

LETTER • OPEN ACCESS

An effective parametrization of gust profiles during severe wind conditions

To cite this article: Henk W van den Brink 2020 *Environ. Res. Commun.* **2** 011001

View the [article online](#) for updates and enhancements.

Environmental Research Communications



LETTER

An effective parametrization of gust profiles during severe wind conditions

OPEN ACCESS

RECEIVED
3 June 2019

REVISED
6 November 2019

ACCEPTED FOR PUBLICATION
13 November 2019

PUBLISHED
28 November 2019

Henk W van den Brink

KNMI, Wilhelminalaan 297, 3731 GA, De Bilt, The Netherlands

E-mail: henk.van.den.brink@knmi.nl

Keywords: parametrization, gust, wind, profile

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/4.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

**Abstract**

A simple and effective parameterization for the profile of extreme wind gusts during severe wind conditions is presented. It is shown that the gust profile follows directly from the logarithmic wind profile. Also the uncertainty in the gust estimates can easily be determined from information of the average wind speed at two different heights. One specification of practical importance is that the maximum 3s-gust in a 10 min period at 10 m height is arithmetically equal to the average wind at 140 m. At larger heights the gusts are equal to the average wind speed at an easily determinable height that is a factor α ($\alpha > 1$) higher. Validation over The Netherlands indicates that this rule applies to heights up to at least 200 m. This outcome is validated both over land and over sea, and is independent of surface roughness. The proposed parameterization reproduces the climatological values of the measured extreme wind gusts. Maximum gusts for individual winter months are better represented than for individual summer months. The mean error in the monthly winter maxima estimates is 5%.

1. Introduction

Extreme windstorms are the most important natural hazards affecting Europe (Schwierz *et al* 2010). Losses are not primarily caused by the sustained wind speed but by the gusts, i.e., the maxima of the wind speed during a few seconds.

Generally, two approaches can be distinguished on how the gusts are parametrized. One approach is to use the local near-surface wind speed and its standard deviation in order to estimate the gust (e.g. Panofsky *et al* 1977, Wichers Schreur and Geertsema 2008) in order to estimate the gust. This approach makes use of similarity theory, and relates the gust to the friction velocity. The approach performs well in flat terrain, but is sensitive to the parametrization of the local roughness length.

A second approach assumes that surface gusts result from deflection of air parcels flowing higher in the boundary layer and brought down by turbulent eddies. Bresseur (2001) also gives bounding limits for the gusts, which are based on the maximum wind speed in the boundary layer (upper bound) and by the local turbulent kinetic energy (lower bound). This approach is less sensitive to the local circumstances than the similarity-based approach, but the gust estimates tend to be too high (Born *et al* 2012), and the bounding limits are large. An overview of the different approaches is given by Sheridan (2011).

Both approaches focus mainly on the gusts at 10 m height. However, also gusts at higher levels above the surface are important. As an example, the International Electrotechnical Commission requires that wind turbines are able to withstand the 3s-gust that occurs once in 50 years. This urges the need for an accurate parametrization of the vertical profile of extreme gusts during severe wind conditions.

Here a parametrization of extreme gusts is presented that is applicable to at least 200 m height, is not sensitive to the local parametrization of the roughness length, is unbiased, and gives a reliable indication of the uncertainty in the estimated gust.

Methods are described in section 2, observational data in section 3, and results in section 4. A summary and discussion is given in section 5.

2. Methodology

2.1. Derivation

In this section, a relation between the mean wind speed and the wind gust during severe wind situations is derived.

As a first step, the dimensionless representation of the vertical wind shear during neutral conditions (e.g. Businger *et al* 1971) is taken:

$$\frac{\kappa z}{u_*} \frac{\partial U}{\partial z} = 1 \quad (1)$$

where κ is the Von Kármán constant (0.41), U the average wind speed, z the height above the surface, and u_* the friction velocity. In this paper it is assumed that in situations with severe wind the atmospheric boundary layer is neutrally stratified and equation (1) is valid (e.g. Stull 1988).

Integration of equation (1) over height leads to the well-known logarithmic profile (e.g. Tennekes 1973):

$$U = \frac{u_*}{\kappa} \ln \left(\frac{z}{z_0} \right) \quad (2)$$

The roughness length z_0 is defined as the theoretical height where the wind speed is equal to 0. In surface layers over homogeneous terrain, u_* is often assumed to be constant with height (Monin and Obukhov 1954) or to decrease linearly with height within the atmospheric boundary layer (e.g. Gryning *et al* 2007).

The second step is to relate the standard deviation of the wind speed σ_u to u_* , which is (via equation (2)) related to the mean wind. A modified relation from Højstrup (1982) for σ_u/u_* (which is called C) is used, that for neutral situations reads:

$$\frac{\sigma_u}{u_*} \equiv C = \frac{c}{(1 + 15z/h)^{1/3}} \quad (3)$$

in which h is the height of the atmospheric boundary layer, and c a constant. Højstrup (1982) takes $c = 2.2$, Verkaik (2000) $C = 2.2$ for $z = 10$ m, and Wieringa (1973) uses $C = 2.5$ for $z = 10$ m. Here $c = 2.5$ will be used.

The height of the boundary layer h in the extra-tropics during neutral conditions can be estimated by (Rossby and Montgomery 1935):

$$h = A \frac{u_*}{f} \quad (4)$$

in which f is the Coriolis parameter ($1.1 \cdot 10^{-4} \text{ s}^{-1}$ at 45°N) and $A \approx 0.1$ (following Gryning *et al* 2007). For severe wind conditions $h \approx 1$ km, which is the value that will be used in this paper. This gives $C \approx 2.4$ for $z = 10$ m.

The third step and last step is to decompose the gust G into a mean wind speed U and a positive fluctuation, which is taken proportional to the standard deviation of the wind speed σ_u (e.g. Beljaars 1987):

$$G = U + g\sigma_u \quad (5)$$

in which g is the normalised gust. If the fluctuations are considered to be normally distributed around the (stationary) mean wind speed U , the distribution of g can be calculated, see [appendix](#) for the derivation.

Combination of equation (3) and (5) gives:

$$G = U + gCu_* \quad (6)$$

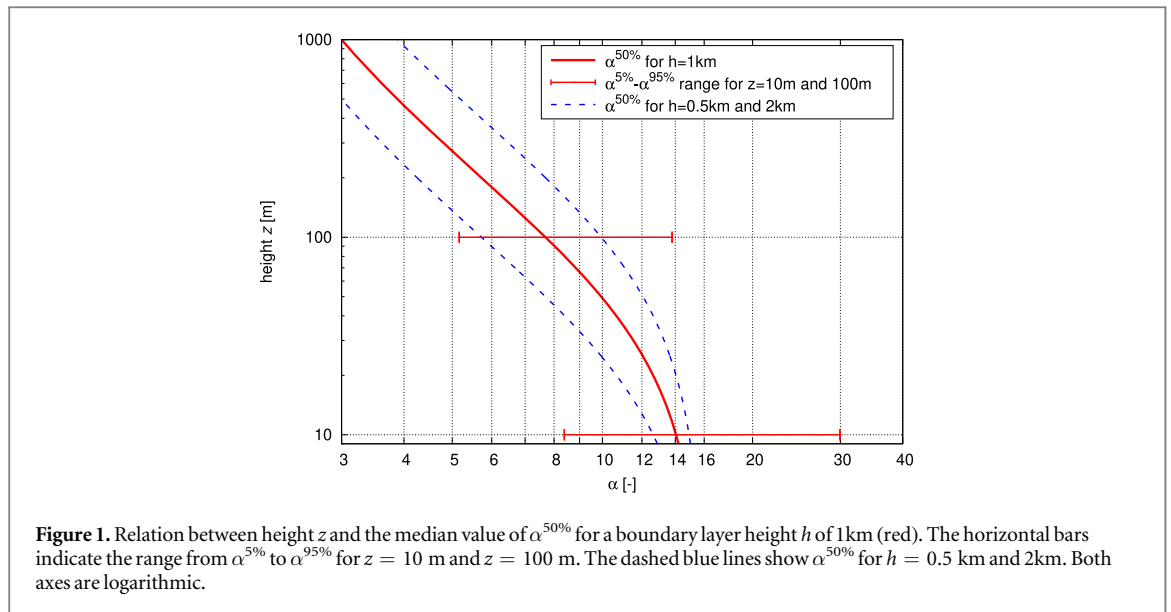
Defining

$$\alpha \equiv e^{\kappa g C} \quad (7)$$

it follows (using equation (2)):

$$\begin{aligned} G(z) &= \frac{u_*}{\kappa} \ln \left(\frac{z}{z_0} \right) + \frac{\ln(\alpha)}{\kappa} u_* \\ &= \frac{u_*}{\kappa} \left[\ln \left(\frac{z}{z_0} \right) + \ln(\alpha) \right] \\ &= \frac{u_*}{\kappa} \ln \left(\frac{\alpha z}{z_0} \right) \\ &= U(\alpha z) \end{aligned} \quad (8)$$

which states that the maximum wind gust speed at a given height equals the mean wind speed at a height that is a factor α higher. It is emphasized that this final result does not depend on either z_0 or u_* , although they are used in the intermediate steps of equation (8).



As g represents a distribution, so do α and G . For WMO standards (maximum 3s-gusts in 10-min periods), the median value of g can be calculated to be 2.70, and the 5% and 95% quantiles are 2.17 and 3.47, respectively (see [appendix](#)). Assuming that the full variability of the gusts is described by the distribution of g , this implies that the probability is 90% for the gust to be between 2.17 and 3.47 times the standard deviation above the mean wind speed, with a most likely value of 2.70 standard deviations above the mean wind.

If the wind speed is not available at height αz , it can be obtained by inter- or extrapolating from two heights z_1 and z_2 (using equation (2)). Equation (8) then reads:

$$G(z) = U(z) + \ln(\alpha) \frac{U(z_2) - U(z_1)}{\ln(z_2) - \ln(z_1)} \quad (9)$$

in which the heights z_1 and z_2 can be chosen arbitrarily, as long as they are in the logarithmic range of the wind speed profile. In the situation that the average wind speed is available at height z , $z_1 = z$ or $z_2 = z$ can be chosen, which implies that the wind speed at only one extra level is needed to estimate not only the extreme gust but also its uncertainty range.

2.2. Estimates for 10 m height

For $z = 10$ m, where $C \approx 2.4$, equation (8) gives:

$$\begin{aligned} G^{95\%}(10\text{m}) &\approx U(300 \text{ m}) \\ G^{50\%}(10\text{m}) &\approx U(140 \text{ m}) \\ G^{5\%}(10\text{m}) &\approx U(84 \text{ m}) \end{aligned} \quad (10)$$

where $G^{95\%}$, $G^{50\%}$ and $G^{5\%}$ are the maximum 3s-gust values that are not exceeded in a 10-min period with a probability of 95%, 50% and 5%, respectively. The median value $G^{50\%}(z)$ is used as the expected gust value.

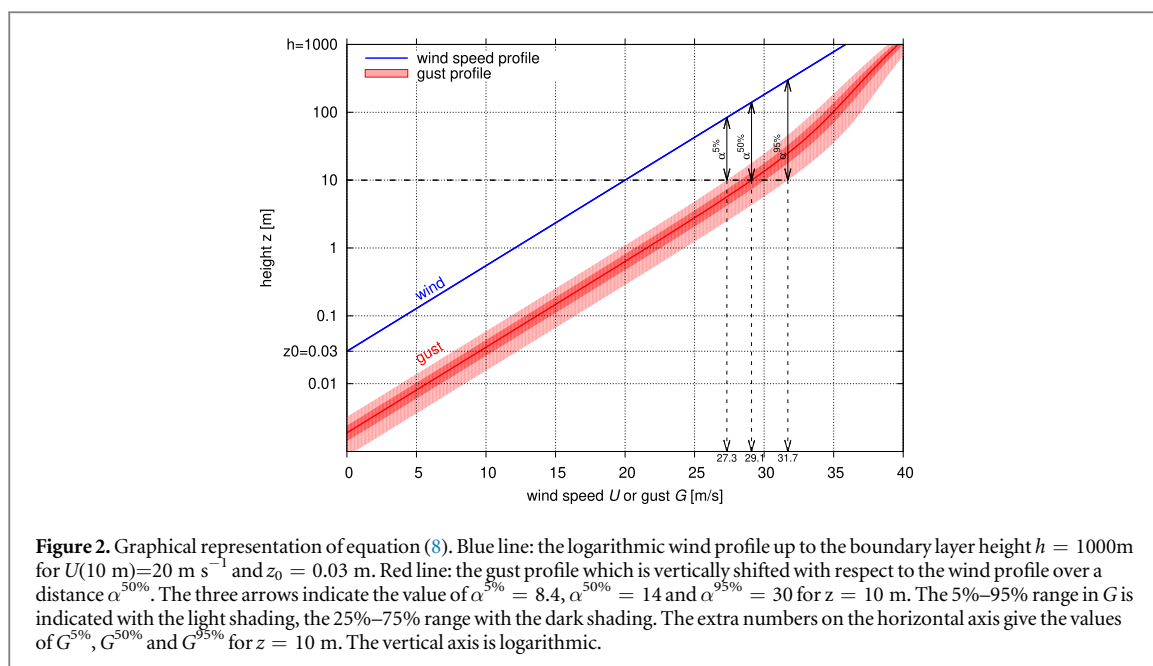
Note that the values of equation (10) are specific for maximum 3s-gusts in 10-min periods. These values vary with either the period or the gust duration. This underlines that the relation between the gust and the wind of equation (8) is not physical, but arithmetical. An implication is that equation (9) holds even if αz is higher than h , as long as z , z_1 and z_2 are within the range where the logarithmic profile is valid.

2.3. Sensitivity analysis

The red line in figure 1 illustrates how the median value of α depends on z according to equation (3). It can be read that the median of the maximum 3s-gust in a 10-min interval at $z = 10$ m is equal to the mean wind speed at 140 m ($\alpha^{50\%} = 14$). The median gust at 100 m is equal to the mean wind speed at 770 m ($\alpha^{50\%} = 7.7$).

The horizontal bars at $z = 10$ m and $z = 100$ m indicate the range of $\alpha^{5\%}$ to $\alpha^{95\%}$. It shows that the probability is 90% that the gust at 100 m is equal to the mean wind speed between approximately 520 m and 1380m ($\alpha^{5\%} = 5.2$ and $\alpha^{95\%} = 13.8$).

The dashed blue lines show the effect on $\alpha^{50\%}$ due to variation of the boundary layer height h between 0.5 km and 2km, according to equation (3). This effect of the boundary layer height is relatively small compared to the $\alpha^{5\%}$ - $\alpha^{95\%}$ range, especially for lower heights. This affirms our choice to fix the value of h to 1km.



2.4. Graphical representation

Figure 2 provides a graphical representation of equation (8). The blue line represents the logarithmic profile of the average wind speed, which turns into a straight line because of the logarithmic vertical axis. Shown is a situation with $h = 1000 \text{ m}$, $U(10 \text{ m}) = 20 \text{ m s}^{-1}$ and $z_0 = 0.03 \text{ m}$. The red line shows the profile of the wind gust. It shows that the profile of the gust is vertically shifted over a distance α with respect to the profile of the mean wind. This distance is indicated by the arrow $\alpha^{50\%} = 14$ for $z = 10 \text{ m}$. The other arrows show $\alpha^{5\%}$ and $\alpha^{95\%}$, which for $z = 10 \text{ m}$ are 8.4 and 30, respectively (see also figure 1). The distribution of G is indicated by the shaded areas. The 5%–95% range is shown in light red shading, the 25%–75% range in dark red. It shows that, in this example, the mean wind speed at 140 m results in $G = 29.1 \text{ m s}^{-1}$, with a 90% probability to be between 27.3 and 31.7 m/s, being the mean wind speeds at 84 m and 300 m, respectively. These numbers are added to the horizontal axis.

It is emphasized that—although the value of z_0 and consequently the slope of the profiles—is location-dependent, the vertical distance between the wind- and the gust-profile is not; this distance is always equal to α , as depicted in figure 2.

It can be concluded that, if the mean wind speeds is known at two heights, not only the vertical profile of the wind speed is determined (under the assumption of neutral stability), but also the profile of the gust can be derived without extra information. Even the 90%-uncertainty range in the maximum gust can be derived, all based on only two wind speed values at different heights.

3. Observational datasets

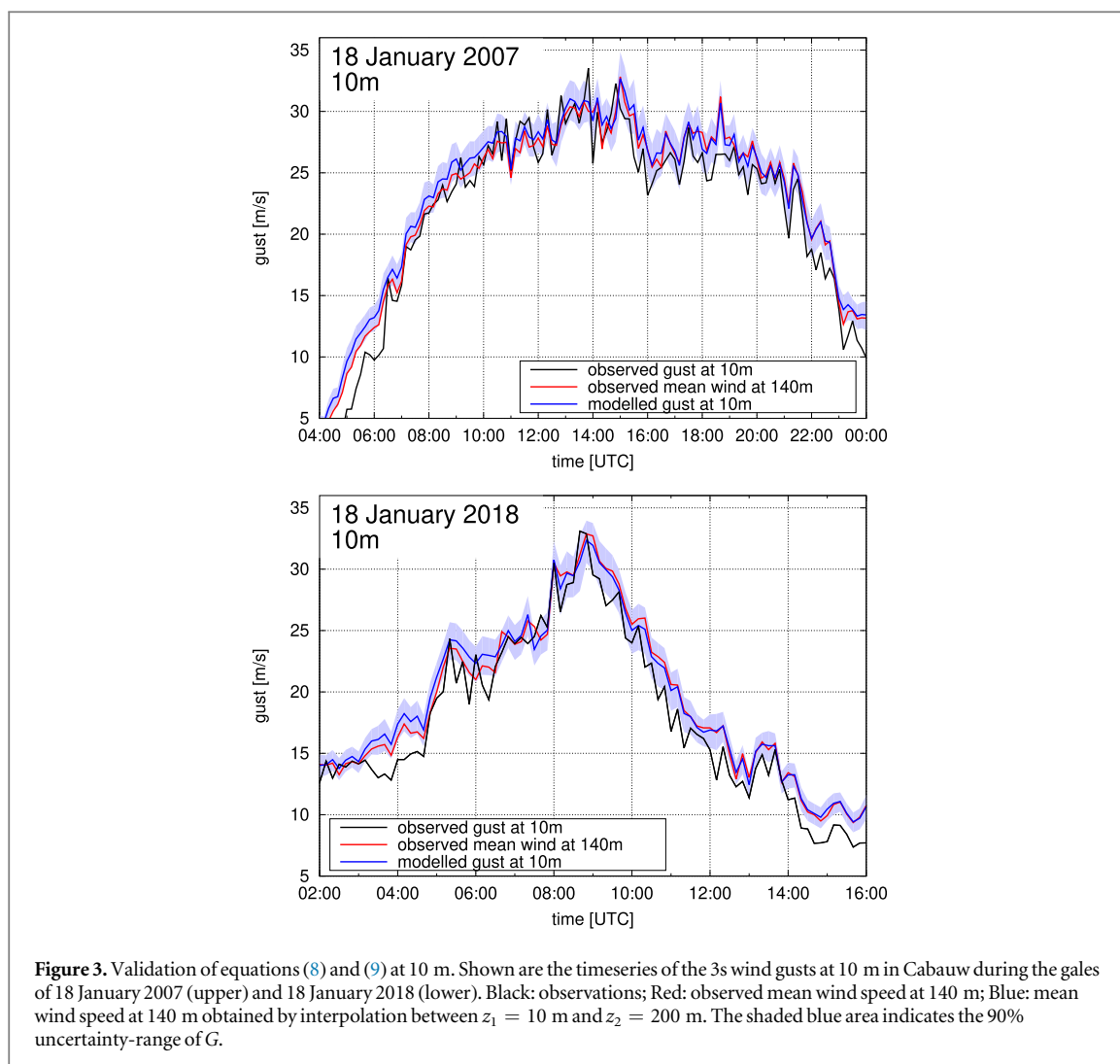
The method and the approximations are validated with datasets from two locations. The first location is Cabauw (51.971N, 4.926E), where the Royal Netherlands Meteorological Institute (KNMI) operates a 213 m tall meteorological tower. See www.cesar-database.nl for more information. In the present work, measurements of wind speed, standard deviation and 3-sec gust data are used at heights of 10, 20, 40, 80, 140 and 200 m above ground level. Data are available from May 2000 till April 2019.

The second location is meteorological mast IJmuiden (MMIJ), located over sea at (52.85N, 3.44E). This mast has been operational from November 2011 to December 2015. Wind speed and gust measurements were done at 27, 58, 87 and 92 m. See www.meteomastijmuiden.nl for more information.

Both datasets contain values with a 10-min time interval.

4. Validation

This validation section starts with time series for two severe gales (18 January 2007 and 18 January 2018), showing how well the model reproduces the temporal characteristics of the severe gusts on a given height. Next, the vertical profiles of the wind and gust for the two severe gales are presented, showing good agreement with



measurements. Last, scatter plots for the gust maxima of all individual months are shown, indicating high correlations and unbiased climatological values.

4.1. Case study: two severe gales

4.1.1. Time series

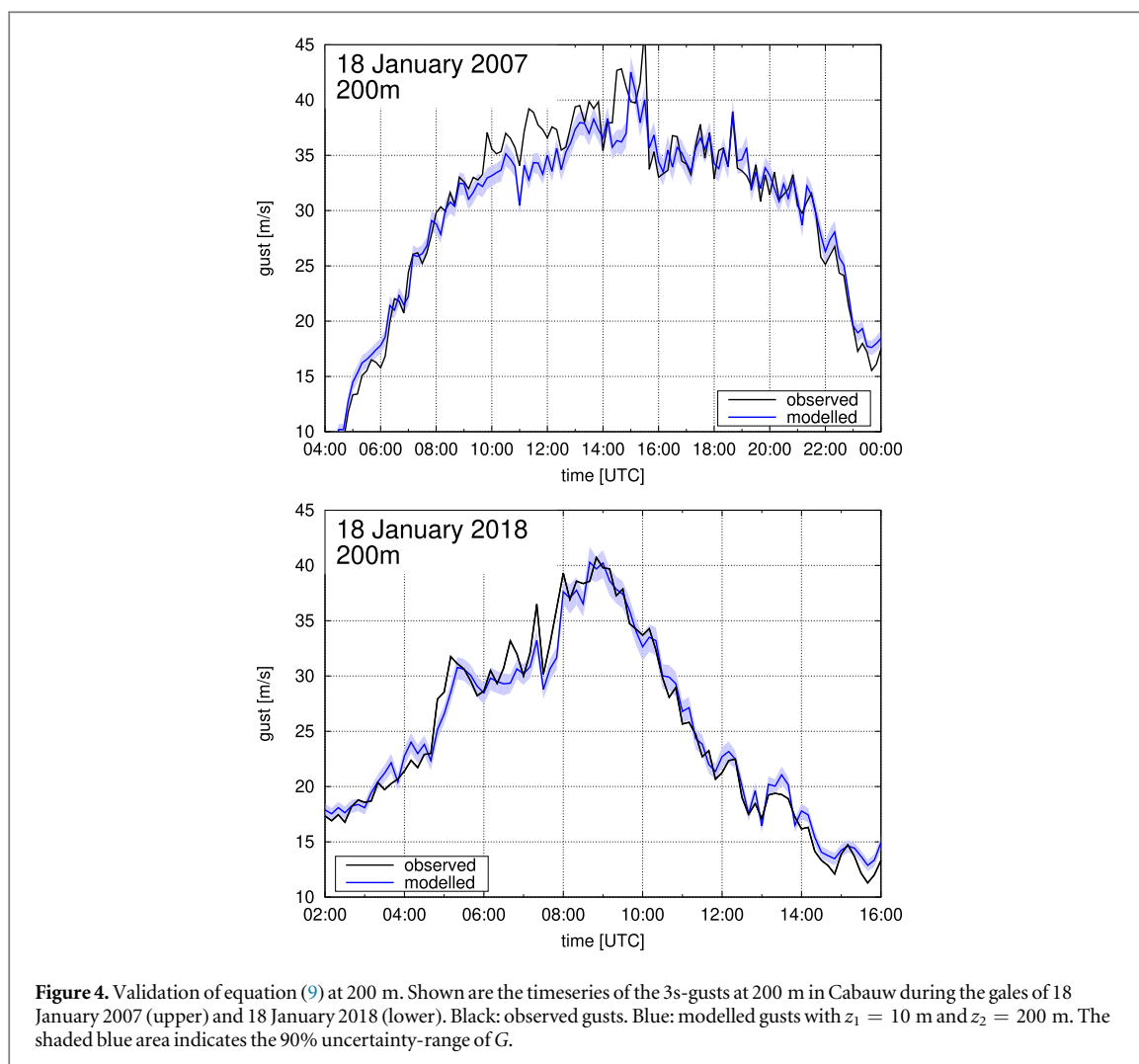
Figure 3 shows the temporal evolution of the 3s-gust at 10 m in Cabauw during the gales of 18 January 2007 (left) and 18 January 2018 (right). Taking $\alpha = 14$, the observed 3s gust at 10 m (black) can directly be compared with the observed mean wind speed at 140 m (red). Another estimate of the 140 m wind speed can be made by interpolating between $z_1 = 10$ m and $z_2 = 200$ m and applying equation (9), which results in the blue line. For both gales, the observed gusts are well modelled both by the red and the blue line. (Note that this implies that equation (8) can also be inverted: the maximum gust at 10 m is a good proxy for the mean wind at 140 m.)

The shaded area indicates the effect of the variation of g between its 5% and 95%-value. Most of the time when the observed gusts exceed 20 m s^{-1} , the observations fall within the shaded area, which means that (most of) the differences between the parameterization and the observations can be explained by the stochastic nature of turbulence.

The time series of the 3s-gusts at 200 m for the same gales are shown in figure 4. The blue lines show the estimated gusts by using $z_1 = 10$ m and $z_2 = 200$ m in order to extrapolate to $z = 1150$ m ($\alpha = 5.7$). Again, a good overall agreement is obtained, although the peak at 15:30 in the 2007 storm is underestimated, and the uncertainty ranges seem to be too small.

4.1.2. Vertical profiles

The vertical profiles of the observed maximum wind (blue) and gust (black) in Cabauw during the gales of 18 January 2007 and 18 January 2018 are depicted in figure 5. Applying equation (9) with $z_1 = 10$ m and



$z_2 = 200$ m results in the red points, with the estimate of the 90%-uncertainty ranges indicated. The observed gusts are shown in black.

For all except one, the observations lie within the 90%-uncertainty range. We conclude that equations (8) and (9) describe the profile of the maximum 3s-gust well. Deviations from the profile can be quantified by the uncertainty in g , which resembles the stochastic nature of the extreme gusts.

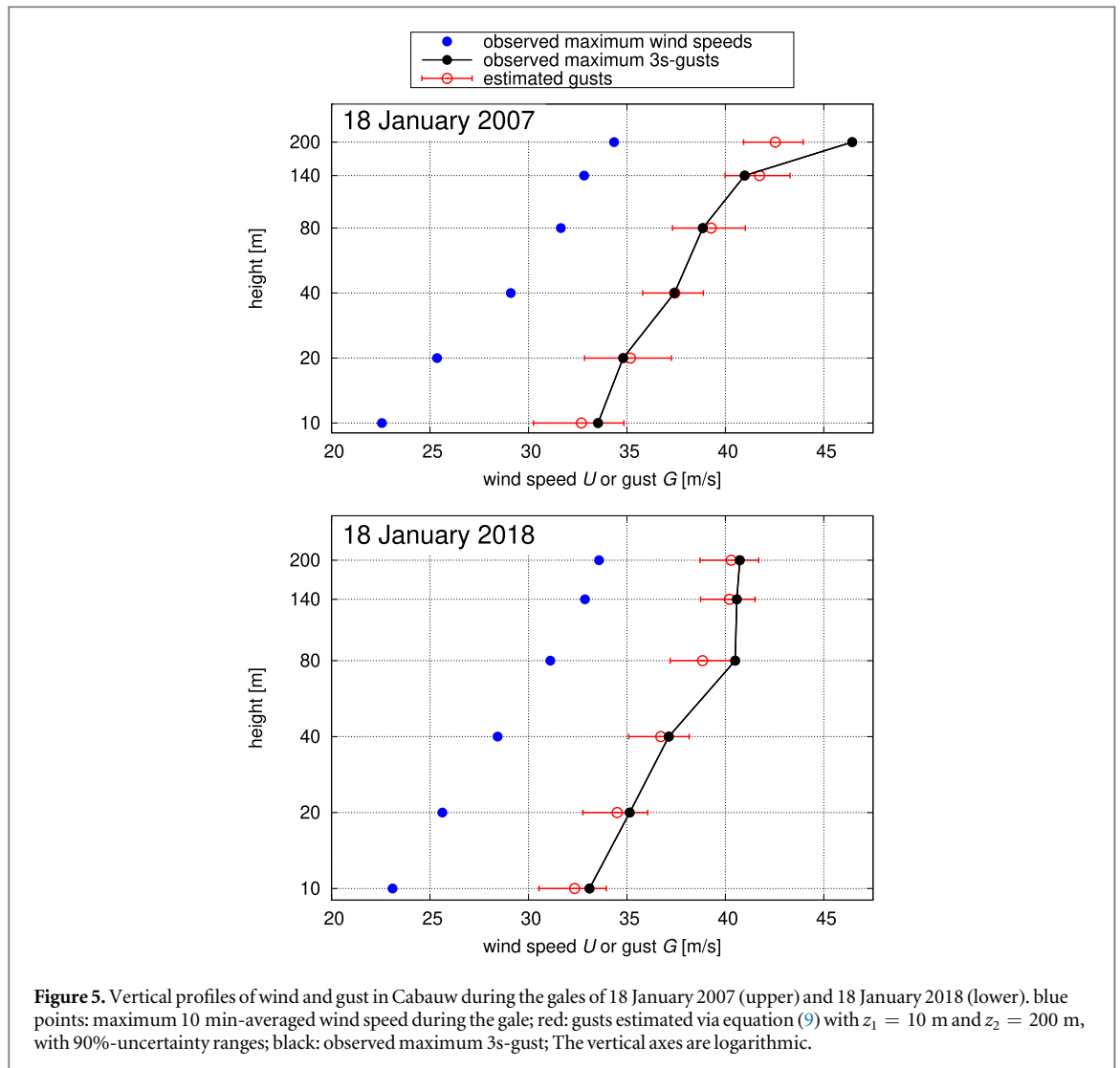
4.2. Validation: climatology

Figure 6 shows the scatter plots of the maximum gusts for all individual months at 10 m in Cabauw as estimated with equation (8) with $\alpha = 14$, i.e. the maximum 3s gust at 10 m is assumed to be equal to the mean wind speed at 140 m. In the right figure, equation (9) is applied with $z_1 = 10$ m and $z_2 = 200$ m. Blue circles indicate monthly maxima from the winter season (October-March), and red circles from the summer season (April-September). The two enlarged circles indicate the January 2007 and the January 2018 events that are shown in figures 3–5. If the moment on which the estimated monthly maximum gust occurs differs less than 12 h from the moment of the observed maximum, it is concluded that the estimated and observed maximum gust belong to the same event. This is the case in 83% of the winter cases, and in 66% of the summer cases. These events are indicated with closed circles. All other situations are indicated with open circles.

The vertical lines in the right figure indicate the estimated 90%-uncertainty range in the gust. In 78% of the cases the observed maximum gust lies within the estimated 90%-uncertainty range, which means that the uncertainty is slightly underestimated.

The figure shows a high correlation (Pearson correlation coefficient $\rho = 0.96$) for the winter events at 10 m. The correlation is much lower in summer ($\rho = 0.77$).

The scatter plots for the estimated gusts at 80 m and 200 m are shown in figure 7. For clarity, the uncertainty estimates are left out. The three most extreme gusts at 200 m show a tendency to be underestimated. The correlations decrease slowly with height (see also table 1). At 200 m, 68% of the points fall within the 90%-



uncertainty range of g , which means that a smaller part of the difference between modelled and observed gusts can be attributed to the stochastic nature of the gusts.

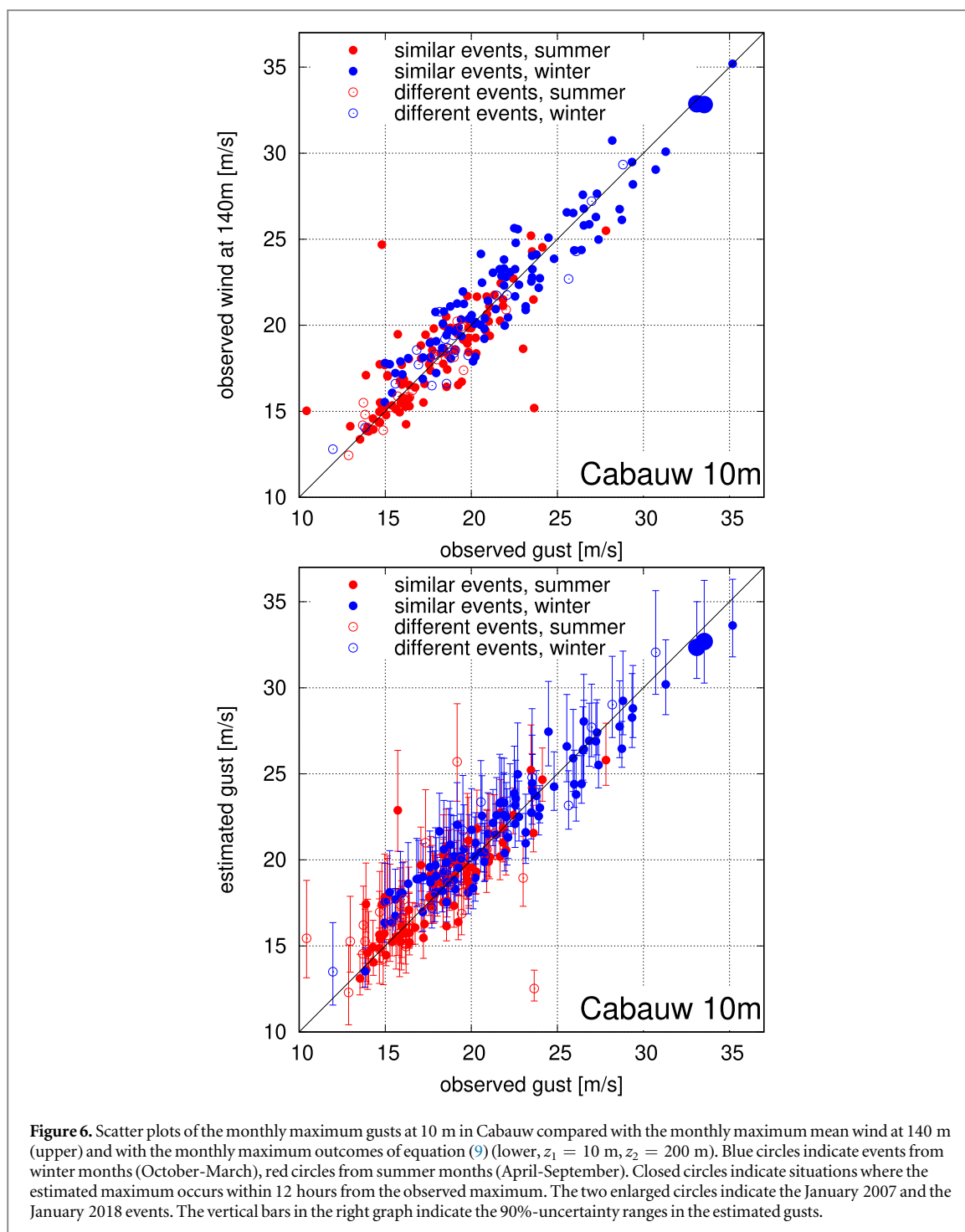
In order to investigate how well equation (8) performs at another location, figure 8 shows the scatter plots of the estimated versus the observed monthly gust maxima for Meteo Mast IJmuiden (November 2011-December 2015) for 27 m and 85 m. Good agreement is achieved for the winter events. This confirms that the results of equation (8) are indeed independent of the roughness length.

4.3. Statistical performance

Table 1 gives the mean error (ME), the mean percentage error (MPE), the mean absolute error (MAE), mean absolute percentage error (MAPE), root mean squared error (RMSE), correlation and reliability for winter (left) and summer (right) for the different measuring heights of Cabauw and Metmast IJmuiden. The reliability is presented as the percentage of observations that lies within the estimated 90%-uncertainty range. By definition, the ideal value is equal to 90%.

The errors in the winter gusts are around 5%, and the correlations 0.90 or higher. The summer results are worse, especially for MMIJ. This might be caused by the larger deviations from neutral stability over sea than over land.

The reliability column shows that the observations are generally in less than 90% of the time within the 90%-uncertainty range ($\approx 70\%$ for the winter events at Cabauw and 80% at MMIJ). A reason might be that the uncertainty in the mean wind speed is not taken into account. The reliability decreases with height, which implies that the provided uncertainty ranges performs best at 10 m, and are slightly too small for larger heights.



5. Discussion and conclusions

5.1. Relation to other gust parametrizations

Two types of gust parametrization can be distinguished. The first type is based on surface-layer similarity theory (e.g. Tennekes 1973, Beljaars 1987, Stull 1988), which relates the gust to the wind at 10 m and the local roughness length. This parametrization is often applied in Numerical Weather Prediction (NWP) models. The accuracy of the estimated gusts relies heavily on the roughness map that is used, especially when the resolution of the NWP model increases and detailed information about the land-use (and the associated roughness lengths) is required. Errors in the supplied roughness lengths will directly influence the calculated gusts, which is a disadvantage of this approach.

The second type is the method of Brasseur (2001), which is based on physical considerations by assuming that surface gusts result from the deflection of air parcels flowing higher in the boundary layer, which are

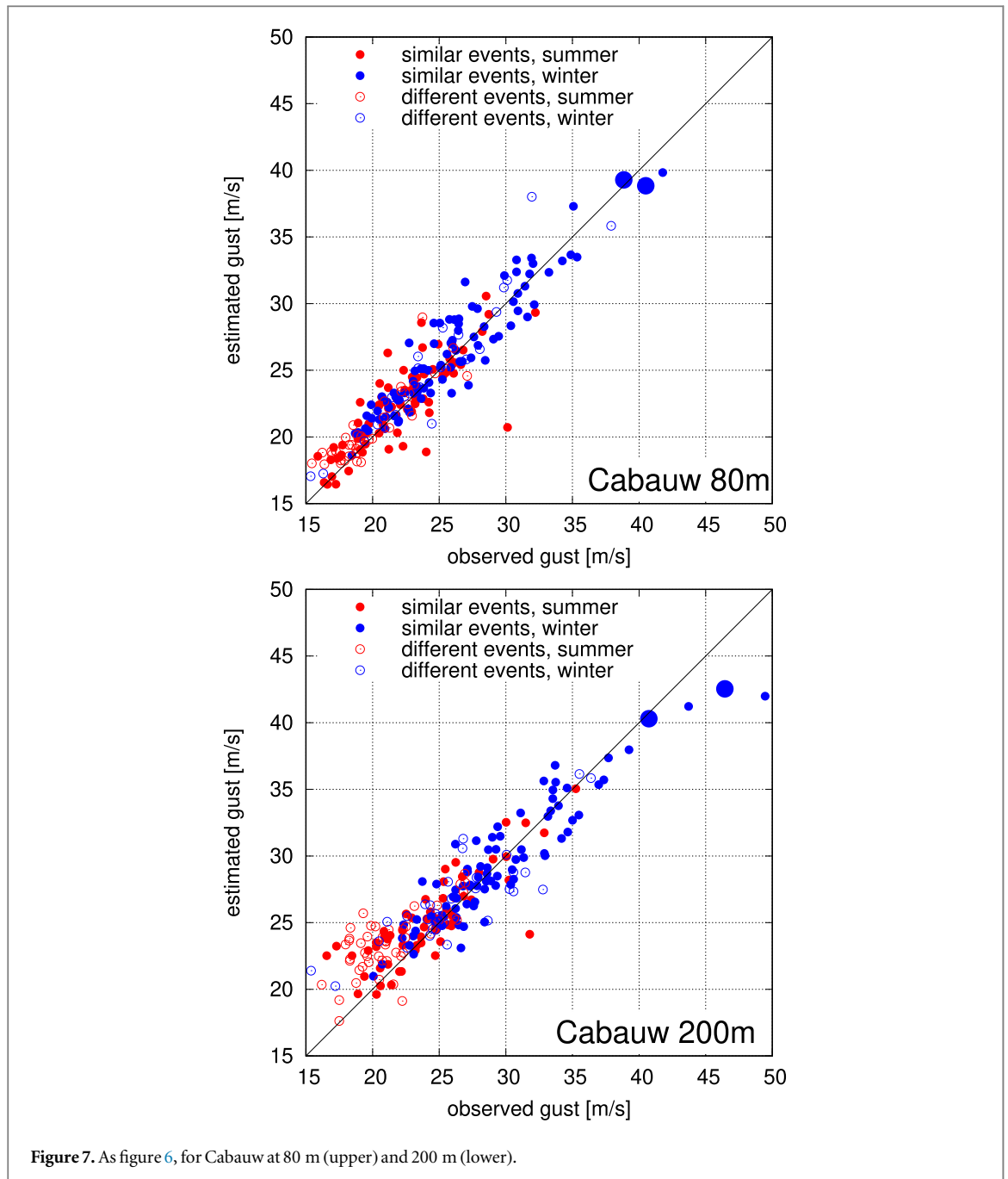


Figure 7. As figure 6, for Cabauw at 80 m (upper) and 200 m (lower).

brought down by turbulent eddies. This approach is much less sensitive to the local roughness, as it assumes that the gust is not induced by the local roughness, but by the large-scale eddies.

Although the currently proposed parametrization belongs to the similarity-theory type, it does not relate the gust estimate at 10 m to the local roughness, but to the wind at 140 m, which is much less sensitive to the local representation of the roughness than the wind at 10 m. This is an improvement of the previously known similarity parametrizations.

It is also an improvement over the Brasseur (2001) method, as it shows that (at least during severe winter gales) not the turbulent kinetic energy or the virtual potential temperature within the whole ABL determines the surface gust, but only the wind at 140 m. As the height of the ABL is much higher than 140 m during these circumstances, taking the maximum wind in the ABL will lead to an overestimation of the extreme gusts (Born *et al* 2012).

5.2. Strengths and weaknesses

It is derived how the profile of maximum gusts relates to the profile of the mean wind under neutral conditions. This leads to the remarkable outcome that the profiles of the wind and the maximum gust can be derived from

Table 1. Mean error (ME), mean percentage error (MPE), mean absolute error (MAE), mean absolute percentage error (MAPE), root mean squared error (RMSE) and correlation of the estimated monthly gust maxima versus the observations in Cabauw and Metmast IJmuiden for winter (left) and summer (right). The last column presents the reliability by the percentage of the observations that lie within the estimated 90%-uncertainty range. The rows show the dependence on height z .

	Height [m]	Winter (Oct-Mar)							Summer (Apr-Sept)						
		ME [m/s]	MPE [%]	MAE [m/s]	MAPE [%]	RMSE [m/s]	correlation [-]	reliability [%]	ME [m/s]	MPE [%]	MAE [m/s]	MAPE [%]	RMSE [m/s]	Correlation [-]	Reliability [%]
Cabauw	10	0.4	2.3	1.2	5.4	1.4	0.96	78	0.2	0.5	1.3	7.1	2.0	0.77	84
	20	0.5	2.3	1.2	5.3	1.5	0.95	74	0.0	-0.7	1.4	7.2	2.2	0.73	81
	40	0.5	2.2	1.3	5.1	1.6	0.95	67	0.2	0.5	1.2	6.0	2.1	0.80	76
	80	0.5	1.9	1.4	5.3	1.8	0.94	65	0.5	2.1	1.3	6.2	1.9	0.84	69
	140	0.4	1.4	1.5	5.5	1.9	0.93	67	1.1	4.9	1.8	7.9	2.3	0.83	51
	200	0.1	0.6	1.7	5.9	2.2	0.92	68	1.5	6.1	2.0	8.3	2.6	0.81	48
MMIJ	27	-0.5	-1.9	1.2	4.2	2.0	0.92	91	1.5	5.0	4.8	18.0	7.1	0.23	50
	58	-0.4	-1.9	1.6	5.8	2.4	0.89	78	3.8	13.2	4.1	14.3	5.5	0.61	31
	85	0.4	1.7	1.5	5.2	2.1	0.94	78	3.9	13.9	3.9	14.1	5.1	0.75	40
	92	-0.3	-1.3	1.6	5.3	2.3	0.90	82	4.3	13.3	4.5	14.1	6.1	0.48	31

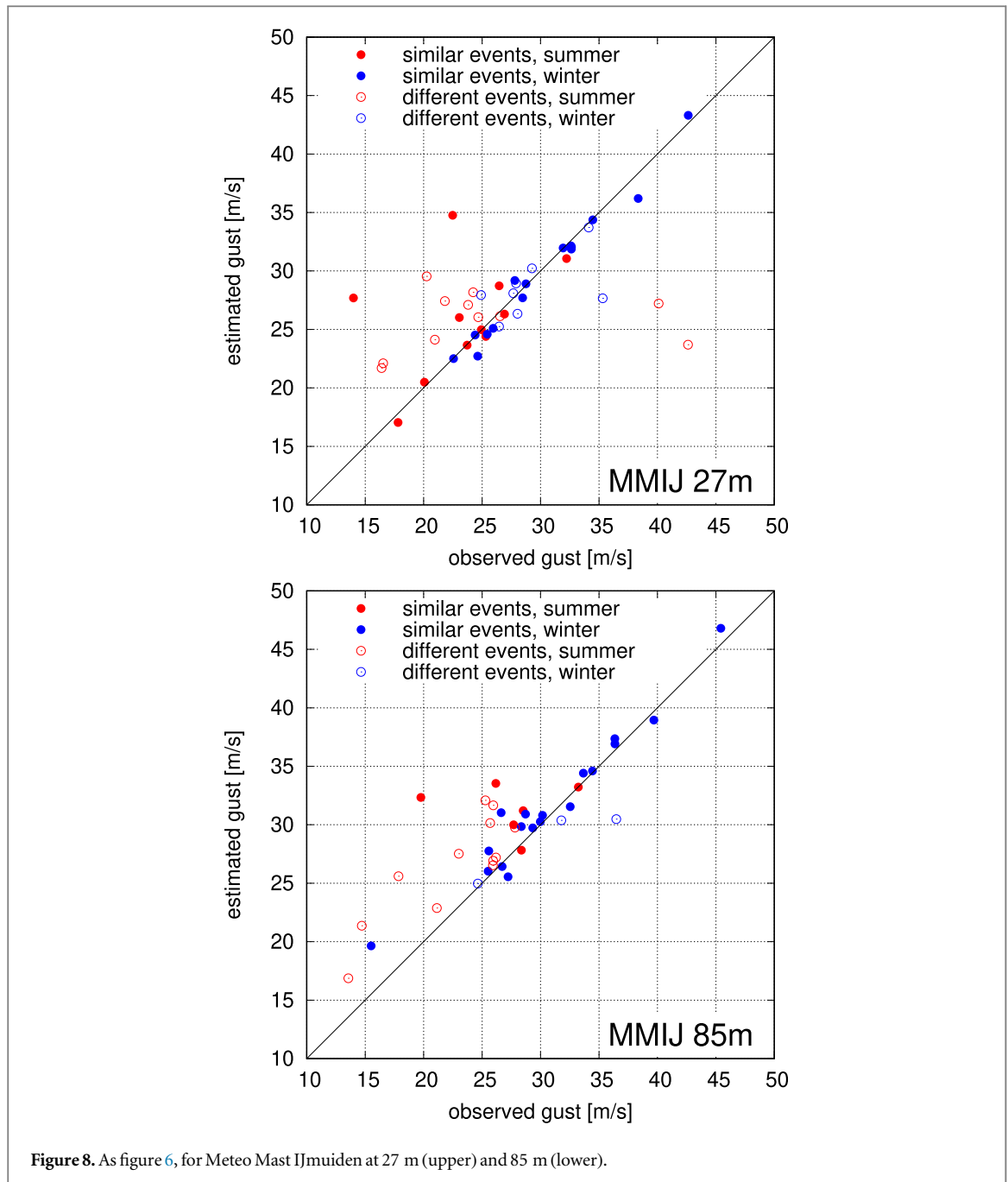


Figure 8. As figure 6, for Meteo Mast IJmuiden at 27 m (upper) and 85 m (lower).

only two wind speed measurements at different heights. Even the 90%-uncertainty range in the maximum gust can be derived with reasonable reliability from this information.

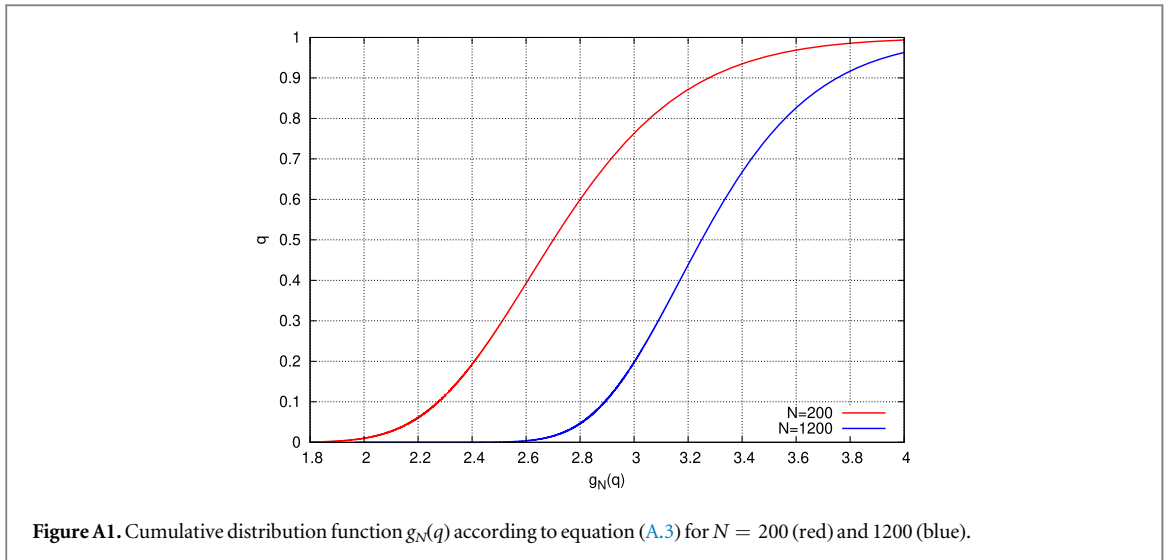
One specification of practical importance is that the maximum 3s-gust in a 10 min period at 10 m height is arithmetically equal to the average wind at 140 m. At larger heights the gusts are equal to the average wind speed at an easily determinable height that is a factor α ($\alpha > 1$) higher. Validation in Cabauw indicates that this rule applies to heights up to at least 200 m. This outcome is valid both over land and over sea, and is independent of surface roughness.

The method fails for weak gusts, over strongly inhomogeneous terrain, and during strong stable and unstable situations. The method performs best in winter with $\rho > 0.9$.

Although the method is validated for maximum 3s-gusts in 10 min periods, it can also be applied to other gust times and/or averaging periods.

Although the derivation follows directly from equations that have been known for decades, it is—to the knowledge of the author—the first time that the gust is validated as the mean wind at a higher fixed level.

The most important requirement for the parametrization to work is that the vertical wind profile is logarithmic with height. This condition assumes that the atmosphere is neutrally stratified, and the upstream roughness is reasonably homogeneous. The results point out that this assumption is generally fulfilled for severe



gales in winter months. In summer months, severe gusts often occur during unstable situations, which explains that the correlations between estimated and observed gusts are worse in summer than in winter.

A large part of the differences between the modelled gusts and the observed gusts at 10 m height can be attributed to the stochastic nature of turbulence. This is quantified by finding that 78% of the monthly maxima agree with the observed maxima at 10 m when the value of g is adjusted somewhere between its 5% and 95% value. This implies that the uncertainty in the other assumptions is of minor importance. For larger heights, only 68% of the observed maxima coincide with the estimated 5%–95% range. This means that the estimation of uncertainty range based on the variation of g is performs best for lower heights.

In the case that the proposed parametrization is applied to the wind from NWP models, it might be necessary to adjust the value of g for several reasons. First, many NWP models have hourly output, i.e. 6 times longer than the 10-min intervals that is considered here. A first-order adjustment is to change the value of the number of independent samples from $N = 200$ to $N = 1200$ in equation (A.3), which increases the median value of g from 2.70 to 3.25. Note that this only works satisfactory if the mean wind is constant over the whole hour (Wieringa 1973). Second, the spatial resolution of the NWP will influence the temporal and vertical smoothness of the wind speed, and consequently of the estimated gusts. Finding the optimal value of g as a function of the spatial and temporal resolution of the NWP lies outside the scope of the current paper.

Appendix. Distribution of the normalised gust

Derivation of $g_N(q)$

If a period of T seconds is divided into N consecutive wind samples, each of τ seconds, then:

$$N = \frac{T}{\tau}. \quad (\text{A.1})$$

The gust is defined as the highest value of these N samples. Following the WMO standard, with $\tau = 3$ s and $T = 600$ s (10 min), gives $N = 200$. For hourly maxima, $T = 3600$ s and $N = 1200$.

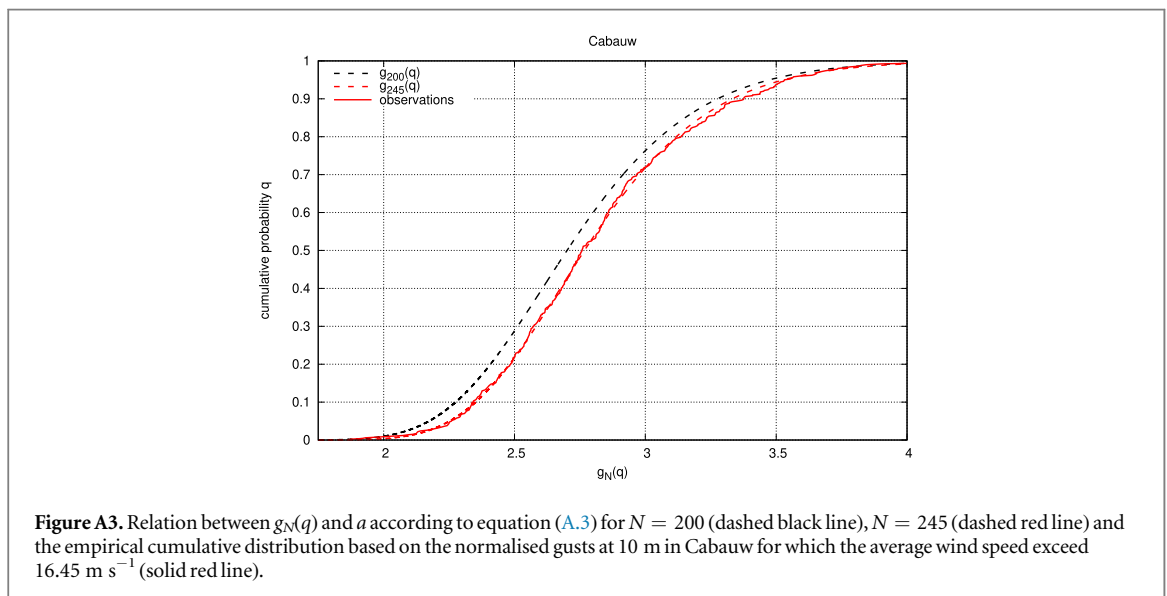
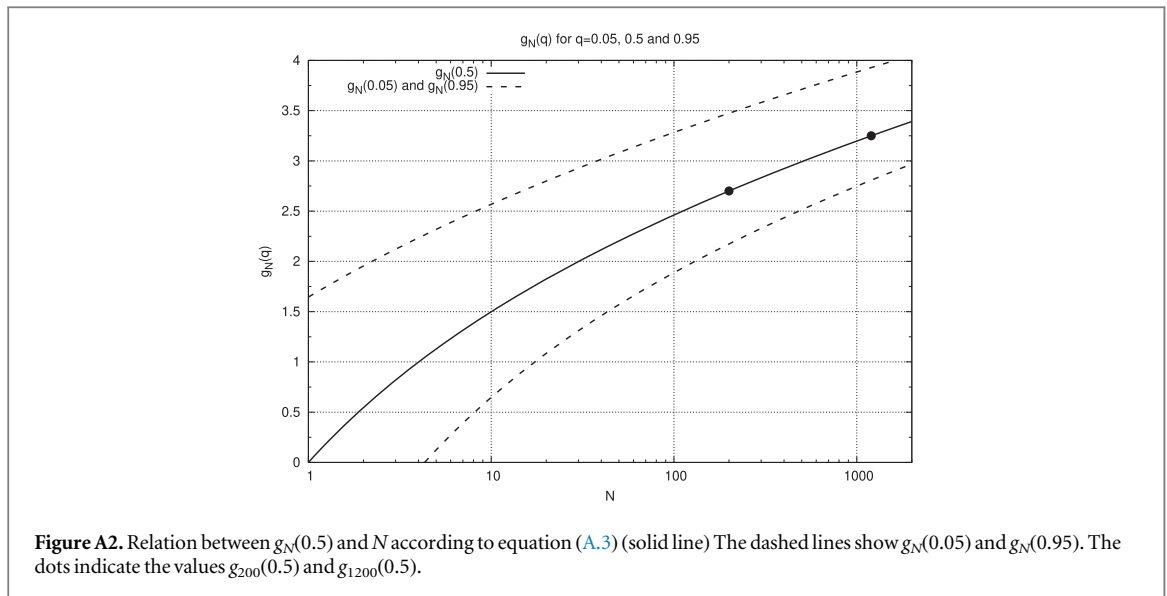
Assuming that the wind fluctuations X_1, \dots, X_N are independent and identically distributed with common cumulative distribution function F , the distribution of the maximum $X_{(N)}$ is:

$$\begin{aligned} F_N(x) &= \Pr(X_{(N)} \leq x) \\ &= \Pr(X_1 \leq x) \Pr(X_2 \leq x) \cdots \Pr(X_N \leq x) \\ &= F^N(x) \end{aligned} \quad (\text{A.2})$$

By definition, the quantile of $F_N(x)$ is the value g for which $F_N(g) = q$. Assuming that the normalised gusts (see equation (5)) are distributed according to the normal distribution Φ gives:

$$g_N(q) = \Phi^{-1}(q^{1/N}) \quad (\text{A.3})$$

with Φ^{-1} the inverse normal distribution. The relation between $g_N(q)$ and q is given in figure A1 for $N = 200$ and $N = 1200$, and between $g_N(q)$ and N in figure A2 for $q = 0.05, 0.5$ and 0.95 .



Validation of $g_N(q)$

In order to validate whether equation (A.3) is applicable to wind gusts at 10 m, all 10-min periods during winter (Oct-Mar) at Cabauw between 1 October 2003 and 31 December 2018 with a average wind speed above 16.45 m s^{-1} are used, resulting in 500 10-min periods. The gusts are normalised with the measured average wind speeds and standard deviations of the corresponding periods (see equation (5)), and the empirical cumulative distribution is estimated by plotting the ordered normalised gusts $g^1 \leq g^2 \dots \leq g^{500}$ versus the estimate of \tilde{F} :

$$\tilde{F}(g^i) = i/501 \tag{A.4}$$

The empirical cumulative distribution of the observed gusts in Cabauw at 10 m is shown in figure A3. The figure also shows equation (A.3) for $N = 200$ as well as $N = 245$, which is the value that optimally describes the observed distribution.

From figure A3 the following can be concluded: First, the normalised extreme gusts at Cabauw can well be described by equation (A.3). Second, the optimal value of $N = 245$ is close to the theoretical value of $N = 200$, with a corresponding value $g_{245}(0.5) = 2.77$, i.e., only 2% higher than the theoretical value $g_{200}(0.5) = 2.70$. The effect of $N = 245$ instead of $N = 200$ on $G^{50\%}(10 \text{ m})$ is 1%. This justifies the choice for $N = 200$. Analysis of other stations in The Netherlands leads to the same conclusion (not shown).

Values used

The theoretical values for the WMO standard, according to equation (A.3), then read:

$$\begin{aligned}
 g_{200}(0.025) &= 2.09 \\
 g_{200}(0.050) &= 2.17 \\
 g_{200}(0.250) &= 2.46 \\
 g_{200}(0.500) &= 2.70 \\
 g_{200}(0.750) &= 2.98 \\
 g_{200}(0.950) &= 3.47 \\
 g_{200}(0.975) &= 3.66
 \end{aligned}
 \tag{A.5}$$

These quantiles indicate that 50% of the maximum gusts in 10-min periods will be larger than 2.70 standard deviations above the mean wind, and 5% will be larger than 3.47 standard deviations above the mean wind.

In this paper, the median value $g_{200}(0.5) = 2.70$ is used as reference, and the 5%–95% range for the uncertainty in g . The expected value $E\{g_{200}(q)\} = 2.75$, i.e., slightly higher than the median value.

ORCID iDs

Henk W van den Brink  <https://orcid.org/0000-0003-4490-0476>

References

- Beljaars A C M 1987 The influence of sampling and filtering on measured wind gusts *J. Atmos. Oceanic Technol.* **4** 613–26
- Born K, Ludwich P and Pinto J G 2012 Wind gust estimation for mid-european winter storms: towards a probabilistic view *Tellus A: Dynamic Meteorology and Oceanography* **64** 17471
- Brasseur O 2001 Development and application of a physical approach to estimating wind gusts *Mon. Weather Rev.* **129** 5–25
- Businger J A, Wyngaard J C, Izumi Y and Bradley E F 1971 Flux-profile relationships in the atmospheric surface layer *J. Atmos. Sci.* **28** 181–9
- Gryning S E, Batchvarova E, Brümmer B, Jørgensen H and Larsen S 2007 On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer *Boundary Layer Meteorol.* **124** 251–68
- Højstrup J 1982 Velocity spectra in the unstable planetary boundary layer *J. Atmos. Sci.* **39** 2239–48
- Wichers Schreur B and Geertsema G 2008 Theory for a TKE based parameterization of wind gusts *HIRLAM Newsletter*
- Monin A S and Obukhov A M 1954 Basic laws of turbulent mixing in the surface layer of the atmosphere *Contrib. Geophys. Inst. Acad. Sci. USSR* **24** 163–87
- Panofsky H A, Tennekes H, Lenschow D H and Wyngaard J C 1977 The characteristic of turbulent velocity components in the surface layer under convective condition *Boundary Layer Meteorol.* **11** 355–61
- Rosby C G and Montgomery R B 1935 The layer of frictional influence in wind and ocean currents *Papers in Physical Oceanography and Meteorology* **3** 1–101
- Schwierz C, Köllner-Heck P, Mutter E Z, Bresch D N, Vidale P-L, Wild M and Schär C 2010 Modelling european winter wind storm losses in current and future climate *Clim. Change* **101** 485–514
- Sheridan P 2011 Review of techniques and research for gust forecasting and parameterisation *Technical Report, UK Met. Office* 570
- Stull R B 1988 *An Introduction to Boundary Layer Meteorology* (Boston: Kluwer Academic Publishers)
- Tennekes H 1973 The logarithmic wind profile *J. Atmos. Sci.* **30** 234–8
- Verkaik J W 2000 Evaluation of two gustiness models for exposure correction calculations *J. Appl. Meteorol.* **39** 1613–26
- Wieringa J 1973 Gust factors over open water and built-up country *Boundary Layer Meteorol.* **3** 424–41