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THE ESTIMATION OF EXTREME WIND SPEEDS OVER STANDARD TERRAIN IN IRELAND

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Summary

Annual maximum gust and mean wind speeds for periods up to and including 1987 are analysed using the statistical theory of extreme values. A simple method of correcting both gust and mean speeds so as to make them valid over a surface of standard roughness is described. An account is given of the methods used in preparing a map of the 60-minute mean speed with a return period of 50 years over standard terrain.

1. Introduction

Estimates of maximum wind speeds with various return periods are frequently required for design purposes. The wind speed which is of interest may be either the maximum in a gust or the maximum mean speed averaged over some period of time.

Estimates of gust speeds over Ireland with a return period of 50 years, based on data for the period 1953-1974, have been prepared (Logue, 1975) and a method has been proposed of deriving the corresponding 60-minute mean speeds over a standard type of terrain. In the present study these estimates are revised to take account of data obtained up to the end of 1987 and the methods used are reconsidered in view of more up-to-date knowledge.

2. Physical Considerations

Virtually all strong winds recorded in Ireland are produced by large-scale mid-latitude depressions (as opposed to intense thunderstorms, tornadoes or tropical cyclones which affect some other countries). Most of these depressions pass to the north or west of the country along tracks which are directed towards the east or north-east. Within a particular depression, the strongest winds are frequently found to the right of its track and within a few hundred kilometres of its centre. The most extreme winds typically affect a swath of width 100-200 kilometres parallel to and to the right of the track, although in the case of some large depressions the whole country may be affected to an approximately equal extent. Although strong winds may be experienced in any month of the year, the intensity of the storms is generally greatest in winter and least in summer.

It follows from what has been said that most strong winds blow from the west or south-west: 84% of all the annual maxima recorded by Irish stations have directions lying between 180^{o} (southerly) and 320^{o} (north-westerly). It is also natural to expect that, leaving aside local effects, the intensity of extreme winds should increase from south-east to north-west. Confirmation of this is provided by a map of wind speed, measured at a height of 900 metres, which is exceeded in only 1% of observations over Great Britain (Caton, 1977). The wind field at this height is not complicated by local differences in surface roughness or small-scale topography and may be expected to show the broad-scale pattern associated with the climatology of depression tracks and intensities. Over Britain, it shows a gradual increase in wind speeds of the stated frequency from south-east to north-west.

When we come to consider surface winds, measured at a height of about 10 metres above the ground, the situation is more complicated and the speeds recorded are modified by a number of factors as follows:

(i) When wind blows over the surface of the earth its speed is reduced (as compared, say, with its speed at 900 m) and the amount of the reduction increases with the roughness of the surface. There is a tremendous variation in roughness over even short distances, from smooth water surfaces to open bog or moorland to farmland with fields and hedges and to very rough surfaces with large obstacles such as forests or large housing estates. Mean speeds are reduced to a much greater extent than gust speeds over rough terrain so that the ratio of the maximum gust in a given interval of time to the mean speed over the same interval (the "gust ratio") is larger over rough than over smooth surfaces.

(ii) Wind speeds measured near the top of hills or ridges are greater than those measured over level country even though there may be no difference in surface roughness. Similarly, wind speeds tend to be reduced in sheltered, low-lying areas. This is often referred to as the "topographic effect". The effect on mean speeds is greater than that on gusts although the contrast is not as marked as in the case of the surface-roughness effect. The topographic effect may be significant even where the surface relief is comparatively gentle; thus many wind-measuring stations may be regarded as "overexposed" (i.e. recording wind speeds too high) or "underexposed" (recording too low).

(iii) When a large-scale airflow meets the coast of an island such as Ireland, there is a tendency for the air to be diverted over the smooth sea surface on either side of the land mass rather than travel straight across it. The field of atmospheric pressure then tends to adjust itself towards balance with the wind field so that the "gradient wind" (i.e. the wind which would be produced by the pressure field alone in the absence of surface effects) is decreased over the land and increased over the surrounding sea. An example of this is the well-known crowding of isobars in St George's Channel and the corresponding increase in isobar spacing over Ireland when the airflow is south-westerly or north-easterly. Thus, independent of differences in surface roughness or local topography, we may expect to find higher wind speeds near the coasts than in the centre of the country.

In preparing a map of maximum wind speed with a given return period it is impossible to depict effects (i) and (ii) in detail because of the small number of wind-measuring stations and the rapid variation of these effects over short distances. Instead, the map is referred to level terrain of some standard roughness. Before using station data in the preparation of such a map it is necessary to devise a method of "correcting" the data to allow for differences between the exposure and surface roughness characteristic of the station and the standard exposure and roughness. Since wind speeds increase with height above the ground it is also necessary to correct for differences between the actual height of the anemometer and the standard height (10 metres). Effect (iii), since it is a large-scale effect, may be shown on the map.

To summarise, physical considerations would seem to indicate that the distribution of extreme wind speeds, corrected to a height of 10 metres above level terrain of a standard roughness, should show an increase from south-east to north-west and a tendency for speeds to be higher near the coast than in the midlands.

3. Instrumentation and Station Network

The standard instrument for the measurement of wind speed in the Irish Meteorological Service is the Dines pressure-tube anemograph. In many other countries wind speeds are measured by means of rotating-cup anemometers. A comparison between a Dines anemograph and a standard rotating-cup instrument (Logue, 1986) has shown that for mean wind speeds, averaged over a 60-minute period, they agree well especially at higher wind speeds. In the case of maximum gust speeds however, it was found that the Dines instrument recorded on average 6-7% higher than the cup anemometer. This must be borne in mind when comparing extreme gust speeds recorded in Ireland with those recorded in other countries. Different types of cup anemometer may also differ from one another in their recording of gust speeds.

A list of wind-measuring stations whose records have been used in this study is given in Table I. The anemometer sensors are located at a height of 12 m above the surface at all stations except Malin Head where from 1966 onwards the height has been 21 m. The anemometers have generally been considered to have "effective heights" of 9 or 10 m (18 m in the case of Malin Head). However, the concept of effective height has been criticised (Wieringa, 1976) and the heights used in this study are the actual heights. In order to make the Malin Head data comparable to those at the other stations, mean speeds recorded since 1966 were reduced by 9% and gust speeds by 4%.

4. Correction of Maximum Wind Speeds to Standard Roughness

The data available consisted of monthly and annual maximum values of (a) gust speed, (b) mean speed over any 10-minute period and (c) mean speed between fixed clock hours. The quantity (c) was available only from 1962 onwards.

For each station-year of data the ratio of the maximum gust to the maximum 10-minute mean was calculated and for each station the arithmetic average of these ratios over all years was determined. The latter quantity is hereafter denoted by R_{10}, the 10-minute gust ratio for the station at a height of 12 metres. Values of R_{10} for each station are given in Table I. (In the case of Galway, R_{10} was determined from the <u>monthly</u> maxima because of the shortness of the record).

R_{10} is not exactly the same as the gust ratio defined in Section 2 above but is closely related to it. (One obvious difference is that the gust and mean speed from which R_{10} is calculated are not necessarily recorded at the same time). It is determined mainly by the roughness of the surface around the anemometer. Roughness, and hence R_{10}, may of course vary with direction from the anemometer but the sample of annual maximum speeds was not sufficiently large to determine the variation in detail. Gust ratio as a function of direction has been calculated for the various stations for winds with mean speeds in the range 9 to 13 m/s (L Burke, personal communication). However, it was decided to use a single value of R_{10} per station, calculated from the annual maxima, for the sake of simplicity and because, at most stations, the variation with direction is rather small over the sector from which the extreme winds blow. The one exception to this was Rosslare where north-easterly winds from the sea have a much lower gust ratio than southerly or westerly winds from the land; the value of R_{10} given for Rosslare is valid for the land sector only.

It has been shown on the basis of Irish data (Logue, 1975) that R_{10} is independent of wind speed, at least over the range of speeds covered by the series of annual maxima, and hence a unique value of the gust ratio may be defined for each station. Besides roughness, the magnitude of R_{10} depends to some extent on the topographic effect which is stronger for mean than for gust speeds.

At Shannon Airport it was observed that the gust ratio, which had been homogeneous from 1946 to 1975, increased significantly over the period 1975-1980 and then steadied off again. On investigation it was discovered that the change had been caused by an increase in roughness due to the growth of trees planted on a nearby golf course. The golf course is located mainly to the north-west, west and south-west of the anemometer and the trees are scattered over it in rows and clumps. This circumstance provided a means of assessing the effect of an increase in roughness on mean and gust speeds separately. The results of a comparison of monthly maximum speeds between the periods 1965-1974 and 1983-1987, using Claremorris, Kilkenny and Valentia Observatory as control stations, is shown in Table II. It may be seen that the change in roughness resulted in a decrease of about 13.1% in maximum mean speeds and 4.5% in maximum gust speeds. Further evidence is provided by Mullingar which in 1973 was moved about 1.6 km to a new site (Mullingar II) with a higher gust ratio. Using Claremorris, Dublin Airport and Kilkenny as controls, it is estimated that the maximum mean speeds and gusts are respectively 10.7% and 2.2% lower at the new site. However, because of the change of site, less weight is given to this result than to the Shannon one. It is concluded that a change in roughness alone affects maximum mean speeds about three times as strongly as gust speeds.

This result may be used to correct maximum gust and mean speeds recorded over a level site of arbitrary roughness so as to make them valid for a surface of standard roughness. Let the standard surface be defined as having a gust ratio of 1.50 (measured by a Dines pressure-tube anemograph at a height of 12 m). (It may be seen from Table I that this value is typical of airfield sites). Then, if M and G are representative, uncorrected mean and gust speeds respectively and M' and G' are the corresponding corrected values

$$G/M = R_{10} \quad : \quad G'/M' = 1.50 \qquad (4.1)$$

The result that mean speeds are affected three times as strongly as gust speeds may be expressed

$$M/M'-1 \quad = \quad 3(G/G'-1) \qquad (4.2)$$

It is assumed that this relationship is valid over the range of gust ratios found for Irish stations. Solving equations (4.1) and (4.2) for $b_M = M'/M$ and $b_G = G'/G$, we get

$$b_M \;=\; R_{10} - 0.50 \quad ; \quad b_G = 1.50 - 0.75/R_{10} \qquad (4.3)$$

These are the factors by which the mean and gust speeds respectively should be multiplied to correct them to standard roughness.

It is also necessary to reduce the wind speeds from 12 m to the standard height of 10 m. Assuming that $R_{10} = 1.50$ corresponds to a roughness length of 0.1 m and using the logarithmic wind profile it follows that 10 m wind speeds are 4% lower than 12 m winds. It is assumed that the corresponding reduction in gust speeds is 2%. Hence, the correction factors incorporating both roughness and height effects are

$$b_M' = 0.96\, b_M \quad ; \quad b_G' = 0.98\, b_G \qquad (4.4)$$

5. Extreme Value Analysis

Tabony (1983) has discussed the problem of statistical estimation of the extreme values of meteorological elements. Wind speeds, like other meteorological data, must be regarded as more-or-less inhomogeneous samples drawn from a mixture of statistical populations, each population corresponding to a particular type of weather system which produces strong winds. However, although the main body of data is inhomogeneous, the series of annual maxima is more likely to be drawn from a single population. Hence, the application of the statistics of extremes to the annual maxima is likely to produce a better estimate of long return-period winds than fitting a distribution to the body of the data. Tabony also shows that, for this purpose, long data records are highly important and that it is preferable to analyse annual rather than monthly maxima.

Consider a series of N annual maxima of some meteorological element X_1, X_2, X_3 ...... X_N arranged in order of magnitude so that X_1 is the lowest annual maximum, X_2 the second lowest and so on. Then the series may be displayed by plotting X against the "reduced variate" y where

$$y = -\ln(-\ln F) \qquad (5.1)$$

F represents the cumulative probability function which is related to the return period T by

$$F = (T-1)/T \qquad (5.2)$$

The appropriate value of y against which the m'th member of the series is plotted is obtained from the relationship.

$$F_m = (m-0.31)/(N+0.38) \qquad (5.3)$$

This plotting position was recommended by Jenkinson (1969) and has been used in previous work on wind extremes in Ireland.

For an individual station, the general extreme-value distribution (Jenkinson, 1955) may be fitted to the data sample in order to predict the values of X for various return periods. This distribution has three parameters: a position parameter equal to the value of X for y = 0, a slope parameter and a curvature parameter. A positive value of the curvature parameter corresponds to a convex-upwards curve of X against y, a negative value to a concave-upwards curve and a zero value to a straight line. These three types of extreme-value distribution are known as Type III, Type II and Type I respectively (Fisher and Tippett, 1928).

For the sample sizes generally available, the slope and curvature parameters of the general extreme-value distribution are rather poorly determined resulting in large random errors in predicted 50-year and 100-year extremes. However, where there are a number of station records for a climatically homogeneous region it should be possible to combine them to obtain more reliable estimates of the parameters. In order to do this it is convenient first to summarise the annual-maximum series for each station by means of a procedure given in the United Kingdom Flood Studies Report (Natural Environment Research Council, 1975). Each ordered series is divided into quartiles and the mean value of X for each quartile is obtained; the highest and second highest values in the series are also noted. The values of the reduced variate appropriate to each of the quartile means have been calculated on the assumption that each quartile lies on a straight line on the extreme-value plot.

The above procedure was applied to the annual maximum series of gust and 10-minute mean speeds for each station (after correction to standard height and roughness as described in Section 4). The mean of the two middle quartiles, which is approximately equal to the median or 2-year return period value and corresponds to y = 0.40, was also calculated. This measure of position of the extreme-value curve was preferred to the mean of the two highest quartiles, which has been used in some other work (for example, see Natural Environment Research Council, 1975), because of its greater stability. A simple measure of the slope of each curve was obtained by subtracting the mean of the two middle quartiles from the highest quartile mean and dividing by the corresponding difference in y (1.87). Use of the lowest quartile in calculating the slope was avoided because of the possibility that it might contain data which were not drawn from the tail of the parent distribution and hence would fail to satisfy one of the basic postulates of extreme-value theory (Tabony, 1983). This method of determining the slope receives subsequent justification from the conclusion that extreme wind speeds follow the Type I (straight line) distribution.

The results of these computations are shown in Table III where M'(2) and G'(2) represent the median corrected 10-minute mean speed and gust speed respectively and a_M and a_G represent the slopes of the mean and gust series on the extreme-value plot. The uncorrected medians M(2) and G(2) and the respective correction factors b'_M and b'_G (based on equations (4.4)) are also given. Only those stations whose record lengths equal or exceed 30 years are given in Table III.

From Table III it may be seen that, in general, M'(2) and G'(2) are highest for western and northern stations and lowest for midland and eastern ones. The slopes a_M and a_G however, have the appearance of being randomly distributed. Kimball (1949) has shown that for the extreme-value Type I (straight line) distribution the standard error of the slope parameter, a, is given by

$$se(a) = 0.78\, a/(N)^{1/2} \quad \text{approx.} \qquad (5.4)$$

where N is the sample size. The median value of N for the stations used (calculated as the mean of the middle half of the distribution) is 33 and the medians of a_M and a_G are 2.28 and 3.66 m/s respectively. Substituting these values in equation (5.4) we get

$$se(a_M) = 0.31 \text{ m/s} \ ; \ se(a_G) = 0.50 \text{ m/s} \qquad (5.5)$$

Eight values of a_M and eight of a_G lie within one standard error of the mean which is what would be expected if the data for the different stations constituted samples drawn from populations with the same slope parameter. Of the remainder, two values of a_M and one of a_G lie more than two standard errors from the mean which is somewhat more than would be expected. Nevertheless it is reasonable to conclude that there is no real variation in slope from station to station or, if there is, the pattern of the variation cannot be discerned above the "noise" of random sampling errors. It follows that more reliable results will be obtained if we replace the individually-estimated slope at each station by the median for all the stations. There is some evidence of correlation between the slope parameters of neighbouring stations e.g. Birr, Claremorris and Clones all have above-average slopes. However, this is only to be expected since annual maximum wind speeds at neighbouring stations are correlated (owing to the large spatial scale of the storms producing them).

With regard to the curvature of the extreme-value curves for the different stations, it is found that if the general extreme-value distribution is fitted to the samples using standard methods, the curvature parameters differ in sign from station to station and are generally small in magnitude (G O'Reilly, personal communication) i.e. the curves deviate little from straight lines. To obtain further information on this subject the sets of quartile means and highest extremes previously obtained for each station were adjusted by deducting the mean of the two middle quartiles (i.e. M'(2) in the case of the 10-minute means and G'(2) in the case of the gusts) from each value in the set. The median over the 11 long-record stations of each adjusted quartile mean and the adjusted highest and second-highest extremes were then calculated. When these are plotted against the values of y appropriate to a sample size of 33 (Figure 1) we have what may be regarded as an extreme-value curve for all stations taken together which gives the difference between the wind speed corresponding to any value of y and that corresponding to y = 0.40. The slopes of the straight lines on Figure 1 are the median slopes derived from Table III i.e. 2.28 m/s for the 10-minute means and 3.66 m/s for the gusts.

It may be seen from Figure 1 that both the extreme gusts and 10-minute means conform to the Type I distribution. The median highest extreme (corresponding to a return period of about 48 years) falls below the line but not significantly so. Thus, the extreme-wind distribution at any given station can be characterised by a single parameter (the intercept of the extreme-value line on a fixed value of y - in this case y = 0.40). The slope parameter is the same for all stations and the curvature parameter is zero.

Although, strictly speaking, wind speed has no upper bound, it is frequently argued (e.g. Tabony, 1983) that the highest extremes of all meteorological variables should follow the Type III extreme-value distribution. This implies that it would be unsafe to extrapolate an apparently Type I distribution much beyond the range of the observations. The fact that the highest wind extreme falls below the straight line is perhaps an indication that, if sufficiently long records were available, the slope of the extreme-value curve would be found to decrease at large values of y.

6. Mapping of 50-year Extreme Winds

The two kinds of data which have been analysed - maximum gust speeds and maximum 10-minute mean speeds corrected to standard surface roughness - are closely related by means of the gust ratio. It was considered that a more reliable estimate of the maximum gust with a given return period could be obtained by taking the arithmetic average of the gust speed and 1.53 times the mean speed with the same return period, 1.53 being the 10-minute gust ratio at a height of 10 metres over standard terrain. This was done and the resultant points are plotted in Figure 2. As might be expected, the differences between Fig. 2 and Fig. 1 (gusts) are quite small.

The question of how the extreme-value curve should be drawn for values of y greater than about 3.0 has been mentioned in Section 5. There are insufficient data to determine the position of the curve exactly. However, if it is accepted that the curve must tend towards a Type III one with increasing y, then the straight line on Fig. 2 may be regarded as a probable upper limit. A lower limit may be obtained by combining the adjusted annual maxima from the 11 long-record stations into one sample and plotting them as if they constituted a series of N = 11x33 = 363 annual maxima from a single station (Natural Environment Research Council, 1975). Since it has already been concluded that the data from the different stations are drawn from populations with the same slope and curvature parameters, this would be a valid method of extending the extreme-value curve if the data from neighbouring stations were independent. However, in the case of wind speed, there is significant correlation between stations. For example, the correlation coefficient between annual maximum gust speeds at Valentia Observatory and Clones over the period 1951-1987 is +0.59; these stations are located 321 km apart. This correlation reduces the effective number of independent observations and hence, if the highest extremes are plotted against values of y calculated on the basis that N = 363, they will give a curve which is too low. On Fig. 2, the dashed curve has been obtained in this way and may therefore be regarded as a probable lower limit on the position of the true extreme-value curve.

Taking an approximate mean between the upper and lower curves on Fig. 2, it is concluded that the 50-year gust (corresponding to $y = 3.90$) is 12.0 m/s higher than the gust for $y = 0.40$. Extreme value curves valid for 10-minute mean speeds may be derived from Fig. 2 by dividing the ordinates by 1.53.

In order to draw a map of 50-year maximum gust speeds it is only necessary to add 12.0 m/s to the mean of the two middle quartiles of the annual maximum series at each station and draw isotachs. However, since recorded gust speeds depend on the type of anemometer in use, it is preferable to work in terms of mean speeds. For Britain, Cook and Prior (1987) have used 50-year hourly-mean speed as their basic parameter. To convert from gust speeds to 60-minute mean speeds it is necessary to know the 60-minute gust ratio over standard terrain. Annual maximum mean speeds between fixed hours from 1962 to 1987 were available for each station and, from these and the corresponding maximum gusts, one-hour gust ratios were calculated. Making use of the result that maximum mean speeds between fixed hours average 98% of those over any 60-minute period (Logue, 1975) it was found that the 60-minute gust ratio (R_{60}) was related to the 10-minute gust ratio by

$$R_{60} = (1.085 \pm 0.007)R_{10} \qquad (6.1)$$

This implies that, over a surface of standard roughness, the 60-minute gust ratio for a Dines anemograph at a height of 10 m is 1.66.

In Table IV are given the estimated 60-minute mean speeds with a return period of 50 years for all stations. From these a map of 50-year, 60-minute mean speed was drawn (Figure 3). In order to obtain smooth isotachs the station values were adjusted by small amounts : the values actually drawn for are given in the second column of Table IV and the differences in the third column. One possible reason for the existence of such discrepancies is that some stations are overexposed and others underexposed owing to the topographic effect. For example, it has always been considered that Roche's Point and Clones are overexposed and Valentia Observatory underexposed. The correction to standard roughness compensates partially for over- or under-exposure but not entirely. Another reason for the discrepancies is simply random sampling error. According to Kimball (1949), the standard error of the position parameter in the Type I distribution is

$$\mathrm{se}(X_0) = 1.05\, a/(N)^{1/2} \quad \text{approx.} \qquad (6.2)$$

Substituting $N = 33$, $a = 2.15$ m/s (the slope parameter for 60-minute means), we find that the standard error is 0.39

m/s. In view of the methods used, the standard error of the 50-year mean speed should be of this order of magnitude. Therefore, discrepancies of the order of magnitude of those in Table IV might be expected to occur as the result of sampling effects.

It should, perhaps, be mentioned that, if 50-year, 60-minute means are estimated using data on 10-minute means only, without making use of the gust data, the values obtained are almost exactly the same. This can be verified by taking the values of M'(2) from Table III, using the slope parameter for 10-minute means (2.28 m/s) and dividing the 50-year, 10-minute means by 1.085 to get the 60-minute means.

It is also possible to estimate the 60-minute extremes from the data on maximum winds between fixed clock hours. This has the serious disadvantage that the record does not exist before 1962 and, in particular, the major storms of February 1957 and September 1961 are excluded. 60-minute means with a return period of 2 years estimated in this way average 0.3 m/s lower than those obtained from the gust and 10-minute mean data (using the full periods of record). In addition, the slope of the extreme-value line comes out as 1.90 m/s instead of 2.15 m/s, resulting in a further reduction of 0.9 m/s in the 50-year estimates.

7. Comparison with previous results

If the values given in Figure 3 are multiplied by 1.66 a map of 50-year maximum gust speed (as recorded by a Dines anemograph) is obtained. If this is compared with Figure 2 of Logue (1975) it will be seen that the estimated extreme gust speeds have decreased by about 2 m/s. The most important reason for this is the lack of major storms in the period 1975-1987 as compared to the previous period. Of the extreme wind events with return periods exceeding 10 years at individual stations over the period 1953-1987, only 20% occurred after 1974. As a result of this, the estimates of the 2-year maximum gust for the individual stations have fallen by amounts averaging 0.6 m/s from the 1975 estimates, the overall slope parameter for gusts has fallen slightly and the deviation of the highest extreme from the straight-line graph, noted in Section 5, has appeared. Another reason for the decrease in the estimates of the 50-year gust is the fact that, for the 1975 estimates, the "effective heights" of the anemometers were used whereas, in the present study, actual heights are used and the gust data were multiplied by 0.98 to reduce them to the standard height.

Cook and Prior (1987) have prepared a map of 50-year hourly-mean wind speed for Great Britain and the north of Ireland which shows a value of less than 26 m/s along the Donegal coast as compared with 30 m/s in Fig. 3. This rather large discrepancy is probably due to the different methods of analysis used. Cook and Prior used data from a period of only 11 years, analysed the body of the wind frequency distribution rather than the annual maximum series and concluded that the square of the wind speed, rather than the wind speed itself, followed a Type I extreme value distribution. The method of correcting for surface roughness and topographic effects was also different. Cook and Prior's estimates are substantially lower than the earlier British results of Hardman, Helliwell and Hopkins (1973).

8. The Case of Rosslare

Rosslare is the only station at which a significant number of annual maximum 10-minute mean winds blow from the north-easterly sector. The station is situated in the south-east corner of Ireland on a north-eastward-facing coast. Well over half the 10-minute annual maxima blow from the seaward sector and have an average gust ratio of 1.39; most of the remainder are southerly or southwesterly in direction and have a gust ratio averaging 1.61. Because of the difference in gust ratio the vast majority of annual maximum gusts are associated with winds from the landward sector.

In the extreme-value analysis, all winds from the seaward sector were excluded thus enabling the single gust ratio 1.61 to be assigned to the station. The principal justification for this is that if the winds were individually corrected to standard roughness the seaward-sector winds would be greatly reduced because of their low gust ratio and would drop out of the analysis anyway. Another reason is that the two sets of winds appear to have different characteristics even after correction and that to combine them together would give an inhomogeneous sample. Thus the corrected slope parameters for the seaward and landward sectors are 1.46 and 2.16 m/s respectively. These may be compared with the all-station median slope of 2.28 m/s with a standard error of 0.31 m/s, though the latter values may not be strictly applicable to data drawn from a restricted range of directions.

From the point of view of synoptic meteorology, strong north-easterly winds are very different from strong southerlies or westerlies since they are located to the left of the track of the depression and are normally opposite in direction to the "thermal wind". Consequently, the rate of increase of speed with height is much less than in the case of south-westerlies leading to lower gust ratios (Smith and Carson, 1974). The exclusion of the north-easterlies from the Rosslare data is therefore likely to result in a more homogeneous sample and in more reliable results. It is interesting that if all the data are lumped together and Rosslare is treated like the other stations, the predicted 50-year 10-minute mean speed (27.2 m/s) is lower than the value obtained by excluding the winds from the seaward sector (29.2 m/s).

9. Use of Figure 3

Figure 3 gives the maximum 60-minute mean wind speed with a return period of 50 years valid for a height of 10 m above level country with a standard roughness corresponding to $R_{10} = 1.50$. R_{10} is the average ratio of the maximum gust speed to the maximum 10-minute mean speed measured at a height of 12 m by a Dines anemograph. $R_{10} = 1.50$ is typical of open country without hedges or other obstructions e.g. moorland or an airfield. Also, it is estimated that it corresponds to a "roughness length" of about 0.1 m although the estimate must be regarded as rather tentative owing to uncertainty about the gust response of the Dines anemograph in actual operation.

Maximum 60-minute mean speeds with return periods other than 50 years over standard terrain may be obtained by adding the amounts given in Table V to the 50-year value. Maximum Dines gust speeds at 10 m over standard terrain may be got by multiplying the 60-minute mean speed by 1.66.

Extremes over a level surface of non-standard roughness may easily be obtained if the value of R_{10} for the site in question is known. This requires that an anemometer be located at the site. A long record is not necessary because a reliable value of R_{10} can be calculated from a reasonably large number of, say, daily maxima recorded during strong winds.

If the anemometer used is not a Dines anemograph the gust ratio will require to be adjusted to allow for the difference in gust response of the two instruments. Also, the gust ratio must be adjusted to refer to a height of 12 m. Given R_{10}, the value of b_M may be calculated from the first of equations (4.3). The map value should then be divided by b_M to give the 50-year 60-minute mean over the actual site. If a return period other than 50 years is required, the Table V correction should be applied before correcting for roughness. Gust speeds may be adjusted to standard roughness by dividing by b_G which may be obtained from the second of equations (4.3).

If anemometer data for the site are not available, R_{10} may be estimated from a visual assessment of the site roughness using the roughness-category descriptions of Davenport (1960). The average roughness category within a radius of about 2 km of the site in the direction sector 180-320° should be evaluated. Roughness category can then be converted to the corresponding R_{10} by means of Table VI which is based on regression of R_{10} against roughness category for the Irish stations. Values of R_{10} obtained in this way, are of course, somewhat less reliable than those obtained by direct measurement.

Figure 3 is not valid for sites with pronounced exposure effects e.g. those on top of hills. The estimation of extreme wind speeds for such locations is beyond the scope of this study.

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References

Caton, P.G.F., 1977: Standardised maps of hourly mean wind speed over the United Kingdom and some implications regarding wind speed profiles. Procedings, fourth international conference on wind effects on buildings and structures (Heathrow Airport, 1975), Cambridge University Press, Cambridge, England, 7-21.

Cook, N.J. and M.J. Prior, 1987: Extreme wind climate of the United Kingdom. *J. Wind Eng. Ind. Aerodyn., 26,* 371-389.

Davenport, A.G., 1960: Rationale for determining design wind velocities. *J. Struct. Div., Proc. Amer. Soc. Civ. Engrs., 86,* No. ST 5, 39-68.

Fisher, R.A. and Tippett, L.H.C., 1928: Limiting forms of the frequency distribution of the largest or smallest members of a sample. *Proc. Cambridge Philos. Soc., 24,* 180-190.

Hardman, C.E., N.C. Helliwell and J.S. Hopkins, 1973: Extreme winds over the United Kingdom for periods ending 1971. *Climatol. Memo. 50A,* Meteorological Office, Bracknell.

Jenkinson, A.F., 1955: The frequency distribution of the annual maximum (or minimum) values of meteorological elements. *Q.J.R. Met. Soc., 81,* 158-171.

Jenkinson, A.F., 1969: Statistics of extremes. In Estimation of maximum floods, *WMO Tech Note No. 98,* Chapter 5.

Kimball, B.F., 1949: An approximation to the sampling variances of an estimated maximum value of given frequency based on the fit of a doubly exponential distribution of maximum values. *Annals of Math. Stats., 20,* 110-113.

Logue, J.J., 1975: Extreme wind speeds in Ireland for periods ending in 1974. *Tech. Note No. 41,* Meteorological Service, Dublin.

Logue, J.J., 1986: Comparison of wind speeds recorded simultaneously by a pressure-tube anemograph and a cup-generator anemograph. *Met. Mag., 115,* 178-185.

Natural Environment Research Council, 1975: Flood Studies Report, Vol. I, Chapter 2, London.

Smith, F.B. and D.J. Carson, 1974: A scheme for deriving day-time boundary layer wind profiles. *Met. Mag., 103,* 241-255.

Tabony, R.C., 1983: Extreme value analysis in meteorology. *Met. Mag., 112,* 77-98.

Wieringa, J., 1976: An objective exposure correction method for average wind speeds measured at a sheltered location. *Q.J.R. Met. Soc., 102,* 241-253.

Table I. Locations,periods of record and 10-minute gust ratios of stations used.

Station name	Grid Ref.	Period of record	R_{10}
Belmullet	F 691 329	1957-1987	1.51
Birr	N 074 044	1955-1987	1.76
Casement Aerodrome	O 041 295	1967-1987	1.47
Claremorris	M 345 739	1950-1987	1.61
Clones	H 500 263	1951-1987	1.65
Cork Airport	W 665 662	1962-1987	1.53
Dublin Airport	O 169 434	1946-1987	1.53
Galway	M 327 256	1979-1987	1.71
Kilkenny	S 494 574	1958-1987	1.70
Malin Head	C 419 586	1956-1987	1.50
Mullingar	N 427 527	1958-1973	1.58
Mullingar II	N 423 543	1974-1987	1.75
Roche's Point	W 831 601	1956-1987	1.42
Rosslare	T 137 122	1957-1987	1.61
Shannon Airport	R 379 603	1946-1975	1.49
Valentia Observatory	V 457 788	1940-1987	1.62

Table II. Ratios of monthly maximum wind speeds recorded at Shannon Airport and three neighbouring stations over the periods 1965-1974 and 1983-1987.

	1965-1974		**1983-1987**		**Reduction (%)**	
	means	*gusts*	*means*	*gusts*	*means*	*gusts*
Shannon/Valentia	1.045	0.948	0.906	0.903	13.3	4.7
Shannon/Kilkenny	1.339	1.141	1.146	1.096	14.4	3.9
Shannon/Claremorris	1.151	1.035	1.018	0.983	11.6	5.0

Table III. Maximum 10-minute mean and gust speeds (m/s) with return period 2 years and corresponding slope parameters for various stations. *(For definition of symbols, see text)*

Station Name	**M(2)**	**b'_M**	**M'(2)**	**a_M**	**G(2)**	**b'_G**	**G'(2)**	**a_G**
Belmullet	26.1	0.97	25.3	2.37	39.6	0.98	39.0	3.16
Birr	17.9	1.21	21.7	2.59	30.7	1.05	32.3	4.30
Claremorris	20.6	1.07	22.0	2.96	33.0	1.01	33.5	4.04
Clones	20.6	1.11	22.8	2.43	33.6	1.03	34.5	4.38
Dublin Apt.	20.8	0.98	20.4	1.65	31.8	0.99	31.4	2.44
Kilkenny	17.5	1.15	20.2	2.20	29.3	1.04	30.4	3.84
Malin Head	26.3	0.96	25.3	2.30	39.4	0.98	38.6	3.24
Roche's Point	25.5	0.89	22.6	1.94	35.9	0.95	34.2	3.56
Rosslare	20.2	1.06	21.5	2.16	32.2	1.01	32.6	3.87
Shannon Apt.	23.1	0.95	21.9	2.39	34.4	0.98	33.6	3.69
Valentia Obsy.	21.8	1.08	23.4	2.12	34.8	1.02	35.4	3.33

Table IV. Estimated 50-year maximum 60-minute mean speed (m/s) for each station, values actually drawn for in preparing Fig. 3 and differences. *(Data valid for a height of 10m above terrain of standard roughness)*

Station name	Estimated	Drawn for	Difference
Belmullet	30.7	30.1	-0.6
Birr	27.0	26.5	-0.5
Casement Aerodrome	27.1	26.3	-0.8
Claremorris	27.5	28.0	+0.5
Clones	28.1	27.1	-1.0
Cork Airport	26.8	27.0	+0.2
Dublin Airport	26.1	26.3	+0.2
Galway	28.2	27.8	-0.4
Kilkenny	25.7	26.2	+0.5
Malin Head	30.5	29.9	-0.6
Mullingar	26.4	26.3	-0.1
Mullingar II	26.2	26.3	+0.1
Roche's Point	28.0	26.9	-1.1
Rosslare	27.0	26.9	-0.1
Shannon Airport	27.5	27.3	-0.2
Valentia Observatory	28.7	29.0	+0.3

Table V. Differences between maximum 60-minute mean speeds of various return periods and the 50-year return-period value.
(Data refer to a height of 10m above level terrain of standard roughness)

Return period (years)	**5**	**10**	**20**	**100**
Difference (m/s)	-4.8	-3.3	-1.7	+1.3

Table VI. Values of the 10-minute gust ratio R_{10} corresponding to the surface roughness categories of Davenport (1960).

Category	**2**	**3**	**4**	**5**	**6**	**7**
R_{10}	1.41	1.49	1.56	1.64	1.72	1.80

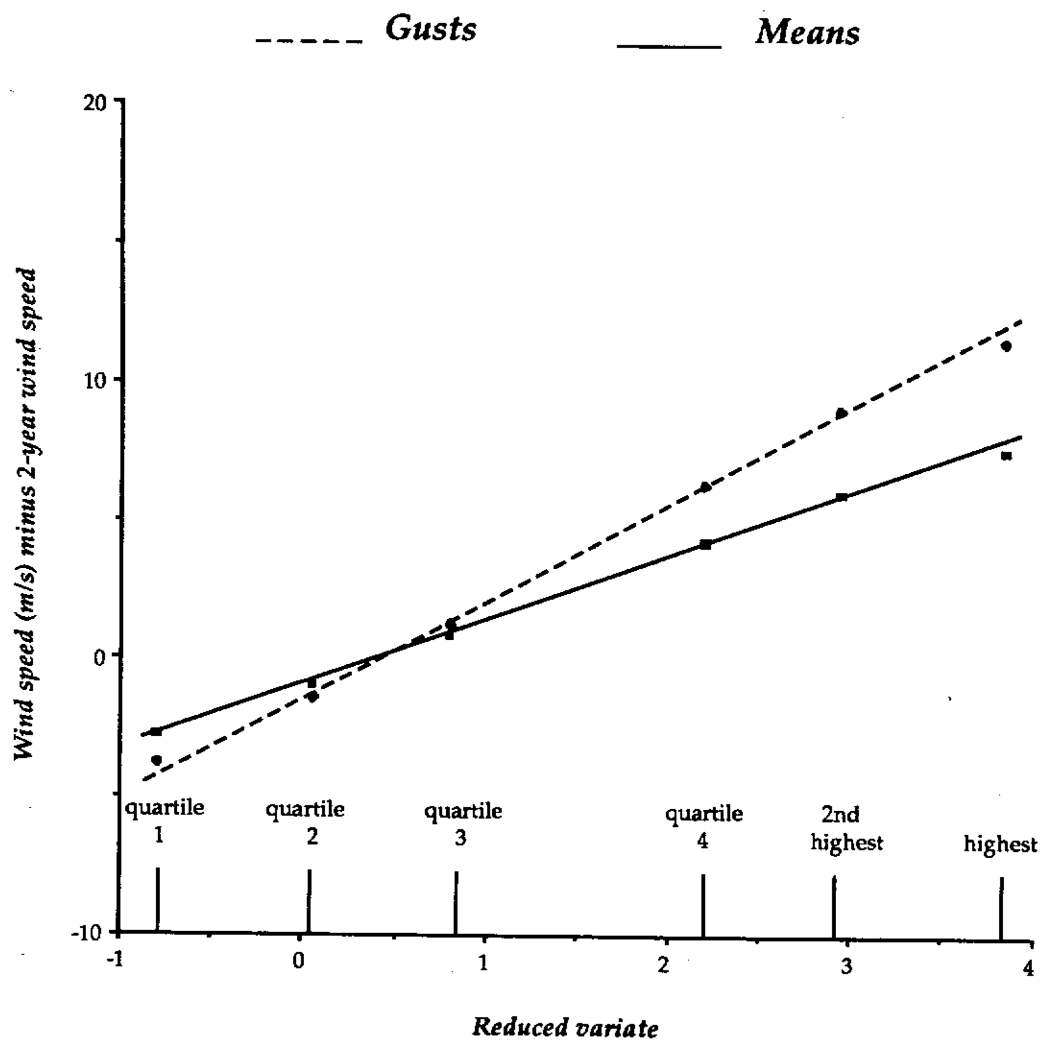

Fig. 1 Maximum gust and 10-minute mean speeds (minus the 2-year return-period values) as functions of the reduced variate. (Medians of data from 11 stations corrected to standard roughness.)

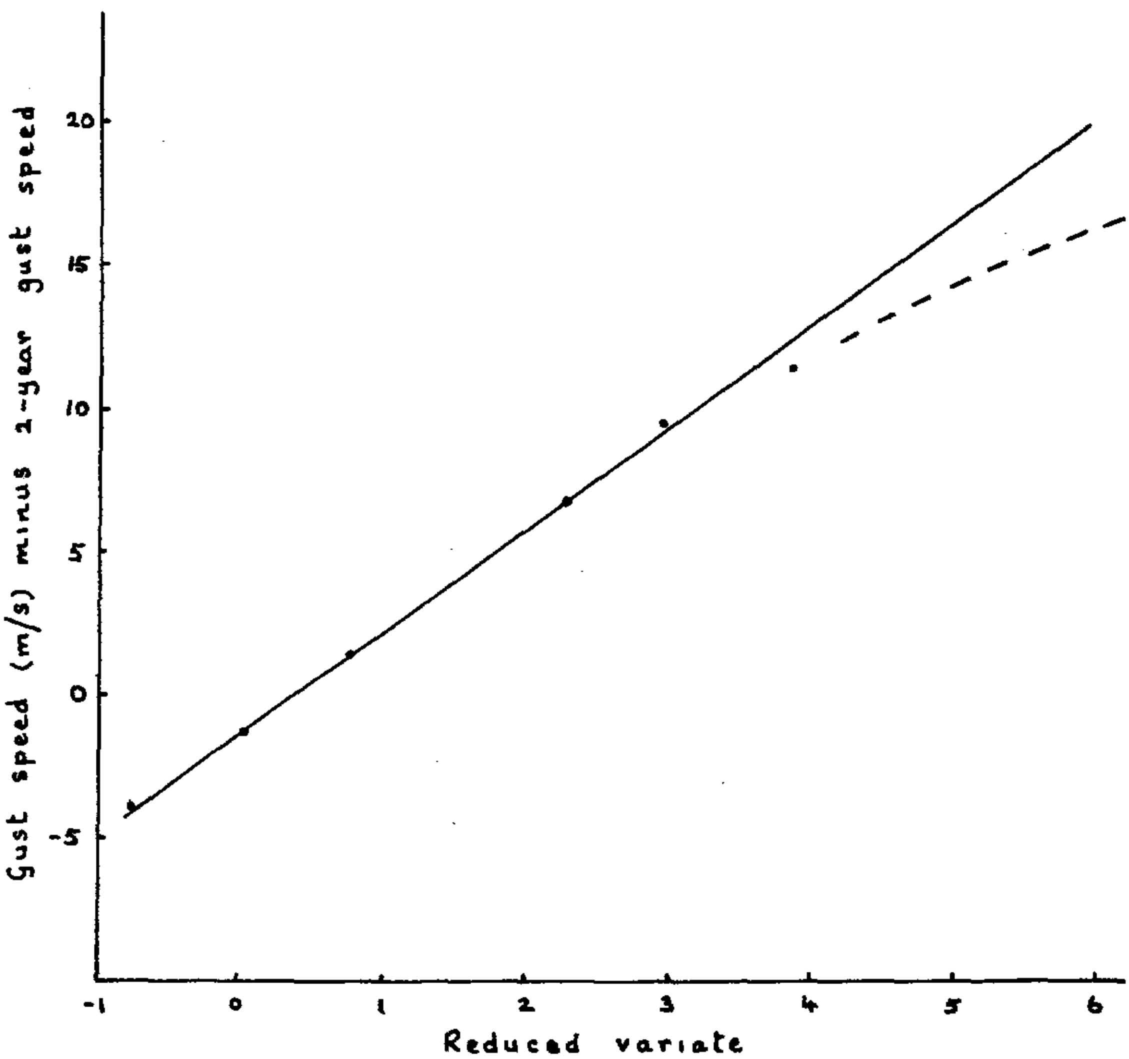

Fig. 2. Estimated difference between the maximum gust speed and the 2-year gust speed as a function of the reduced variate. Valid for a height of 10 m above a surface of standard roughness. See text for full explanation.

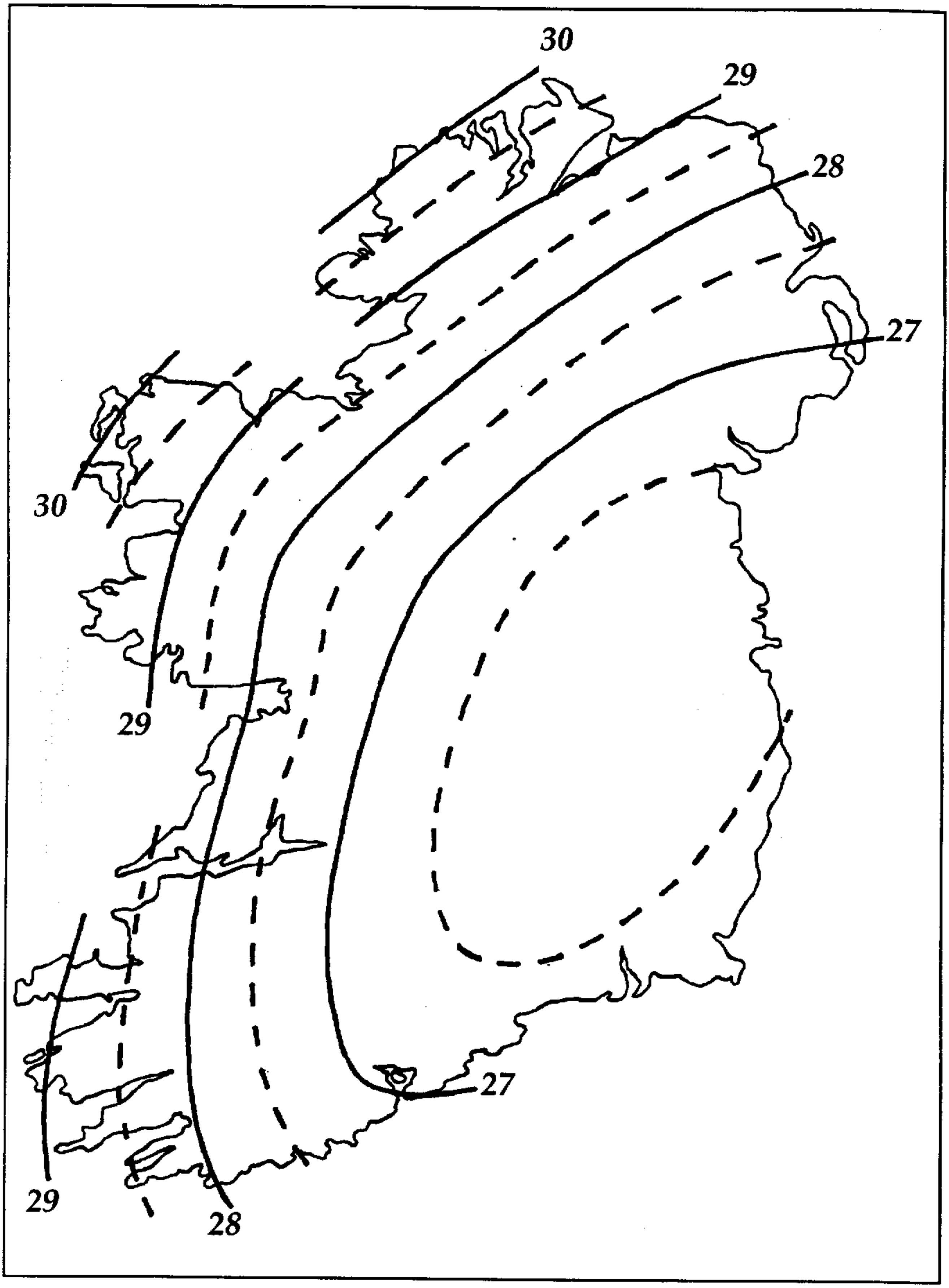

Fig. 3 Maximum 60-minute mean wind speed (m/s) with return period 50 years.