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1980-2010 variability in UK surface wind climate

Nick Earl[1], Steve Dorling[1], Richard Hewston[2], Roland von Glasow[1]

[1] School of Environmental Sciences, University of East Anglia, Norwich, UK

[2] Department of Meteorology, University of Hawaii at Manoa, Honolulu, Hawaii, USA

[1]*Corresponding author address*: Nick Earl, School of Environmental Sciences, University of East Anglia, Norwich, Norwich Research Park, Norwich, NR4 7TJ, UK
E-mail: n.earl@uea.ac.uk

Abstract

The climate of the north-east Atlantic region comprises substantial decadal variability in storminess. It also exhibits strong inter- and intra-annual variability in extreme high and low windspeed episodes. Here we quantify and discuss causes of the variability seen in the UK wind climate over the recent period 1980-2010. We consider variations in UK hourly windspeeds, in daily maximum gust speeds and in associated wind direction measurements, made at standard 10m height, recorded across a network of 40 stations. The Weibull distribution is shown to generally provide a good fit to the hourly wind data, albeit with shape parameter, k, spatially varying from 1.4-2.1, highlighting that the commonly assumed k=2 Rayleigh distribution is not universal. We find that the 10th and 50th percentile HM windspeeds have declined significantly over this specific period, whilst still incorporating a peak in the early 1990s. Our analyses place the particularly 'low wind' year of 2010 into longer term context and our findings are compared with other recent international studies. Wind variability is also quantified and discussed in terms of variations in the exceedence of key windspeed thresholds of relevance to the insurance and wind energy industries. Associated inter-annual variability in energy density and potential wind power output of the order of ±20% around the mean is revealed. While 40% of network average winds are in the SW quadrant, 51% of energy in the wind is associated with this sector. Our findings are discussed in the context of current existing challenges to improve predictability in the Euro-Atlantic sector over all timescales.

1. Introduction

Located in one of the most common regions for atmospheric blocking, while also situated towards the end point of a major mid-latitude storm track, the UK has one of the most variable wind climates and NW Europe is a challenging region for prediction on all time scales (Barriopedro et al. 2006 2008; Dacre and Gray 2009; Woollings 2010). Regional wind climate variability in the UK is large, governed by latitude (proximity to storm track), altitude and type of fetch (the UK has an exceptionally long coastline). Seasons dominated by blocking or cyclonic weather types, especially winter, can strongly skew the magnitude of annual insured losses (Munich Re 2002), as well as have profound effects on the variability of wind power generated by the expanding UK wind energy sector (Sinden 2007).

The cold European winter of 2009-10 and the extreme cold of December 2010 have prompted much discussion about long-term climate variations and their possible impacts. However, Cattiaux et al. (2010) show that the cold European surface temperature anomaly of up to 6˚C for winter 2009-10 was in fact not as great as might have been expected given the associated record-breaking North Atlantic Oscillation (NAO) and blocking frequency indices. These authors concluded that the event was a cold extreme which was not in any way inconsistent with an otherwise generally warming climate. Focusing on predictability at the monthly, seasonal and decadal timescale, many forcing agents are thought to modulate European climate, for example sea surface temperatures, stratospheric circulation and solar variability (Rodwell et al. 1999; Lockwood et al. 2010 2011; Woollings et al. 2010). Regional responses also arise from the dynamical reaction of the climate system to this forcing (Woollings 2010; Jung et al. 2011) and internal atmospheric dynamics can be an important source of low-frequency atmospheric inter-annual variability. Solar activity in 2009/10 fell to values unknown since the start of the 20th century and Lockwood et al. (2010), linking this to the occurrence of recent cold European winter months, estimate an 8% chance that the decline, which began around 1985, could continue to Maunder minimum levels within 50 years, from the previous grand solar maximum. On the other hand ECMWF experiments (Jung et al. 2011), testing the sensitivity to reduced ultra-violet radiation of the onset of the cold 2009-10 European winter, show that the unusually low solar activity contributed little, if any, to the observed NAO anomaly. Much research is ongoing to improve our predictive capability in Europe.

In Europe, windstorms remain the most economically significant weather peril when averaging over multiple years. The winter storms of the early 1990s had some dramatic effects on the UK, the winter of 1989-90 being one of the most damaging on record, exemplified by windstorm Daria on 25th January (McCallum 1990). The storm tracked across a large swath of England and Wales, causing widespread damage amounting to £1.9bn (equivalent to £3.2bn in 2010 values) of UK insured losses (Munich Re 2002). A second storm, Vivian, buffeted the UK between 26th and 28th February 1990 and contributed to UK weather related property losses that year reaching their highest mark on record. In the winter of 1991-1992 the New Year’s Day Storm affected northern Scotland and (far more severely) Norway (Gronas 1995), producing stronger UK surface winds than Daria and Vivian, though causing less UK damage due to reduced vulnerability to insurance losses in the affected regions. Meanwhile winter storm Xynthia in February 2010 caused insured losses totaling almost $3bn in Germany, France and

Spain, representing the world's 3rd most costly catastrophe of that year (Swiss Re 2011), more costly than any 2010 North Atlantic hurricane. Indeed total European windstorm damage is considerable, equivalent to that of worldwide hurricanes when averaged over longer time scales (Malmquist 1999). Total annual losses attributed to windstorms depend, for example, on the precise track and intensities of storms, the relative vulnerability of the affected areas, whether trees are in leaf or not and the relative dryness or wetness of the ground at the time of windstorm passage (Hewston and Dorling 2011).

Wang et al. (2009) demonstrated that storminess in the North-Atlantic-European region, based on atmospheric sea-level pressure gradients, undergoes substantial decadal and longer time scale fluctuations and that these changes have a seasonality and regionality to them. In particular, these authors showed that winter storminess reached an unprecedented maximum in the early 1990s in the North Sea and showed a steady increase in the north-eastern part of the North-Atlantic-European region, significantly correlated with variability in the NAO index. The link to the NAO is found in all seasons except autumn. As the NAO swings from one phase to the other, large changes to windstorm intensity and track and to mean windspeed and direction are observed over the Atlantic (Hurrel et al. 2003). Both Atkinson et al. (2006), analyzing the period 1990-2005, and Boccard (2009), 1979–2007, showed that the NAO is a good approximation for synoptic weather type indices such as Grosswetterlagen (Hess and Brezowsky 1952; James 2007) and the Jenkinson-Collison weather type classification (Jenkinson and Collinson 1977; Jones et al. 1993) and for wind indices in Northern Europe over the respective periods. A decrease in post-1990 northern European windiness is clearly revealed in these studies. By considering the longer term Grosswetterlagen and Jenkinson variability through the 20th century, these authors concluded that care is needed in selecting the most appropriate long-term period on which to base wind energy investment decisions and that access to reliable and longer term windspeed measurements is highly desirable. Recent industry discussion of the low-wind year of 2010 requires further supporting analysis and discussion of the wider context. As greater reliance on wind power for the UK's electricity generation needs increases, so will the magnitude of risk due to exposure of the performance of the turbines to climate change (Harrison et al. 2008).

Both the wind energy and insurance industries are sensitive to windspeed distributions. The Weibull distribution function has become widely used in meteorology to estimate how observed windspeeds tend to vary around their mean at sites where only a long term average is known. Originally used to describe the size distribution of particles, the Weibull distribution has numerous applications, including in general insurance to model reinsurance claim sizes (Kremer 1998). The use and importance of the Weibull distribution has grown immensely in the wind power industry and has been used to help site many thousands of wind turbines (Petersen et al. 1998; see section 2c).

Numerous authors have also been considering the possible impact of climate change over the 21st century on the wind climate of north-west Europe, in the context of the decadal variability seen over the last century (Brown et al. 2009; Ulbrich et al. 2009; Pryor et al. 2011). While this is clearly a complex question, one point which models do seem to currently agree on for the future climate of the region is an increasing frequency of intense cyclones in the region of the British Isles (Ulbrich et al. 2009) and increased winter storminess (Scaife et al. 2011).

Hewston (2006) and Hewston and Dorling (2011) introduced for the first time an hourly windspeed database for a network of 43 UK surface stations, extending through the period 1980-2005 and providing good spatial coverage. Based on this they presented a climatology of the strongest wind gusts in the context of insurance weather perils. These authors presented evidence of an apparent downward trend in the strongest wind gusts over the UK since the early 1990s. In addition, Vautard et al. (2010), also using surface station data, reported that mean windspeeds have also been declining over the same period across most areas of the world, including Europe, a phenomenon which they termed "global stilling" and which they linked to changes in land-based biomass. However, while a decline was also found in Australian 2m windspeed observations by Troccoli et al. (2012), their equivalent 10m measurements actually showed a positive tendency.

Here we build on the earlier UK-focused work of Hewston and Dorling (2011) described above by also considering mean windspeeds in the UK. The objectives of this paper are to

- Update analysis of temporal variability to 2010 and extend the quality control of the Hewston and Dorling database.
- Deepen understanding of each of the stations in the network by investigating applicability of the Weibull distribution across locations, interpreting the results from a topographic perspective.
- Analyze variations of exceedences of a wider range of windspeed thresholds of interest to both the insurance and wind energy sectors, compare these with the

larger-scale findings of Vautard et al. (2010) and discuss them in the context of key features of the regional-scale atmospheric circulation.

- Quantify the impact of the observed spatial and temporal variations in wind power on output from a synthetic network of 3.6MW wind turbines, one located at each of the monitoring stations.

The results presented in this paper include analysis and discussion of windspeed threshold exceedence frequencies, the proportion of time that the hourly winds or daily gust speeds are above a set of specific speeds, at individual sites and on average across the network of 40 (39) hourly windspeed (gust speed) sites. This follows the approach adopted by Vautard et al. (2010) but provides detail for the UK rather than a more general continental or global scale. The further novelty of the study presented here comes from using hourly data, rather than 6-hourly, by considering a high spatial density of stations in the UK, by incorporating gusts and wind directions with mean windspeeds and by including the anomalous conditions of 2010. Furthermore we present the implications of a variable wind climate for wind energy density and wind power output, building on the work of previous UK wind resource studies (e.g. Sinden 2007).

2. Data, methods and tools

a. Observed Wind Data

This study extends the 1980-2005 database described by Hewston and Dorling (2011) of hourly surface windspeed observations (measured at the standard 10m height) from UK Meteorological Office (UKMO) stations across the UK, to the end of 2010, incorporating the anomalous European winter months in 2010. Wind data for all 31 years were extracted from the MIDAS (Met Office Integrated Data Archive System) Land Surface Observations Station database (UKMO 2011), archived at the British Atmospheric Data Centre (BADC). Unfortunately, three of the 43 sites used in the original network (Coltishall, Durham and St Mawgan) have been discontinued since 2005 and have been removed from the database. The hourly mean (10-minute average, recorded from 20 to 10 minutes prior to the hour in question; hereafter HM) windspeeds and daily maximum gust speeds (DMGS; maximum 3 second average), with their associated wind directions, are extracted as described in detail by Hewston and Dorling (2011). The site at Ringway (Manchester Airport) no longer records gusts, only mean windspeeds, leaving a 31 year (1980–2010) UK network of 40 sites for HM windspeeds and 39 sites for DMGSs whose geographical locations are displayed in Fig.1. Hewston and Dorling’s (2011) primary focus was the DMGSs, whereas this study makes more use of the HM windspeeds. The 40 sites used in this study have on average 98.5% HM data completeness, substantially higher than previous studies using HM MIDAS data (e.g Sinden 2007, 77% HM data completeness). All of the sites used in this study meet the stringent UKMO site exposure requirements (available at http://badc.nerc.ac.uk/data/ukmo-midas/ukmo_guide.html). Since the sites in this study possess such a wide variety of topographies and therefore wind regimes, it is thought that when averaged together they give a good representation of the UK wind regime as a whole.

b. Data quality

The windspeed and direction data has undergone rigorous quality control, with checks on the equipment and raw data performed at the UKMO and the BADC. Further information on quality control performed on the MIDAS database and other possible sources of error is available at the BADC website (http://badc.nerc.ac.uk/data/ukmo-midas/ukmo_guide.html) (UKMO 2011) and in Hewston and Dorling (2011). Once downloaded, a series of steps were followed to further test the reliability of the information, removing duplicate data, detecting missing values and checking data consistency. Analysis of Weibull distributions, discussed below, was also helpful in highlighting potential anomalies. The MIDAS data does not normally include an HM value of 1 knot (0.515 ms^{-1}) and often uses a value of 2 knots (1.03 ms^{-1}), when the wind vane indicates gusty conditions (BADC website), to represent a mean speed of 0 or 1 knot. This leads to an over-representation of HM wind values of 2 knots and an under-representation of 0 and especially 1 knot at many sites. We have, however, made no attempt to re-distribute these extra 2kt values into neighboring bins.

c. Weibull distribution

The Weibull distribution came to prominence in meteorology during the 1970s (Takle and Brown 1977). As a two-parameter density function it can be calculated as

$$P(U) = 1 - \exp\left[-\left(\frac{U}{A}\right)^k\right] \qquad (1)$$

Where P(U) is the probability distribution of windspeed U, A is the Weibull scale parameter and k is the shape parameter (Pryor and Barthelmie 2010). For a narrow distribution, with a marked peak, k will take a relatively high value. Numerous statistical methods have been proposed to calculate Weibull scale and shape parameters (Pryor et al. 2004), Seguro and Lambert (2000) recommending the maximum likelihood method when windspeed data is available in a time series format. When the Weibull shape parameter has a value of 2, it is known as the Rayleigh distribution, and this is often used as the standard for wind turbine manufacturers' performance figures (Weisser 2003). The Weibull distribution, however, has been found to produce a better fit to observed windspeeds than the simpler Rayleigh distribution (Celic 2004).

Nevertheless it is problematic fitting a Weibull distribution at low windspeeds, as highlighted by Justus et al. (1976) who assessed potential output from wind-powered generators. On the other hand, it is generally accepted that sites with regular moderate or high windspeeds can almost always be approximated by the Weibull distribution (Petersen et al.1998), Jamil et al. (1995) estimating this moderate windspeed threshold to be 12 ms^{-1} or higher. It would therefore be expected that a Weibull distribution would more realistically simulate a DMGS distribution than an HM distribution.

Both the 31 year UK HM windspeed and DMGS data can be used to assess whether the Weibull distribution function is a good fit to these observations. The HM data contains periods of low windspeeds (including many calm hours/periods) which have been highlighted as not being well represented by the Weibull distribution. The DMGS set however, by definition, should be more Weibull compatible. This study examines the capability of the Weibull distribution to represent the variance of land-based wind monitoring sites, by calculating the 31-year shape parameter at each site for both HM windspeed and DMGSs. This also reveals how well the commonly used Rayleigh distribution approximates the sites' windspeed variance. There have been numerous methods and modifications to the Weibull distribution to deal with zero and low windspeed values, however it is not the intention here to assess which of these best represents the DMGS and HM datasets, therefore this study simply uses the commonly adopted basic maximum likelihood method (Seguro and Lambert 2000). It must be noted that the basic method used is unable to accommodate calm conditions, although the approach can be modified to account for these (Wilks 1990). Tests were carried out assigning a negligible value (0.00001 ms^{-1}) to reports of 0 ms^{-1}, however the results for HM windspeeds (not shown) displayed strong positively skewed, poorly fitting Weibull distributions and k values as low as 0.3.

d. Wind turbine power

The 31 year UK HM windspeed database enables an assessment of the potential impact of spatial and temporal variations in the UK wind regime on the wind energy sector. Power generated is proportional to the cube of the windspeed and the variability of the wind around the mean is therefore critical to the amount of power produced. Wind power generation potential can be quantified using the concept of energy density (aka power density)

$$E = \frac{1}{2}\rho U^3 \qquad (2)$$

where E is energy density (W m^{-2}), ρ is air density (kg m^{-3}) and U is the hub-height windspeed (ms^{-1}) (Pryor 2011). For this study, the energy density for each of the 40 HM observation sites is calculated to first-order with equation (2), using an air density of 1.225 kg m^{-3} (15˚C at sea level) and assuming negligible density variations (Pryor et al. 2004; Jamil et al. 1995), ignoring altitude and temperature variability between sites (which could theoretically lead up to an associated ±8% air density variation compared to the average value adopted).

A limitation of the applicability of the energy density quantity is that even the most modern wind turbines cannot harvest power below and above specific windspeed thresholds (Table 1). Outside this range, the windspeed is either too low to turn the blades or too high, forcing the turbine to be shut down in order to prevent damage (AEA 2011). Based purely on the cubic relationship between windspeed and power generation, energy density returns an overestimation of wind turbine performance, especially during stormy periods such as the early 1990s. For comparison, another method is also used to quantify wind turbine performance to second-order, including cut-in and cut-out windspeed thresholds and sensitivity to windspeed variations within that range (Oswald et al. 2008). For each of the 40 HM observation sites, a synthetic state of the art 3.6MW wind turbine is considered for the duration of the recorded observations and the 10m winds are adjusted to the typical hub height of 100m using the power law approximation, ignoring the important effect of variable atmospheric stability and surface roughness (z_0) for this simple estimate (Petersen et al. 1998; Motta et al. 2005).

$$\frac{U(z_1)}{U(z_2)} = \left(\frac{z_1}{z_2}\right)^p \qquad (3)$$

Where $U(z_1)$ and $U(z_2)$ are the windspeeds at heights z_1 and z_2, respectively, and p is the power law exponent taken to be equal to 0.14 (Petersen et al. 1998) (giving $U_{100} = U_{10}$ x 1.38) . The value of p typically ranges from 0.05 (very unstable atmosphere with z_0=0.01m) to 0.69 (stable atmosphere with z_0=3m), the adopted value 0.14 representing a neutral atmosphere for a small z_0 (0.01-0.1m) and a typical value for areas with variable stability (Irwin 1979). Once the height conversion has been performed, the power output is then estimated for each hour at each site based on the power output curve of the 3.6MW wind turbine (Table 1). Energy density and power output are calculated for each site and averaged across the network, weighting for any missing data, and the observed temporal variability is discussed.

e. North Atlantic Oscillation

The HM and DMGS 1980-2010 windspeed database presents an excellent opportunity to investigate the relationship between the NAO index and UK windspeeds and assess the impacts of the phase changes of the NAO on land based wind measurements and wind energy output estimates. This furthers the work of Cheng et al. (2011) who used satellite observations to investigate inter-annual variability of high wind occurrence in the North Atlantic over the period 1988-2009. The particular NAO index used for this study is based on normalized sea-level pressure observations made at Gibraltar and Reykjavik in Iceland, with homogeneous records that date back to the 1820s, allowing for a long term monthly NAO index (Jones et al. 1997) [available on the University of East Anglia's Climatic Research Unit (CRU) website: http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm; hereafter CRU website]. There are numerous methods to calculate the NAO index, however this monthly index has the advantage of the longest record, helping place the 1980-2010 UK HM wind variability into context (see http://www.cru.uea.ac.uk/cru/info/nao/ for more detail).

3. Results and discussion

a. Inter-annual variability

Fig. 2 shows a timeseries of annual average 10m HM windspeeds in the form of the 10th, 50th and 90th percentiles, quantifying the inter-site variability. The 10th and 50th percentile 5-year moving averages exhibit peaks in the early 1980s and early 1990s, with a general statistically significant decrease visible over the full 1980-2010 period (confidence levels of 99.9% and 95% for the 10th and 50th percentiles respectively; using ordinary least squared linear regression analysis). The 90th percentile shows a much more pronounced early 1990s peak, without the general decline seen in the 10th and 50th percentiles, but with a statistically significant decrease since 1990 (at the 99% level). The 10th and 50th percentiles show that in the mid-late 2000s windspeeds began to recover, however the anomalously low winds of 2010, discussed in detail below, are at odds with this recovery. Fig. 2 highlights large year to year variability in windspeeds for all percentiles, for example the median varying from 4.3-5.3 ms^{-1}. Our results and those of other authors highlight the presence of strong decadal variability and we include linear trend analyses here only for completeness. Behind these results from the network as a whole, it should be noted that 32 of the 40 sites display a decrease in annual mean windspeed over the full period, 15 of which are statistically significant (95% confidence level), while 8 show an increase, 2 of which are statistically significant. There is no clear geographical pattern to the distribution of stations exhibiting statistically significant changes.

To learn more about the nature of winds experienced in the UK over the 1980-2010 period, several HM windspeed exceedence thresholds were selected and the frequency of exceedence at each site calculated. Fig. 3 displays results, expressed as a network average, for two particular thresholds, $11ms^{-1}$ and $13ms^{-1}$, a ‘strong breeze’ on the Beaufort scale. These thresholds have been chosen here because when adjusted to wind turbine hub height, 3.6MW wind turbines begin to work at full capacity (Table 1). Furthermore, all of the 40 sites in the network experience such windspeeds, unlike for higher thresholds which are only exceeded at a minority of sites. Throughout the paper, we have chosen to focus on wind speed thresholds which are both consistent with those highlighted by Vautard et al (2010) and, especially, on those for which it is known that building damage of varying degrees would be expected. It is acknowledged however that the latter actually vary with geography according to build quality as show by Klawa and Ulbrich (2003) and so the implication of our threshold results should be seen as indicative only.

The proportion of time when the network average HM windspeed exceeds the $11ms^{-1}$ threshold ranges from just over 2% of the time in 2010, due to the cold and relatively calm months of January and December that year (see 2010 windspeed and direction in Fig. 4d), to 6.7% in 1990, associated with the storminess of January and February. The inter-annual variation is striking with, for an extreme example, 1986 experiencing winds in excess of $11ms^{-1}$ for twice as many hours as in the previous and following years, a feature also reported by Vautard et al. (2010) for Europe as a whole, though less pronounced. The $13ms^{-1}$ threshold exceedences exhibit a similar pattern to that of $11ms^{-1}$ ranging between just below 1% and just below 3% also in 2010 and 1990, respectively. The early 1980s and early 1990s, particularly the latter, have the highest proportion of HM windspeeds over each threshold, with a statistically significant decrease from 1980 (95% and 99% confidence for $13ms^{-1}$ and$11ms^{-1}$ exceedences respectively). The more intense threshold exceedence peak in the early 1990s compared with that of the early 1980s is in keeping with the 90^{th} percentile of the HM annual average windspeed shown in Fig. 2. This reinforces the findings of Wang et al. (2009), suggesting a more volatile wind regime in the early 1990s with more 10m winds reaching in excess of $11ms^{-1}$ and $13ms^{-1}$ but with a lower average windspeed compared to the early 1980s.

Figs. 2 and 3 reveal a large change between the adjacent years 1986 and 1987, 1986 recording far higher windspeeds. To further investigate this difference, network average wind roses were produced for both years (Fig. 4b and c; along with the 1980-2010 climatology (a) and the extreme year of 2010 (d)), 1986 revealing a much more pronounced tendency for south-westerly winds. This is to be expected with stronger south-westerly winds associated with the extra-tropical cyclone storm track. Increased south-westerly winds are positively correlated with the NAO (Cheng et al. 2011) and the monthly NAO index is significantly more positive in January, October, November and December in 1986 than in the equivalent 1987 months.

The peaks of the early 1980s and early 1990s are further highlighted by the five year running mean of network average HM windspeed threshold exceedence shown in Fig. 5, though the early 1980's peak is not as pronounced as in the 10^{th} and 50^{th} percentiles of site HM windspeeds shown in Fig. 2. In Fig. 5, in addition to the $11ms^{-1}$ and $13ms^{-1}$ exceedence thresholds shown in Fig. 3, further thresholds of $3ms^{-1}$, $5ms^{-1}$, $7ms^{-1}$, $9ms^{-1}$ and $15ms^{-1}$ are also included. Although the logarithmic scale somewhat reduces the visual impact of the variability, nevertheless a statistically significant decrease (≥99% confidence) over the last 20 years remains visible for exceedence thresholds in the range 7-15ms^{-1}. As expected, the contribution of individual sites to the total exceedence percentage varies throughout the network, especially as the exceedence thresholds rise and become of interest for the insurance sector. This is discussed in detail below (section 3*e*), with Fig. 10a highlighting the site contribution variations for the 15ms^{-1} threshold.

One of the findings of Vautard et al. (2010) was a general decline in European windspeeds over the last 30 years, especially for extreme winds, whereas UK results presented here more strongly emphasize an early 1990s peak and a marked decline over the last 20 years, highlighting the importance of not assuming a simple overall linear trend. We might not be surprised by this difference due to the UK's location on the edge of Europe, more exposed to the Atlantic, compared to the continental scale of the Vautard et al. (2010) study. Results presented here extend and are consistent with the UK, NAO and Grosswetterlagen indices presented by Atkinson et al. (2006) and with the broader spatial scale findings of Wang et al. (2009) and Boccard (2009).

The DMGS exhibits a similar long-term variability to that of the HM as depicted by the five year moving average of network average DMGS threshold exceedence shown in Fig. 6. Higher thresholds are included here compared with the HM analysis, ranging from 9ms^{-1} - 35ms^{-1}, revealing peaks in the early 1980s and early 1990s with the exception of the highest 35ms^{-1} exeedence threshold which does not have such a marked peak in the early 1980s but a more extreme maximum in the running mean around 1991/2. The 35ms^{-1} 1980-2010 decline is statistically significant (with 99% confidence) accommodating a peak in 1993, with the windspeed exceeding the threshold 0.5% of days (at all sites), compared to 2001 and 2010 when this threshold was not breached at all (not shown). Lerwick (station 40) and Kirkwall (39), in the Northern Isles (Fig. 1), contributed to 16 and 15 days respectively of the total 69 DMGS values in excess of this extreme wind threshold in 1993 (not shown). Note that 20ms^{-1} is generally accepted as a starting DMGS threshold for minor structural damage in connection with insurance claims.

Sensitivity tests of the inter-annual variability of threshold exceedences to the network configuration have been carried out (not shown), based on the removal of the most significant contributor stations to the 15 (HM) and 25ms^{-1} (DMGS) exceedence thresholds in Figs. 5 and 6 respectively. While the removal of these stations leads to inevitable quantitative changes of exceedence percentage, the interpretation of the periods of enhanced and reduced exceedence remains unchanged, indicating low sensitivity to specific station choice.

b. North Atlantic Oscillation – driver of temporal wind climate variations

Positive peaks in the NAO index are seen in the early 1980s and particularly in the early 1990s when the 10-year Gaussian-weighted filter was at its highest during the whole 189 year time period (CRU website). The decrease since the early 1990s is apparent, and partly explains the declining tendency in HM and DMGS UK wind observations and DMGSs over the last 20 years as shown in Figs. 2, 3, 5 and 6. The winter of 2009/10 had substantially more negative NAO index than any other winter measured during the record (Osborn 2011), explaining the anomalously low windspeeds observed. The consecutive winters 1994/5 and 1995/6 produced the greatest year to year contrast since the NAO series began in 1823, however this was not seen in the station observations (Figs. 2, 3, 5 and 6) showing that winter NAO index is not the only important factor contributing to the UK wind regime and hence the importance of studying intra-annual variability as discussed below.

To investigate the effects that the NAO index variations have on the observed UK wind climate, two network average wind roses are presented in Fig. 7, highlighting the difference in windspeed and direction observed during months when the NAO index is in strong negative ($\leq$ -2) and strong positive phase ($\geq$2). When the NAO is in strong positive phase, observed winds are stronger and very much dominated by the south-west sector, whereas during periods of strong negative phase, the speeds are more often lower and the direction much more evenly spread, with a greater tendency for north-easterlies. During negative NAO phase, the anomalous increase in pressure over Iceland suppresses westerly winds, diverting the storm track southwards over the Mediterranean and encouraging a more northerly and easterly flow over the UK (Hurrell et al. 2003).

c. Intra-annual variability

The considerable intra-annual wind variation in the UK is highlighted in Fig. 8 by the seasonal network averages of HM windspeed for 15ms^{-1} threshold exceedences. The winter peak of HM windspeeds exceeding 15ms^{-1} during the early 1990s is apparent, displaying the impact of the associated intense winter storminess (Wang et al. 2009). The statistically significant winter decline since 1990 (99% confidence) is particularly marked, generally following a similar progression to that of the NAO winter time series. The winter of 1989/90 witnessed the highest 15ms^{-1} threshold exceedence percentage of ~3.5%, with the lowest (complete) winter being in 2009/10, exceeding 15ms^{-1} just 0.3% of the time, lower than in most autumn and spring seasons.

The spring $15ms^{-1}$ exceedence percentage (Fig. 8) generally hovers around 0.5%, peaking at over 1% in 1994. Autumn meanwhile does not reveal a peak during the early 1990s, but was more extreme instead at the start of the observation period during the early 1980s and also peaked in the late 1990s before declining once more, partially consistent with the findings of Vautard et al. (2010), during 1979 - 2008, that the most substantial linear decrease in Europe occurred in the autumn season in this particular period. The relatively high $15ms^{-1}$ exceedences of the early 1980s in autumn is consistent with the early 1980s peak in UK observations (Figs. 2, 3, 5 and 6) are not as apparent in the NAO winter time series. Meanwhile, summer season threshold exceedences remain low and relatively consistent throughout the observation period. From this we can deduce that the threshold exceedence peak of the early 1980s is associated with higher winds in both winter and autumn seasons, whereas the early 1990s peak is caused mainly by the winter storminess alone.

As the seasonal variation of the HM wind exceedence threshold of 15 ms^{-1} is so strong, especially between winter and summer, we show in Fig. 9 the network average wind direction distribution for each season over the 1980-2010 period. All of the seasons are dominated, on average, by winds from the south-west quadrant, winter unsurprisingly having the strongest such winds, associated with the storm track moving south during the northern hemisphere winter (Dacre and Gray 2009). Autumn has a similar looking wind rose to that of winter, whereas summer and spring have different appearances, summer having a more influential north-west quadrant (and lower windspeeds overall) and spring a more significant north-easterly component. During summer the Atlantic westerlies are less dominant with the storm track pushed north by the Azores High, leading to climatologically more high pressure systems centred to the west of the UK producing comparatively more north-westerly winds. This means that summer winds are generally less extreme in speed despite the increase in thunderstorm activity seen in the summer and the associated potential for damaging downdrafts (Wheeler and Mayes 1997). Conditions during spring and early summer are more favorable for blocking situations over northern Europe (Barriopedro et al. 2006), leading to comparatively more wind with a north-easterly component as confirmed in Fig. 9b.

d. Spatial variability

When dealing with the network average of exceedence thresholds, spatial variability is hidden. Spread across the UK, the network sites possess characteristics that vary considerably, both in topography and exposure to the storm track (Fig. 1). Exposure to fetch over the Atlantic Ocean and Irish Sea is important, along with the latitude and altitude; the higher and further north a site is, the stronger the wind due to reduced friction and greater proximity to the higher storm track density region to the south and east of Iceland (Dacre and Gray 2009). Surface roughness and vegetation also play key roles as highlighted by Vautard et al. (2010). These points in mind, the relative contributions of each site to threshold exceedence, especially for higher thresholds, are expected to vary significantly. Fig. 10 shows the relative contributions of each site to the exceedences of HM $15ms^{-1}$ (speed at which insured property damage begins) and $25ms^{-1}$ windspeed thresholds over the period 1980-2010, the circle size representing the contribution percentage. The $15ms^{-1}$ site contributions are dominated by the west coast sites exposed to the Atlantic and Irish Sea, for example Aberporth (station 13 – Fig. 1) and Ronaldsway (27), while the two sites furthest north, Kirkwall (39) and Lerwick (40), also make up more than 25% of the exceedences. This is unsurprising considering that the latter areas, closer to the Icelandic low, are susceptible to more intense storms, especially during positive NAO (Serreze et al. 1997). Meanwhile the west coast stations experience reduced friction when flow is onshore. This is further highlighted in the $25ms^{-1}$ site contribution map (Fig. 10b) with even more weight towards exposed sites and the most northerly Kirkwall (39) and Lerwick (40) stations.

Inland sites rarely contribute to either exceedence threshold compared with their more coastal neighbors. The inland northern sites of Eskdalemuir (31) and Salsburgh (33) are situated only 50 miles from each other and have similar altitudes of 242 and 277m respectively, however Salsburgh contributes far more to the $15ms^{-1}$ and $25ms^{-1}$ exceedence thresholds (just under 10% for each), with Eskdalemuir not exceeding $25ms^{-1}$ at all during the 1980-2010 period. Eskdalemuir is situated in a north-south orientated valley, with tree covered ridges on either side, whereas the Salsburgh monitoring site is located on an exposed grass covered hill with a large flat top to the north and east. Centrally located in Scotland’s heavily populated central belt, Salsburgh is broadly representative of the insurance risks associated with windstorms transitioning across this important area. The Salsburgh- Eskdalemuir contrast is highlighted in the 1980-2010 HM wind roses in Fig. 10, with wind direction distribution affected by the site characteristics, meaning that Eskdalemuir is somewhat sheltered from the strong westerly winds. Many of the site characteristics are highlighted by their respective wind roses, with Bala (17) located in a south-west to north-east orientated valley in Snowdonia, dominated by south-westerly and north-easterly winds, whereas the relatively flat and open site of Heathrow possesses a similar wind direction distribution to that of the network average with a prevailing south-westerly (Fig. 4a). Table 2 shows the network average proportion of wind direction for each quadrant of the compass, revealing that despite the south-westerly predominance, there is an easterly component to the UK HM wind 38.1% of the time.

Wind roses are shown for the directions of HM winds exceeding the thresholds of $15ms^{-1}$ and $25ms^{-1}$, to confirm where the strongest winds originate (Fig. 11). The $15ms^{-1}$ and the $25ms^{-1}$ thresholds are dominated by south-westerly winds with the south-west quadrant (190° - 270°) accounting for 59.9 and 78.9% respectively, as Hewston and Dorling (2011) found for extreme (top 2%) DMGSs.

The DMGS 1980-2010 39-site network average wind rose (not shown) is similar to that of the HM (Fig. 4a), with the proportion of wind direction for each quadrant (Table 2) also extremely similar. This is the same when comparing individual site HM wind roses (Fig. 10) with equivalent DMGS wind roses (not shown). This suggests that the factors, be it site aspect, local scale flow or synoptic scale flow which contribute to the direction of HM winds, are the same for DMGSs.

e. Application of the Weibull function to describe windspeed distributions

The spatial variation of windspeeds in the UK is considerable, as shown above, and this contrast is also seen when the Weibull distribution is fitted to the HM and DMGS data. Fig. 12 shows the relationship between the Weibull shape parameter (k) and mean windspeed at each of the 40 HM locations, along with histograms for some prominent sites. Generally there is a slight positive correlation (not statistically significant) between mean windspeed and k. The spread of k ranges from ~1.45–2.1, values similar to those reported in the literature by Celik (2004) based on hourly observations in Turkey (1.1-1.89), and by Pryor et al. (2004) for buoy measurements around the coast of North

America (1.4-2.5). Different Weibull parameter calculation methods and ways of dealing with zero values have an effect (see section 2c), along with the fact that the locations used in this study are geographically heterogeneous leading to highly varied wind regimes. Just 6 out of the 40 sites have k values of more than the commonly used Rayleigh distribution value of 2 and the majority of sites range from 1.7 - 1.9 highlighting the dangers of simply using the Rayleigh distribution to describe wind distributions for wind farm siting.

The Weibull distribution describes the observed HM winds well as shown by the histograms in Fig. 12. The Weibull distribution provides a better fit to the sites with comparatively few low windspeeds, as shown when comparing the sites of Lerwick (40) and Kirkwall (39) to Eskdalemuir (31) and East Malling (8). This is partly due to the method of low value recording in the MIDAS database producing an overrepresentation of 2 knots (1.03ms $^{-1}$) at certain sites (e.g. Eskdalemuir (31) and Heathrow (10)). This slightly negatively skews the Weibull distribution and affects the k values. It is also due to the nature of the Weibull distribution best approximating well measured sites with moderate or high windspeeds (Petersen et al. 1998).

Weibull shape parameter (k) values seem to be a function of both the strength of the mean wind and the impact of site characteristics. Sites with very low windspeeds such as East Malling (8) produce low values of k , due to the high counts of low wind values, however other sites with higher means but with anomalous wind roses (varying greatly from that of the network average, affected by local site characteristics – Fig. 10) such as Bala (17) and West Freugh (30) also have low k (not shown), associated with topographic effects such as local valley flows. Sites with low means but evenly distributed (similar to network average) wind roses like Heathrow (10) (Fig. 10) and Nottingham (18) (not shown) have relatively high k with regard to mean wind (Fig. 12). Valley (22) has high mean windspeed but is located in a valley, so local topography affects the wind direction and windspeed distributions.

The Weibull distribution does not approximate the DMGS distribution as accurately as for the HM winds as shown by Fig. 13. The k values are much higher than for the HMs, ranging between ~2.4 and ~2.9, which is unsurprising given that the use of the DMGS metric eliminates many low values. The windspeed threshold of 12 ms^{-1} required for good Weibull fit according to Jamil et al. (1995) seems not to be reliable for DMGSs, with sites possessing averages above and below 12ms^{-1}, being underestimated for the most frequent values and overestimated for the lower windspeeds (Fig. 13). Generally the tails of the distributions are well approximated for the higher average DMGS sites and slightly overestimated for the sites with lower average DMGS.

f. Wind energy implications

The HM windspeeds have been converted into network average energy density and potential power output (PPO) of a synthetic wind turbine network. Table 2 highlights just how important the SW quadrant is for wind power production. Both methods show significant year to year variability of power output over the 1980-2010 period (Fig. 14), as originally seen in the annual average percentile HM windspeeds (Fig. 2), in the HM threshold exeedences (Figs. 3, 5), in the DMGS threshold exceedences (Fig. 6) and in the NAO index (CRU website). Peaks in energy density and PPO are seen in the early 1980s and early 1990s and are clearly displayed by the 5 year moving averages. The anomalous year of 2010 stands out in both energy metrics, representing the lowest values of the whole period; the extreme variability of consecutive years 1986-7 is also clear. The main difference between the two methods is the more marked peak in the early 1990s in energy density. The unprecedented storminess described by Wang et al. (2009) of the early 1990s produced the most extreme winds of the period in the UK, often above the cut-out speed of even the most modern and largest turbines. The 10m windspeeds of above $18ms^{-1}$ are too high to be captured by the 3.6 MW turbines in the PPO, but account for extremely high levels of energy production in the energy density output (Table 1) due to the cubic relationship with windspeed. The PPO results are in accordance with those of Sinden (2007) during corresponding years of study. In addition the load factor of 30% is in keeping with the predetermined value used in the Sinden (2007) study. This load factor was found by Sinden to approximate the UK wind power output figures well, especially since 1997.

The range of annual mean PPO is large, 867-1265kW (2010 and 1986 respectively) with an average of 1087 kW. During the highest production year, the synthetic 3.6MW wind turbine network was working on average at 35% efficiency (aka load factor; with the assumption of steady winds) and at 24% efficiency for the lowest production year. The year 1986 saw 16 % more energy generated than the 1980-2010 average whereas 2010 was 20% below. The energy produced in 1987 was just 73% of that of 1986, a much larger difference than the inter-annual variability in wind energy density that Petersen et al. (1998) found across many regions in Europe (±10 –15%). This shows that basing wind farm decisions on a single year of monitored data can be a dangerous practice (Brayshaw et al. 2011).

The demand for electricity in the UK fluctuates strongly, varying from hourly to annual timescales (Pöyry 2011). Users need electricity at different times of the year for different reasons (eg summer cooling demand and warming in winter) (Sinden 2007), which may not match the periods of low and high wind output (AEA 2011). Winter is the season when electrical power output is most important, with colder temperatures and shorter days, domestic and commercial users require energy for heating and lighting, so how does our synthetic wind turbine network simulate seasonal PPO variation over the 1980-2010 period? Fig. 15 shows the evolution of seasonal mean PPO, highlighting the prominence of the winter season, though not as dominant in power production as might be expected given the dominance of winter windiness (Fig. 8). The efficiency of synthetic power harnessed is at its greatest in winter 1995 (47% efficiency), and at its lowest (18%) in summer 1983. PPO is very low in the winter of 2009-10 and comparable to the summer averages. This shows that storage and backup generation schemes will become crucial to energy suppliers in the future, with ever increasing reliance on wind power and other renewable sources.

4. Conclusions and outlook

The characteristics of the UK HM and DMGS wind regimes, with applications to the insurance and wind energy industries, are presented here, based on data from a 40-station wind monitoring network over the continuous 1980-2010 period. The main findings are summarized as follows:

- The 10th and 50th (but not the 90th) percentile HM windspeeds have declined significantly over this specific period, whilst still incorporating a peak in the early 1990s. 2010 recorded the lowest annual 10th and 90th percentile and second lowest (behind 1987) 50th percentile windspeed over the whole 1980-2010 period [Fig. 2]. This is all, however, in the context of longer term decadal variability.

- The Weibull distribution is more suited to representing HM winds rather than DMGS distributions at typical land-based sites, the former revealing site-specific shape parameter values ranging from 1.4-2.1 [Fig. 12] somewhat in contrast with the often assumed k=2 Rayleigh distribution, with associated implications for turbine site selection.

- As the HM exceedence thresholds rise, the early 1980s peak in exceedence frequency diminishes, while the early 1990s peak becomes more apparent [Fig. 5], with a declining tendency since, confirming the early 1990s unprecedented peak in NE Atlantic winter storminess reported by Wang et al. (2009). This is not fully consistent with Vautard et al. (2010) who highlighted a temporally broader decline for the whole of Europe over the period 1979-2008.

- The DMGS exceedence thresholds exhibit similar variations to those of the HM, with the highest thresholds (30 and 35 ms^{-1}) displaying the most marked early 1990s peak and a decline since [Fig. 6], indicating that the decrease of extreme

DMGSs highlighted by Hewston and Dorling (2011) has continued through to 2010, contributing to the reduction in UK storm-related insurance claims.

- The network average 1980-2010 HM prevailing wind direction is in the south-west quadrant (40% of the time). However significant seasonal and inter-annual variation is apparent in the relative frequency of all wind directions and this needs to be accounted for in wind energy assessments.

- The 40% frequency in south-west quadrant winds translates into a 51% proportion of energy in the wind [Table 2].

- The range of network average annual mean Potential Power Output is significant, from -20% to +16% around the average, with the synthetic energy produced in 1987 just 73% of the previous year, 1986, and 2010 the lowest producing year of all [Fig. 14].

The recent variability in UK mean wind and gust climate, including the particularly anomalous atmospheric circulation patterns of 2010, quantified and discussed here, naturally leads to related questions about the future, both within the scientific community and from other stakeholders. 2010 was an anomalously low wind year, a relatively bad year for wind energy production but a good year for the insurance industry in terms of reduced claims volumes. The two sectors are, however, also positively related if one considers the growing underwriting role that insurance is now playing, reducing the risk of weather-sensitive wind energy revenue streams.

Future climate projections have a large spread between models and low signal-to-noise ratio over Europe compared with other mid-latitude areas (Hawkins & Sutton 2009), Europe being one of the hardest regions for which to predict weather and climate on all timescales (Woollings 2010; Ulbrich et al. 2009). Recent extreme events such as the European winter of 2009-10 have led to alternative causal interpretations, including an emphasis on the important role of recent declining solar output (Lockwood et al. 2010, 2011) and on internal dynamical responses to varied forcing (Jung et al. 2011). While further research seeks to improve models and reduce key uncertainties, both in the prediction of extreme event onset and of persistence, it seems wise to anticipate further significant variability in the UK wind climate and concentrate upon building resilience to this.

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List of Figures

FIG. 10. Contribution (percentage) of each site to 15 ms^{-1} (a) (total counts 74154) and 25 ms^{-1} (b) (total counts 323) HM windspeed threshold exceedence plus selected all-windspeed 1980-2010 individual site wind roses.

FIG. 11. 1980-2010 HM wind roses for exceedences of 15ms^{-1} (a - total counts 74154) and 25ms^{-1} (b - total counts 323) thresholds (all sites).

FIG. 12. HM windspeeds compared with Weibull shape parameter, k, for each site plus selected site wind distributions.

FIG. 13. DMGSs compared with Weibull shape parameter for each site, along with selected site DMGS distributions.

FIG. 14. Bottom – Network average energy density (W m^{-2}). Top - network average potential power output (kW) of a synthetic network of 100m hub height 3.6MW wind turbines.

FIG. 15. Network average seasonal mean potential power output (kW) of a synthetic network of 100m hub height 3.6MW wind turbines (note that the winter of 1980 only includes Jan and Feb 1980 and the winter of 2010 only includes Dec 2010).

TABLE 1. Power produced by a present-day state of the art 3.6MW wind turbine and Energy Density (from equation 2) for windspeeds in the range 0-26 m s^{-1} converted to 100m using the power law approximation (equation 3).

Surface windspeed m s^{-1}	Windspeed m s^{-1} at 100m	Power kW	Energy Density W m^{-2}
0	0	0	0
1	1.38	0	1.61
2	2.76	0	12.88
3	4.14	102	43.46
4	5.52	361	103.02
5	6.90	770	201.21
6	8.28	1386	347.69
7	9.67	2175	553.84
8	11.04	2965	824.16
9	12.42	3411	1173.47
10	13.80	3565	1609.69
11	15.18	3595	2142.50
12	16.56	3600	2781.55
13	17.95	3600	3542.42
14	19.33	3600	4423.86
15	20.71	3600	5440.59
16	22.09	3600	6602.27
17	23.47	3600	7918.54
18	24.85	3600	9399.08
19	26.23	0	11050.50
20	27.61	0	12888.75
21	28.99	0	14920.34
22	30.37	0	17154.93
23	31.75	0	19602.18
24	33.13	0	22271.77
25	34.51	0	25173.35
26	35.89	0	28316.59

TABLE 2. Network average HM wind direction, Energy Density and daily maximum gust direction divided into compass quadrants.

Quadrant of wind direction	Percentage of Wind Direction	Percentage of Energy Density	Percentage of DMGS Wind Direction
North-east (10° - 90°)	17.9	11.1	17.5
South-east (100° - 180°)	20.2	17.8	19.6
South-west (190° - 270°)	39.8	51.8	40.2
North-west (280° - 360°)	22.2	19.3	22.7

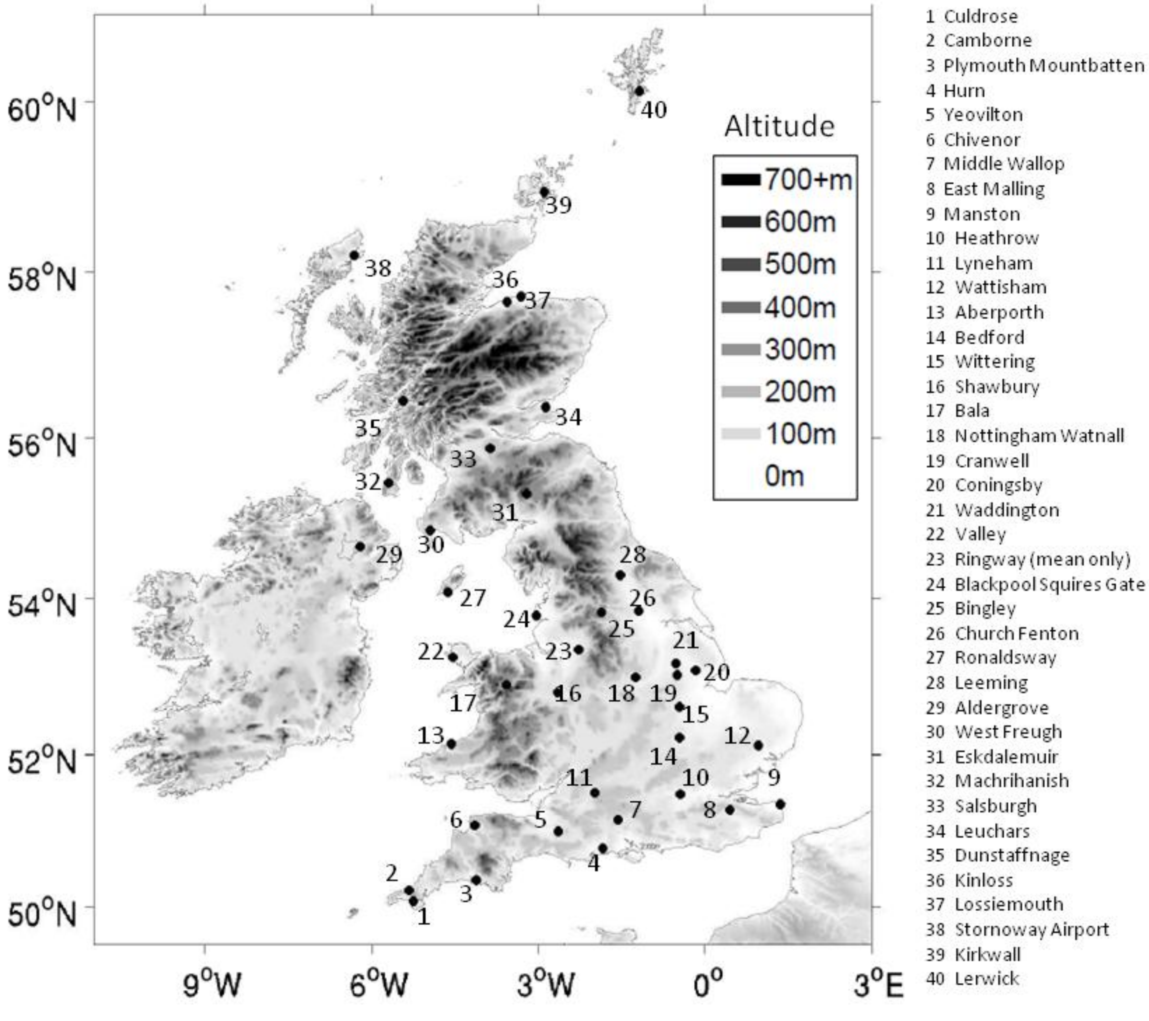

FIG. 1. Location of observation stations in the network. Note that Ringway (23) has no DMGS data, only recording hourly mean windspeed.

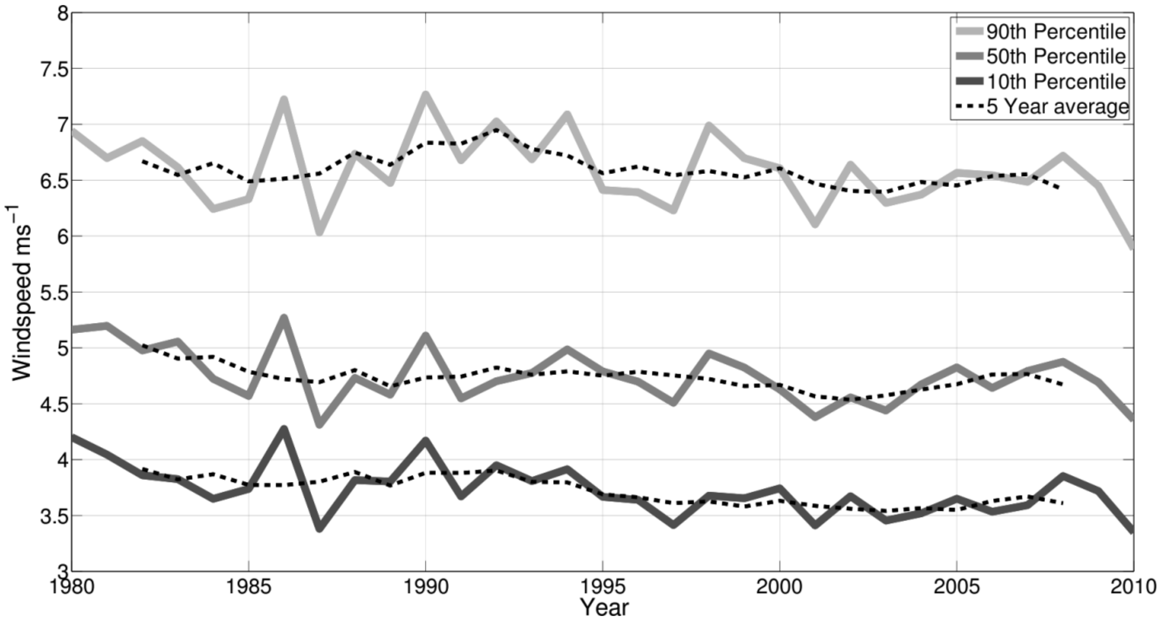

FIG. 2. 10th, 50th and 90th percentiles of annual average HM windspeeds (ms^{-1}), 1980-2010, from the 40- station network.

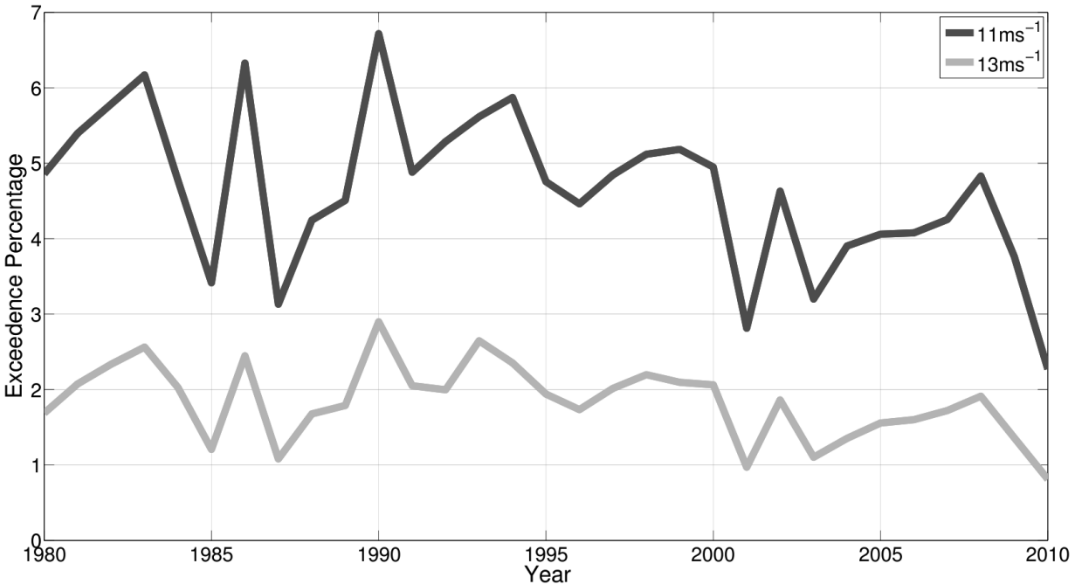

FIG. 3. Network average threshold exceedence percentages for 11 and 13ms^{-1} HM windspeeds.

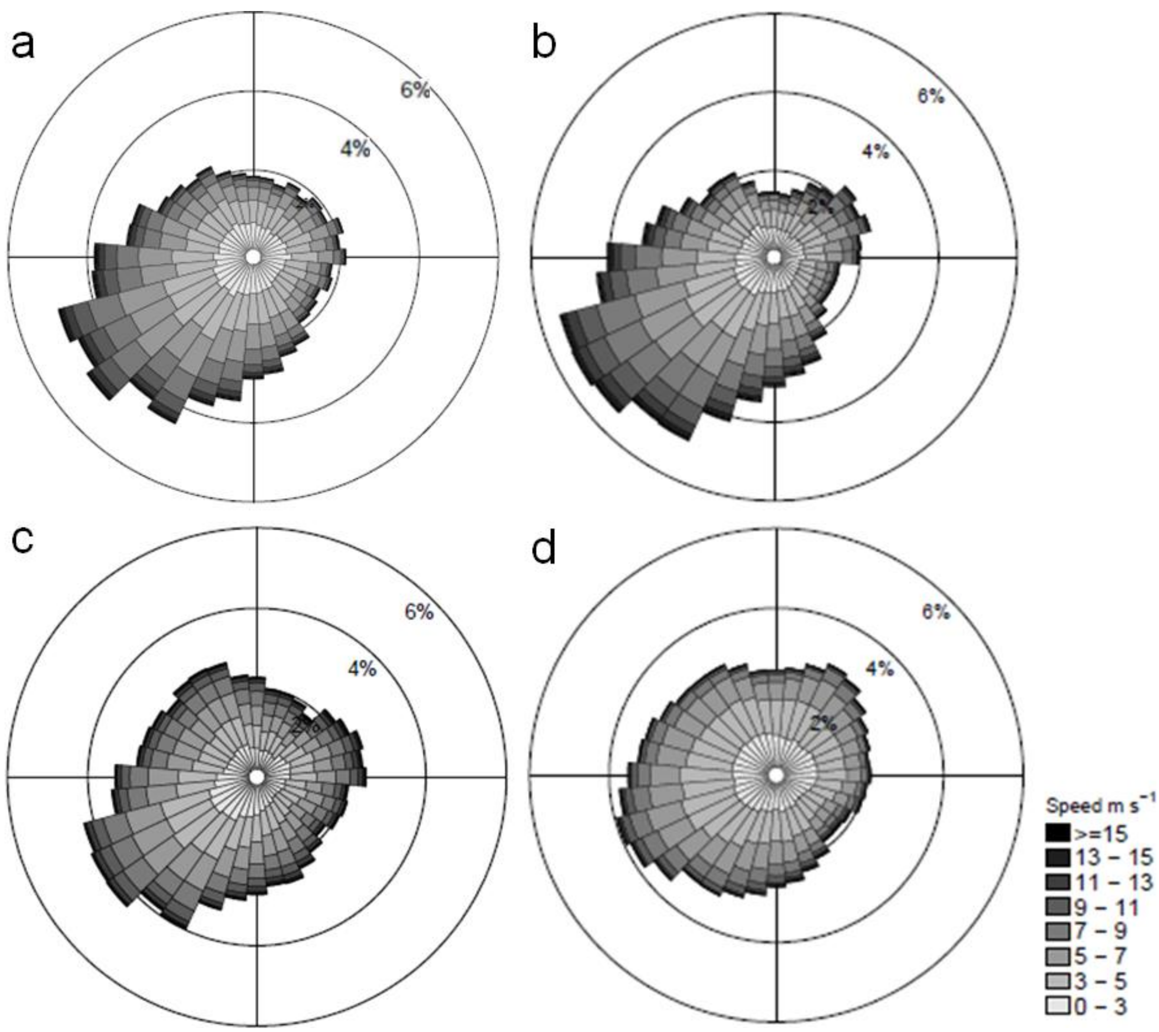

FIG. 4. Network average HM wind roses for 1980-2010 (a), 1986 (b), 1987 (c) and 2010 (d).

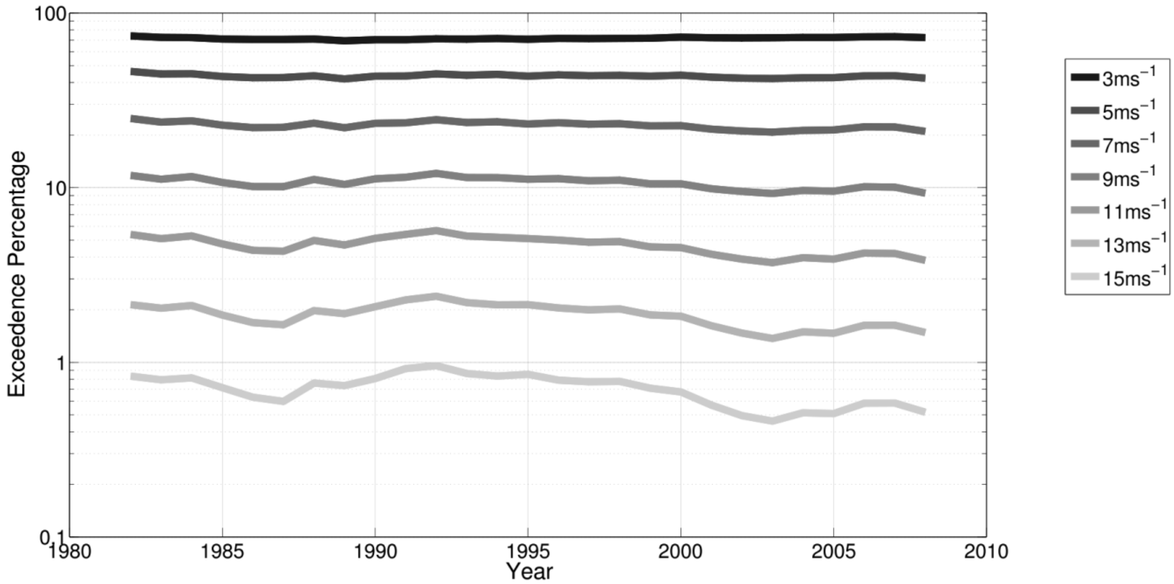

FIG. 5. Network average 5-year running mean HM threshold exceedence percentages for 3, 5, 7, 9, 11, 13 and 15ms^{-1} HM windspeeds.

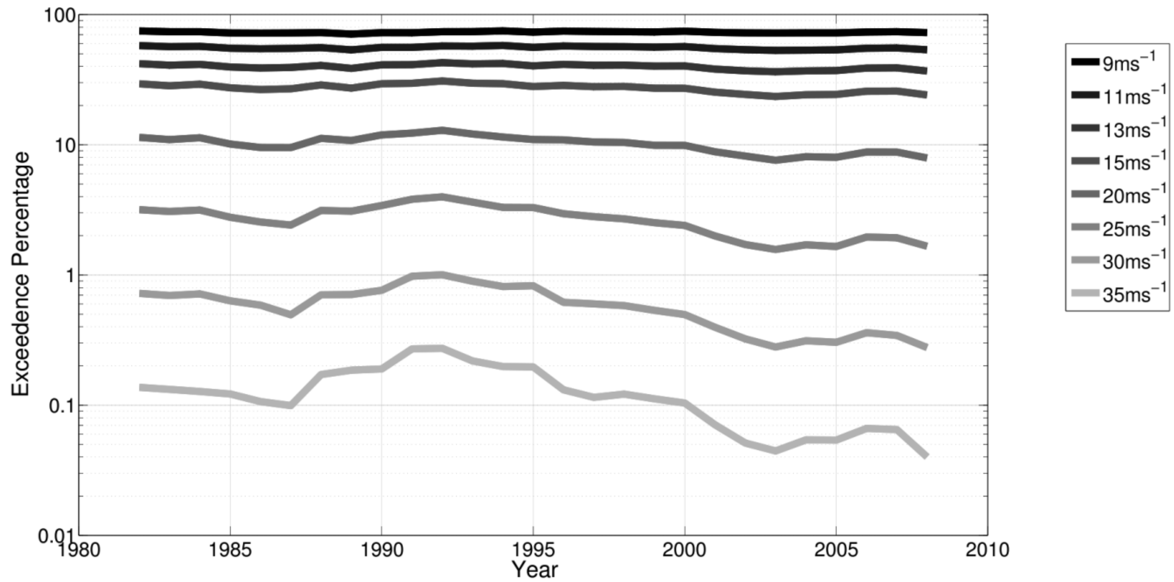

FIG. 6. Network average 5-year running mean threshold exceedence percentages for 9, 11, 13, 15, 20, 25, 30 and 35 ms^{-1} DMGS.

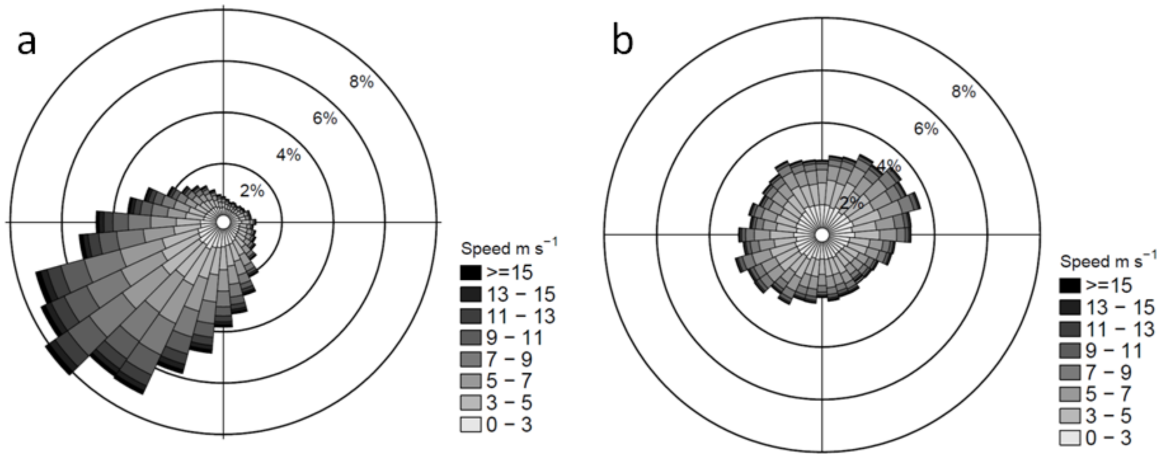

FIG. 7. 1980-2010 network average HM wind roses when NAO index is ≥ 2(a) and ≤-2 (b).

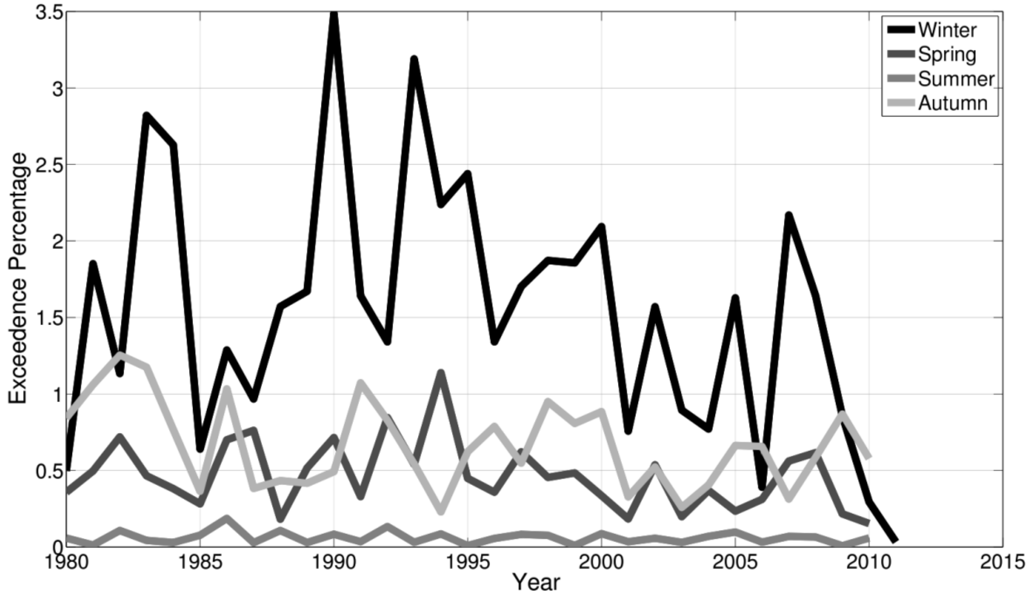

FIG. 8. Network average threshold exceedence percentages for 15 ms^{-1} HM windspeeds during each season, winter (DJF), spring (MAM), summer (JJA) and autumn (SON) (note that the winter of 1980 only includes Jan and Feb 1980 and the winter of 2010 only includes Dec 2010).

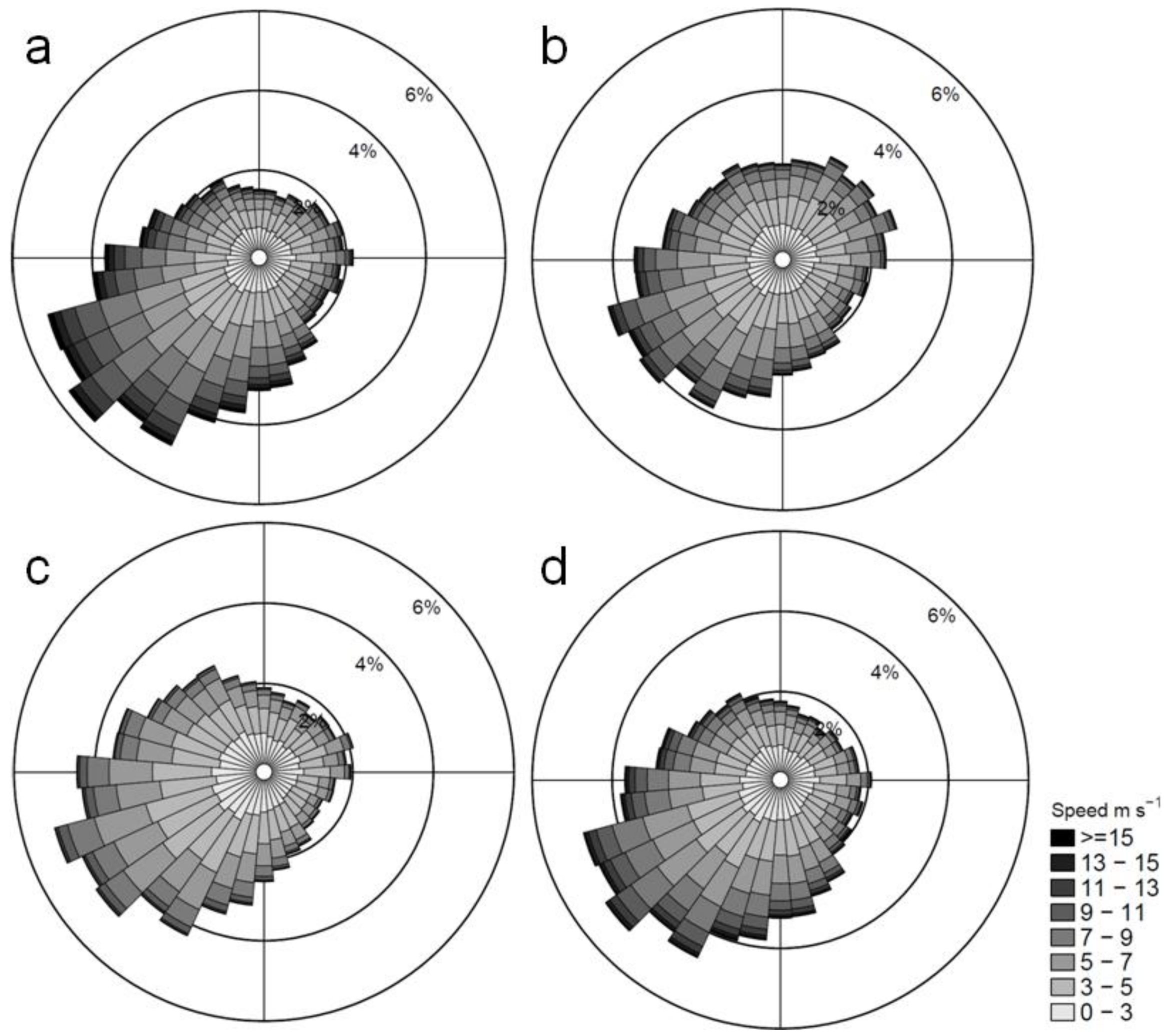

FIG. 9. Network average HM seasonal wind roses, 1980-2010, winter (a), spring (b), summer (c) and autumn (d).

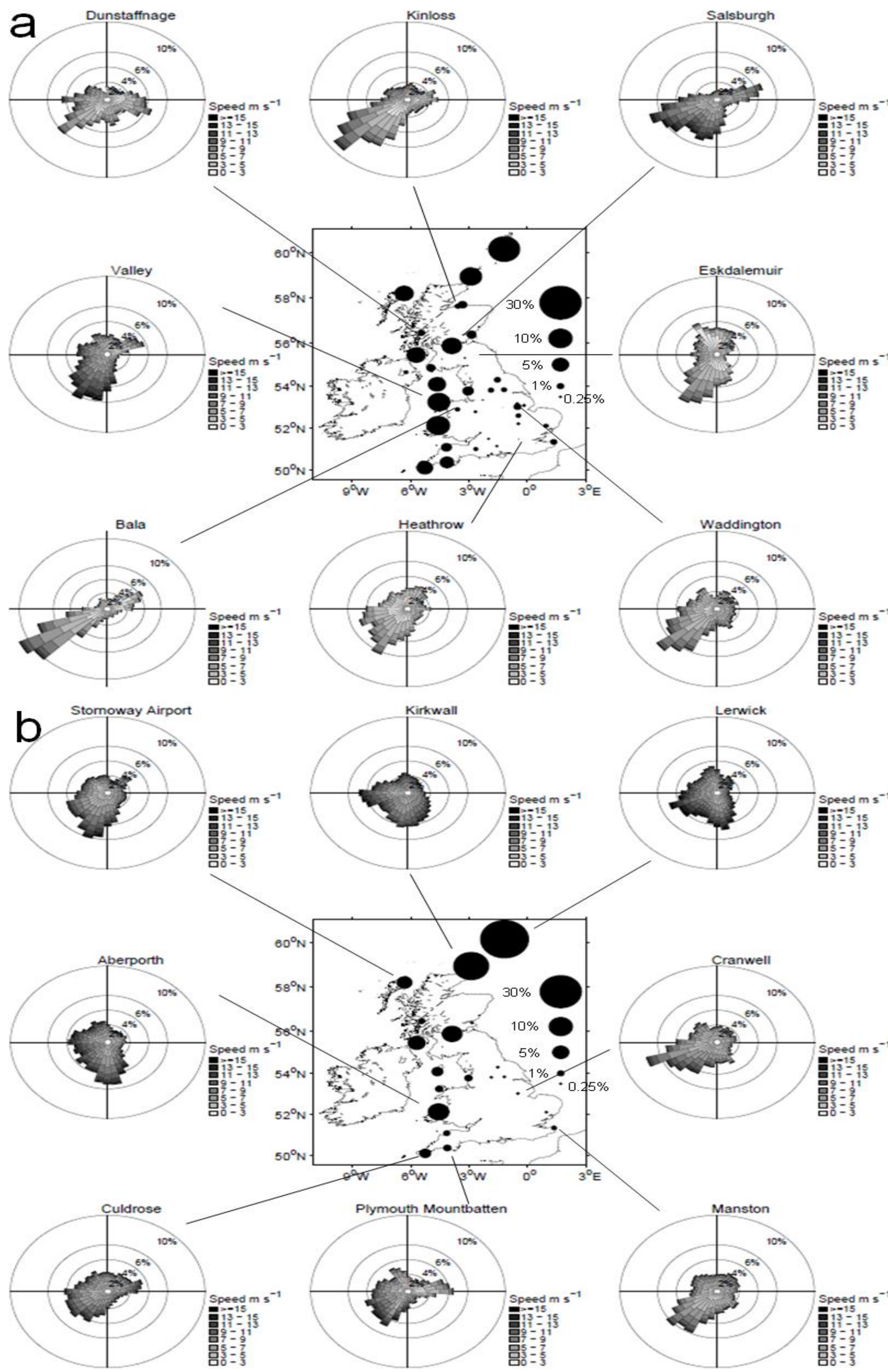

FIG. 10. Contribution (percentage) of each site to 15 ms^{-1} (a) (total counts 74154) and 25 ms^{-1} (b) (total counts 323) HM windspeed threshold exceedence plus selected all-windspeed 1980-2010 individual site wind roses.

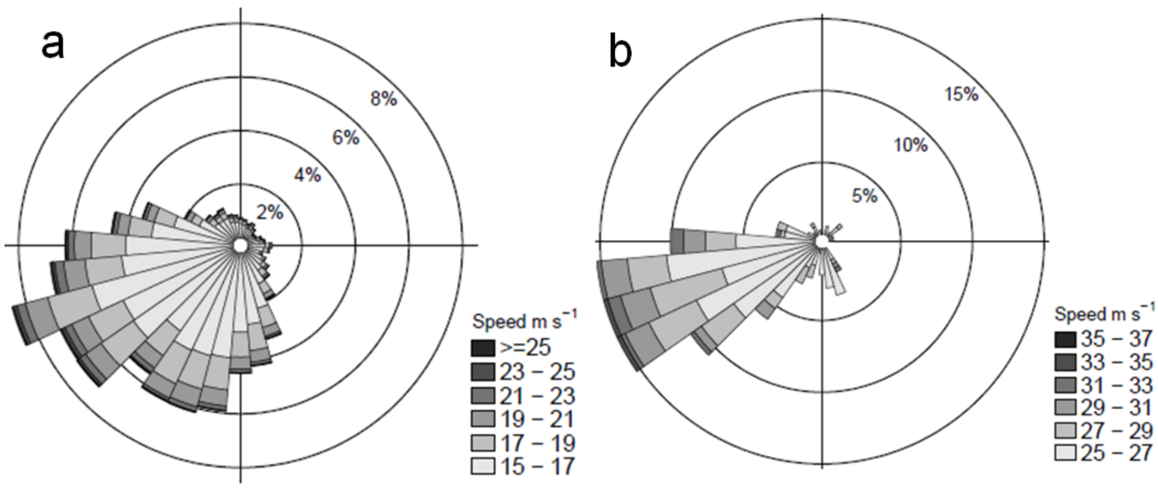

FIG. 11. 1980-2010 HM wind roses for exceedences of 15ms^{-1} (a - total counts 74154) and 25ms^{-1} (b - total counts 323) thresholds (all sites).

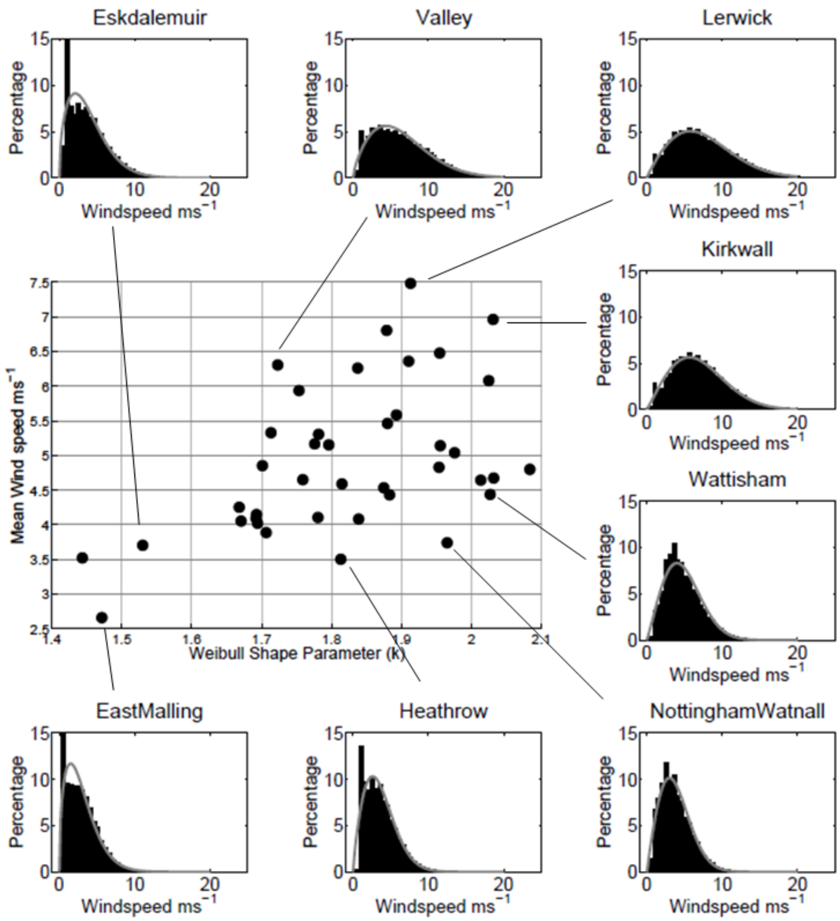

FIG. 12. HM windspeeds compared with Weibull shape parameter, k, for each site plus selected site wind distributions.

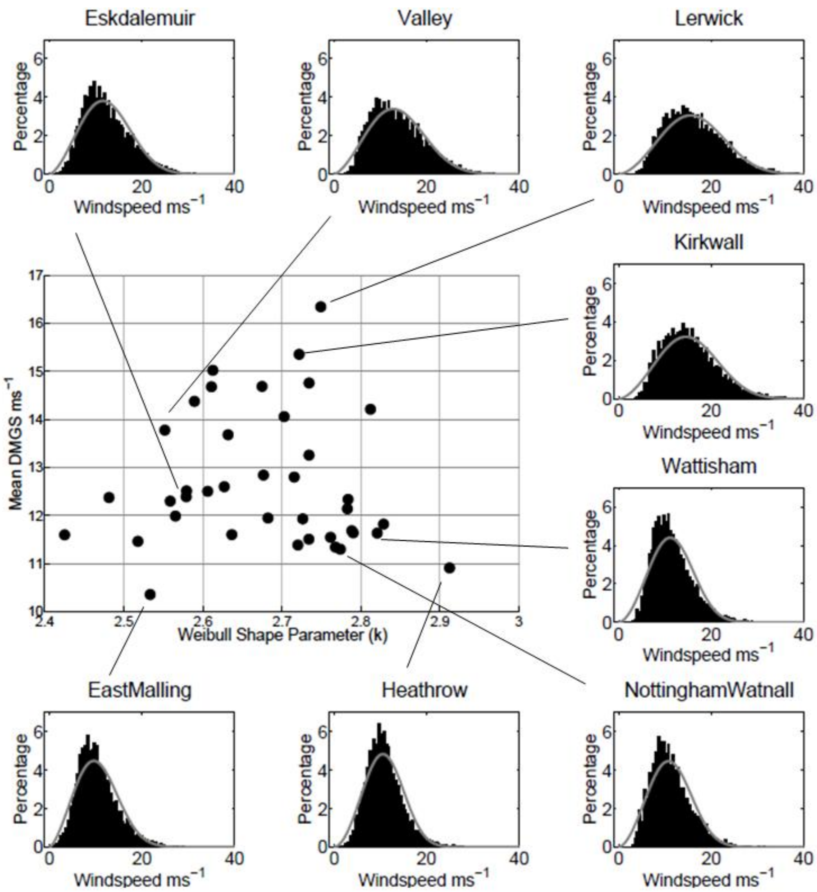

FIG. 13. DMGSs compared with Weibull shape parameter for each site, along with selected site DMGS distributions.

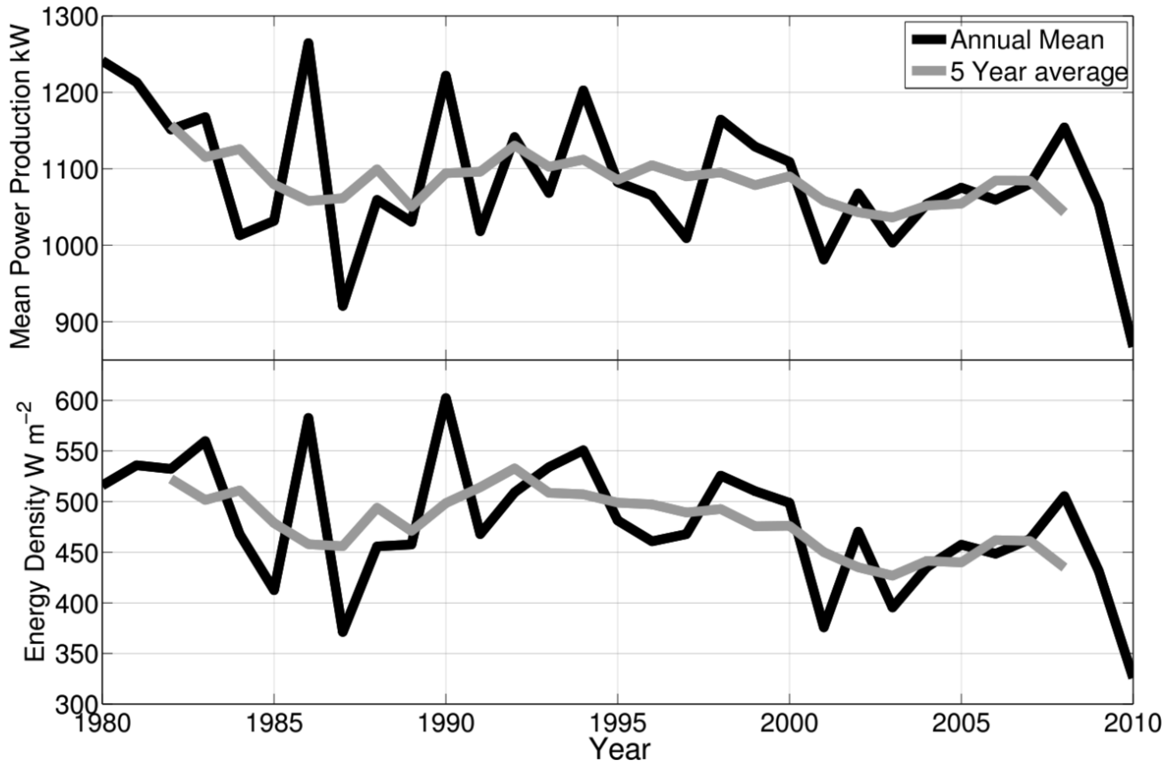

FIG. 14. Bottom – Network average energy density (W m^{-2}). Top - network average potential power output (kW) of a synthetic network of 100m hub height 3.6MW wind turbines.

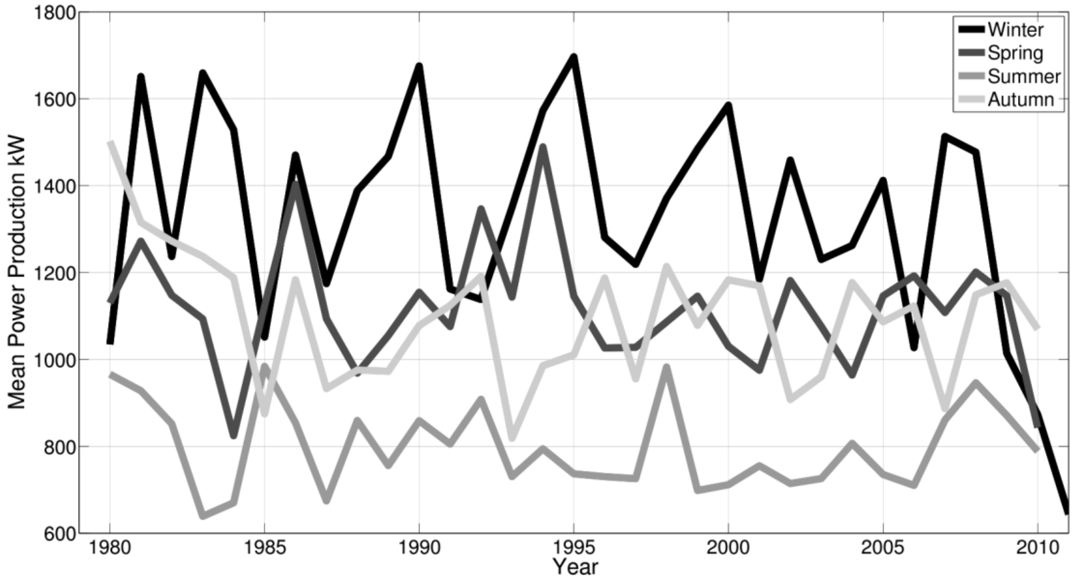

FIG. 15. Network average seasonal mean potential power output (kW) of a synthetic network of 100m hub height 3.6MW wind turbines (note that the winter of 1980 only includes Jan and Feb 1980 and the winter of 2010 only includes Dec 2010).