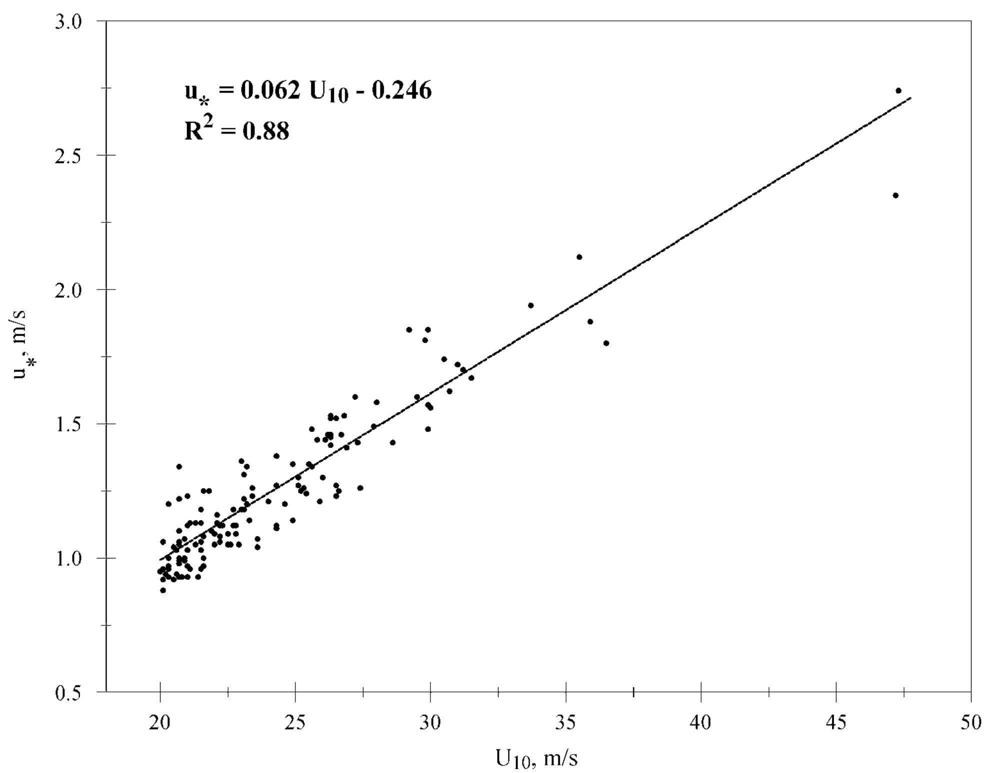
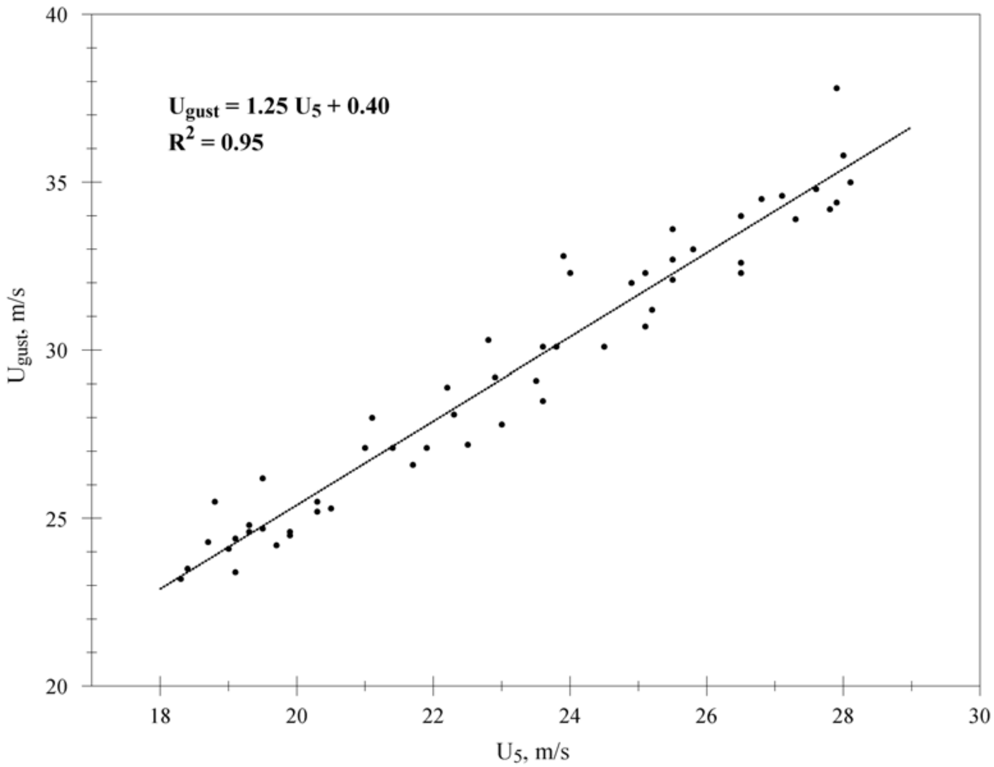



**Figure 2**



$U_{gust} = 1.25\ U_5 + 0.40$
$R^2 = 0.95$
40
35
30
25
20
$U_{gust}$, m/s
18
20
22
24
26
28
30
$U_5$, m/s


**Figure 3**