A New Approach to the Specification of the Design Wind Speed Considering Long-term Trends in the Wind Climate

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Abstract

Any analysis of extreme values of wind climates with the aim of estimating design wind speeds suffers from statistical uncertainties induced by short observation periods. As can be shown by simulations, the identification of the 'true' parameters of a wind climate is virtually impossible. The situation is even worse if trends have to be evaluated in regard to their statistical significance. These trends may result from a global climate change which can also affect the wind climate. Particularly, trends in the number and intensity of storms seem to be of basic interest. The corresponding probability distributions are the Poisson distribution with describing parameter λ (average number of storms per year) and the Generalized Pareto distribution with describing parameters s and k (scale parameter and shape factor). The new approach is based on the idea that the observed parameters λ_{obs}, s_{obs}, k_{obs} and the corresponding linear trends $a_{\lambda, obs}$ and $a_{s, obs}$ may be obtained from a large range of combinations of λ, s, k, a_λ and a_s. In a first step, the probabilities are calculated that the observed parameters will be obtained for each combination λ, s, k, a_λ and a_s. Then, for each combination, the design wind speed is calculated (for different target probabilities and different design working lives). Sorting the obtained design wind speeds and integrating their corresponding probabilities gives the non-exceedance probability curve of the probable design wind speed. The 'best estimate' is obtained by applying a target confidence interval of 75% which has previously been introduced as a basis for estimating design values for the resistance side when dealing with statistical uncertainties from confined ensembles. Based on the findings for the wind climate at Düsseldorf, it is strongly recommended to consider non-stationary features when specifying design wind speeds. The assumption of a stationary wind climate may lead to considerable underestimations of design wind speeds.

Key words: extreme wind climate, design wind speed, statistical uncertainties, long-term trends, climate change

1. Introduction

Although the appropriate specification of the design wind speed is of vital importance to the wind resistance of a structure, experts have failed to agree on a uniform method for estimating this value based on meteorological observations of wind speeds. The discussions deal with almost any aspect of the problem, starting with the question on the basic ensemble (extremes over a certain threshold or yearly extremes), the appropriate extreme value distribution (Gumbel or Reverse Weibull), the representative variable (v or v^2 or even v^3), the fitting method (BLUE or least-square fit), the sampling period (calendar year or meteorological year) and so on (Kasperski, 2009). Furthermore, many codes hide the actual design value by specifying a partial factor and a characteristic value which refers to a specific return period. The large variety of code-concepts – with return periods from 5 to 1000 years and recommended partial factors from (at first sight confusing) 0.93 to 1.6 – reflects the basic uncertainty of the experts rather than the different demands in regard to the reliability of the structures.

The basic cause of the never-ending discussions lies in the low statistical stability of the extreme-value analysis which usually is based on only a few decades of meteorological observations. This can be shown by simulations which are based on a probabilistic model with two key variables for the extreme wind climate: the number of storms per year N and the intensity per storm v. The corresponding model is shortly described in section 2. Specifying the design target values for wind speed in terms of an appropriate exceedance probability then allows identifying the large uncertainties (section 3).

The ongoing discussions on global climate change and its possible impacts on the extreme wind climate form a further challenge when specifying the design value of the wind load. For an appropriate wind resistant design of future buildings and structures, long-term trends in the wind climate have to be considered. However, the available observation periods are usually too short to identify the shape and the intensity of non-random long-term trends with sufficient statistical stability.

Accepting that the 'true' parameters of the extreme wind climate, including long-term trends, cannot be identified leads to the understanding that virtually any wind climate may hide behind the observed parameters, though with different probabilities. Based on simulations, these probabilities can be identified. They provide the probabilistic basis for a new concept of getting the best estimate of the design wind speed. The basic idea of this new approach is described in section 4 and one first example of its application is provided in section 5.

2. Basic Variables of the Extreme Wind Climate and Target Design Values

A general approach to the analysis of the extreme wind climate considers at least the following two basic variables: the number of events, N, per year and the intensity, v, of an individual event. For this approach, an appropriate threshold value has to be chosen. As sufficient condition for independent events, often the time between two exceedances of the threshold value can be used, e.g. 12 to 24 hours for strong frontal depressions. Sampling the events for an appropriate aeolian year (continuous twelve-month period in which a complete annual climatic cycle occurs) prevents that a single storm may be discontinued by the sampling unit 'year.'

The non-exceedance probability of a reference value v_{ref} per year is obtained as follows:

$$p(v \le v_{ref} \mid \text{year}) = \sum_{N=0}^{\infty} p(N) \cdot p(v \le v_{ref})^N \tag{1}$$

N : number of storms per year
p(N) : probability of N storms per year
$p(v \le v_{ref})$: non-exceedance probability per event.

The non-exceedance probability of a reference value v_{ref} for the whole design working life of the structure is accumulated over a set of single years as follows:

$$p(v \le v_{ref} \mid \text{lifetime}) = \prod_{i=y_s}^{y_s+L} p_i(v \le v_{ref}) \tag{2}$$

y_s : starting year of exposure
L : design working life in years
p_i : non-exceedance probability of v_{ref} in year i

It is important to note, that in the presence of long-term trends the parameter y_s plays a significant role.

For a stationary wind climate, i.e. for the non-exceedance probability of v_{ref} being the same in each year, equation (2) becomes:

$$p(v \le v_{ref} \mid \text{lifetime}) = p(v \le v_{ref} \mid \text{year})^L \tag{3}$$

A reasonable model for the number of events per year is obtained with the Poisson distribution:

$$p(N) = \frac{\lambda^N}{N!} \cdot e^{-\lambda} \tag{4}$$

λ : average number of events per year

For the intensity of the single events, the Generalised Pareto distribution may be used (Holmes & Moriarty, 1999):

$$p(v \le v_{ref}) = 1 - \left[1 + \frac{v_{ref} - v_s}{s} \cdot k\right]^{-1/k} \tag{5}$$

v_s : threshold value
s : scale parameter
k : shape factor

In case of a negative shape factor, the distribution has a finite upper tail which can not be exceeded. The corresponding largest value is given as:

$$v_{max} = v_s - s / k \tag{6}$$

For k = 0, the exponential distribution is obtained:

$$p(v \le v_{ref}) = 1 - \exp\left(-\frac{(v_{ref} - v_s)}{s}\right) \tag{7}$$

The two parameters s and k can easily be obtained from the mean value m and the standard deviation σ of the exceedances of the threshold value, i.e. from the new variable $(v - v_s)$:

$$s = \frac{1}{2} \cdot m \cdot \left[1 + (m/\sigma)^2\right]$$
$$k = \frac{1}{2} \cdot \left[1 - (m/\sigma)^2\right] \tag{8}$$

For the specification of the appropriate design target values it is reasonable to distinguish structural classes in regard to their importance level. The recently published

Table 1 Target values of the exceedance probability of the design value w_{des} of the wind load or wind load effect for the ultimate limit state.

structural class	A	B	C	D
p_{target} / year (ISO 4354, 2009)	1/2000	1/1000	1/500	1/200
p_{target} /working life (Kasperski, 2009)	0.025	0.05	0.10	0.20

ISO 4354 (ISO 2009) distinguishes four classes:

A : structures with a special post-disaster function (hospitals, schools, transmission lines, bridges)
B : buildings which as a whole contain people in crowds (high-rise buildings, stadia, concert halls)
C : normal structures (office buildings, commercial buildings, factories, residential buildings)
D : structures presenting a low degree of hazard to life and other properties (farm buildings, house chimneys, roofing tiles)

The corresponding target values for the ultimate limit state are specified in ISO 4354 with reference to a single year and are summarized in Table 1. In a more general approach the target probabilities refer to the design working life of the structure. The respective values are also given in Table 1. Both demands are approximately the same for a 50-year design working life. Strictly speaking, the target values refer to the design wind load. For a general solution it is reasonable to demand the same target exceedance probabilities for the design wind speed.

3. Statistical Uncertainties in the Describing Parameters of the Extreme Wind Climate

The statistical stability of the estimated parameters λ, s and k can be studied based on simulations. In the following, a wind climate is assumed with v_s = 14.1 m/s, λ = 2, s = 2.0 m/s and k = –0.1. A single simulation run leads to a random number of M storms in K years observation period and a corresponding ensemble of M random wind speeds. From these data, a random value λ of the average number of storms per year is obtained plus random values of the shape parameter s and the scale factor k. Based on 10^6 independent simulation runs, 90% confidence intervals are estimated for the three describing parameters for different observation periods. Based on these simulations, Fig. 1 shows the change in the confidence interval for observations periods of 20 to 100 years. Even an observation period of 100 years is not long enough to suppress the random scatter in the identified parameters.

The statistical uncertainties in the estimated values of λ, s and k lead to uncertain estimates for the design wind speed. Basically, the effect of the uncertainties will increase with decreasing target exceedance probability, i.e. with longer design working life and higher importance of the structure.

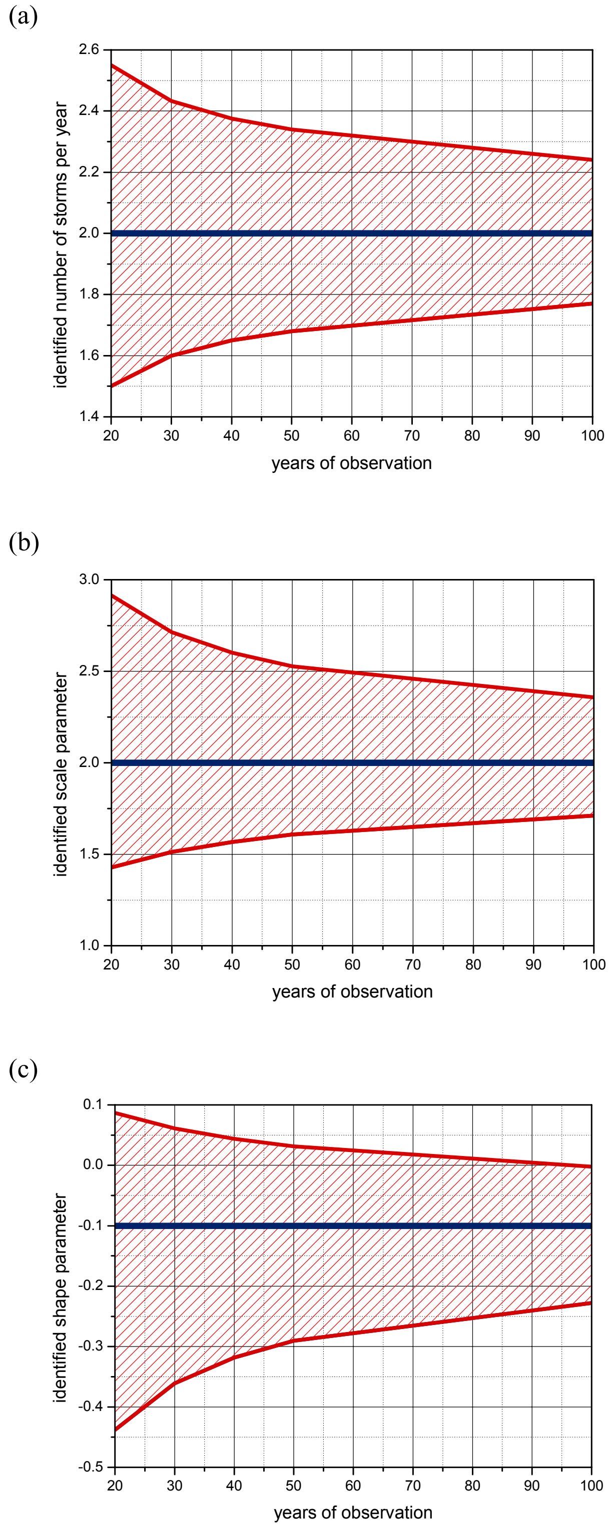

Fig. 1 Influence of the observation period on the 90%-confidence interval of the statistical parameters of extreme wind climate.
(a) number of events per year λ, (b) scale parameter s, (c) shape factor k

The basic influences of uncertain scale parameters and shape factors on the trace of the non-exceedance probabilities of the wind speed are shown in Fig. 2 considering a range from 1.5 to 3 for the scale parameter and a range from –0.45 to 0.1 for the shape factor. The

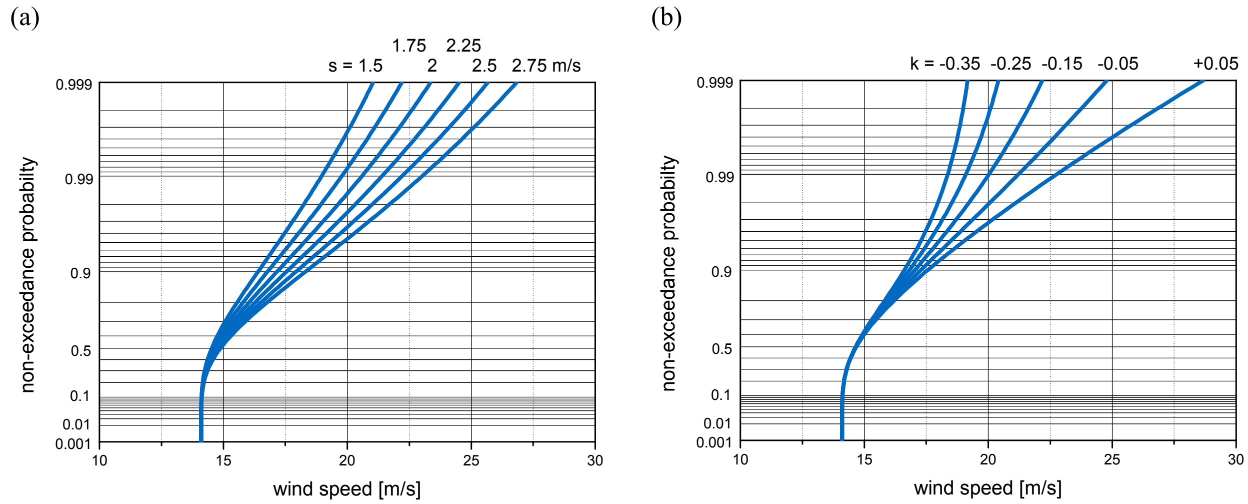

Fig. 2 Influence of s and k on the trace of the non-exceedance probability of the wind speeds. (a) $\lambda = 2$, $k = -0.1$, (b) $\lambda = 2$, $s = 2$ m/s

average number of storms per year is assumed to be 2. Assuming a design working life of 50 years, the design wind speeds for class B and class C buildings are obtained approximately as the 99.8% and 99.9% fractile. Depending on the actual combination of s and k, considerably different design wind speeds are obtained.

4. Best Estimate of the Design Wind Speed

The simulations suggest that the 'true' parameters of the extreme wind climate cannot be identified. It has to be concluded that virtually every wind climate may hide behind the observed parameters, though, with different probabilities. The probability p, that a specific triple (λ, s, k) randomly leads to the observed triple (λ_{obs}, s_{obs}, k_{obs}), can be obtained from simulations. In the next step, for each triple (λ, s, k), a design wind speed can be estimated. Sorting the design wind speeds in ascending order with their corresponding probabilities allows constructing a probability distribution of the uncertain design wind speed:

$$p\left(v_{des} \le v_{des,\,i}\right) = \sum_{j=1}^{i} p_j\left(v_{des}\left(\lambda_j,\ s_j,\ k_j\right)\right) \tag{9}$$

This new approach can easily be extended to long-term trends. Assuming only linear trends in the first approach leads to two further variables, the slope for the number of storms per year a_λ and the slope for the intensity of individual events a_v. Equation (9) then becomes:

$$p\left(v_{des} \le v_{des,\,i}\right) = \sum_{j=1}^{i} p_j\left(v_{des}\left(\lambda_j,\ s_j,\ k_j,\ a_{\lambda,j},\ a_{v,j}\right)\right) \tag{10}$$

The final design wind speed can be obtained based on a chosen confidence level. Basic demand of any estimation of a design value of actions or action effects is to avoid an underestimation of the design value by applying an appropriate one-sided confidence. The probability of underestimation can be understood as the error probability; the complementary probability is the confidence. The question arises, how small the error probability should be. An intuitive choice would lead to small values, say in the range of 1% to 5%. It is however important to note that the probability of overestimation increases with decreasing error probability. In civil engineering, the question on the appropriate error probability has already been answered in the context of estimating the design value for the resistance based on experiments. The Eurocode (CEN, 2002) for instance recommends 75% as an appropriate confidence interval, i.e. the corresponding error probability would be 25%. Consequently, the best estimate of the design wind speed is obtained as the 75% fractile value of the probable design wind speeds.

5. Example of Application

The new method is applied to the extreme wind climate at Düsseldorf, Germany. The governing storms are strong frontal depressions which mainly occur during the period from October to March. As representative value, the largest hourly mean wind speed of independent events is used. Figure 3 shows the identified probability density for the average number of storms per year and the identified probability distribution for the strongest hourly mean value of individual storms. It is worth mentioning that the respective ensembles are obtained applying the German aeolian year which extends from the 1st of May of one year to the 30th of April of the consecutive year (Kasperski, 2007). Although the observation period at Düsseldorf consists of 55 years, there is a considerable uncertainty in the identified parameters of the extreme wind climate. Based on simulations, in Fig. 4 the probability densities of the triples (λ, s, k) are shown which randomly lead to

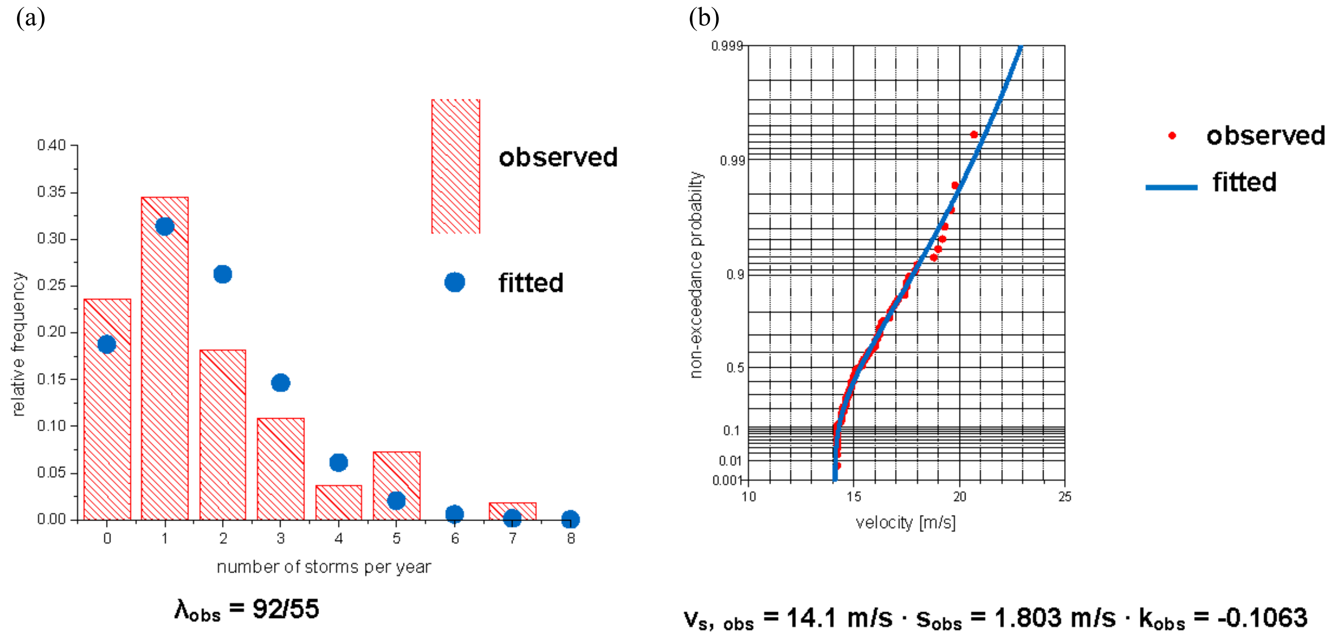

Fig. 3 Observed parameters of the extreme wind climate at Düsseldorf airport (1952-2007).

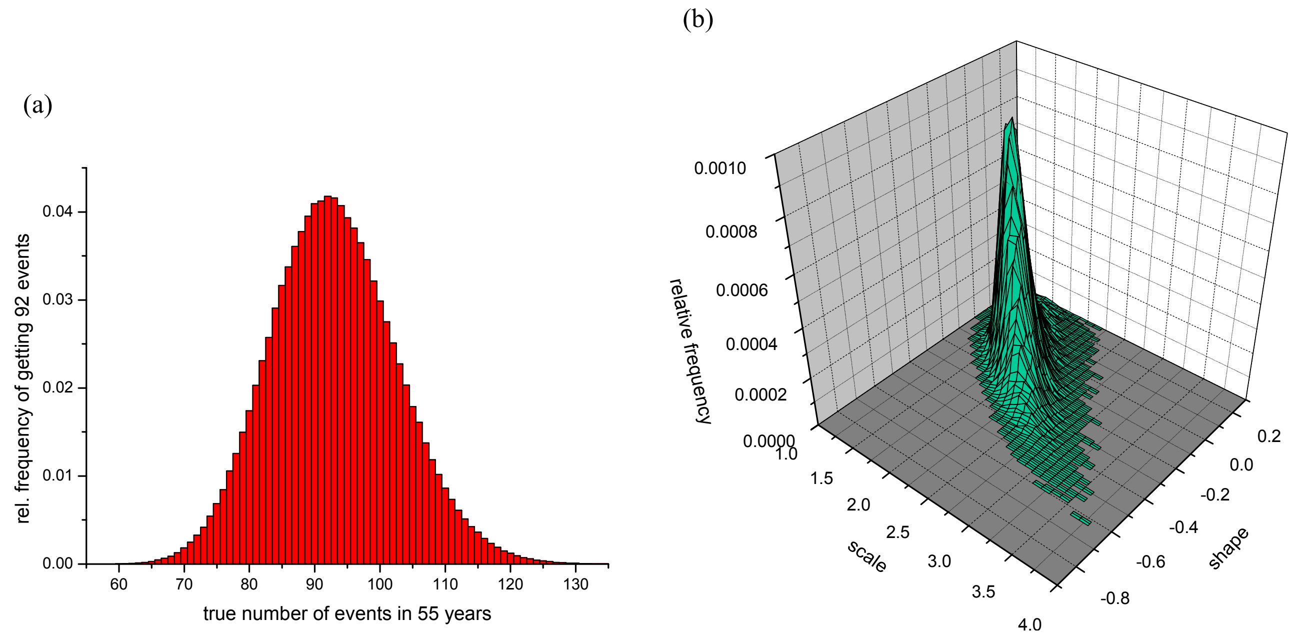

Fig. 4 Randomness in identified parameters.
(a) probability density for observing 92 events in 55 years for different λ-values
(b) joint-probability density for getting the observed parameters s_{obs} and k_{obs} from an ensemble with 92 events

the observed values, assuming that the number of storms per year and the intensity of the storms are statistically independent. The full simulation involves 10^6 independent runs each corresponding to the sub-period of 55 years. The resulting possible range for λ is from 1.18 to 2.27. For the scale parameter, the simulation identifies a range from about 1.0 to 3.5 m/s, while the shape factor probably lies between – 0.5 and +0.25.

A more refined analysis of the wind climate at Düsseldorf suggests that there might be long-term trends in the number of storms per year and in the intensity of the storms. Applying a linear shape for the trends leads to the identified increases shown in Fig. 5. The observed trends are not negligibly small. Over the observation period of 55 years, the study suggests that the number of storms has increased by about 60% from 1.3 to 2.1 storms per year. Similarly, the average intensity of a storm has increased by about 5% from 15.4 to 16.1 m/s. In terms of wind loads this increase corresponds to 10%. A step of 10% wind load approximately corresponds to a doubling of the exceedance probability over a lifetime of 50 years, i.e. the observed increase in wind speeds corresponds to a difference of one structural class.

It is important to note, that a confined ensemble may contain a random trend although the 'true' process is stationary. However, without knowing the 'true' parameters of the underlying process, there is no way to study the randomness of trends in confined ensembles. Only the new concept provides the basic possibility of considering long-term trends in the scope of a consistent probabilistic approach.

The new approach therefore introduces the linear trends in the number of storms per year and the intensity of the individual storms as further uncertain variables. Simulations then lead to the joint probabilities of λ and s and their corresponding trends which randomly lead to the observed parameters. Sufficiently stable estimates of these joint-probabilities, however, require an enormous number of independent simulations. For the joint probabilities in Fig. 6, approximately 55.4 and 77.5 billion simulations have been performed. Both joint probabilities suggest only a small probability that there is no increasing trend in the number of storms per year and/or the intensity of the individual storms with values of about 10%.

The last step in the analysis is to combine the joint probabilities of all the parameters to obtain a cumulative probability distribution of the uncertain design wind speeds. As input parameters, the design working life and the structural class may be varied. Figure 7 shows the corresponding traces for stationary and non-stationary wind climate assuming a class B building. For the non-stationary wind climate, two different years have been chosen for the actual start of the exposure.

The corresponding final design wind speeds are summarized in Table 2. Additionally, design wind speeds are given which are obtained by directly using the observed parameters. The new concept reveals the basic danger of underestimating the design wind speed when using the observed parameters without any further

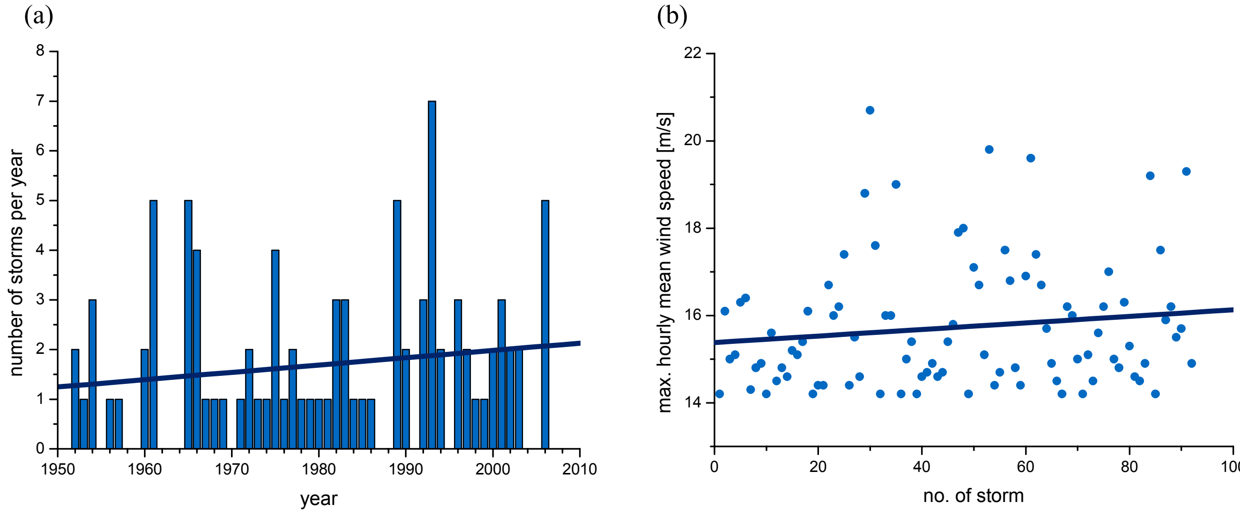

Fig. 5 Identified linear trends in the number of storms per year and the intensity of the individual storms.
(a) slope $a_N = 0.01472$ / year, (b) slope $a_v = 0.00749$ per storm

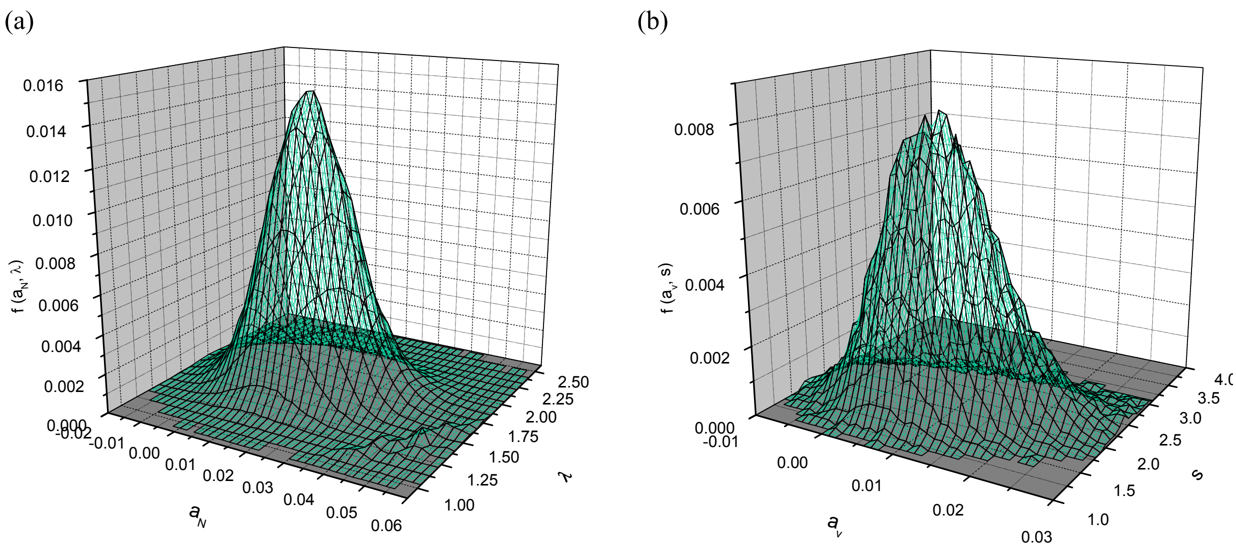

Fig. 6 Joint probabilities of parameters leading to the observed trends.
(a) a_N and λ, (b) a_v and s

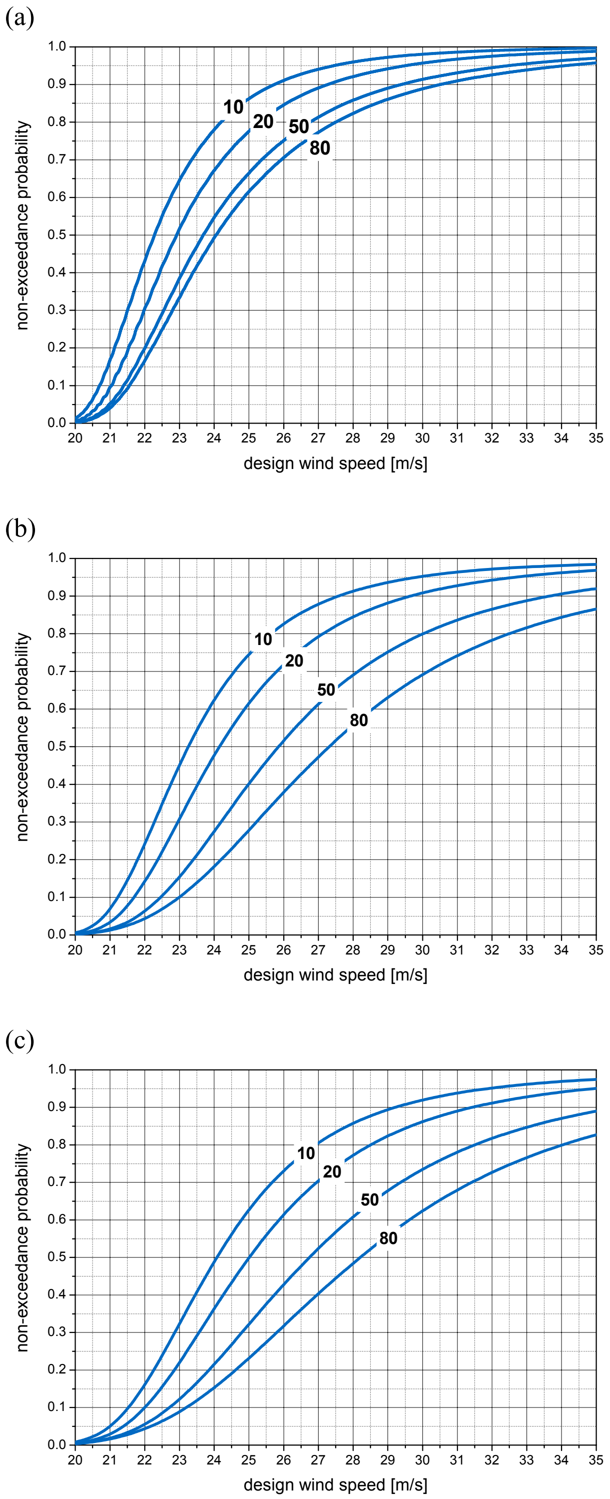

Fig. 7 Cumulative probability distributions for design wind speed.
(a) stationary wind climate, (b) non-stationary wind climate beginning of exposure in 2009, (c) non-stationary wind climate beginning of exposure in 2029.

considerations. Even for the assumption of a stationary wind climate, the best estimates for the design wind speeds are 8.4% to 12.3 % larger than the design wind speeds directly based on the observed data. In terms of wind loads, the differences are 17.5% to 26.1% for lifetimes from 10 to 80 years. Consideration of long-term

Table 2 Best estimate of the design wind speeds for different values of the design working life, class B.

	L [years]	10	20	50	80
stationary wind climate	observed parameters	21.90	22.55	23.34	23.71
	new concept	23.74	24.71	25.98	26.62
non-stationary wind climate	new concept, $y_s = 2009$	25.05	26.39	28.97	31.19
	new concept, $y_s = 2029$	26.23	27.65	30.31	32.57

(all design wind speeds in m/s)

trends in the wind climate leads to further increases of the design wind speeds. The further into the future the exposure starts, the larger the design wind speeds will be. For an exposure starting in 2009, there is an additional increase of about 11% to 37% for wind loads. If the exposure starts in 2029, a further 10% increase in the wind load will be required to counterbalance the effects of the probable long-term trends.

6. Conclusions

The low statistical stability of extreme-value analysis of wind speeds has led in recent decades to completely diverging concepts for wind resistant design. As can be shown by simulations, the identification of the ‘true’ statistical parameters of a wind climate is virtually impossible. It has to be concluded that a set of observed parameters can be obtained for a large variety of ‘true’ parameters. However, the probability of getting the observed parameters differs for different sets of ‘true’ parameters. This has led to the basic idea of developing a probabilistic approach to the most probable design wind speed, considering the statistical uncertainties in the observed parameters for the extreme wind climate, including the presence of long-term trends. Based on simulations, the non-exceedance probability of an uncertain design wind speed can be obtained. The best estimate of the design wind speed is given with a 75%-confidence level. The new method allows overcoming the discrepancies between the actually used concepts for the specification of the design wind speed. Based on the findings for the wind climate at Düsseldorf, it is strongly recommended to consider non-stationary features when specifying design wind speeds. The assumption of a stationary wind climate may lead to considerable underestimations of design wind speeds.

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References

C.E.N. (2002) EN 1990 – *Basis of Structural Design*.

Holmes, J.D. and W.W. Moriarty (1999) Application of the generalised Pareto distribution to wind engineering, *Journal of Wind Engineering and Industrial Aerodynamics,* 83: 1-10

ISO (2009) ISO 4354 – *Wind Actions on Structures*

Kasperski, M (2007) Design wind loads for a low-rise building taking into account directional effects, *Journal of Wind Engineering and Industrial Aerodynamics*, 2007: 1125-1144

Kasperski, M. (2009) Specification of the design wind load – a critical review of code concepts, *Journal of Wind Engineering and Industrial Aerodynamics*, 2009: 335-357

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Born in Herne, Germany on 25 September 1958, Michael Kasperski graduated with a degree in Civil Engineering in 1983 at Ruhr University Bochum. He obtained his doctorate in engineering in 1988 at the same University for his work on cooling towers under wind load. Finally, in 1998 the Department of Civil and Environmental Engineering Sciences of Ruhr University Bochum awarded him a habilitation doctorate in engineering for his research work in the field "Bases of Design in Structural Engineering." This research field comprises the theory and application of development of probabilistic models of actions and action effects, of structural resistance and of static and dynamic behaviour of structures. Beside theoretical approaches, further design tools include field and laboratory tests and simulations. Finally, the field involves study of problems dealing with the specification of basic design targets in terms of limit states for structural safety and serviceability.

Since 2002 Michael Kasperski has headed the Research Team EKIB at Ruhr University Bochum. Additionally he serves as BIT Part Time Professor at the Beijing Institute of Technology in Beijing, China. One of his major research interests lies in the field of wind engineering. He is currently member of the editorial board of the International Journal of Wind and Structures. His other major research topics are structural dynamics, especially under human-induced actions, serviceability of structures in regard to vibration and reliability of structures.

The research results of the Research Team EKIB form the basis for his consultancy and codification work. Currently, Michael Kasperski is a committee member of the ISO TC 98 – Bases of Design of Structures and some of the related working groups. In the national codification field he is member of the German Committee NABau 00.02.00 Actions on Structures.

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