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Extreme wind prediction and zoning

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Abstract. The paper describes the work of the IAWE Working Group WGF - Extreme Wind Prediction and Zoning, one of the international codification working groups set up in 2000. The topics covered are: the international database of extreme winds, quality assurance and data quality, averaging times, return periods, probability distributions and fitting methods, mixed wind climates, directionality effects, the influence of orography, rare events and simulation methods, long-term climate change, and zoning and mapping. Recommendations are given to promote the future alignment of international codes and standards for wind loading.

Keywords: codes; extreme; probability; wind speeds.

1. Introduction

This paper reviews the methods of extreme wind prediction for use in wind loading codes and standards on behalf of WGF, one of the working groups set up by the International Association of

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Wind Engineering to review and make recommendations for harmonization in international codification for wind loads.

The following sections cover the following topics: the international database of extreme winds, quality assurance and data quality, averaging times, return periods, probability distributions and fitting methods, mixed wind climates, directionality effects, the influence of orography, rare events and simulation methods, long-term climate change, and zoning and mapping. The principal recommendations from the working group are given in italics in the body of the paper, and listed in full at the end of the paper.

2. Database of extreme wind speeds

With the general expansion of world trade in goods and services – the latter including structural design – the need for widely available data on design wind speeds for all countries will become more obvious. At the present time, there exists a multitude of national wind loading codes and standards with a range of defined averaging periods and return periods. However, there are a large number of publications that are publicly available – in published papers and reports, national wind codes and standards, that the designer, or consultant, can use for structural design purposes.

2.1. Sources of regional and world-wide information

There is no single document that provides world-wide data on extreme wind speeds at present. Wieringa (1996) reviewed the general situation with respect to the quality of recorded data covering issues such as siting of anemometers; he also reviewed some data sources for individual countries. Holmes (2001) summarized briefly the sources of basic design wind speeds for 56 countries, and classified these countries or territories into five levels, with respect to the magnitude of their extreme wind speeds.

The European Community is in the process of developing structural Eurocodes, which includes one on wind actions on structures. This document does not include basic design wind speeds – it is intended that these be provided by national application documents. However, an earlier draft (European Convention for Standardization 1994) included basic design wind speeds (10-minute mean speeds) for 18 countries. There were some obvious discontinuities at national boundaries. Miller (2002) has, with some success, resolved these differences by making predictions based on gradient wind speeds derived from historical recordings of synoptic pressure gradients.

Design wind speeds for the Asia-Pacific region have been summarized by Holmes and Weller (2002), making use of national codes and standards and a five-level zoning system.

For the Caribbean region, Shellard (1972) and Davenport, *et al.* (1985) have made predictions of extreme wind speeds using traditional extreme value methods in the first case, and a simulation method in the latter case.

2.2. National sources

Many papers describing extreme value analyses of recorded wind speeds are available in publicly accessible literature. A representative list of these was assembled by the Working Group, and is available on request.

3. Quality assurance and data quality

For purposes of extreme wind speed zoning, wind speed data used to predict the design wind speed values should fulfil several requirements. It would be intended that for a whole country, if not for a region, wind speed measurements should be made:

- using the same instruments or the instruments with the same dynamic characteristics, (in particular the time constant)
- in the same type of terrain: open, flat terrain
- at the same height above terrain level
- during the same, long enough period, preferably longer than 30 – 40 years.

Often not all of these requirements are fulfilled, unfortunately. Observation errors in extreme wind speeds can arise from several different sources. The first can be the dynamic characteristics of an anemometer, depending on its kind, mass and dimension. A comprehensive description of anemometers and their characteristics has been given by Sachs (1972).

The Working Group recommends that design wind speeds should be measured in (or corrected to) the standard meteorological conditions of 10 metres height in open country terrain.

Over a period of 40 or 50 years at a measurement station, the instrument used to measure wind speeds is unlikely to have remained the same. If regular calibration (both static and dynamic) of the measuring instruments is not carried out, significant errors can arise from this source.

Siting of the tower, or mast, supporting the anemometer is another potential source of error. For many years it was quite common to mount anemometer masts on, or near, buildings of significant size. The aerodynamic influence of the building can be corrected by use of wind-tunnel tests but such corrections may not be reliable if they are large. It is not advisable to use wind data obtained from a city centre anemometer, unless there is none available from a better- sited station such as an airport.

Urban development over a long period of years may justify correction of anemometer records for the effect of boundary-layer changes, so that the corrected values are representative of those obtained over fully-developed open country terrain, at 10 metres height. Such corrections are difficult to make when a wind gust is produced by a severe downdraft from a thunderstorm. However, in these cases, the effects of segments of varying terrain roughness in the upwind fetch are expected to be small, and correction may not be justified.

4. Averaging times and return periods for design

The averaging time of a designated wind speed may vary from 1 hour to 2-3 seconds. In the latter case, it refers to the time constant of the effective filter of wind gusts represented by the anemometer (e.g. the Dines pressure tube type, or cup anemometer) used for the measurement of extreme wind speeds.

Choice of an averaging time in a national code or standard for wind loads may depend on the type of windstorm that generates extremes. For example, in countries or regions, where thunderstorm downbursts are dominant, use of a 2-3 second gust is usual, as a 1-hour or 10-minute mean, has little, or no, meaning when storms typically only last for a few minutes. When synoptic winds dominate, a longer averaging time gives mores stability to values used in extreme value analyses. The most common averaging periods in these situations are 10 minutes and 1 hour. The former period is more appropriate in regions affected by tropical cyclones (hurricanes, typhoons), in which 1 hour may be too long to assume stationarity at the height of a storm.

Gust wind speeds are usually measured continuously, and are therefore truly representative of the gust wind speed climate at a particular location. The same is not necessarily true when it comes to mean wind speeds. While some countries do measure the mean wind speed continuously (for example the UK and the Netherlands measure hourly mean wind speeds every hour, while the Swiss measure the 10-minute mean wind speed every 10 minutes), most countries only measure the mean wind speed over the appropriate averaging period immediately before the reporting hour. Thus, for most European countries the 10-minute mean wind speed is representative of the conditions during the 10-minute period immediately before the reporting hour, with no information about the mean wind speed over the other 50 minutes of the preceding hour. As a result, the reported 10-minute mean wind speed is not necessarily representative of the maximum 10-minute mean wind speed over that hour. Any thunderstorms that occur during the unrecorded 50 minutes will not be represented at all in the record.

The Working Group recommends that the averaging time should be one of : 3 seconds (gust), 10 minutes, or 1 hour, with the 3-second gust preferred in climates where thunderstorms are dominant.

The most common choice of return period (equal to the reciprocal of the complementary cumulative probability distribution of annual extremes) in international codes and standards, is 50 years, although the Australian/New Zealand building codes recommend a value of 500 years for normal structures, in common with earthquake engineering practice.

The risk of exceedence of a particular wind speed for design is also related to the load factor, γ_W, that is applied to the calculated wind loads when calculating the structural resistance. Thus if a wind load factor of 1.5 is applied to a nominal 50-year return period value of wind speed in the design process, a design wind speed equal to $\sqrt{(1.5)}$ times the 50-year return period value is, in effect, being used.

5. Probability distributions and fitting methods

5.1. General

As in the case of methodology and techniques of wind speed measurements, it would be preferable for all analysts and code-writers to use the same probability distribution and fitting methods to predict design wind speeds. However, there are a number of varying opinions and preferences amongst statisticians, on this topic.

5.2. Parent distribution

For some design applications, such as the estimation of fatigue damage, it is necessary to have information on the distribution of the complete population of wind speed at a site. Sometimes, due to the lack of the extreme values of wind speed recorded for long enough, the parent distribution was used to predict the design wind speed. Examples were given by Davenport (1968). Usually a Weibull probability distribution is used. However, this distribution, although bounded by zero at the lower end, is unbounded at the upper end; this will force the extreme value distribution derived from it to be unbounded.

5.3. The Gumbel approach

In the nineteen-twenties, Fisher and Tippett (1928) identified the mathematical forms of three limiting extreme value distributions - thereafter known as Type I, II and III. These represent the probability distributions for the largest (or smallest) from a sample population, in which the number in the sample tends towards infinity. The most commonly-used distribution of these three is the Type I, also commonly called the 'Gumbel Distribution'. It has the advantage of having only two adjustable parameters, of being closely linked to the Weibull parent distribution, and being relatively simple to apply. It can be written in the form:

$$F_U(U) = \exp\{-\exp[-(U-u)/a]\} \tag{1}$$

$F_U(U)$ is the cumulative probability distribution function of the maximum wind speed in a defined period (e.g. one year). a is a scale factor, and u is a position parameter - in this case it is also the mode of the distribution.

The simplest method of fitting the Type I distribution proposed by Gumbel (1958), and applied to wind speeds by Shellard (1963), involves ranking the recorded values of annual maxima from lowest to highest, assigning a probability of non-exceedence, p, according to the formula $p = m/(N+1)$, where m is the rank order, and N is the total number of values. A reduced variate, y, is formed from:

$$y = -\ln(-\ln p) \tag{2}$$

The wind speed is then plotted against y, and a line of best fit is calculated, usually by linear regression.

It is known that the Gumbel plotting position formula gives distorted estimates of the probability of non-exceedence for low and high values of p. Several alternative methods, which reduce this bias have been proposed. Amongst these are the alternative plotting position formula of Gringorten (1963), and the methods proposed by Lieblein (1974), and Harris (1996).

Cook (1982) has proposed the use of extreme dynamic pressure (or windspeed squared) in extreme value analyses using the Gumbel distribution, to accelerate the convergence of the extreme value distribution to the theoretical asymptotic distribution for a Weibull parent.

Strictly speaking, annual extremes are not the correct basis of analysing extreme wind speeds. Since storms tend to occur in families or clusters, the second strongest storm in one year may be considerably larger than the strongest storm in another year. An analysis confined to annual extremes is therefore neglecting important information. The appropriate ensemble is obtained as independent storms above a minimum threshold. An engineering approach then uses the expression in Eq. (3) for the reduced variate, in place of Eq. (2).

$$y = -\ln(-\ln p^{\overline{N}}) \tag{3}$$

where, $\overline{N}$ - average number of storms per year.

Not all sampled events have to be understood as extremes of the process, i.e., only the right tail of the obtained trace of non-exceedence probabilities has to fit the theoretical expression of an extreme value distribution (Kasperski 2002).

5.4. The generalized extreme value distribution and 'Peaks over Threshold' methods

The three limiting Types of Extreme Value Distribution, established by Fisher and Tippett (1928) can be represented in a single common mathematical form, known as the Generalized Extreme Value Distribution (GEV).

The Generalized Extreme Value distribution has three parameters, including an additional parameter, the shape factor, k, and can be written in the form of Eq. (4).

$$F_U(U) = \exp\{-[1-k(U-u)/a]^{1/k}\} \tag{4}$$

When $k < 0$, the GEV is known as the Type II Extreme Value (or Frechet) Distribution; when $k > 0$, it becomes a Type III Extreme Value Distribution (a form of the Weibull Distribution). As k tends to 0, Eq. (4) becomes Eq. (1) in the limit - i.e., the Type I distribution results.

The method of 'probability-weighted moments' (Hosking, *et al.* 1985) is a convenient method of fitting the GEV. Correct fitting methods of extreme wind speeds for the GEV usually result in a distribution with a small positive shape factor, k.

An alternative indirect method fits the related Generalized Pareto Distribution to 'peaks over threshold' data (e.g. Simiu and Heckert 1999, Holmes and Moriarty 1999). It requires all independent storms above a minimum threshold, and use with annual maxima can lead to incorrect predictions (Holmes 2003).

The Working Group suggests that any recognised extreme value analysis method can be use for extreme winds, but the probability distribution used should be a member of the family of asymptotic distributions (Generalized Extreme Value Distribution).

5.5. Sampling errors

Sampling errors are errors in predicted wind speeds of specified return periods arising from uncertainties in the parameters of the distribution used to make the predictions. These errors arise when data from relatively short data records are used to make predictions to high return period. Note when assessing sampling errors, it is assumed that the correct probability distribution has been chosen - the errors arise from the uncertainties in the parameters of the chosen distribution.

Simiu, *et al.* (1978) have studied the sampling errors resulting from fitting the GEV to extreme wind speeds. Simiu, *et al.* found that the sampling error in estimating a wind speed with a 50-year return period from 25 years of data, with a 68% confidence level, is about ±7%. The error in estimating the 1000-year return period value from 25 years of data is calculated to be ±9%. These estimates are based on an assumption of a shape factor, k, fixed at 0 (Type I extreme value distribution).

To get around the problem of short historical records for individual stations, data from several stations have often been combined to form an equivalent time history of greater length. Such an approach was adopted to analyse United States wind speeds by Peterka and Shahid (1998), following an earlier approach in Australia by Dorman (1983). When such approaches are used it is necessary to ensure that the meteorological characteristics of individual stations are genuinely similar to each other - for example, the effects of topography and orography should be similar or adequately corrected (see Section 8). Also the stations should be sufficiently well separated that the data are statistically independent.

In summary, the Working group recommends that the record length for analysis of individual *stations should be at least 30 years, unless aggregation of stations into 'superstations' is adopted (e.g. Peterka and Shahid 1998). The latter should be justified on grounds of meteorological and topographical similarity, and statistical independence.*

6. Mixed wind climates

Many locations in the world experience strong winds from more than one wind type - for example, thunderstorm-generated downbursts combined with larger scale synoptic winds. The correct approach to this is to separately analyse for the distributions of extreme wind speeds from each storm type and then combine the resulting distributions to a single distribution for winds from any source, e.g., Gomes and Vickery (1977), Holmes (2001), Choi and Tanurdjaja (2002), Cook, *et al.* (2003).

The Working Group proposes that separate extreme value analyses for extreme winds from different storm types should be carried out when this is possible, and known to be a feature of particular stations or regions.

For a place subjected to a mixed weather system, there are the possibilities of different scenarios of extreme wind characteristics. (a) Although strong winds are generated by both weather systems, one system is clearly more dominating than the other. (b) The weather systems have stronger winds over different ranges of the probability domain, e.g., system 'A' is stronger over the lower return period range whereas system 'B' has stronger wind over the higher return period range. (c) The weather systems have stronger winds over different averaging periods, e.g., system 'A' is stronger for a longer averaging period (hourly mean), whereas system 'B' has stronger wind for the shorter averaging period (gust). For scenario (a), the usual extreme analysis method (without separation of storm types) can be used without introducing much error. However for scenario (b), a separate extreme analysis of the two wind systems and combining their resulting distributions is needed. For scenario (c) the analysis needs to be made with care. Although results obtained from the usual extreme analysis are more or less similar to those obtained from the separate analysis method, they may introduce inconsistency to other wind characteristics (e.g. gust factor).

In any case, for a location with mixed weather, it is always advisable to identify the source storm type of the wind data. This will help to give a clear picture on the subsequent analyses.

7. Directionality effects

Simiu and Scanlan (1996) and Holmes (2001) describe various probabilistic approaches to the effect of the directional variation of parent and extreme winds. These methods are too complex to be included directly in codes and standards. The preferred approach for codification, is to make some simple assumptions on the directional variations of force and pressure coefficients, allowing directional wind speeds, or direction multipliers applied to the all-directional design wind, to be adopted. The approach used in the British Standard (British Standards Institution 1997) is described by Cook (1983). The method used in the Australia/New Zealand Standard (Standards Australia/ Standards New Zealand 2002) is described in Holmes, *et al.* (1990) (method due to W.H. Melbourne).

General statistical reduction factors, which do not rely on knowledge of a building orientation with respect to that of the extreme wind, have also been adopted in codes and standards. However, these have sometimes been 'disguised' within shape factors, and have generally proved to be controversial.

8. Influence of orography

Wind speed depends not only on the height above the local terrain, but also on the altitude above sea level. This dependence should be taken into account in mountainous territories. The main problem may be to have a number of meteorological stations located at different altitudes to produce some dependence of design wind speed on the height above sea level. An example of such an approach was presented by Żurański (1992). Four meteorological stations in the Polish part of Carpathians are located at altitudes from 400 m to 2000 m, where strong foehn winds occur. Dependence of wind speed can be found also even at lower altitudes, as it is taken into account in the British Standard (British Standards Institution 1997) using an altitude factor (Cook 1985).

Orographic (altitude) effects should be considered in mountainous regions. The best way of codifying this is with a special factor on design wind speed.

9. Rare events and simulation methods

In a number of regions around the world, the extreme wind climate at longer return periods is dominated by events that occur relatively infrequently, such as tropical cyclones (including hurricanes and typhoons). Regions where tropical cyclones dominate the extreme wind climate include the Gulf and Atlantic coasts of the United States, the Caribbean, and the west and east coasts of Australia. In these regions, because of the lack of observed wind speed data associated with the passage of tropical cyclones, the usual approach is to make use of some form of statistical simulation of such events to determine the local extreme wind climate. This approach was first described by Russell (1968, 1971) in a study of wind speeds along the Texas coast, and has since been expanded and improved upon by a number of authors, including Batts, *et al.* (1980), Georgiou (1985), and Vickery and co-authors (1995, 2000).

The basic approach in all cases is to take a simplified parametric model of the surface wind field of a tropical cyclone, and to combine it with statistical distributions of the parameters used to define the wind field, together with additional parameters describing the storm tracks and rate of occurrence of such events at a particular location. In the first instance, the gradient level wind field is usually modelled as a function of the central pressure difference, the radius to maximum winds, and the translational speed of the storm, although some authors have also included an additional parameter, the pressure profile shape parameter (Holland 1980), to provide more control over the shape of the pressure field. The gradient level wind field is then reduced to an equivalent surface wind field using one of a number of methods, ranging from a simple parametric approach, through to the use of a numerical model for the vertically averaged velocity over the depth of the boundary layer, in combination with an appropriate boundary layer parameterization scheme.

The wind field model is then combined with some form of statistical model for the storm tracks, in order to calculate the wind speeds at a particular location. If site-specific wind speeds are required, the simplest approach is to model the storm tracks as straight lines, with statistical distributions for the direction of travel and distance of closest approach to the site defined on the basis of the historical storm tracks for the region of interest. A more recent approach has been the development of track models based on the random-walk methodology used in turbulent diffusion studies, where the full track of the storm is modelled starting from its birth over the ocean, and ending with its final dissipation. Unlike the straight line track approach, where the central pressure difference associated with each storm is held constant while the storm is offshore and then allowed to decay or 'fill' following landfall, the use of the 'random-walk' approach to the modelling of storm tracks also requires that the variation of the central pressure of each simulated storm with time be modelled in a realistic fashion. More detailed descriptions of this type of approach can be found in Vickery, *et al.* (2000) and Drayton (2000).

Statistical distributions for the various parameters used in the wind field and storm track models are determined using historical data from sources such as the North Atlantic tropical cyclone database maintained by the National Hurricane Centre in the United States (Jarvinen, *et al*. 1984). The distributions themselves are derived by considering the statistics of historical storms either crossing the coastline within a certain distance of the point of interest, or entering a circular subregion centred on the point of interest. There is no particular advantage to using one approach in preference to the other, and both are subject to the limitation that a certain amount of subjective judgement about the size of the region over which the underlying hurricane climatology can be considered uniform is required (see, for example, Vickery and Twisdale (1995), for a discussion of the effect of using circular subregions of various radii on the wind climate for Miami and New York).

Once statistical distributions for the various parameters have been determined, a Monte Carlo approach is used to sample from each distribution to generate many thousands of simulated storms affecting the point of interest. By recording the maximum surface wind speed at the point of interest associated with each simulated storm, and knowing the rate at which such storms occur, an estimate of the local extreme wind climate due to such storms can be obtained for various return periods.

Simulation methods have been used, directly or indirectly, to determine design wind speeds for regions affected by hurricanes or typhoons in several codes and standards, notably the American Standard - ASCE-7 (American Society of Civil Engineers 2002).

At stations affected by rare extreme events, for example hurricanes or typhoons, simulation methods, as described above, can be used for design wind speeds in codes and standards. However, these methods should be quality assured, and peer-reviewed, and calibrated against recorded historical wind speeds, when this is possible.

10. Long-term climate change

The design wind speeds for a structure imposed to the wind climate for a projected lifetime of L years usually is estimated based on the assumption of a stationary wind climate. Then, observations in the past can be used directly as predictions for the future. Strictly speaking, this assumption is convenient but not true. Global warming, or more precisely, global climate change is a fact that can hardly be denied. What is still in debate is how the climate will develop, and to what extent it is influenced by man or nature.

For the prediction of the design wind speed considering long term trends, basically two parameters have to be taken into account as possible subject to long-term trends: the number of storms per year and the intensity of the storms (Kasperski 1998). If the number of storms per year has an increasing long-term trend, the exceedence probability of the design wind speed is increasing with any further year as follows:

$$p_i^* = 1-(1-p_1)^{N_i/\overline{N}} \tag{5}$$

p_i^* - exceedence probability for nonstationary wind climate in year i

p_1 - exceedence probability in a single year assuming a stationary wind climate
N_i - expected number of storms in the respective year i
$\overline{N}$ - average number of storms in the observation period

The accumulated exceedence probability over the projected life-time of L years for a stationary wind climate is obtained as:

$$p_L = 1-(1-p_1)^L \tag{6}$$

For a non-stationary climate, the accumulation follows:

$$p_L = 1-\prod_{i=K+1}^{K+L}(1-p_1)^{Ni/\overline{N}} \tag{7}$$

where K is the zero point of the long-term trend, e.g., for a supposed linear trend the middle of the observation period.

Since p_L has to meet the specified target value for the exceedence probability, e.g., 5% in the life time of the structure, p_1 has to be a smaller value in case of an increasing long term trend than in case of a stationary wind climate.

If, additionally, the intensity of storms is subject to a long-term trend, the non-exceedence probability $(1-p_i^*)$ in a single year is obtained from introducing respective trends in the characteristic parameters of the extreme value distribution, e.g., a trend in the mean value.

The question of the existence of long-term trends in the wind climate can only be answered with a limited confidence. In structural engineering, a value of 75% is recommended as acceptable level of confidence for specifying the resistance based on testing. An analysis of the randomness of the possibly observed trends by Kasperski (1998) assuming a stationary wind climate leads to non-exceedence probabilities of actually observed trends that are considerably larger than the 75% limit, i.e., the wind climate has to be treated as a non-stationary process.

Trends in long-term climate changes, and meteorological opinion on the effect on extreme windstorms should be monitored by code-writers with a view to incorporating the effect on design wind speeds in future codes and standards.

11. Zoning and mapping

Zoning and contouring systems are both commonly used to specify design wind speeds in codes and standards; in at least one case - ASCE-7 (American Society of Civil Engineers 2002), a mixture of the two systems is used. A third system adopted in the National Building Code of Canada (National Research Council Canada 1995) is a tabulation of design wind pressures for all significant towns and cities in the country.

The main advantages of a zoning system are firstly that it is easily administered - boundaries can be adjusted to follow the boundaries of administrative units like provinces, counties and shires. Secondly, it is less prone to misinterpretation, and misreading of maps, than a contouring system. However, it gives rise to step changes in design wind speed.

A contouring system allows better definition of the inland penetration by tropical cyclones (hurricanes, typhoons), but may give a false impression of the accuracy of the predicted values, if the contours are too closely spaced.

Given the uncertainty in design values caused by sampling errors (Section 5.5) there would appear to be little point in drawing contours for increments of gust speed any smaller than 3 m/s for 50-year return period values, or 5 m/s for 500 or 1000-year values. For the same reasons, the wind speeds in adjacent zones should not differ by less than about 5 m/s or 8 m/s for 50-year and 500/1000-year values, respectively. The minimum intervals for 10-minute or 1-hour means should be about two-thirds of these values.

In summary, the Working Group suggests that step changes between zones and contour intervals in wind maps in codes and standards should reflect the uncertainty resulting from sampling errors. Recommended minimum intervals in gust speeds between adjacent zones are: 5 m/s for 50-year return period winds, and 8 m/s for 500-year return period values. The recommended minimum contour spacing for gust speeds is: 3 m/s for 50-year return period values, and 5 m/s for 500-year values. The corresponding minimum values for mean wind speeds are two-thirds of the preceding values.

12. Conclusions

(1) Design wind speeds should be measured in (or corrected to) the standard meteorological conditions of 10 metres height in open country terrain.
(2) The averaging time should be one of 3 seconds (gust), 10 minutes, or 1 hour.
(3) Any recognised extreme value analysis method can be used for extreme winds, but the probability distribution used should be a member of the family of asymptotic distributions (Generalized Extreme Value Distribution).
(4) Record length for analysis of individual stations should be at least 30 years, unless aggregation of stations into ‘superstations’ is adopted. The latter should be justified on grounds of meteorological and topographical similarity, and statistical independence.
(5) Separate extreme value analyses for extreme winds from different storm types should be carried out when this is possible, and known to be a feature of particular stations or regions.
(6) Orographic (altitude) effects should be considered in mountainous regions. The best way of codifying this is with a special factor on design wind speed.
(7) At stations affected by rare extreme events, for example hurricanes or typhoons, simulation methods, as described in Section 9, can be used for design wind speeds in codes and standards. However, these methods should be quality assured, and peer-reviewed, and calibrated against recorded historical wind speeds, when this is possible.
(8) Trends in long-term climate changes, and meteorological opinion on the effect on extreme windstorms should be monitored by code-writers with a view to incorporating the effect on design wind speeds in future codes and standards. A methodology for doing this is given in Section 10.
(9) Step changes between zones and contour intervals in wind maps in codes and standards should reflect the uncertainty resulting from sampling errors. Recommended minimum intervals in gust speeds between adjacent zones are: 5 m/s for 50-year return period winds, and 8 m/s for 500-year return period values. The recommended minimum contour spacing for gust speeds is: 3 m/s for 50-year return period values, and 5 m/s for 500-year values. The corresponding minimum values for mean wind speeds are two-thirds of the preceding values.

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