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Towards a revised base wind speed map for the United Kingdom

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Abstract. Observations of extreme wind speeds in the United Kingdom from 1970 to 1980, corrected for the influence of upwind ground roughness and topography, have been analysed using the recently-developed "Improved Method of Independent Storms" (IMIS). The results have been used to compile two new maps of base wind speed and to confirm the climatic factors in current use. One map is 'irrespective' of wind direction and the other is 'equally weighted' by direction. The 'equally weighted' map is expected to be more consistently reliable and appropriate for use with the climatic factors for the design of buildings and structures.

Key words: extremes; design wind speed; exposure corrections; Method of Independent Storms.

1. Introduction

1.1. Base wind speeds

In most countries of the world the safety of buildings and structures in extreme winds is achieved through the provisions of codes of practice and regulations. One of the key components is the appropriate design wind speed for the particular site being considered. In the current UK code this is obtained by multiplying a base wind speed by a series of factors which, taken together, define the exposure of the site in terms of the effects of the surrounding topography, ground roughness, and site altitude. The base wind speed is defined as the hourly mean wind with a mean recurrence interval of 50 years, irrespective of direction, at a height of 10 m above flat open terrain.

The map of base wind speed, V_B, used in the current UK code is based on the work of Cook and Prior (1987). It was derived from extreme value analyses of wind data between 1970 and 1980 for

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50 locations across the UK, using the "Method of Independent Storms" (MIS) (Cook 1982). Cook & Prior used UK Meteorological Office estimates of the "effective height" of the individual anemometers to correct for the effects of site exposure. "Effective height" is the height at which the anemometer would need to be set in order to give the same results in the meteorological standard exposure. However, this concept is flawed because the assessment of site exposure is limited to the terrain immediately surrounding the anemometer and, furthermore, is assumed to be uniform by direction. In reality, each anemometer is exposed differently by direction and changes of ground roughness remain significant for many kilometres.

1.2. Extreme value analysis

In classical Gumbel method of extreme value analysis, the cumulative probability distribution (CDF) P of annual maxima X_{max} is estimated from the order statistics:

$$P\{X_{max}\} = \frac{m}{N+1} \tag{1}$$

where N is the number of years and m is the rank of the annual maxima in ascending order of value. The CDF is fitted to an appropriate model distribution, usually the Fisher Tippett FT1 asymptotic model:

$$P\{X_{max}\} = \mathbf{exp}(-\mathbf{exp}(-y)) = \mathbf{exp}(-\mathbf{exp}(-a(X_{max}-U)) \tag{2}$$

where U is the mode, $1/a$ is the dispersion and $y = a(X_{max}-U)$ is the "reduced variate". The fit is often made graphically by plotting the extreme values as abscissa against the probability transformed to $-\ln(-\ln(P))$ as ordinate, giving a linear fit with slope $1/a$ and intercept U. This is usually called a "Gumbel plot", in which the integer values of rank m in Eq. (1) result in standard plotting positions.

Although other model distributions have been proposed and used, Eq. (2) is the asymptote for the largest of n values as $n \to \infty$ drawn from any parent distribution of the form $P\{X\} = 1-\exp(-g\{X\})$, where $g\{X\}$ is a function increasing faster than $\ln(X)$. The parent distribution of wind speed V is usually a very good fit to the Weibull distribution:

$$P\{V\} = 1 - \exp\left(-\left[\frac{V}{C}\right]^k\right) \tag{3}$$

In the UK the shape parameter k lies in the range $1.8 < k < 2.2$, i.e., around the Rayleigh distribution ($k = 2$). Eq. (3) meets the criteria for the FT1 distribution as the asymptote for the largest of n values as $n \to \infty$. For annual maxima, the population n is the annual rate of independent wind speed events which, for hourly mean or hourly maximum gust values, cannot be greater than the number of hours in a year (8766), but is typically around 300. Cook (1982) and Lagomarsino *et al.* (1992) have demonstrated the rate of convergence for various values of k. The Rayleigh distribution converges very slowly to the asymptote and even the maximum possible annual population is insufficient to achieve convergence. As the FT1 distribution is Exponential in its upper tail, the Exponential distribution (Weibull with $k = 1$) converges extremely rapidly, giving good convergence for $n > 10$. Fastest convergence of Weibull parents is obtained by preconditioning the variable by raising it to the power of the shape factor k, producing a transformed parent X^k that is Exponentially distributed (Harris 1996, Palutikof *et al.* 1999).

With $k \approx 2$ for wind speed V in the UK, it follows that extreme dynamic pressure q_{max} gives a better fit to the FT1 distribution than extreme wind speed V_{max}. This may not be the case in other climates: Lagomarsino *et al.* (1992) report $k \approx 1$ for wind speed V in northern Italy, while downburst wind speeds at Moree in Australia (Holmes and Moriarty 1999, Cook and Harris 2001) correspond to $k \approx 1.5$.

As there is less confidence in the order statistics of the upper and lower tails of the CDF than in the body, Eq. (1) introduces a bias to the fitted values of mode U and dispersion $1/a$ when each value is given equal weight. There are two approaches to remove this bias:

1. by applying the correct weight to each value (Lieblein 1974, Harris 1996), or
2. by modifying Eq. (1) to change the probability and hence plotting position of each value (Gringorten 1963) to allow equal weighting.

Gringorten's modified form of Eq. (1) :

$$P\{X_{max}\} = \frac{m - 0.44}{N + 0.12} \tag{4}$$

is convenient because the fit can be made using the equally-weighted Least-Mean-Squares method.

The Method of Independent Storms (MIS) improves the accuracy over standard extreme-value methods by including sub-annual extremes. Individual storms are identified and the maximum value abstracted from each to form the CDF of storm maxima, P_{storm}. The distribution of annual maxima is obtained from the average annual rate of storms by assuming the storm maxima to be statistically independent :

$$P_{max} = P_{storm}^{r} \tag{5}$$

Using the average annual rate of storms has the advantage of removing year-to-year variations within the observation period, but it produces plotting positions on the standard Gumbel axes that depend on the value of r and are incompatible with the commonly used unbiased fitting methods. The original method (Cook 1982) interpolated to the standard Gumbel plotting positions from Eq. (1) to apply the Lieblein (1974) weightings, so that the fit is made over the same range of reduced variate as the classical method. Although the number of storms per year in this analysis is high

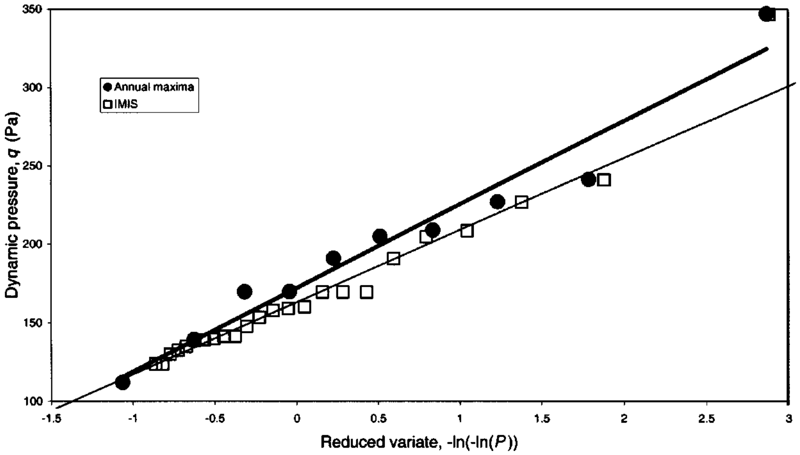


Fig. 1 Comparison of IMIS with annual maxima at Marham, 1970-1979

(≈ 150), only the strongest lie in the classical plotting range, so that only about 5 storms per year contribute to the analysis. Nevertheless the increase in data is substantial, compared with one per year in the classical Gumbel analysis, leading to greatly reduced analysis variance.

In a recent paper, Harris (1999) developed an Improved Method of Independent Storms (IMIS) that assigns the correct weight to each sub-annual extreme to give an unbiased fit. This revealed that the previous MIS analyses gave a small (~2.6%), systematic bias to lower values. Fig. 1 illustrates the improvement in linearity and scatter of the Gumbel plot that IMIS gives over the classical annual maxima for the case of dynamic pressure at Marham. Note how the correct weighting for the additional points in IMIS reduces the influence of the highest ranked value.

When the classical Gumbel method is used to assess extreme wind speeds by direction, problems occur due to the frequency variation between sectors, sometimes leading to higher predicted 1 in 50-year values in a sector than for all directions. MIS and IMIS circumvent this problem because the frequency variation is characterised by the annual rate of storms, r, so Eq. (5) accounts for these variations.

1.3. Stages of work

The work reported herein was performed in a number of stages :

- **Stage 1.** Initial calibration and analysis
  - Calculation of the exposures in 30°-wide sectors for the anemometers used in the original MIS analysis (Cook and Prior 1987), from the terrain roughness and topography. (Four anemometers were excluded from this stage, Abbotsinch, Dyce, Watnall and Wittering, because they had been moved during the observation period – four times in the case of Dyce).
  - Extreme-value analysis of the dynamic pressure at each station, using MIS in 30°-wide sectors and irrespective of direction.
- **Stage 2.** Quality assurance of methodology
  - Assessment of the effectiveness of the exposure corrections by comparing the sectorial analyses from each station with the predictions.
  - Preparation of interim maps of base wind speed.
  - Predictions of the base wind speeds by 30°-wide sectors for a further 23 anemometers in preparation for a "blind test". That is, these predictions were made without prior knowledge of the corresponding observations. (These records had been prepared for the 1987 analysis, but not analysed because the anemometers were considered to be too poorly exposed.)
- **Stage 3.** Analysis of the 23 additional anemometers
  - Calculation of anemometer exposures and extreme-value analysis using MIS using the same procedures as Stage 1.
  - Comparison of the results with the "blind" predictions for the poorly exposed anemometers.
- **Stage 4.** Interim base wind speed maps
  - Quality assurance of results and rejection of "rogue" data.
  - Preparation of a conventional "irrespective of direction" base wind speed map.
  - Development of methodology and preparation of an "equally-weighted by direction" base wind speed map.
  - Presentation at 10th ICWE conference, Copenhagen 1998 (Miller, Cook and Barnard 1999).
- **Stage 5.** Reanalysis using Improved Method of Independent Storms

- Calculation of the exposure of the anemometers that had moved position during the observation period for each of their locations.
- Correction for exposure of the anemometer records prior to reanalysis[1]. In the cases of stations that had moved position (Abbotsinch, Dyce, Watnall and Wittering), the exposure corrections for each location were applied to the appropriate section of record.
- Reanalysis of the original "Stage 1" and the new "Stage 3" stations using IMIS.
- Recalculation and confirmation of the previous conclusions based on MIS.

The interim results (Miller, Cook and Barnard 1999) were published before IMIS became available. This paper consolidates the previous work, but having refined the analysis by using IMIS, reports only the final results.

2. Site exposure correction factors

2.1. Calculation

In a conventional extreme wind analysis irrespective of direction, a single design value is obtained. The base wind speed, V_B, is typically the value with an annual risk of exceedance $Q = 0.02$, i.e., with a mean recurrence interval of 50 years or "1 in 50-year return period".

However, when the exposure for each individual anemograph site is split into twelve 30°-wide sectors by direction θ, the observations from each individual sector give an estimate of the base wind speed $V_{B,\theta}$ that can be represented by :

$$V_{B,\theta} = \frac{V_\theta}{S_\theta k_\theta} \tag{6}$$

where :

- V_θ is the once in 50-year wind speed for that sector, determined from observations
- k_θ is the site exposure factor which represents the effect of anemometer exposure by direction.
- S_θ is the climatic factor representing the climatic variation by direction, due to climate alone. In this context, S_θ is the once in 50-year wind speeds in the sector, V_θ, divided by the once in 50-year wind speed irrespective of direction for a site with perfectly uniform exposure.

It will become evident later that the absolute values of S_θ are not important in this work. They serve only to provide the appropriate weight to the contribution from each sector. Initial values were adopted directly from Cook & Prior (1987).

The required site exposure gain factor k_θ was calculated using an expression of the form :

$$k_\theta = S_f\, S_t\, S_a \tag{7}$$

where S_f, S_t and S_a are factors that enumerate the effect of roughness fetch, orography and altitude, respectively.

The fetch factor, S_f, was calculated using the BRE*Ve* computer program, developed from the earlier

[1]The sectorial results may be corrected for exposure after analysis only when the exposure is consistent for the whole observation period. The data should always be corrected for exposure before "irrespective of direction" analysis because large differences in gain between sectors may result in selection of the extreme from the wrong sector.

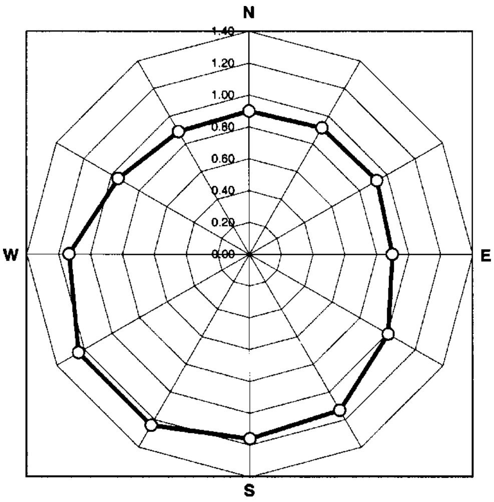


Fig. 2 Fetch factor S_f for Mount Batten, Plymouth

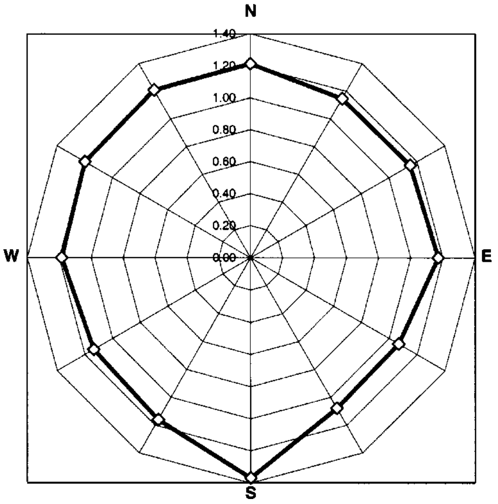


Fig. 3 Orography factor S_t for Mount Batten, Plymouth

STRONGBLOW program of Building Research Establishment (BRE). This implements the roughness-change model of Harris & Deaves (1980), in conjunction with a database of UK ground roughness at a horizontal resolution of 1 km^2. The value of S_f enumerates the cumulative effects of changes in upwind aerodynamic roughness z_o and of any difference in height between the actual anemograph height and the standard height of 10 m. The fetch factor for Mount Batten, Plymouth is illustrated in Fig. 2. This station has open sea exposure to the south-west and the city of Plymouth to the north, giving values above and below unity, respectively.

The orography factor S_t was calculated using a three-dimensional linear CFD model in conjunction with the Ordnance Survey's Landform PANORAMA digital terrain database for the UK. The particular CFD model used was "MS-Micro", a PC based version of the "MS3DJH" model developed at the Atmospheric Environment Service, Canada (Walmsley, Salmon and Taylor 1982) (Taylor, Walmsley and Salmon 1983). In this context, $S_t = 1 + \Delta s$, where Δs is the "fractional speed-up" produced by MS-Micro. The orography factor for Mount Batten, Plymouth is illustrated in Fig. 3. This station lies at the crest of a small hill on a promontory, so that values are above unity in all directions.

Finally, the altitude factor, S_a, which represents the observed increase in wind speed with altitude over flat terrain in the UK, reported by Caton (1976), was calculated using Caton's the empirical equation :

$$S_a = K \times A \tag{8}$$

where A is the altitude. So that the effects of altitude and orography were not double-counted, the altitude was taken to the base of any orography, when significant, otherwise to the ground around the anemometer. Following the work of Cook and Prior (1987), $K = 0.001$.

2.2. Assessment

An assessment of the improvements to be gained by using site exposure gain factors was made as follows. For each site an estimate of the base wind speed $E\langle V_B \rangle$ was obtained by taking the average of the sectorial base wind speed estimates for all 12 sectors. This yields:

$$E\langle V_B\rangle = \frac{1}{12}\sum_{\theta}\frac{V_\theta}{S_\theta k_{\theta 1}} \tag{9}$$

where $k_{\theta 1}$ is the *predicted* site exposure gain factor calculated using the methodology outlined above and S_θ is the climatic factor, as before.

The sectorial average base wind speed was then used to calculate a set of *observed* site exposure gain factors $k_{\theta 2}$ for the observed site variations, corrected for the overall climatic variations, to give :

$$k_{\theta 2} = \frac{V_\theta}{S_\theta E\langle V_B\rangle} \tag{10}$$

Note that the value of $k_{\theta 2}$ is insensitive to the absolute values of S_θ, because S_θ appears in the

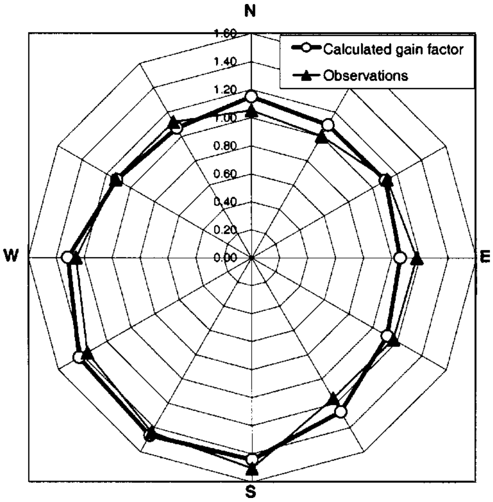


Fig. 4 Calculated site gain factor k_θ for Mount Batten, Plymouth, compared with observations

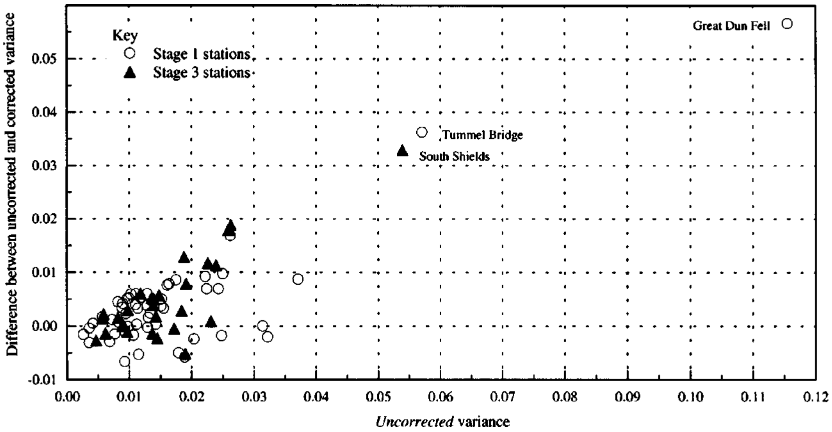


Fig. 5 Difference between corrected and uncorrected variances

denominator of both Eqs. (9) and (10). Effectively, it serves only to control the weight of the contribution from each sector in the summation of Eq. (9).

The calculated site exposure gain factor $k_{\theta 1}$ for Mount Batten, Plymouth, is compared with the observed gain factor $k_{\theta 2}$ in Fig. 4.

The overall benefit of site exposure corrections was assessed by considering the variance of the residuals obtained from two types of fit :

1. "Corrected" – the *observed* site gain factors $k_{\theta 2}$ fitted to the *predicted* gain factors $k_{\theta 1}$, and
2. "Uncorrected" – the *observed* site gain factors $k_{\theta 2}$ fitted to a circular distribution, which is equivalent to assuming that the exposure of the site is uniform by direction.

The variance of the "corrected" fit will be smaller than the variance of the "uncorrected" fit when applying the predicted site exposure gain factors is better than assuming a uniform exposure.

Comparing this variance by direction gives only a relative calibration between the exposure for each sector at each site. No absolute value of base wind speed can be obtained because all measurements are affected by the site exposure. However, accounting for the relative difference between widely different sectorial exposures gives confidence in the absolute calibration of the site gain factors.

Results for all 70 anemograph stations considered are shown in Fig. 5 as the difference between the "corrected" and "uncorrected" variances plotted against the uncorrected variance. An improvement in the fit is indicated by a positive difference, while a worsening fit is indicated by a negative difference. Overall it is found that 60% of the sites considered show a reduction in the variance, 10% show little or no change and 30% show a very small increase in the variance. Sites that show a small increase tend to be located in open, flat countryside, uniformly exposed by direction. Conversely, those sites that are not uniformly exposed by direction show significant improvements when the exposure corrections are applied. This may be taken to imply that, while the corrections make a poor site better, they can also make a good site appear worse. However, even the uniformly exposed sites still require correction if the anemometer is not 10 m above ground and/or the site is at altitude.

3. Results of applying site exposure correction factors to wind speed data

3.1. Quality control

A quality control check was made by comparing the observed value irrespective of direction at each station against the corresponding value predicted by interpolation between or, for the outlying stations, extrapolation from its nearest neighbours. The results in Fig. 6 show that two of the Stage 1 stations stand out :

1. Tummel Bridge: The observed value is very low. The location is sheltered by steep orography from all directions and always lies in separated wake flow. The exposure correction method is unable to cope with separated flows.
2. Lynemouth : The observed value is very high. There are three very high values in the record that distort the fit. These appear to be due to a different climatic mechanism, perhaps lee-waves from the Pennines, or may be anomalous.

The observed values remain within 1.5 m/s of the predicted values for the remainder of the Stage 1 stations. However, the more poorly exposed Stage 3 stations exhibit significantly greater scatter than

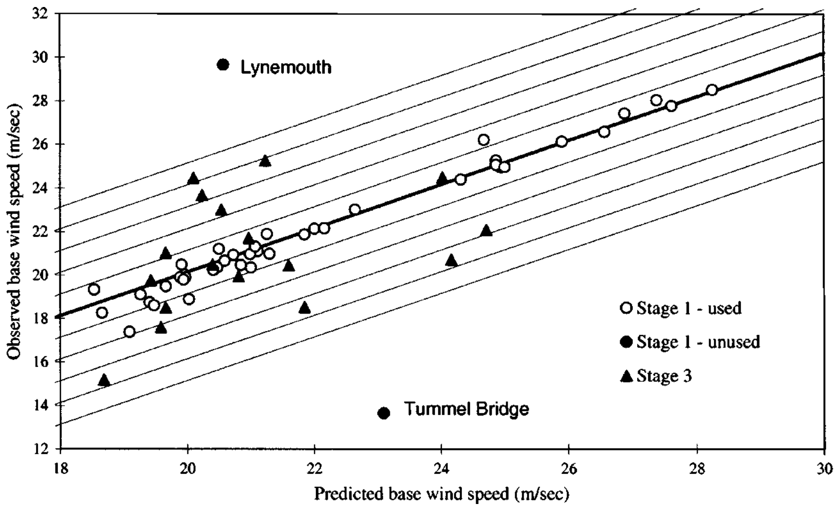


Fig. 6 Quality control on geographical trend

the better-exposed Stage 1 stations.

3.2. Climatic factor S_θ

The new base wind speed estimates allowed the values for the climatic factor, S_θ, to be recalculated. Cook and Prior (1987) assumed that averaging the results from 50 anemometer stations would average out any variation in exposure by direction, assuming also that no geographical variation of S_θ exists across the UK. Using the exposure-corrected values removes the need for the first assumption and allows the second to be tested.

As shown in Fig. 7 the results are almost identical to those given by Cook and Prior (1987), confirming their first assumption to be good. Fig. 8 shows the standard deviation around the mean, representing the analysis errors, including any location dependent components. Applying the site exposure gain factors significantly reduces the variance associated with the well-exposed Stage 1 stations, but the variance rises again when the poorly exposed Stage 3 stations are included. This suggests that there are still aspects of the site exposure that are remaining uncorrected partly due to imperfect exposure assessments and partly due to effects still not accounted for, such as wakes from buildings and flow separation from steep orography.

The exposure corrections give sufficient confidence to estimate the climatic factor for smaller groups of stations, selected regionally. The sites were split into three groups by latitude, corresponding to Scotland, northern and southern England, and into two groups by longitude, corresponding to east of west of the Pennines. The mean value of S_θ for each group was indistinguishable from the complete set in Fig. 7, confirming Cook and Prior's second assumption.

4. "Irrespective of direction" and "equally weighted" base wind speeds

It is clear from an examination of the climatic factors shown in Fig. 7 that the values of base wind speed will be controlled by the strongest winds from the sectors $\theta = 210^{\circ}$ to $\theta = 270^{\circ}$. This is

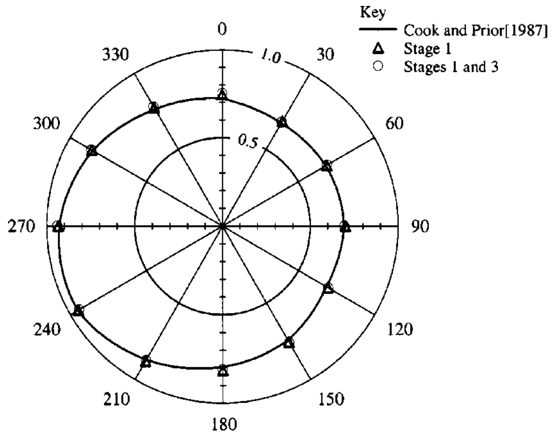


Fig. 7 Comparison of mean climatic factor S_θ

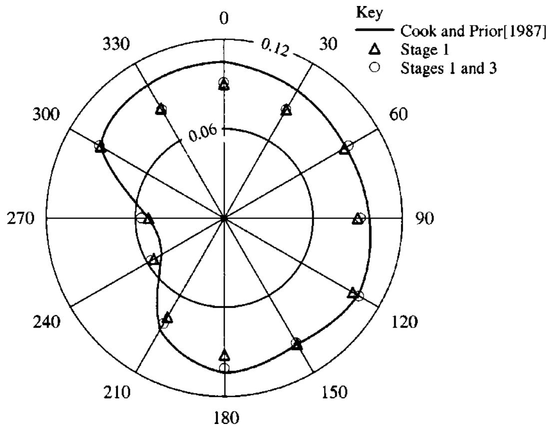


Fig. 8 Comparison of standard deviation of climatic factor S_θ

because the lower values from the less windy sectors are excluded more frequently when the extreme value is selected irrespective of direction. The description "irrespective of direction" does not imply independence from direction - instead it implies weighting to the quadrant of strongest winds.

More appropriate, "equally weighted" values can be derived by considering Eqs. (6) and (9). Having determined the climatic factor S_θ from all the stations and shown that it is independent of location, it follows that Eq. (6) gives an individual estimate of the base wind speed for each location from each of the twelve sectors. Averaging these estimates over all 12 sectors gives an estimate of base wind speed in which each directional sector contributes an equal weight.

5. Base wind speeds

The additional "Stage 3" stations were previously required to restore adequate cover to areas of the UK affected by the rejection of Abbotsinch, Dyce, Lynemouth, Tummel Bridge, Watnall and Wittering. But Fig. 6 shows that these stations remain less reliable than the Stage 1 stations, despite the exposure corrections. Many of the "Stage 3" anemometers are mounted on buildings and/or are affected by wakes from upwind buildings, neither effect included in the exposure corrections. Reinstating the four Stage 1 stations that moved position restores almost the same coverage of the UK as in Cook and Prior (1987), i.e., 46 "Stage 1" stations lacking only Tummel Bridge and Lynemouth, removing the need for the less reliable Stage 3 stations. Accordingly, Tummel Bridge, Lynemouth and all the Stage 3 stations were rejected from the base wind speed maps.

Maps of the "irrespective of direction" and "equally weighted" base wind speed estimates obtained using IMIS on dynamic pressure at the 46 Stage 1 stations are shown without any smoothing in Figs. 9(a) and (b), respectively. The circles indicate the location of each station, with the corresponding value shown alongside. Both maps show the large scale south-east to north-west gradient of wind speed seen in previous studies, but on a smaller scale there is still considerable local variation between adjacent stations that is attributable to residual site exposure effects, analysis errors and statistical variance. The anomalous values for Lynemouth, indicated by the solid black circle, shows that it predicts the highest wind speed anywhere in the UK.

6. Discussion

6.1. Ensemble averaging

The approach uses ensemble averaging to force independence of location and direction. In the calculation of the climatic direction factor averaged over all locations, Fig. 7, each station contributes 1/47th (Stage 1) or 1/70th (Stages 1 & 3) of the value of S_θ for a particular sector. Strictly, the contribution of each location should be removed from S_θ when using Eq. (9) to estimate the base wind speed for that location, but the effect is insignificant. It is also possible to use the equally-weighted estimates of base wind speed, instead of the irrespective of direction estimates, in the calculation of the climatic direction factors, but this makes no significant difference to the final values. As a scalar on the individual sectorial base wind speed estimates, the value of S_θ effects only the weighting of each anemometer station in the ensemble average.

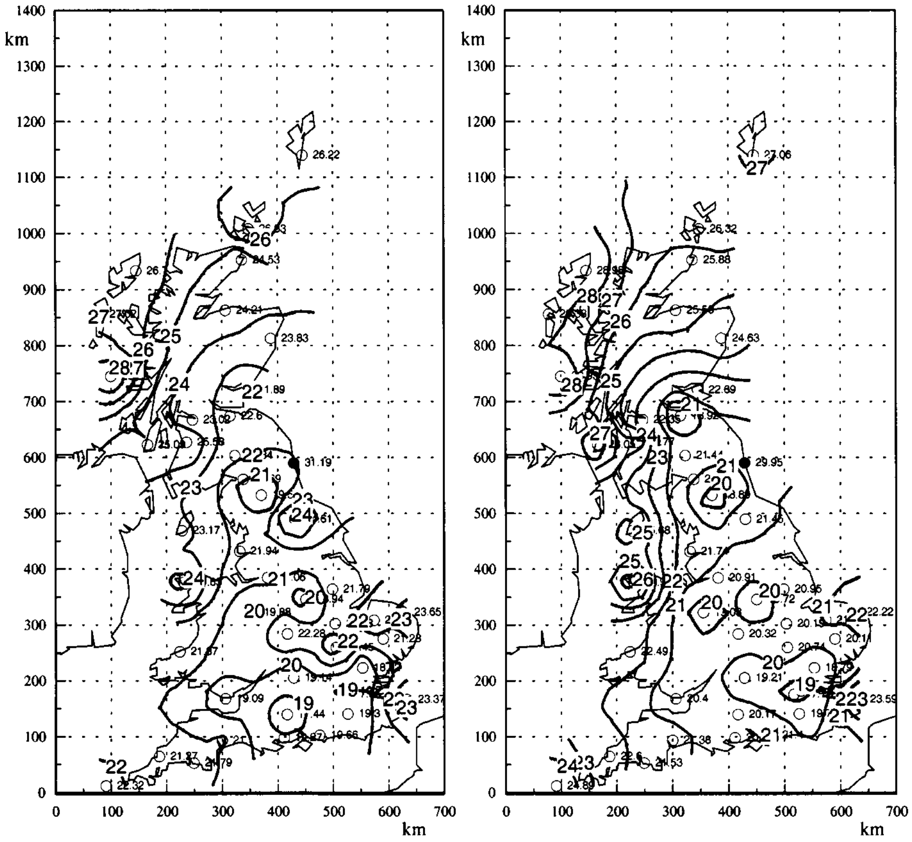
Forcing independence of location and direction suppresses any systematic dependence that might exist, treating it as a random error. In the case of S_θ any systematic dependence is included in the standard deviation shown in Fig. 8. Our earlier work (Cook and Miller 1999) shows a systematic variation across the UK of the parameter k_V, the factor that accounts for correlation between adjacent sectors. It is possible that the comparison of regional ensemble averages for Scotland, Northern, and Southern England was too crude to identify subtle dependencies.

6.2. Smoothing residual errors

The use of Eq. (9) to derive the equally-weighted values is a form of directional smoothing, since it takes the average of 12 independent estimates of the base wind speed. In this context, the base wind speed for Stornoway on the Isle of Lewis rises from 26.1 m/sec when estimated irrespective of direction to 28.5 m/sec when the equally-weighted estimate is taken. For the prevailing westerly winds the anemometer at Stornoway lies in the lee of steep orography, so that the irrespective of direction estimate is expected to be low. Contributions from the other wind directions compensate for this anomaly.

When the density of the anemometer sites is greater than the minimum needed to express the geographical variation of wind speed, residual geographical errors may be reduced by the application of inter-station smoothing. The quality control procedure in Fig. 6 was a form of spatial smoothing by rejecting stations farthest removed from the general trend. Further spatial smoothing reduces the residual station-to-station variance at the cost of reducing valid geographical variation.

As the raw data are exposure-corrected to a common base, spatial smoothing does not need to account for coastlines and urban areas : these effects are accounted for in the factors that define the exposure of a particular site. The smoothing may be purely mathematical over a Cartesian grid. Fitting the data to a Mclaurin series (two-dimensional polynomial) provides controlled spatial smoothing, with higher order polynomials giving less smoothing than lower orders. This has the additional advantage of yielding a mathematical expression for the contour surface that can then be incorporated into the appropriate building code. A balance is required between eliminating random station-to-station variations and maintaining the underlying geographical trends. Figs. 10(a) and (b) present the results of fitting the results in Figs. 9(a) and (b), respectively, to a 3 by 6-order polynomial surface. This



(a) Irrespective of direction (b) Equally weighted by direction

Fig. 9 Comparison of unsmoothed basic wind speed maps in m/s

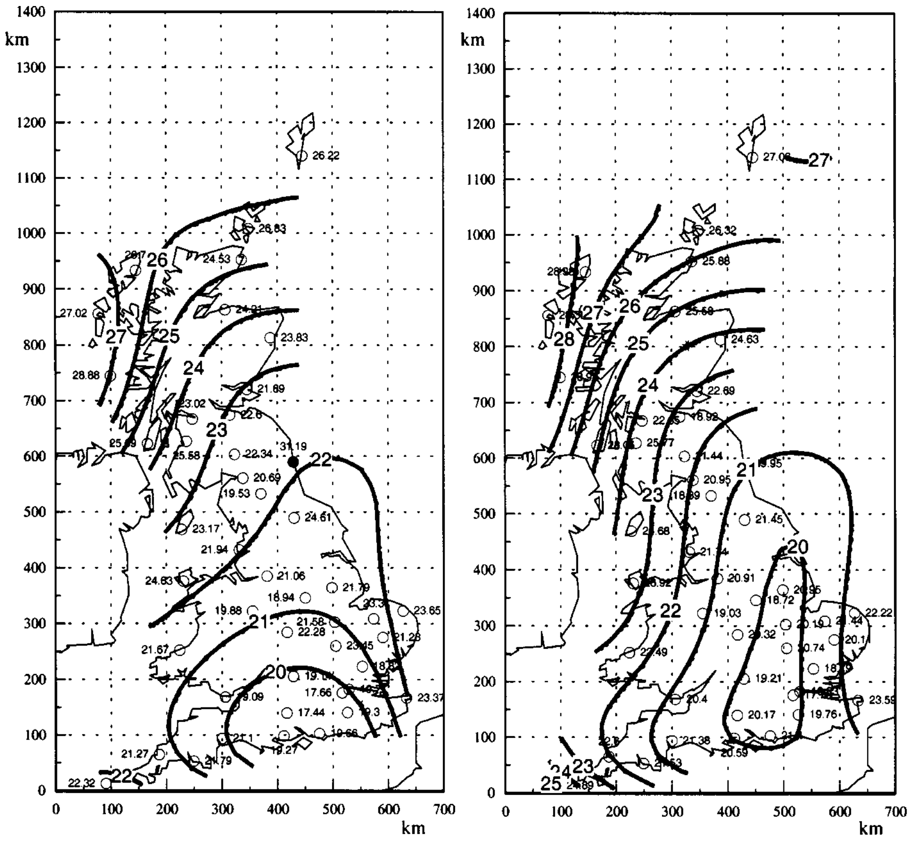
appears optimal for the present study, since higher orders make little difference to the contours, but lower orders force the contours to tend towards equally spaced south-west to north-east diagonals.

The observed base wind speeds "irrespective of direction" for each of the used stations are compared with the predictions from the smoothed base wind speed map in Fig. 11. This shows a significant increase in scatter over Fig. 6 – the major remaining question is whether this scatter represents residual error, best removed, or valid geographical variation, best retained.

6.3. Implications for design

The current design wind speed map for the UK (BSI 1986, 1997) is based on a MIS analysis on the same Stage 1 stations and for the same observation period. But the wind speed data was corrected for exposure using UK Meteorological Office estimates of the 'effective' height for each anemometer station. The maps presented in Fig. 9 are based on an IMIS analysis of data corrected for exposure by direction, using the same methodology on which the codes are based. So for the first time, the meteorological analysis and the design synthesis are completely compatible.

Base wind speeds in Scotland and Northern England remain largely unchanged, although the local minimum over the Grampians has been eliminated. This stems from rejecting the data from Tummel



(a) Irrespective of direction (b) Equally weighted by direction

Fig. 10 Comparison of smoothed basic wind speed maps in m/s

Bridge. Minimum wind speeds in Southern England are also similar. Principal changes are a reduction in wind speed of 2 m/s across the Midlands and a 3 to 4 m/s reduction in East Anglia, the latter due to exposure correction of the Coltishall station.

If all the exposure corrections were perfect, the "irrespective of direction" and "equally weighted" maps would be identical. However, as the world is not perfect and we must build to withstand the strongest wind, the "irrespective of direction" map would seem to be more appropriate. But this places a strong reliance on the quality of the exposure assessment for south-westerly winds. Where this is likely to be poor, including estimates from other well-exposed directions reduces the potential for error. Hence the "equally weighted" map should be more consistently reliable, and more appropriate for use with the climatic direction factors than the "irrespective of direction" map. The difference between Fig. 6 of BS6399-2 (BSI 1997) and Fig. 10(a) represents the improvement gained by applying directional exposure corrections to the observed wind data and the removal of bias by IMIS. Conversely, the difference between Figs. 10(a) and (b) represents the removal of bias to the prevailing wind direction and the use of 12 times more data to obtain the "equally weighted" map.

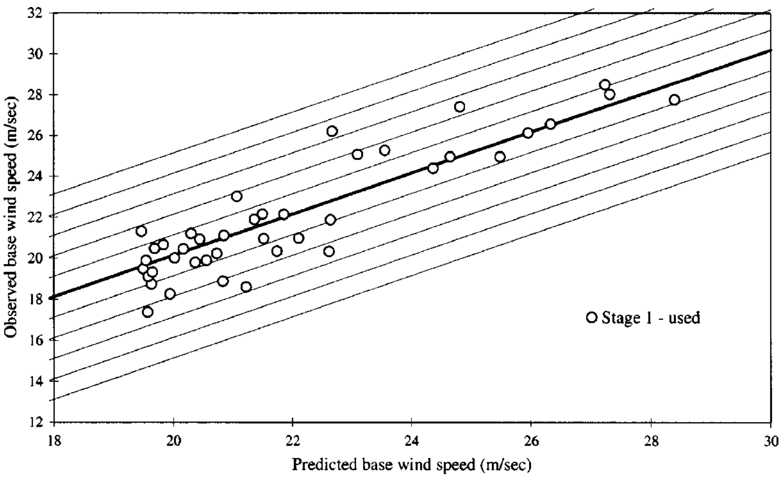


Fig. 11 Quality control on smoothed basic wind speed map

6.4. Future work

The principal aim of the work reported herein was to validate the exposure correction methodology and IMIS, and to verify their effects on the base wind speeds. The base wind speed maps are, in effect, a bonus. However, they are based on records of only 11 years (1970-1980), whereas continuous records suitable for IMIS analysis now exist for a 30-year period. While the additional accuracy given by a threefold increase in record will be welcome, a suspicion that the 1970-1980 period is not representative of the long-term wind climate is the main reason for wishing to extend the analysis. Despite excluding the notable storm events in 1987 and 1990, the 1970-1980 period appears to have been windier than average. This is illustrated by Fig. 12, which extends the analysis for Marham to 1994, showing a further improvement in linearity but a significant reduction in the dispersion (slope) of the fit. Most discussions on the minimum record length for extreme-value analysis focus on the accuracy of the analysis methods (Palutikof *et al.* 1999), and neglect the

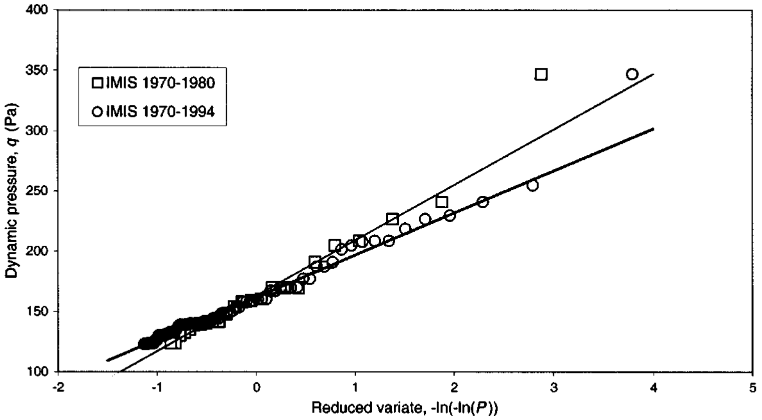


Fig. 12 Comparison of IMIS on 1970-1980 and 1970-1994 periods at Marham

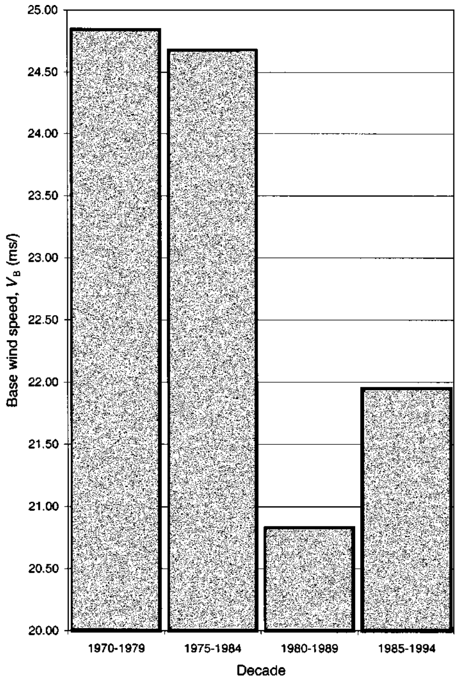


Fig. 13 Base wind speed, V_B (m/s) at Marham, assessed by decade

question of how well the period represents the long-term climate. It is becoming clear that the extreme wind climate of the UK varies significantly from decade to decade. The improvement in accuracy given by IMIS allows reliable decennial analysis as shown in Fig. 13 for 1970-1994 at Marham. This reveals considerable decennial variation and a trend over the period that decreases by 1.6 m/s per decade – apparently opposing the predictions for climate change.

7. Conclusions

- The climatic direction factors determined by Cook and Prior (1987) are confirmed.
- Bias in the Method of Independent Storms is removed by the use of the Improved Method of Independent Storms.
- The methodology used to derive the base wind speed maps from meteorological data is compatible with the methodology used to calculate design wind speeds.
- A revised map of base wind speeds “irrespective of direction” has been derived for the UK that shows a reduction in wind speeds across the Midlands and in East Anglia.
- An alternative “equally weighted” base wind speed map has been proposed that is considered to be both more consistently reliable, and to be more appropriate for use with the climatic direction factors.
- Preliminary analysis of the longer period 1970-1994 suggests that 1970-1980 was windier than average, so that the base wind maps are conservative.

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