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Climate change and design wind load concepts

Michael Kasperski†

Ruhr-Universität Bochum, Aerodynamik im Bauwesen, 44780 Bochum, Germany

Abstract. In recent years, the effects of a possible climate change have been discussed in regard to wind loading on buildings and structures. Simple scenarios based on the assumption of global warming suggest an increase of storm intensities and storm frequencies and a possible re-distribution of storm tracks. Among recent publications, some papers seem to verify these scenarios while others deny the influence of climatic change. In an introductory step, the paper tries to re-examine these statements. Based on meteorological observations of a weather station in Germany, the existence of long-term trends and their statistical significance is investigated. The analysis itself is based on a refined model for the wind climate introducing a number of new basic variables. Thus, the numerical values of the design wind loads used in modern codes become more justified from the probabilistic point of view.

Key words: climate change; extreme value analysis; overloading risk; directional variation; storm duration; design wind load concept.

1. Introduction

The design wind loads of a structure are based on the analysis of wind climate to which they will be subjected. In particular they refer to prediction of extreme wind speed due to storm, which is not exceeded (within a certain probability) in the envisaged life-time of the structure. Since this extrapolation to the future is based on historic records of meteorological observations, as fundamental assumption, stationarity has to be assumed, i.e., the existence of long-term trends with a period of some decades or so is not taken into account. This assumption obviously is not generally true for all climatic characteristics. From historical records of e.g., changes in the near-surface temperature (Karl, Nicholls, Gregory 1997), considerable non-stationary characteristic are obtained (Fig. 1). Although the data need careful consideration e.g., regarding the influence of considerably varying spatial density of meteorological stations over the years, climatologists are confident that over the past century the near-surface temperature has increased about half a degree Celsius. While some experts argue that using a longer observation period clearly identifies the chosen starting point to be near a local minimum of the historic records – which means the trend in the temperature has to be understood as a natural phenomenon – other experts interpret the increasing trend to be at least partly the result of human activities such as the burning of fossil fuels. For the designing engineer, however, it is almost of secondary importance whether or not the observed long-term increasing trend has its cause in the possible man-induced greenhouse effect. More important are the observed and future effects on the wind climate and especially on the

† Dr.-Ing.

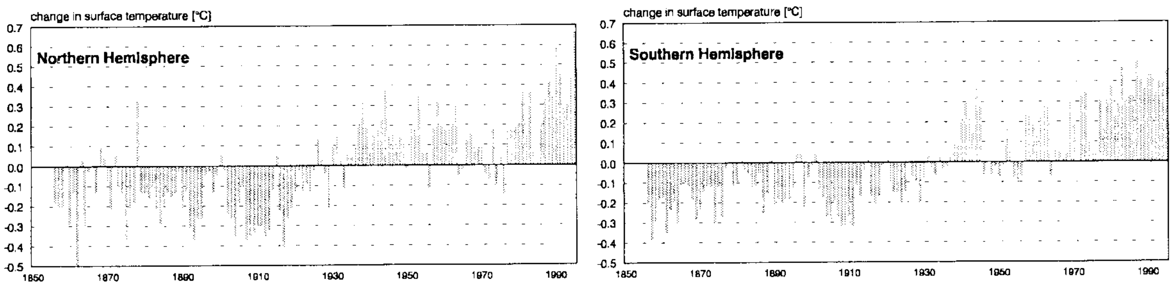


Fig. 1 Changes in near-surface temperature from 1856 to 1995 in the Northern and Southern Hemisphere

extreme wind conditions. Basically, the global warming means an increase of energy in the atmosphere. Consequently, it seems to be reasonable to expect more activity in regard to e.g., weather systems. Considering extreme wind conditions, three possible effects affecting the storms have to be taken into account, namely :

- an increase of the number of events per year,
- an increase in their intensity,
- a redistribution of storm tracks for tropical and extra-tropical cyclones.

For a deeper understanding of recent meteorological observation, it is important to recognise that the globally-averaged records represent an over-simplification. Significant latitudinal and regional differences exist in regard to the extent of warming. In Fig. 2, regional satellite-image trends regarding the lower tropospheric temperatures are shown based on the recent 18 years. It can be seen from this figure that in some areas cooling trends are observed instead of a warming. Hence, it is more appropriate to talk about a global climatic change instead of global warming. Looking at the differences in the temperature-trends, it is not longer contradictory

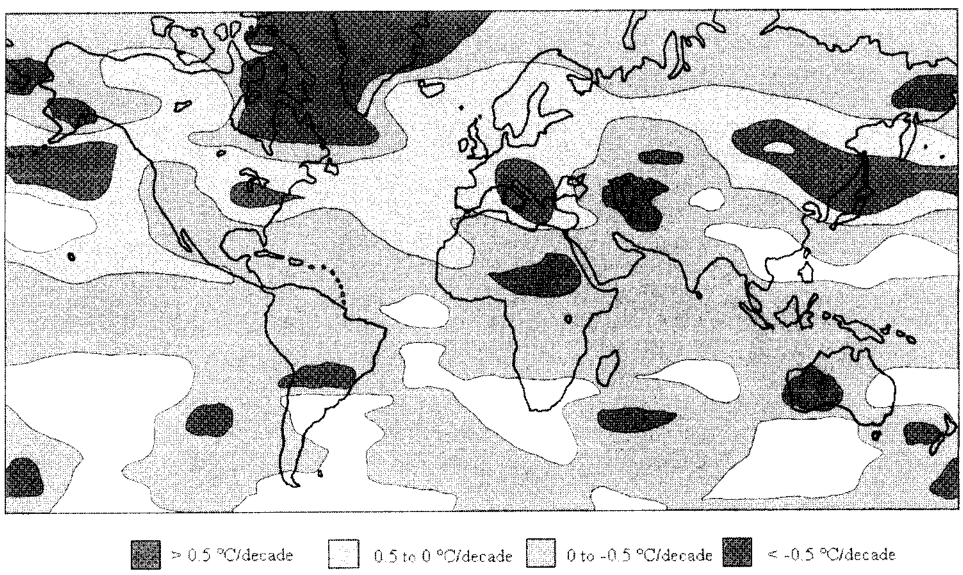
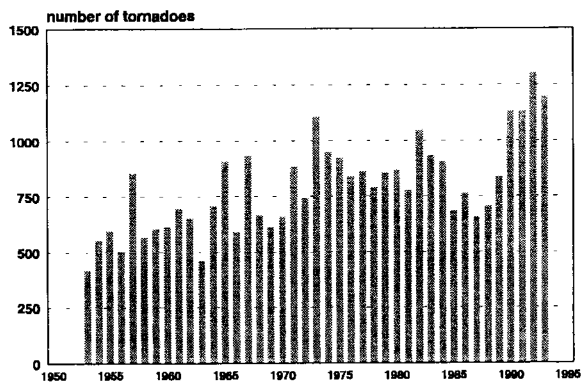
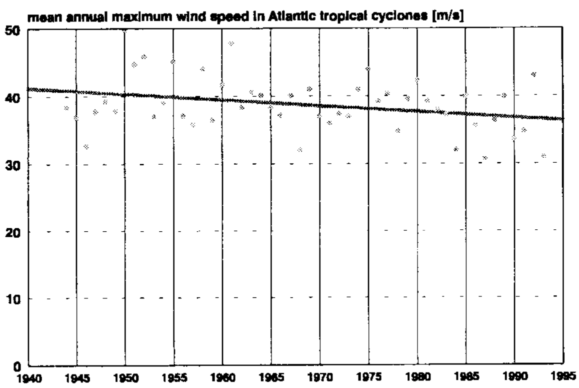


Fig. 2 Regional trends in the near-surface temperature in the last 18 years (reproduced from P.J. Michaels 1997)



tornadoes



hurricanes

Fig. 3 Development of extreme wind conditions in the U.S.A. (NCDC 1997)

that recent findings for different sites and/or different phenomena may suggest different conclusions in regard to the possible effects of the climatic change on the wind climate. In Fig. 3, recently published data (NCDC 1997) are reproduced, presenting the number of tornadoes in the U.S.A. for an observation period from 1953 to 1993 and the mean annual maximum wind speed in Atlantic hurricanes from 1943 to 1993. A considerably increasing number of tornadoes is seen while on the other hand the intensity of hurricanes shows a decreasing trend. Correlating these findings with the corresponding temperature trends, the decrease in the intensity of hurricanes can be related to the observed cooling trend in parts of the Atlantic Ocean, while the increase in the numbers of tornadoes may correspond to an increasing temperature difference over the North-American subcontinent.

In a similar way, the increasing temperature difference over the northern part of the Atlantic Ocean can be interpreted as the cause of the observed increase in number of strong low-pressure systems over the North Atlantic and Europe (Schinke 1992) which has been risen since 1930 by about 40%. The question arises, if and to what extent a similar increasing trend can be found for the extreme wind conditions over land. The paper tries to answer this question on the example of the weather station Düsseldorf airport, Germany, using observations from 1960 to 1995. In chapter 2, a refined model of describing the wind climate is presented which – in a first step – assumes stationarity. Then, in chapter 3, the number of storms and their respective intensities are analysed in regard to long-term fluctuations. The statistical significance of observed trends is investigated using the Monte-Carlo simulation technique. As appropriate measure for the impact on the structural reliability, the overloading risk – i.e., the risk of exceeding the design wind load in the projected life-time of the structure – can be used. The design wind load usually is specified by a reference wind speed having a certain exceedence probability per year, a partial safety factor and a characteristic load or load effect coefficient. Consequently, the overloading risk is obtained from a convolution of the probabilities of exceeding a certain wind speed level and that of exceeding a certain load or load effect coefficient. The basic influence parameters and the convolution integrals are summarised in chapter 4. Finally, the significance of the new parameters and the climatic change are discussed.

2. Extreme wind conditions at Düsseldorf airport

The analysis of the extreme wind conditions at Düsseldorf airport is based on a record of hourly mean wind speeds (and the corresponding direction) and daily gust wind speeds from 1960 to 1995, i.e., 36 years of continuous observation. In general, the extreme wind climate of Düsseldorf – or more general of Germany and Western Europe – is governed by two wind phenomena : frontal depressions and thunderstorms. For a proper statistical analysis, these two phenomena have to be separated (Gomes, Vickery 1978). This can easily be done, since thunderstorms usually are characterised by a lower mean wind speed and a high gust wind speed. Thus, two independent ensembles are obtained by applying two thresholds : one for the mean wind speed and one for the gust wind speed. For the frontal depressions, the independent storms are identified by introducing as a basic variable the maximum hourly mean wind speed of a single storm and by setting a minimum separation of consecutive maxima of e.g., two days. For Düsseldorf airport, the following values have been chosen as threshold : for the mean wind speed 14 m/s and for the gust wind speed 17.2 m/s.

As basic model of the extreme value distribution, the Generalised Extreme Value Distribution is used. For certain parameters, this distribution has an upper finite tail which seems from geophysical aspects to be especially appropriate for extreme wind speeds (Simiu 1995). A similar approach recently has been applied to the analysis of gust wind speeds in thunderstorms (Holmes, Moriarty 1997).

The extreme value distribution for a process x is given as follows :

$$F(x) = \exp\left[-\left(f_1 - f_2 \cdot \frac{x-m}{\sigma}\right)^{1/\tau}\right] \tag{1}$$

where

$$f_1 = \Gamma(1+\tau) \qquad f_2 = \sqrt{\Gamma(1+2\tau) - f_1^2}$$

and

Γ is the Gamma function,
m is the mean value,
σ is the rms value of x and
τ is the curvature parameter.

If the curvature parameter τ is greater than 0, a largest value is obtained as follows :

$$x_{max} = m + \sigma \cdot \frac{f_1}{f_2} \tag{2}$$

For τ=0, the Gumbel Distribution (extreme value distribution type I) is obtained :

$$F(x) = \exp\left[-\exp\left(-\left[\gamma + \frac{\pi}{\sqrt{6}}\;\frac{x-m}{\sigma}\right]\right)\right] \quad \gamma - \text{Euler constant} = 0.5772 \tag{3}$$

The first step in an extreme value analysis is the order statistic, i.e., sorting of the ensemble in ascending order. From this list, the relative frequency f_{rel} of non-exceedence of the value x_i

can be estimated. If the ensemble size N is large enough, the relative frequency becomes the probability.

Generally, the main purpose of fitting observed extreme values to an extreme value distribution is to extrapolate to very rare events, i.e., the main interest lies in the right tail of the distribution. Hence, for estimating the three parameters of the Generalised Extreme Value Distribution (mean value m, rms value σ and curvature parameter τ), the values with a lower non-exceedence probability should have less weight than those at the right tail. On the other hand, the confidence interval increases for both tails, i.e., an overweighting of the highest values has to be avoided. As a synthesis of these two contradictory demands, a fitting method is used which is based on the least error sum of absolute deviations of the observed values x_i to the theoretically predicted values starting at the kth sample of the ensemble. The starting point k generally is set for $p_i > 0.1$. However, it has to be checked, if all samples belong to the same family. If not, k has to be increased. Especially for fitting extreme wind speeds from an ensemble with a more or less arbitrary chosen threshold, it has to be expected that k may become larger than the corresponding value to p_i=0.1.

The extreme value statistic has to be based on an ensemble of independent events of similar geophysical origin. Obviously, a subdivision in e.g., different ensembles for arbitrary chosen sectors of wind direction is not able to meet this demand. Hence, the appropriate extreme value analysis for the frontal depressions should be based on all events over the threshold. For thunderstorms, it might be necessary, to further subdivide the ensemble, if significant differences can be identified for different directions e.g., from a correlation of geographic characteristics and observed intensities.

For each independent storm mechanism, the probability of non-exceedence of a certain threshold v_i can be estimated from order statistics introducing an exponent for adjusting to the period of one year. As estimator for the non-exceedence probability in one year, the following term has been used (Cunnane 1968) :

$$p\,(v \le v_i) = \left(\frac{i - 0.3}{N + 0.4}\right)^{\frac{N}{K}} \tag{4}$$

i rank in list of ascending order, highest value rank N, lowest value rank 1
N ensemble size
K number of years of observation
N/K average rate over the whole observation period

Wind fields in thunderstorms may considerably differ from those obtained in frontal depressions. Since an adequate experimental technique to obtain the aerodynamic coefficients c for such storm types is missing, the observed extreme gust speeds of thunderstorms have to be translated to equivalent mean wind speeds of frontal depressions. For the duration, it is reasonable to introduce a typical length of the equivalent frontal depression of 10 minutes.

The relation of gust wind speed to equivalent mean wind speed can be obtained from the observed ratios in the identified individual frontal depressions. For Düsseldorf Airport, a characteristic value 1/1.6 is obtained.

Furthermore, a considerable difference can be observed in the intensities of thunderstorms for different directions in Düsseldorf. The highest intensities are obtained for southerly to westerly directions (150°~270°), weaker intensities for easterly directions (60°~120°). The corresponding

Table 1 Relative frequency of thunderstorms (Düsseldorf airport) for different wind directions

Type of thunderstorm					
strong		moderate		weak	
sector Φ	$p(\Phi)$	sector Φ	$p(\Phi)$	sector Φ	$p(\Phi)$
150°	0.125	300°	0.476	60°	0.484
180°	0.089	330°	0.333	90°	0.258
210°	0.303	360°	0.079	120°	0.258
240°	0.325	30°	0.011	-	-
270°	0.158	-	-	-	-

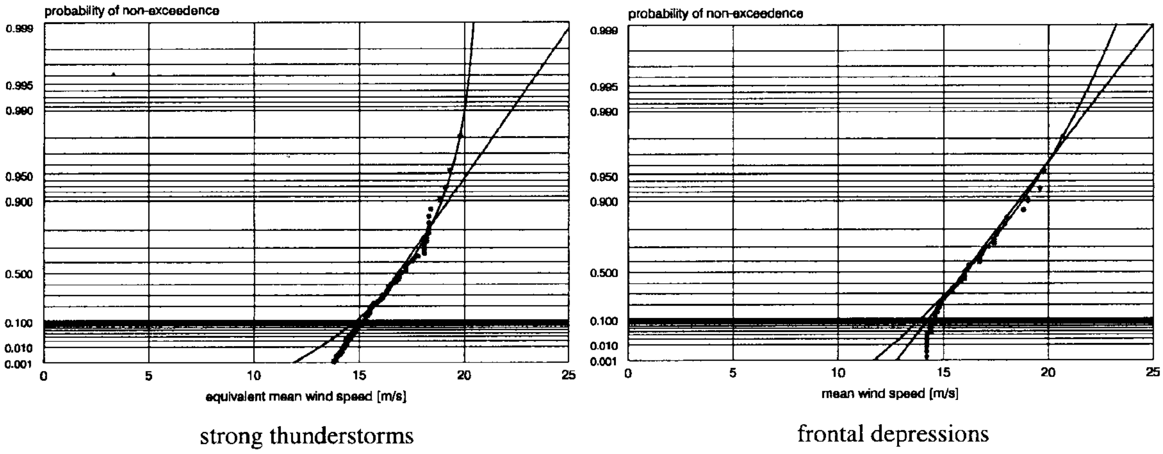


Fig. 4 Extreme value distribution for stronger thunderstorms and frontal depressions (Düsseldorf airport 1960~1995)

relative frequencies of the contributing sectors are summarised in Table 1.

As threshold for the strong thunderstorms, a gust wind speed of 20 m/s has been defined. Altogether, 387 strong thunderstorms are identified in the observation period from 1960 to 1995. The result of the order statistics are plotted in a Gumbel probability paper (Fig. 4). The starting point for fitting the Generalised Extreme Value Distribution has to be increased to $k(p=0.2)$ since at this position a 'kink' in the trace can be distinguished. The corresponding fit of the Generalised Extreme Value Distribution leads to the following values : m=16.9 m/s, σ=1.54 m/s, τ=0.375. From Eq. (2), the largest equivalent mean wind speed for strong thunderstorms at Düsseldorf airport becomes v_{max}=20.7 m/s.

A fit of the strong thunderstorms to a Gumbel distribution (type I, τ=0) leads to considerable overestimation in the right tail and thus to uneconomic design values. For exceedence probabilities of p=0.001 in one year (appr. 0.05 in 50 years) the reduction is about 30% in terms of wind loads.

The results of a similar analysis for the moderate thunderstorms leads to the following values : m=11.0 m/s, σ=3.96 m/s, τ=0.375 and for the weak thunderstorms the parameters are : m=11.1 m/s, σ=1.81 m/s, τ=0.175

Finally, the non-exceedence probability of the maximum hourly mean in frontal depressions can be compared to the Generalised Extreme Value Distribution (Fig. 4). The optimum parameters are : m=16.2 m/s, σ=1.89 m/s, τ=0.125. The corresponding largest possible value of a mean wind speed in a frontal depression becomes 28.9 m/s.

For Düsseldorf airport, frontal depressions with a maximum mean wind speed of at least 14 m/s are obtained only for four sectors : 180°, 210°, 240° and 270°. The corresponding relative frequencies of frontal depressions in these sectors are 0.065, 0.403, 0.435 and 0.097.

Frontal depressions may have a duration of high intensity winds which considerably exceeds one hour. With each additional hour, the probability of exceeding the design value increases. Hence, at least two further parameters have to be introduced : the mean duration T of a frontal depression and the mean relative intensity in the 2nd, 3rd, 4th to Mth-strongest hour. For Düsseldorf airport, the mean duration of a frontal depression is T_m=3.33 hours. The corresponding mean relative intensities are 0.957, 0.927 and 0.904 for the 2nd, 3rd and 4th hour.

Additionally, during a single storm, the mean wind direction may change. To estimate the probability $p(\Theta(k))$, i.e., the probability that in the kth-strongest hour the mean wind direction is different from that of the strongest storm hour, discrete sectors have to be defined. The meteorological data usually allow to identify differences of 10°, however to obtain sufficient large ensembles, a sector-grid of 30° seems to be more appropriate. For Düsseldorf airport, the possible pairs of direction changes have to be limited to the following pairs :

- for one sector difference : (180-210), (210-240), (240-270), (210-180), (240-210), (270-240)
- for two sector difference : (180-240), (210-270), (240-180), (270-210)

The relative frequencies of sector change in kth-strongest storm hour are summarised in Table 2. These results suggest that for Düsseldorf area the probability of a direction change of wind in frontal depressions remains small enough to be neglected. This assumption is valid unless the characteristics of the aerodynamic coefficients of a structure show no sudden change with direction.

Table 2 Relative frequencies of a sector change in the kth-strongest storm hour of frontal depressions

kth-strongest hour	2	3	4
one sector change	0.103	0.100	0.114
two sector change	0.026	0.033	0.000

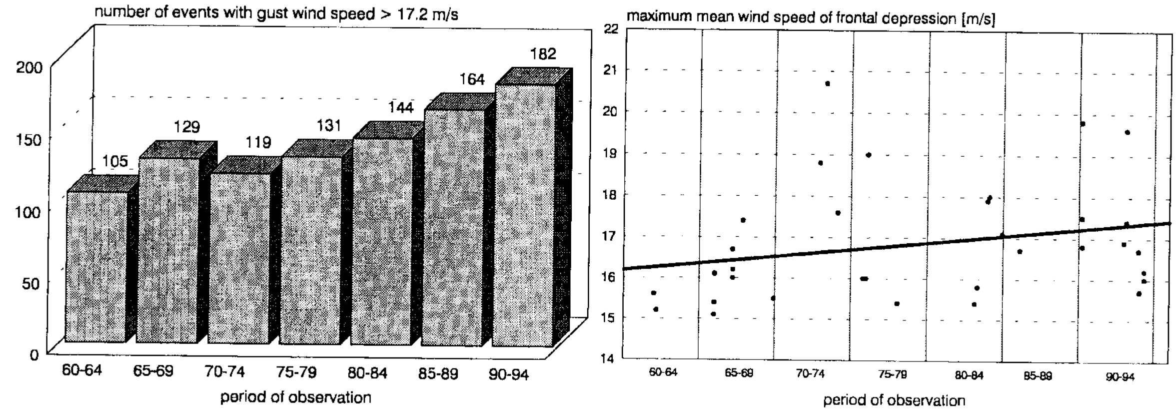
3. Identification of long-term trends

As already mentioned above, long-term trends could occur for the number of storms per year and the intensity. The number x of storms per year itself forms a stochastic process which is usually represented by a Poisson distribution as follows :

$$f(x) = \frac{v^x}{x!} \cdot e^{-v} \tag{5}$$

x random number of storms per year
v average number of storms per year

For Düsseldorf airport, the average number of events per year with gust wind speeds above 17.2 m/s (this gust wind speed forms the 'litigation' limit used by the insurance industry) is about 28 per year. In Fig. 5, the yearly distribution of these events is presented. Note that in order to

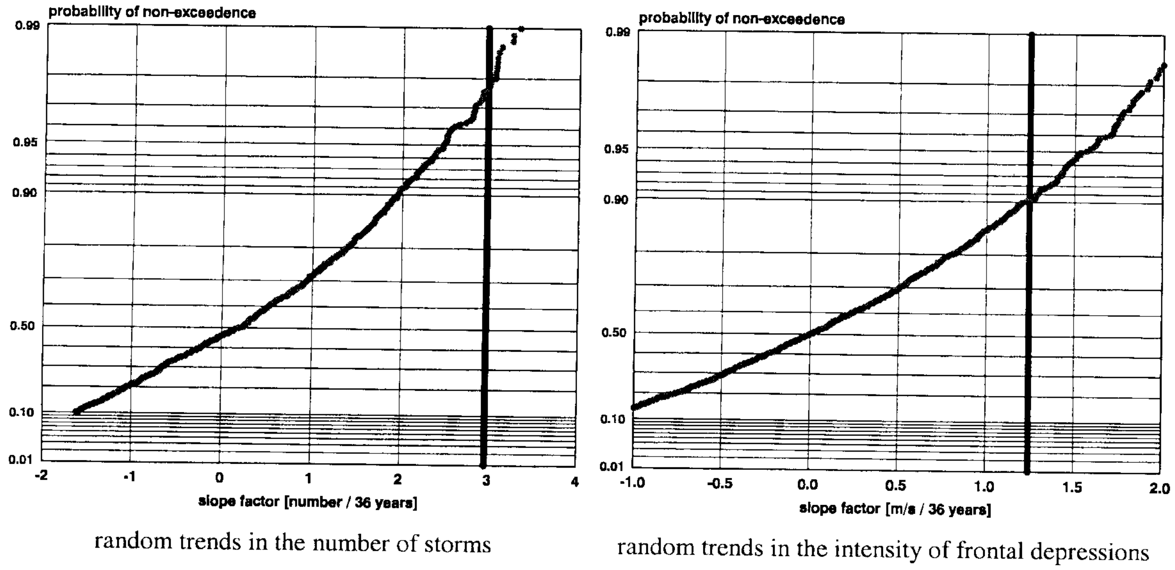


trend in number of storms per five year period — trend in maximum mean wind speeds

Fig. 5 Observed trends for the number of storms per five year period and the maximum mean wind speeds of frontal depressions (Düsseldorf airport 1960~1995)

reduce the scatter, 5-year-periods have been considered in this graph. A significant trend is obtained leading to an increase of the average number of storms per year from roughly 21 in the sixties to 36 in the nineties, i.e., the number of possible liability conditions for insurance companies has been drastically increasing. With no doubt, this increase can not be explained by a natural scatter. Furthermore, this observation is in agreement with the increasing trend in the number of minor claims made in Germany under houseowners' insurance policies (Berz 1993).

In regard to structural safety, a higher threshold for extreme wind conditions should be used. A reduced ensemble is obtained introducing as threshold 14 m/s for the mean wind speed and 22.4 m/s for the gust wind speed. The average number of extreme wind conditions per year then becomes 1.8 for frontal depressions and 4.5 for strong thunderstorms. Again, an increasing trend in the



random trends in the number of storms — random trends in the intensity of frontal depressions

Fig. 6 Cumulative probability of the slope factors of a linear trend from 1000 samples of 36 years observation periods applying the identified models for Düsseldorf airport number of events per year is obtained. Applying as easiest model a linear trend leads to an increase of roughly 8% per year in the total number of extreme wind conditions or 3 events per year in 36 years.

To consider also a possible increase in the intensity of the frontal depressions, all events with a mean wind speed above 15 m/s are plotted on a time axis (Fig. 5). Over the last 36 years, a slight trend is obtained, changing the mean wind speed from 16.1 m/s to 17.3 m/s. Fitting a linear trend leads to an increase of 1.25 m/s in 36 years.

The statistical significance of both trends can be evaluated by applying the Monte-Carlo simulation. For the number of storms per year, 1000 samples of 36 years each with a random number of storms per year have been generated. The number of storms follows a Poisson distribution with mean value of 6.3. For each sample, a linear trend is fitted. The corresponding cumulative probability of increase in 36 years (slope factor) is shown in Fig. 6. The data from 1960 to 1995 suggest a trend with a slope factor of 3 which has a non-exceedence probability of 98%, i.e., the probability that the observed increase in the number of storms is due to natural scatter becomes extremely small. The numerical simulation for the mean wind speeds uses the above identified model of the extreme value distribution for frontal depressions. The observed trend of 1.25 m/s in 36 years has a non-exceedence probability of 90%. Again, the probability for the observed trend being an effect of the natural scatter remains small.

4. Significance for the design

Modern codes like e.g., the Eurocode 1 (ENV 1995) or the Australian Standard (AS 1989) define the design wind load basically by three characteristic variables : the reference wind speed v_{ref} given with a certain exceedence probability in one year, a partial factor γ_w and an aerodynamic coefficient c for a load or load effect. For the characteristic value of c, different models are used. The first models have been based on the mean extreme which has an exceedence probability of 43%. This approach however neglects the influence of a possible dispersion of the extremes in the time window of turbulence. For larger dispersions of the extremes of c, this approach may lead to considerable inconsistencies. Cook and Mayne (1980) therefore improved the approach by introducing the 78%-fractile. A similar approach has been introduced in Canada based on the 80%-fractile. However, it is worth mentioning that not all of the actual coefficients in e.g., the Eurocode 1 are those 'Cook-and-Mayne-coefficients'.

The overloading risk is obtained from convoluting the probabilities of both fluctuating contribution to the wind load, i.e., the wind speed and the action or action effect coefficient. The basic form of this convolution integral is given as follows :

$$p\,(w > w_{des}) = \int_{v=0}^{\infty} p(v) \cdot \int_{c_{gr}}^{\infty} p(c)\,dc\,dv \tag{6}$$

The lower limit of the second integral is determined by the design wind load and the respective wind speed level in the first integral :

$$c_{gr} = \frac{2 \cdot w_{des}}{\rho \cdot v^2} \tag{7}$$

The design wind load itself is given as follows :

$$w_{des} = \gamma_w \cdot \frac{1}{2} \rho \cdot v_{ref}^2 \cdot \hat{c}_{ref} \tag{8}$$

γ_w partial factor for wind load
ρ density of air
v_{ref} reference wind speed, exceedence probability p_v in one year
$\hat{c}_{ref}$ reference action or action effect coefficient,
exceedence probability p_c in 1 hour or 10 minutes

If the dispersion of the extreme coefficients c tends to zero, Eq. (6) can be rewritten as follows :

$$p\,(w > w_{des}) = \int_{v_{des}}^{\infty} p(v)\,dv \tag{9}$$

The lower limit of the integral is obtained as :

$$v_{des} = \sqrt{\gamma_w} \cdot v_{ref} \tag{10}$$

Thus, the basic overloading risk is determined by the choice of the exceedence probability of v_{ref} and the value of γ_w. As a matter of fact, any combination of p_v and γ_w can be used to obtain (for a given wind climate) the introduced target overloading risk. However, there is only one combination leading to the same basic overloading for any wind climate. This is shown in Fig. 7 on the example of a target risk of 5% in a life-time of 50 years, which is explicitly the target of the Australian Standard and is almost the number obtained by combining p_v=0.02 and γ_w=1.5 for the wind climate of Western Europe. The three diagrams (for three dispersions of the extreme wind speeds v) present curves of the corresponding partial safety factor for any arbitrary chosen reference wind speed with an exceedence probability between 0.1 and 0.0001 per year for different curvature parameters τ for the extreme value distribution of v. For each wind climate, the curves cumulate in one and the same point which forms the

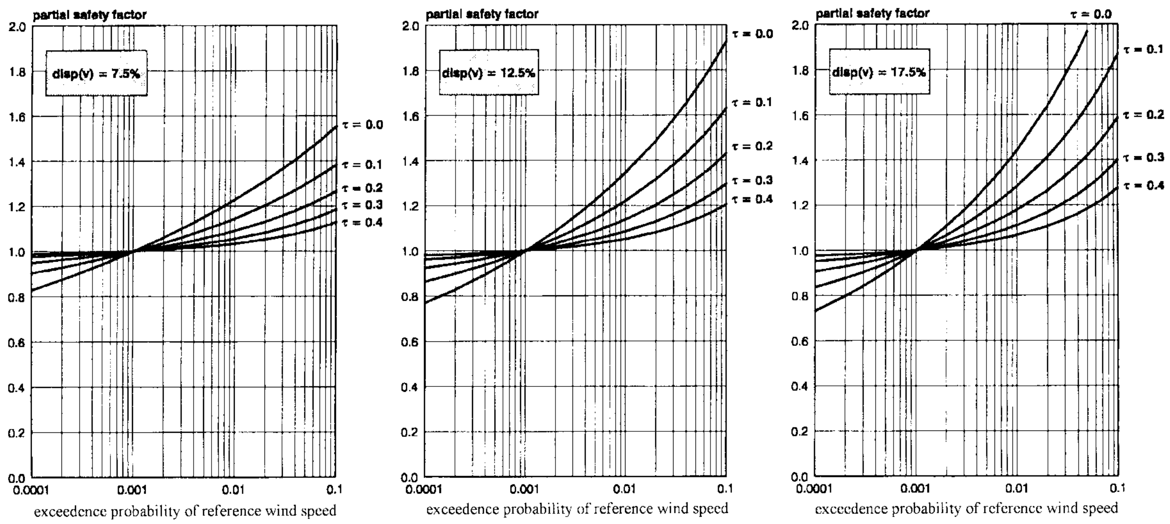


Fig. 7 Possible combinations of partial factors γ_w and exceedence probability of v_{ref} to achieve a basic overloading risk of 5% in 50 years for different wind climates

optimum combination with p_v=0.001 and γ_w=1.0.

Eq. (9) defines the overloading risk in one year for a stationary process, i.e., with constant number of storms per year and constant characteristic values. The basic overloading risk in a life-time of L years is then obtained as :

$$p_L\,(w > w_{des}) = 1 - p_1(w < w_{des})^L \qquad (11)$$

p_L overloading risk in L years
p_1 overloading risk in one year

The trends in the number of storms per year and in the mean intensity of the storms discussed in Section 3 imply that in each subsequent year the exceedence probability of w_{des} – or v_{des} if the dispersion of c is small – increases. Thus, the overloading risk accumulated over the lifetime L is as follows :

$$p_L\,(w > w_{des}) = 1 - \prod_{i=k}^{k+L} p_i\,(w < w_{des}) \qquad (12)$$

p_i non-exceedence probability in year i
k start of exposure
L life-time in years

The non-exceedence probability p_i in a specific year can be obtained by applying the identified linear trend to the respective mean value m of the theoretical extreme value distribution of the wind speeds and using additionally an exponent to introduce the increasing number of storms per year :

$$p_L\,(w > w_{des}) = 1 - \prod_{i=k}^{k+L} F_i\,(v_{des}\,,\, m_i\,,\, \sigma,\, \tau)^{\frac{N_i}{N}} \qquad (13)$$

F extreme value distribution
σ, τ identified characteristic values assuming stationarity

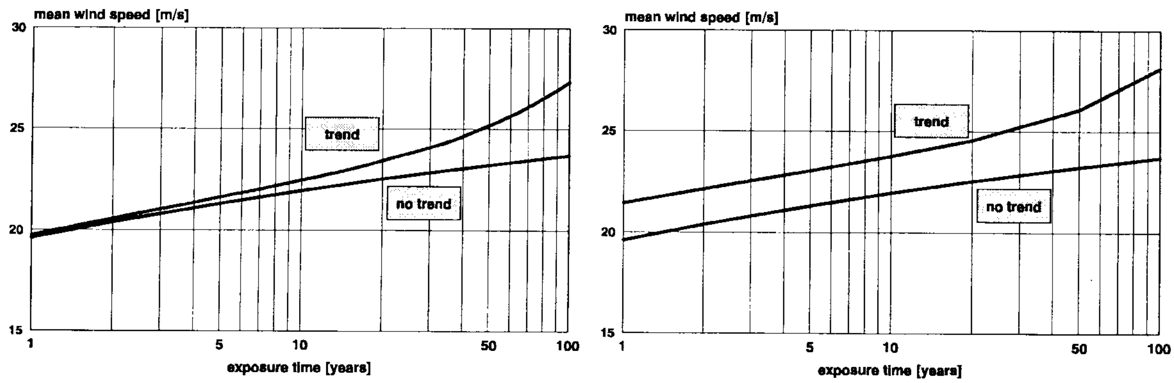
Table 3 Extreme mean wind speeds of frontal depressions which are exceeded with a probability of 5% in a specific period (all values in [m/s]) including prognosis for climatic change

exposure time [years]	no trend	with trend: begin of exposure 1978	1988	1998	2008	2018	2028
1	19.61	19.73	20.70	21.42	22.03	22.58	23.09
2	20.38	20.55	21.45	22.13	22.72	23.25	23.75
5	21.31	21.62	22.41	23.04	23.59	24.10	24.58
10	21.94	22.46	23.17	23.75	24.27	24.75	25.21
20	22.52	23.43	24.03	24.55	25.04	25.49	25.94
50	23.22	25.17	25.63	26.08	26.51	26.92	27.33
100	23.69	27.34	27.74	28.14	28.53	28.92	29.31

m_i expected characteristic value m in year i in accordance to identified trend
N average number of storms per year from observations
N_i expected number of storms in year i in accordance to identified trend

To illustrate the significance of the observed climatic changes, the overloading risk accumulated in L years from a starting point in k years can be compared to the target risk. Additionally, the inverse problem is analysed, i.e., the adjusted reference wind speed is estimated which leads to the target overloading risk of 5% in L years life-time. The respective reference or design wind speeds have to be estimated iteratively. As an example, the dominant wind phenomenon i.e., storm due to frontal depressions is used. Since the reference point for estimating the extreme value distribution lies in the middle of the observation period from 1960 to 1995, the starting point of the exposure has to be set back to 1978. In Table 3, the results for the design wind speed are summarised for exposures starting in 1978, 1988, 1998 and so on and are given for a range of exposure times from 1 year to 100 years. The corresponding results for the situation excluding the trends are also given. Fig. 8 shows the dependence on the time of exposure for two different starting points. The effect of the trends basically become stronger the longer the exposure time will be and the further the begin of the exposure is shifted from the reference point. Thus, for each structure erected this year, the curve of the design wind speeds including the trend is well separated from the curve without trend since e.g. the expected number of storms per year is already considerable higher then the average number of storms in the observation period from 1960 to 1995. To achieve the target risk of 5%, the design wind load with no trend has to be increased by an adjusting factor. For 1998, this factor starts from roughly 20% for 1 year exposure time and increases to 40% for exposure times of 100 years.

For standard buildings with a projected life-time of 50 years, the erection in 1978 based on a design with no trend leads to an underdesign of 18% in terms of design wind loads. The corresponding overload risk is 14% instead of the target of 5%. The same building erected in 1988 has an underdesign of 22% and an increased overloading risk of 23%. Erecting the building this year (1998), leads to an underdesign of 26% and a corresponding overloading risk of 38%. For buildings erected in 2008, the overloading risk increases further to 52%, for 2018, the over-



begin of exposure 1978 begin of exposure 1998

Fig. 8 Extreme mean wind speeds of frontal depressions which are exceeded with a probability of 5% in a specific period-prognosis of an increasing intensity and number of storms per year (Düsseldorf airport) loading risk will be 72% and for 2028 about 92%.

The above analysis is confined to the dominant wind phenomenon and is appropriate as long as directional effects are not taken into account. If however directionality should be included in the design, Eq. (6) has to be refined. Firstly, the accumulation for both storm mechanisms has to be introduced :

$$p\,(w > w_{des}) = 1 - p_{fd}\,(w < w_{des}) \cdot p_{th}\,(w < w_{des}) \tag{14}$$

p_{fd} non-exceedence probability accumulated in frontal depressions
p_{th} non-exceedence probability accumulated in thunderstorms

If more than one thunderstorm mechanism has to be taken into account, the number of multipliers in Eq. (14) has to be increased. The non-exceedence probability p_{th} can be obtained as the accumulation of non-exceedences over the different sectors, i.e., :

$$p_{th}\,(w < w_d) = \prod_{\Phi} \left[1 - \int_{v=0}^{\infty} p(v)^{p(\Phi)} \cdot \int_{c=c_{gr}}^{\infty} p(c(\Phi))\, dc\, dv \right] \tag{15}$$

$p(\Phi)$ relative frequency of a thunderstorm from wind direction Φ
$p(v)$ probability distribution for the mean wind speed of an equivalent frontal depression
$p(c)$ probability distribution of load or load effect coefficient (for flow direction Φ)

$$c_{gr} = \frac{2 \cdot w_d}{\rho \cdot v^2}$$

In Eq. (15), the averaging time to obtain the peak coefficients corresponds to the 10 minute duration of the equivalent frontal depression. If one uses the results corresponding to hourly means, an adjustment is needed to cater for the exceedence probability of the load or load effect coefficient. The convolution of v and c then becomes :

$$\int_{v=0}^{\infty} p(v) \cdot \left(1 - \left[1 - \int_{c=c_{gr}}^{\infty} p(c(\Phi))\, dc \right]^{1/6} \right) dv \tag{16}$$

The calculation of the non-exceedence probability in frontal depressions additionally has to take into account the duration and the corresponding relative intensity and the possibility of a direction change, i.e., eventually more than one probability distribution of $c(\Theta)$ may be needed. The non-exceedence probability now becomes :

$$p_{fd}\,(w < w_d) = 1 - \prod_{\Phi} \int_{v_s=0}^{\infty} p\,(v_s)^{p(\Phi)} \cdot \left[1 - \prod_{k=1}^{T} h_{c,k} \right] dv_s \tag{17}$$

where

$$h_{c,k} = \prod_{\Theta} \left(1 - \int_{c=c_{gr,k}}^{\infty} p(c(\Theta))\, dc \right)^{p(\Theta,\,k)}$$

$p(\Phi)$ relative frequency of a frontal depression from wind direction Φ
$p(v_s)$ probability distribution for the maximum mean wind speed of a frontal depression
T mean duration of a storm
$p(\Theta)$ probability distribution of sector Θ in kth-strongest hour
(first hour : $\Theta = \Phi$)
$p(c)$ probability distribution of load or load effect coefficient (for flow direction Θ)

$$c_{gr,k} = \frac{2 \cdot w_d}{\rho \cdot v_s^2 \cdot (1 - a_k)^2}$$

$(1 - a_k)$ mean intensity of the wind speed in the k-th storm hour

Depending on the dispersion of the load effect coefficient, neglecting the duration of a single storm could lead to considerable higher exceedence probabilities. This is especially true for wind phenomena with a more or less constant intensity over several hours like e.g., hurricanes and gravity winds. For frontal depressions, this effect usually is neglected. Applying the identified parameters of frontal depressions at Düsseldorf airport, the influence of duration is shown in Table 4 for a 78%-fractile-coefficient as it is widely used in the Eurocode 1 and for the most often used mean extreme coefficient. The results clearly show, that the duration might increase the exceedence probability in a single storm and thus may influence the overloading risk in regard to wind loads.

Table 4 Increase of the exceedence probability, if the duration T of a storm event is neglected

dispersion of c	0%	5%	10%	15%	20%	25%	30%
mean extreme	0.430	0.470	0.562	0.625	0.665	0.692	0.711
78%-fractile	0.220	0.243	0.299	0.342	0.371	0.391	0.407

The above formulas unfortunately do not allow to separate the effects of the dispersions of the extreme wind speeds and that of the extreme load or load effect coefficient. To resolve this dilemma, Cook (1983) proposed for directional effects to use design wind speeds with a reduced exceedence probability as follows :

$$p\,(v > v_{ref} \mid \Phi) = 1 - (1 - p_{aim})^{\frac{1}{M}} \tag{18}$$

p_{aim} target probability
M number of sectors

For the strongest wind direction, this method inevitably leads to direction factors larger than one. Thus, application of the directional factors is recommended only for structures with considerable varying stiffness with direction and only if the weakest axis is not oriented to the strongest wind direction. The main advantage is that the proof for the limit states is separated for each wind direction. The method however does not allow an optimised design of a structure having only directional effects due to aerodynamics like a portal frame of a low-rise building.

Adjusting the direction factors for effects of a probable climatic change leads to the same procedure as already described for adjusting the mean wind speed of frontal depressions. However, as a further step, for each family of thunderstorms the time history of the intensities has to be analysed to detect and define an appropriate statistical significant trend.

5. Conclusions

The analysis of the wind climate at Düsseldorf airport suggests that for extreme wind speeds, an extreme value distribution with a finite upper tail is an appropriate model. For each type of storms, a curvature parameter considerably larger than 0 has been found. This generally enables a more economic design. The analysis has been refined to some parameters which usually are neglected, e.g., the duration of frontal depressions and the corresponding relative intensity in the further storm hours. For Düsseldorf airport, an average storm lasts for more than 3 hours with an average decrease of 5% and 7% in the second and third strongest hour.

For the observation period of 36 years, a distinct trend in the number of storms is observed. Fitting the most simple model of a linear trend, suggests an increase of 8% per year. A Monte-Carlo simulation based on 1000 samples of 36 years rejects natural scatter with a probability of 98%. The intensities of frontal depressions show a weak trend as well, however, the Monte-Carlo simulations allows to interpret the observed increase as natural scatter with a probability of 20%.

The significance of these trends for the design of structures can be evaluated based on the overloading risk, i.e., the risk of exceeding the design wind load in the projected life-time of the structure. It is obtained from a convolution of the probabilities of extreme wind speeds v and extreme load or load effect coefficients c. Only for small dispersions of c, the duration of a storm generally may be neglected. Then, the overloading risk is obtained as the exceedence probability of the design wind speed in the life-time of the structure. This basic overloading risk is set by the exceedence probability of the reference wind speed and the partial factor. For the typical wind climate in Western Europe, the Eurocode concept with an annual exceedence probability of 0.02 for the reference wind speed and a partial factor of 1.5 leads to an overloading risk of 5% in 50 years or an annual exceedence probability of 1/1000. Taking 5% in the life-time as target value, overloading risks for a changing wind climate can be estimated. Additionally, the differences between estimating the overloading risk with and without trend are worked out in terms of wind loads. The increase in the number of storms per year and the increase in their intensity lead to an increasing overloading risk. For a structure with a projected life-time of 50 years, the load differences exceed 20%, i.e., the effects on the design become significant enough to be addressed in the wind load codes. As first step, an adjusting factor for climatic changes explicitly should be introduced in the codes thus advising the designing engineer of a further possible uncertainty in the wind loading model. Since the extrapolation to the future is sensitive to the basic form of the trend and the observation period today is too short to fit sophisticated trends, the first approach for specifying the adjusting factor has to based on a linear trend. A verification of the trend can be performed e.g., each ten years. Then, each approach should use as reference point the middle of each prognosis-period.

References

Karl, T.R; Nicholls, N. and Gregory, J. (1997). "The coming climate", *Scientific American Magazine.*

Michaels, P.J. (1997). "Satellite-based temperature trends", http://www.gcrio.org/ocp97/temptrend.html.

Schinke, H. (1992). "Zum Auftreten von Zyklonen mit Kerndrücken ≤ 990 hPa im atlantisch-europä ischen Raum von 1930-1991", *Spezialarbeiten aus der Arbeitsgruppe Klimaforschung des Meteorologischen Instituts der Humboldt-Universität Berlin*, Humboldt-Universität Berlin.

NCDC – National Climatic Data Centre U.S.A. (1997), http://www.ncdc.noaa.gov.
Holmes, J.D. and Moriarty, W.M. (1997). "Application of the generalised Pareto distribution to wind engineering", *Proc. IVAPSOWE*, Surfers Paradise, Australia, July 1997.
Gomes, L. and Vickery, B.J. (1978). "Extreme wind speeds in mixed climates", *Journal of Wind Engineering and Industrial Aerodynamics* **2** 331-344.
Cunnane, C (1968). "Unbiased plotting positions – a review", *Journal of Hydrology*, Vol. 37.
Simiu, E. (1995). "Estimation of extreme wind speeds", A State of The Art in Wind Engineering, *Ninth International Conference on Wind Engineering*, New Delhi, India.
Berz, G. (1993). "The world-wide increasing wind storm risk : Damage analysis and perspectives for the future", *Proc. 6th ICOSSAR*, Innsbruck, Austria, August.
ENV (1995). Eurocode 1 – Basis of Design and Action on Structures.
AS (1989). Australian Standard AS 1170, Minimum Design Loads on Structures, Part 2 : Wind Loads.
Cook, N.J. and Mayne, J.R. (1980). "A refined working approach to the assessment of wind loads for equivalent static design", *Journal of Wind Engineering and Industrial Aerodynamics*, **6**, 125-137.
Cook, N.J. (1983). "Note on directional and seasonal assessment of extreme winds for design", *Journal of Wind Engineering and Industrial Aerodynamics*, **12**, 365-372.