This is the pre-peer reviewed version of the following article: Watson S J, Kritharas P and Hodgson G J (2013). 'Wind Speed Variability across the UK between 1957 and 2011', Wind Energy (2013) Early View, which has been published in final form at http://onlinelibrary.wiley.com/doi/10.1002/we.1679/abstract.

Wind Speed Variability across the UK between 1957 and 2011

(Short Title: Wind speed variability across the UK between 1957 and 2011)

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Abstract: Using surface data from 57 UK meteorological stations, a national (BADC-57) and regional wind index for the UK has been calculated for the period 1983 to 2011. For a subset of seven stations, an additional national index (BADC-7) has been calculated for the period 1957 to 2011. The indices show an annual variability of 4% over their respective periods corresponding to a variation in typical wind turbine capacity factor of 7%. These indices are compared with indices calculated from other sources, namely: an index generated using a gridded dataset of observed values interpolated across the UK; an index calculated from an area bounding the UK using the ERA-40 reanalysis dataset; indices calculated from bilinear interpolation of the ERA-40 reanalysis dataset to the 57 and seven stations; and another independent UK wind index. The indices show variation in trends with all showing some level of decline with the exception of that generated using the ERA-40 reanalysis dataset averaged over the UK which shows a significant increase. The various indices show varying degrees of agreement with correlation coefficients, after trends are removed, ranging between 0.611-0.979. The effect of changes in site exposure, instrument bias and measuring height were considered for the BADC-7 and BADC-57 indices. The change in instrument measurement height appears to have a significant biasing effect and it is likely that this along with changes in exposure at urban sites have caused the decline in annual wind speeds observed for some of the indices. There does not appear to be evidence for significant changes in large area (mesoscale) surface roughness. The correlation between annual mean wind speeds at the seven surface station sites used to calculate the BADC-7 index is seen to be quite weak indicating very localised variations in inter-annual variability. When regional differences in the index are investigated, it is seen that wind speeds show a very slight decline across the UK in all regions except the south-east, which shows a slight increase. The greatest decrease is seen in the north-west. These changes are in the same direction as the tentative predictions given by climate models for future changes in wind speed across the UK, though the uncertainty is large given the large degree of inter-annual variation.

Keywords: wind, index, variability, long-term, reanalysis

1. INTRODUCTION

An understanding of variation in long term wind speed is important in several sectors such as where wind loading on structures needs to be assessed or where long term energy yields for wind farms needs to be evaluated. Knowledge of wind variability is particularly important for wind farm developers and operators to minimise long term risk due to fluctuations in annual revenue.

A wind index provides an indication of the mean wind speed, usually annually and/or monthly, relative to the calculated long-term mean wind speed (Garrad Hassan, 2008). An alternative method is the concept of a wind index based on ‘significant wind events’ e.g. (Mason *et al*, 2005) for the purpose of predicting certain oceanic events relevant to fish reproduction. However, an index based on anomalous events is not useful for the prediction of long-term energy yields from wind farms. What is required is a time history of mean wind speed values at regular (say annual) intervals.

Using a wind index it is possible to estimate the energy production of a wind farm based on a historical record of mean wind speed. The wind index can also provide an indication of long term trends in mean wind speed and can be used to provide a financial estimate of the impact of any periods of unavailability (Harman and Morgan, 2005). Trend information is particularly useful given that a wind farm might have a 20-30 year production lifetime and therefore the wind climate might change significantly from that assumed at the planning stage.

The aim of this work was to reconstruct, from surface observations of wind speed, a wind index which would indicate the variability of the wind climate on a timescale at least as long as the expected lifetime of a wind farm site (>25 years) and would allow a regional analysis of wind speed variability across the UK. This was extended (>50 years) using as long a period as possible from the observations available, whilst still giving a representative UK average. The index was analysed both nationally and regionally and compared with wind indices calculated from other sources including reanalysis data and surface observations interpolated onto a regular grid.

The research reported here is the first known published analysis of a UK wind index using surface station observations for a period of greater than 50 years and with an analysis of regional variation. It also provides a contrast between wind indices derived from spatially smoothed data sets, e.g. analysis data, and point values from meteorological stations.

2. BACKGROUND

2.1. Historic long term wind speed trends

There has been a volume of work investigating historic wind speed trends using indirect indications of wind speed, including reanalysis datasets and historic pressure fields.

An analysis of six-hourly cyclone activity between 1959 and 1997 from the NCEP-NCAR reanalysis (McCabe *et al*, 2001) suggested a decrease in cyclone frequency but a slight increase in intensity for mid-latitudes (30^0N-60^0N) and an increase in cyclone frequency and intensity for high-latitudes (60^0N-90^0N). Another study of the six-hourly NCEP-NCAR reanalysis dataset between 1949-1999 produced six winter indices including extreme wind speed (Paciorek *et al*, 2002). This work suggested an increasing wind speed trend for the UK over the period of between 1.5-2.5 m/s per 50 years. In (Wang *et al*, 2009), a number of pressure triangles over the north-eastern Atlantic were studied to infer the geostrophic wind over the period 1874-2007. The results of this study indicated maximum storminess in the North Sea around 1990. A steadily increasing trend in the geostrophic wind was determined in the north-eastern extent of the region studied, whereas a decline was observed in the western extent. Over Great Britain, the geostrophic wind was found to be reasonably steady, except during the summer where a slight decline was observed. For the north-eastern Atlantic region as a whole, it was found that during the summer, storminess appeared to have declined, except that the south-western areas (including north-west Scotland) showed no noticeable trends. From a similar analysis of pressure data from Sweden for the period 1780 to 2005 using an Eulerian framework, no overall change in storminess was observed, though significant decadal swings were observed (Bärring and Fortuniak, 2009). This work highlighted the importance of studying a long enough period when trying to determine climate changes.

A study of wind speed trends in north-western Europe (Atkinson *et al*, 2006) concluded that there was a reasonable degree of correlation between indices in the UK, Germany, Denmark and the Netherlands with a similar declining trend over the 15-year period 1990-2005. A study of 850hPa winds from the NCEP-NCAR reanalysis dataset, focussing primarily on the Baltic (Pryor and Barthelmie, 2003), showed for the grid cell at 55^0 N, 5^0 E, that the time series displayed a number of features, namely a peak in 1967, an increase during 1970s and 1980s, a low around 1987 and a declining trend during the 1990s.

2.2. Future projected trends

There is an increasing interest in projected changes to the wind climate over the next century and a number of authors have studied the output from several GCMs (Global Climate Models) and RCMs under different CO_2 forcing scenarios.

The output of the ECHAM5 GCM for several climate change scenarios was studied indicating an increase in extreme winds with higher wind speeds over Britain, the North Sea, the Baltic Sea and nearby coastal regions during the 21st century (Pinto *et al*, 2007). In (Pryor *et al*, 2006) when HadCM3 output data were examined under the SRES A2 high emissions scenario, it was found that there was a high degree of correlation of latitudinally integrated wind indices in Europe, balanced around 45°N. This research also found that there was evidence for a slightly reduced annual cycle amplitude European wide comparing 1990-2001 with 2088-2099. It is concluded in (Pryor *et al*, 2006) that though there is generally little evidence for future changes in spatial or temporal variability of wind indices, this is uncertain due to model biases. In (Cradden et al. 2012) future projections for wind speed are shown comparing HadCM3 and ECHAM5 for several climate change scenarios. Both models indicated decreasing wind speeds during the summer and increasing during the winter by the end of the 21st century. However, this work also highlighted significant uncertainties and discrepancies between the models.

Another analysis of HadCM3 output data, considering the SRES A2A and B2A scenarios over the period 1990-2099 (Leckebusch and Ulbrich, 2004), showed projected increasing winter (Oct-Mar) 10m wind speeds over south-eastern England and slightly decreasing wind speeds over the north-west. However, in the same research, it was found that the regional HadRM3H model output gave a slightly different pattern with an increase to the north-east and a slight decrease in the central and southern UK. Although, differences are seen for the different climate change scenarios, research looking at the RCA3 RCM model suggests projected future change in 60m wind speeds across the British Isles for the period 2021-2060 with wind speeds increasing in the south-east and decreasing in the north of Scotland under the A2 scenario, albeit with some localised inhomogeneities across this south-north gradient (Nolan *et al*. 2012).

An analysis of nine simulations from six GCMs under the SRES A1B scenario (Donat *el al*, 2010) showed a projected future increase in storms in the Eastern Atlantic, near the British Isles and in the North Sea. The research also suggested an associated increase in storm intensity over large parts of central Europe towards the end of the 21st Century.

A simulation by the RCAO regional climate model of the percentage change in the 90th percentile of winter (DJF) daily maximum wind speed in Europe, between the 1961–1990 and the 2071– 2100 periods (Beniston *et al*, 2007) showed a projected gradient south-east to north-west with an increase in south-east Europe (5-10%) and a much lower increase in the north-west (0-2.5%). A further regional climate model analysis (Rockel and Woth, 2007) showed a projected change in the total number of storm peaks from 1961–1990 to 2071–2100, as simulated by the RCMs CHRM and CLM with a decline in the north-west and an increase in the south-eastern UK.

Recent UK climate projects have considered a range of meteorological variables, though projected changes to wind speeds over the UK are particularly uncertain. Nevertheless, the UK Met. Office Hadley Centre has produced two reports which are relevant in this regard. The first (Brown *et al*, 2009) suggests that there is evidence for an overall slight reduction in wind speeds over the UK, but largest in the north-west with possibly a slight increase in the south-east, most pronounced in the summer, by 2070-2099. The report does, however, note an RCM bias to lower than observed wind speeds in Scotland and Wales and higher in low-lying regions of England. The second report (Sexton and Murphy, 2010) suggests that averaged over the entire UK, there is expected to be a small reduction in mean wind speeds, though regional differences are not so clear. However, there is some evidence for a slight reduction in Scotland and a smaller reduction or no change in southern England by 2070-99. An analysis of the UKCIP02 climate change scenarios (Harrison *et al*. 2008) suggested by 2080, significant reductions in wind speeds over Northern Ireland particularly in the summer and smaller increases in Northern Scotland most notably in late spring/early summer. In England and Wales, wind speeds were projected to slightly reduce in the autumn and increase in winter.

2.3. A comparison of wind indices

With the growth in wind power world-wide, there has been an increased interest in assessing inter-annual variation in temporal 'windiness' of a region for the purposes of evaluating variability in wind energy generation. This is important from an economic viewpoint to know the variation in likely annual revenue from a wind farm over its lifetime. Wind indices fall into four broad categories:

- Those derived directly from surface wind speed observations, e.g. (Früh W-G. 2013, Hodgetts, 2011)

- Those derived from observations of wind energy generation, e.g. the Danish wind energy index (Nielsen, 2004), the German IWET index and Windex-CBS in the Netherlands;
- Those derived from pressure gradients in the form of geostrophic winds triangulated from site pressure observations, e.g. (Bakker and van den Hurk, 2012, Bärring and Fortuniak, 2009, Wang *et al.* 2009);
- Those derived from numerical weather prediction (NWP) models such as reanalysis data, with or without regional downscaling, e.g. (Pryor and Barthelmie, 2003, Pryor *et al*. 2006).

The first type of index relates directly to observations of surface wind speed and is thus capable of indicating variations in regional wind climate. The disadvantage of this type of index is the sensitivity to very localised effects. The second category has similar benefits and also relates directly to wind energy. However, changes over time of the portfolio of turbines used to generate such indices and non-availability of machines due to outages can create inhomogeneities (Bakker *et al.* 2012). The third and fourth categories have the advantage over the first two of filtering out most local scale anomalies due to factors such as local microclimates, local orography, changes in site exposure, changes in instrumentation, etc. On the other hand, using such spatially smoothed datasets can also mask local and regional differences in wind variability. Regional Climate Models (RCMs) can be used to try and downscale reanalysis datasets, but it has been found that the datasets so derived significantly underestimate inter-annual variability (Rasmussen *et al.* 2011). In addition, such models do not capture the variable spatial characteristics of the wind (Pryor *et al*. 2009, Pryor and Barthelmie 2010, Höglund *et al.* 2009).

Differences in surface wind speeds and large scale circulations have been reported by researchers (Vautard *et al.*, 2010) and much of the difference has been attributed to changes in surface roughness. Site specific gust factors were used in a study of meteorological stations in the Netherlands to assess the impact of surface roughness on long term wind speed trends suggesting an approximately equal influence of climate, large scale (mesoscale) surface roughness changes and local roughness changes (Wever, 2012). It is possible to distinguish to some extent the influence of these factors comparing trends inferred from different indices (Bakker *et al.* 2012). For example, indices inferred from pressure gradients and NWP models are relatively insensitive to changes in surface roughness.

3. DATA

3.1. Surface Observations from the UK MIDAS via the BADC

The UK Met Office produces a data set of land surface observations from 1853 to the present date. This data set is held on the Met Office Integrated Data Archive System (MIDAS) and is available via the British Atmospheric Data Centre (BADC). The MIDAS data set contains a large number of observations covering a variety of meteorological parameters including mean wind speed (British Atmospheric Data Centre, 2009). Wind observations are typically 10-minute means in knots, with the 10-minute mean recorded on the hour and are typically made at a height of 10m above the land surface, though this has not necessarily been the case historically as will be discussed later in this paper.

3.2. ERA-40 Re-analysis Dataset

The ERA-40 re-analysis was produced by assimilating a large number of different meteorological datasets including: satellite measurements, ship-borne and buoy observations, land-based surface observations, upper air measurements and remote sensing observations (Uppala *et al*, 2005). The assimilated data have been output onto both a 2.5^0 x 2.5^0 grid and a 1^0 x 1^0 grid at six hourly intervals covering the period 1957-2002. It should be noted that land-based surface wind speed observations were not used as input to the assimilation, though the assimilating model produces output surface wind speeds on the regular array of grid points including those over land. In this work, 10m values of the *u* (eastward) and *v* (northward) wind speed components from the $1^0 \times 1^0$ grid were used.

3.3. UKCIP Met. Office Gridded Dataset

Monthly and annual averages of a range of meteorological parameters, initially for the period 1961-2001, were generated by the UK Meteorological Office (Met. Office) using data observed from all of the available surface stations, with gaps in data filled to avoid biasing the results. Gap filling was carried out by spatially interpolating the missing data at a site from the six closest stations for 13 of the meteorological parameters, though not wind speed (Perry and Hollis, 2005a). In the case of wind speed, some data substitution was carried out, but the details of this are not reported (Perry and Hollis, 2005b). The resulting dataset was produced for the UK Climate Impacts Programme

(UKCIP) to provide a consistent time series of climatological variables which could be used in long term climate studies. The data have been interpolated onto a 5km x 5km grid using spatial interpolation and multiple linear regression taking into account a number of parameters including easting/northing, altitude, proximity to the coast, and local urbanisation. Errors in interpolating to this grid were assessed and for monthly mean wind speed, the root mean squared error was found to be 5.5 knots (2.8m/s). It should be noted that time-varying urban effects were not considered. No mention is made in (Perry and Hollis, 2005a, Perry and Hollis, 2005b) of any correction made for time-varying changes in instrument height. Station openings and closures over the period used to generate this climatological dataset meant that the number of stations used to infer the gridded climatological data has changed over the period. This will have some implications for continuity of the wind speed data. The average number of stations available for the generation of the wind speed gridded data over the period was 70. Here we have used the mean monthly values of wind speed which were available for the period 1969-2006.

3.4. The Garrad Hassan Wind Index

The renewable energy engineering consultancy company Garrad Hassan (now known as GL-Garrad Hassan) formerly published a UK wind index. When compared with other European indices this showed a reasonable level of agreement (Thomas *et al*, 2009). Although, the methodology behind this index and the exact list of stations used to generate the index was not publicised, it was stated by Garrad Hassan that this index was calculated using data from 50 meteorological stations spread throughout the UK

(Hodgetts, 2011). The index used in this work was a 13-year index normalised over the period 1995-2007.

4. METHODOLOGY

4.1. Criteria for Station Selection to Calculate Index from the BADC MIDAS Data

There are a large number of UK sites which report data to the Met. Office (~50,000) which are organised into a number of categories according to the type of data message produced. For a wind index, the most appropriate stations are in the synoptic network. These stations have an average spacing of less than 50km. Some of these stations are part of the global synoptic network and data are exchanged internationally in near real-time. It is thus expected that the synoptic network will have the most complete observational record and that the majority of these stations will continue to provide observations in the future. The availability of a complete record of observations is crucial for an accurate wind index. Future continuity is important as any index should be continually updated with new data. However, for the wind indices to be accurate they must be representative in terms of both temporal and geographical coverage. The observations from the synoptic stations within the MIDAS database did not alone meet these criteria and so the synoptic data were augmented with observations from selected stations within the Met Office climatological station network. Two indices were generated from the MIDAS data: one for the period 1983 to 2011 (29-year index) and the second for the period 1957 to 2011 (55-year index). The first index was generated to encompass a relatively large number of stations with a good geographical coverage. The second index was constructed with the purpose of producing as long a continuous index as possible but still encompassing a representative number of sites.

Prior to the selection of the stations, a quality assessment procedure was applied to the data to avoid discrepancies and erroneous, missing or duplicated values. The MIDAS data contain a number of quality flags relating to the recorded values. For the mean wind speed, a value of zero in the associated quality flag indicates an unreliable observation. In order to exclude any unreliable records, a condition was set that observations would be included only if they met the non-zero quality flag criterion. As a consequence of this criterion, there were significant gaps in the data for some stations. Therefore, a supplementary criterion for selecting the stations was the completeness of the data recorded and stored. An initial requirement was set for the total available recorded hours to be ≥75% of the total theoretical hours. The availability figure of 75% was chosen so that there were enough data to accurately represent the wind climate at each individual station but not to exclude too many stations from the index. Similarly, the available recorded hours per annum had to be ≥75% of total number of hours in the year. A further criterion was that any station that met the previous requirements must have no more than 15 days per month (i.e. half of each month) of missing consecutive records. If so, the station was excluded. This was necessary as long periods of missing data would skew the results by missing some of the seasonal variation. In fact, once this initial criterion had been set, the actual average availability of data for the stations filtered was 98% with the lowest individual station data availability being 89% as shown in Table 2. A final criterion was set that the stations used in the study were still operational. The reason for this being the intention that a future consistent index could be maintained. When the criteria were applied, 57 stations were included in the 1983-2011 BADC MIDAS Index and from these 57 stations (known henceforth as the

BADC-57 stations), 7 stations were selected to be included in the 1957-2011 BADC MIDAS Index (known henceforth as the BADC-7 stations). The reason for the much lower number of stations for the longer index was simply that fewer stations met the required criteria over this much longer period. Each station was assigned to one of six UK regions, based on its geographical location. The BADC-57 and BADC-7 stations selected are as shown in Table 2 along with their UK Met. Office station identifier, region number to which they have been allocated and data availability for the 29-year and 55-year index (if applicable). Figure 1 shows a map of the stations.

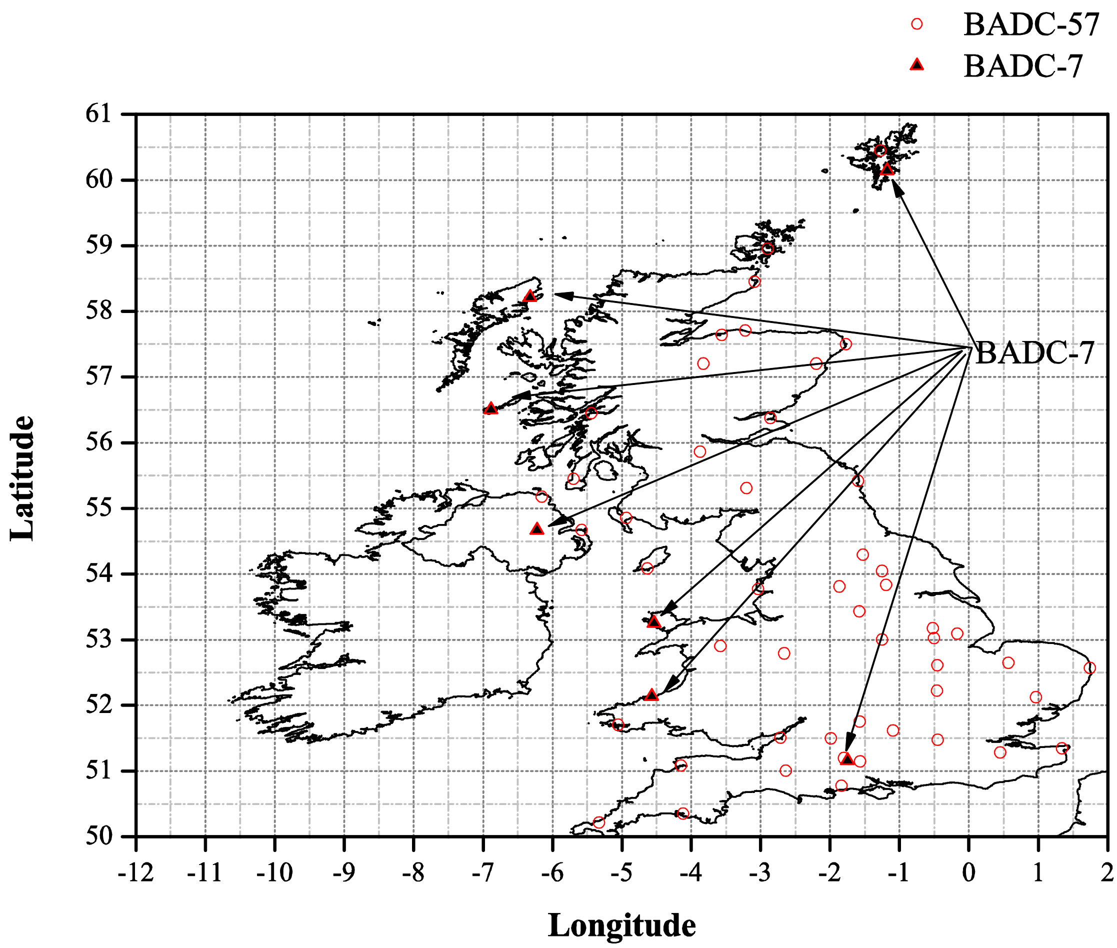

Figure 1: The BADC-57 (open circles) and BADC-7 (closed triangles) stations used in the generation of the 29-year and 55-year indices, respectively. Latitude and longitude are in degrees north and east respectively.

4.2. Analysis of local factors that may affect wind speed measurements

The principal difficulty in producing a reliable wind index based on observed surface wind speed measurements is ensuring consistency and homogeneity of the data. Over time, site exposure can change, instruments can be replaced or recalibrated and measurement heights or locations can be altered.

Instrument and height measurement changes

Using information from the UK Meteorological Office Archive, instrument changes were deduced for the BADC-7 and BADC-57 stations. Table 3 summarises the changes for the BADC-7 stations used in the study. It can be seen that on average four different instruments were used to record wind speed over the 55-year period of interest. Different types of anemometers have been used at different periods. The Dines pressure tube type anemometer tended to have a better response to lower wind speeds than the Munro anemometer (British Atmospheric Data Centre, 2009). In addition, the newer Vector anemometers have a better response at lower wind speeds than the Munro type. These facts will have some biasing effect on the wind speed measured, though it is difficult to quantity this. It is also worth noting that the effective height of measurement has also changed significantly over the period, generally reducing over time, though there are some exceptions to this, e.g. Lerwick.

In order to ensure a consistent height for all wind speed values, wind speed data at all sites (both the BADC-7 and BADC-57 stations) were corrected to an effective height of 10m using an adiabatic logarithmic profile:

$$u = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (1)$$

where u is wind speed at the height of interest z, u_* is the friction velocity in the surface layer (assumed constant), κ is von Kármán's constant (=0.4) and z_0 is the surface roughness length assumed to be 0.03m for all sites. This value is appropriate for short grass which is typical of a rural meteorological station. Figure 2 shows an example of the annual mean wind speed values for Boscombe Down with and without correction to an effective height of 10m. It can be seen in this case that the correction makes a significant difference to the wind speed values in the earlier years of the time series.

The value of roughness length (0.03m) was chosen as being fairly representative of a rural site. It is possible that this might vary anywhere in the range of 0.01m to 0.08m for the sites studied. Therefore, a sensitivity analysis of the change in wind speed as a function of roughness length between 0.01m and 0.08m was performed. However, it was found that there was negligible difference to the wind speed when corrected to 10m using this range of roughness values.

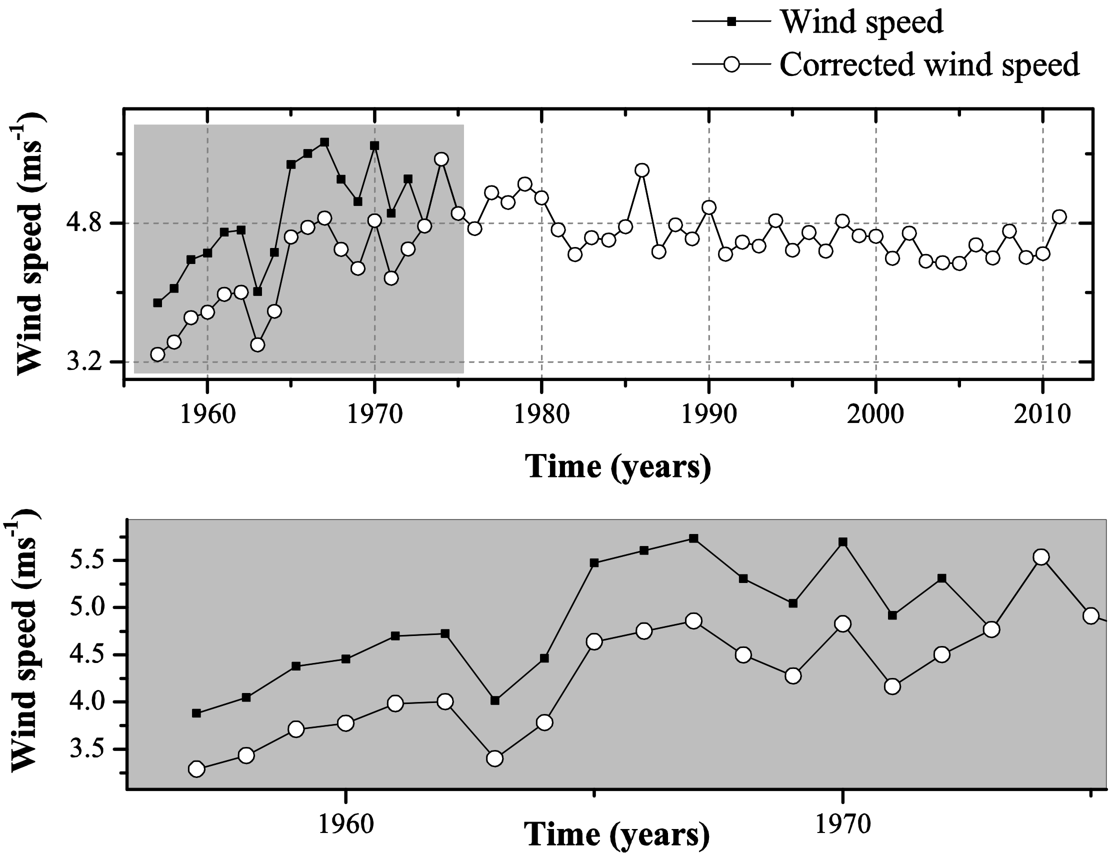

Figure 2: Time series of annual mean wind speeds at Boscombe Down with and without height correction to 10m above ground level. The lower plot shows the grey section expanded for clarity.

Site exposure

In producing the 55-year index, the BADC-7 stations were partly chosen to ensure that they were isolated rural sites to avoid changes associated with urbanisation. Figure 3 shows wind roses for the seven sites. In each case, the wind is shown to come predominantly from between the south and the west which is common for UK sites, though Valley, on the west coast of Anglesey, North Wales, shows a relatively large proportion of winds from the East. This is due to the different topographical features of the sites. According to (Lapworth and McGregor, 2008), the high ground over Wales, northern England and Scotland has a significant effect on the pressure gradient, as the isobars back (turn anti-clockwise) over the western coasts and veer (turn clockwise), over the eastern half of the country. There is no obvious evidence for significant sheltering at any of the sites.

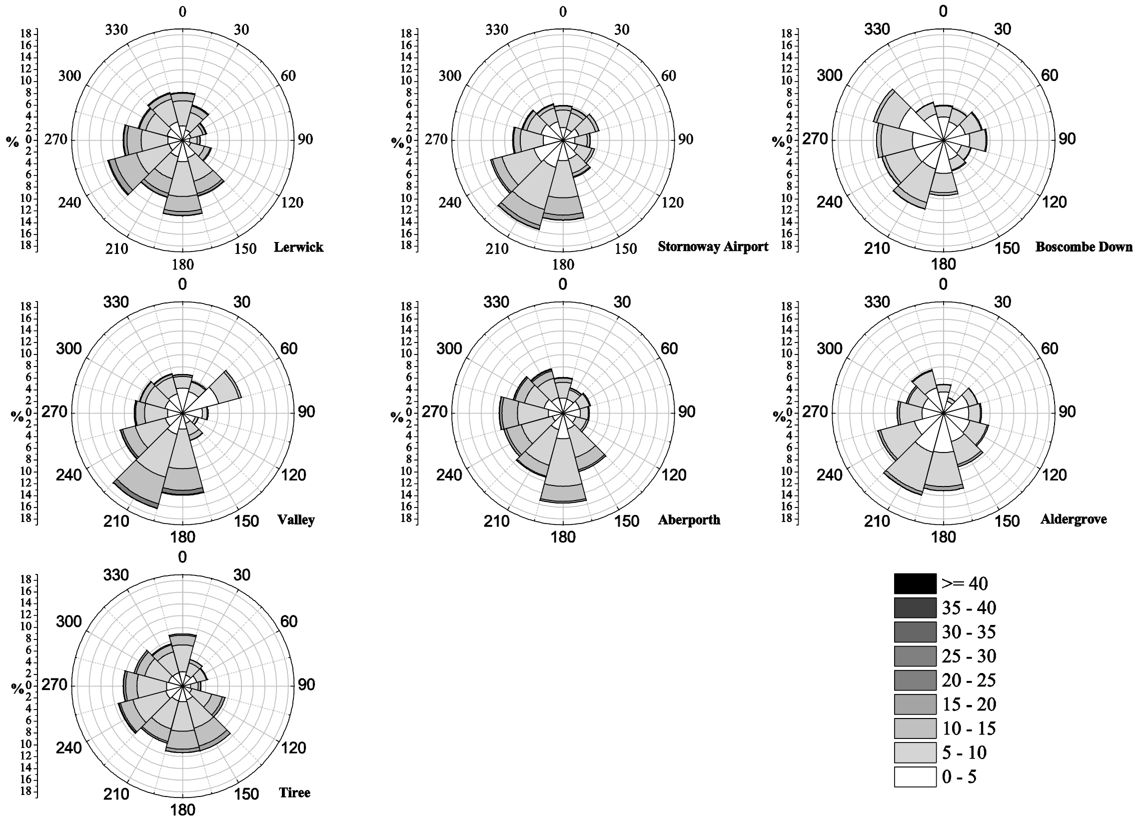

Figure 3: Wind roses for the seven sites used to construct the 55-year index.

In addition, the mean wind speed by direction was examined over time to see whether there was any evidence of changes in site exposure. Figure 4 to Figure 6 show the annual mean wind speed by 30 degree direction sector for three of the BADC-7 stations (Stornoway, Aldergrove and Tiree). The grey shading represents one standard deviation calculated from the hourly values in each year. In each case a standard least squares linear fit is made to the yearly wind speed values over the period 1957 to 2011 and 95% confidence limits on the equation for the fit are shown. Stornoway Airport (Figure 4) shows an overall decline, but in all direction sectors, the wind speed declines from 1957 to the early 1990s and then shows an increase. An analysis of gale days for Stornoway Airport over the period 1884-1996 (Dawson *et al*, 2002) shows a steady decline from around 1940 to the early 1980s and then evidence for an increase thereafter which is broadly consistent with the present analysis, albeit that the upturn seems to start around a decade earlier. Although, there is not a direct correspondence between wind speed extremes and mean wind speeds, the two should show similar trends. The fact that the same trend is seen by direction sector would suggest that this trend is synoptic rather than exposure related, though it is difficult to be definitive. Aldergrove (Figure 5) shows some decline in wind speed but this is in all directions. There is evidence of some urbanisation to the south-east of the site, but for directions between the south-west and the north, the site is open with Lough Neagh 3km to the west. Therefore, changes in wind speed at this site are unlikely to be due to changes in exposure. Tiree (Figure 6) shows evidence of some decline in wind speed to the east to south-east, however, this site is extremely exposed, so it is unlikely that such a change is due to increased shelter and the wind blows least frequently in these sectors. The remaining sites do not show any significant trends by direction sector when considering the level of inter-annual variation.

It should be stressed that the analysis above does not rule out changes in local exposure as a factor in any changes in long-term mean wind speeds, but no significant anomalies would appear to be present. In addition, changes to levels of mesoscale roughness due to long-term changes in land usage over a wide area cannot be ruled out.

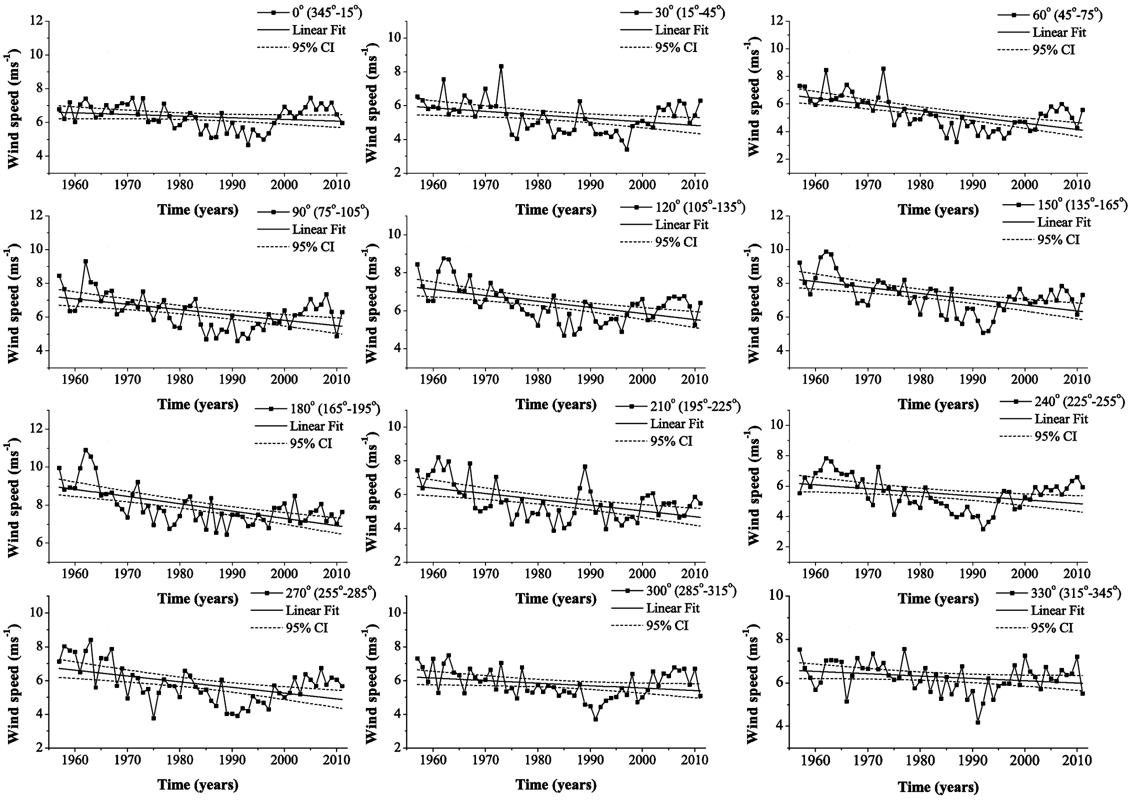

Figure 4: Mean wind annual wind speed by 30 degree direction sector for Stornoway Airport.

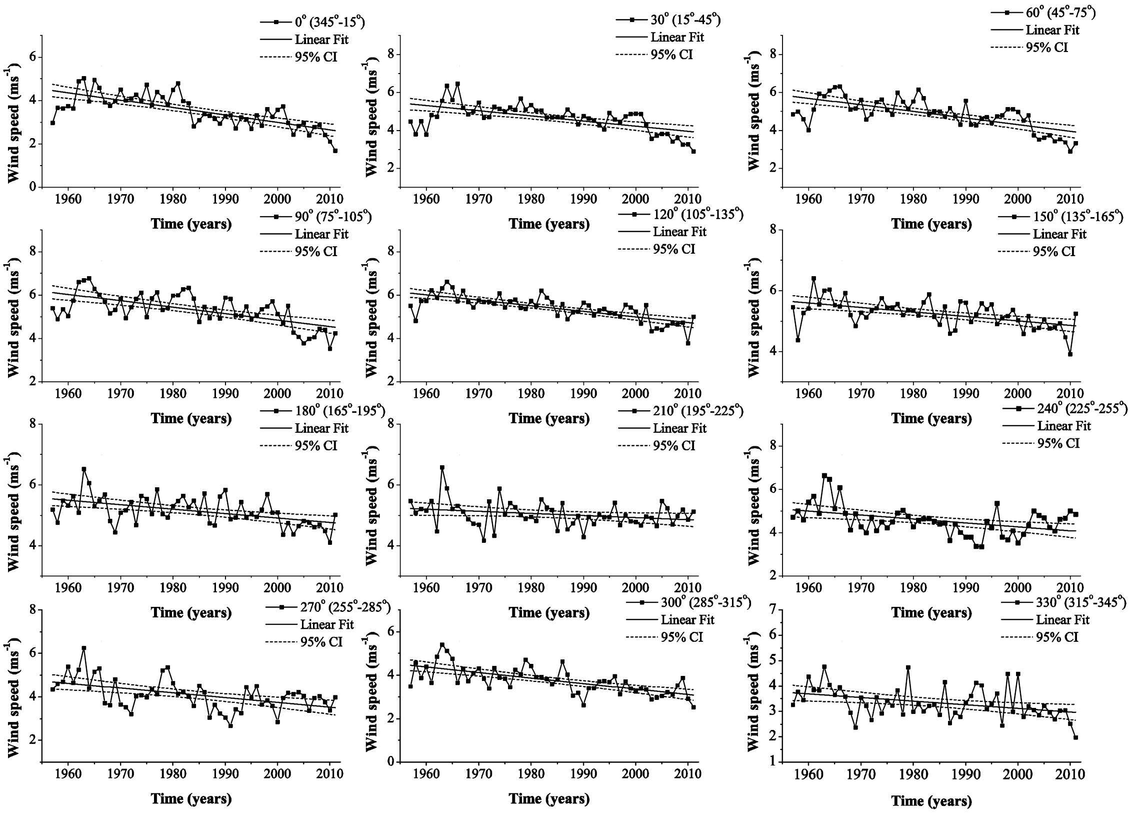

Figure 5: Mean wind annual wind speed by 30 degree direction sector for Aldergrove.

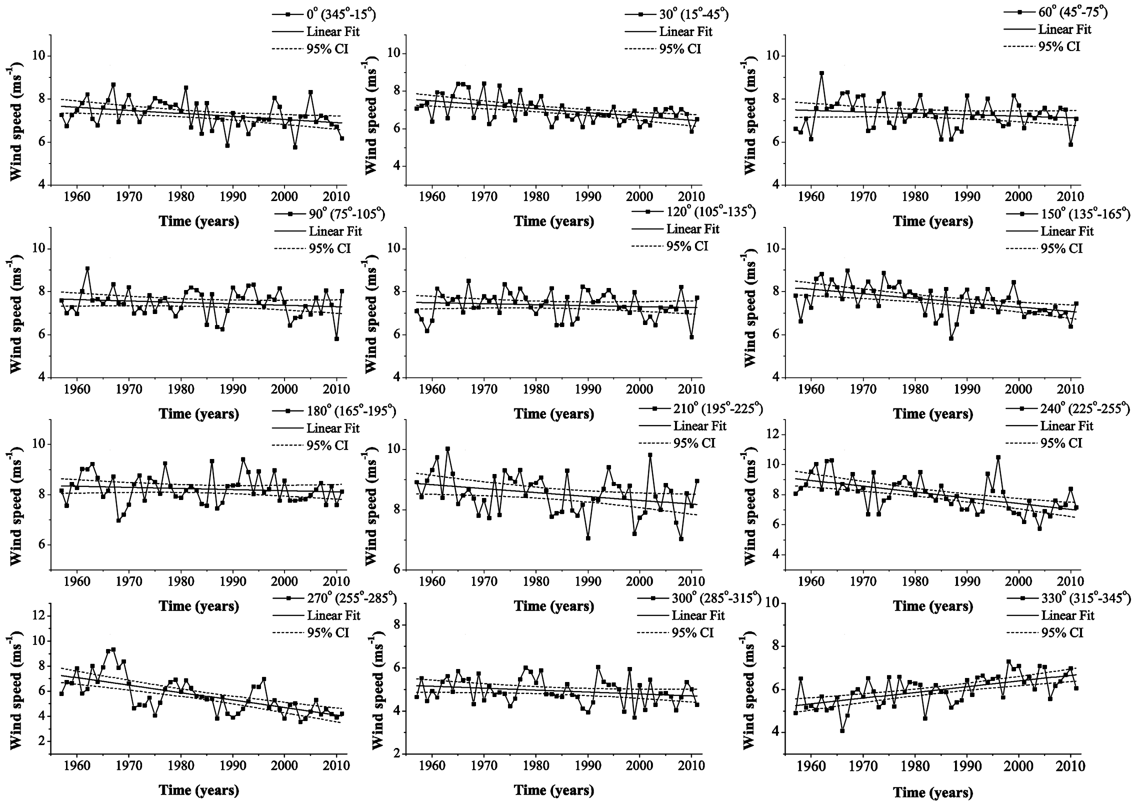

Figure 6: Mean wind annual wind speed by 30 degree direction sector for Tiree.

4.3. Calculation of the different indices

A wind index, I_j is normally defined as the average wind speed over a region for a given averaging period divided by the overall average wind speed over that region over the normalisation period of interest, i.e.:

$$I_j = \frac{\frac{1}{n}\sum_{k=1}^{n}\left(\frac{1}{m_j}\sum_{i=1}^{m_j} U_{i,j,k}\right)}{\frac{1}{l}\sum_{j=1}^{l}\left(\frac{1}{n}\sum_{k=1}^{n}\left(\frac{1}{m_j}\sum_{i=1}^{m_j} U_{i,j,k}\right)\right)} \quad (2)$$

Where $U_{i,j,k}$ is the wind speed at station (or grid point) k and time i within averaging period j. The value m_j depends on the number of values in the averaging period j and the number of sites (or grid points) used to generate the index is n. The normalisation period consists of l averaging periods. For example, if an annual index is being generated over a period of l years, then m_j would be the number of hours in year j.

Indices were calculated using Equation 2 from:

1. the hourly wind speed values from the BADC-7 and BADC-57 stations;
2. six-hourly wind speed values from the $1^0 \times 1^0$ u (eastward) and v (northward) $10m$ wind speed components of the ERA-40 reanalysis dataset averaged over the UK extending from 8^0W to 2^0E and 51^0N to 60^0N (132 grid points);
3. six-hourly wind speed values bilinearly interpolated to the BADC-7 and BADC-57 stations from the $1^0 \times 1^0$ u (eastward) and v (northward) $10m$ wind speed components of the ERA-40 reanalysis dataset;
4. monthly wind speed values at the 5km × 5km grid points covering the UK from the UKCIP Met. Office gridded data set.

Table 1 summarises the parameters used in Equation 2 for the generation of the different indices. The BADC indices were calculated over several normalisation periods for comparison with the indices calculated using the ERA-40 reanalysis data and the UKCIP Met. Office gridded dataset. In the case of the Garrad Hassan index, this was pre-calculated. The details of how this was done are not publicised, but given that it is based on observed hourly values, the calculation will be done using an equation similar to Equation 2 with a normalisation period $l = 13$ years.

5. RESULTS

5.1. The annual 29-year and 55-year UK wind indices

Figure 7 shows the 29-year and 55-year wind indices based on the BADC-57 and BADC-7 stations respectively. Standard least squares linear trend line fits to each series are shown with 95% confidence limits on the slope of each line. The values of each index are tabulated in Table 4. In the case of the BADC-7 index, the value is tabulated normalised to the full 55-year period and to the 29-year period concurrent with the 29-year index derived from the BADC-57 stations.

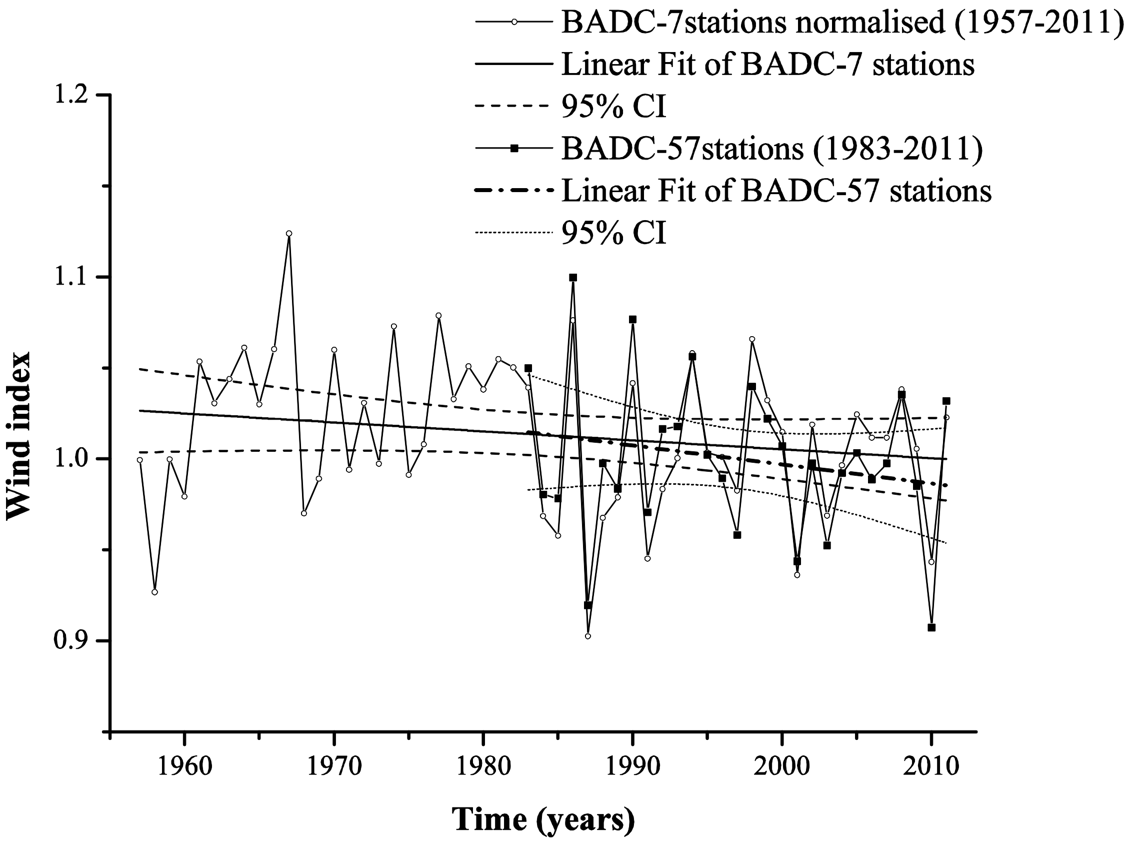

Figure 7: The 29-year and 55-year wind indices with linear trend line fits to each series.

There is a good degree of agreement between the two indices for the period 1983-2011 with a Pearson correlation coefficient of 0.89. Averaged over the longer 55-year period, there does not seem to be any significant change in annual mean wind speeds, though there is a slight decrease when averaged over the shorter 29-year period. It can be seen that from the late 1950s until the late 1960s, there was a significant increase in annual mean wind speeds followed by a rapid decrease and another increase throughout the 1970s into the early 1980s. Between the mid-1980s and 2011, there have been some significant low wind speed years including 1987, 2001 and 2010. Although 2010 was the lowest wind speed year over the 29-year period, it was not unusual when compared with the 55-year period, an observation consistent with (Früh, 2013). The standard deviation of both indices was found to be 0.04.

Figure 8 shows a comparison between the BADC-7 station wind index calculated over the shorter normalisation period 1958-2001 for comparison with the wind index calculated using the ERA-40 reanalysis data averaged over the UK. It can be seen that the BADC-7 index shows a slight declining trend whereas the ERA-40 data shows a slight increasing trend over the same period. The features in the two series are similar, but there are also noticeable differences. Figure 9 shows a similar comparison between the BADC-7 index and the wind index calculated using the ERA-40 reanalysis data interpolated to the locations of the seven stations over the period 1958-2001. The two indices show similar behaviour, though in the latter half of the period, there is some difference. In this case, both indices show a slight decline with the ERA-40 index showing a greater decline than the BADC-7 station index.

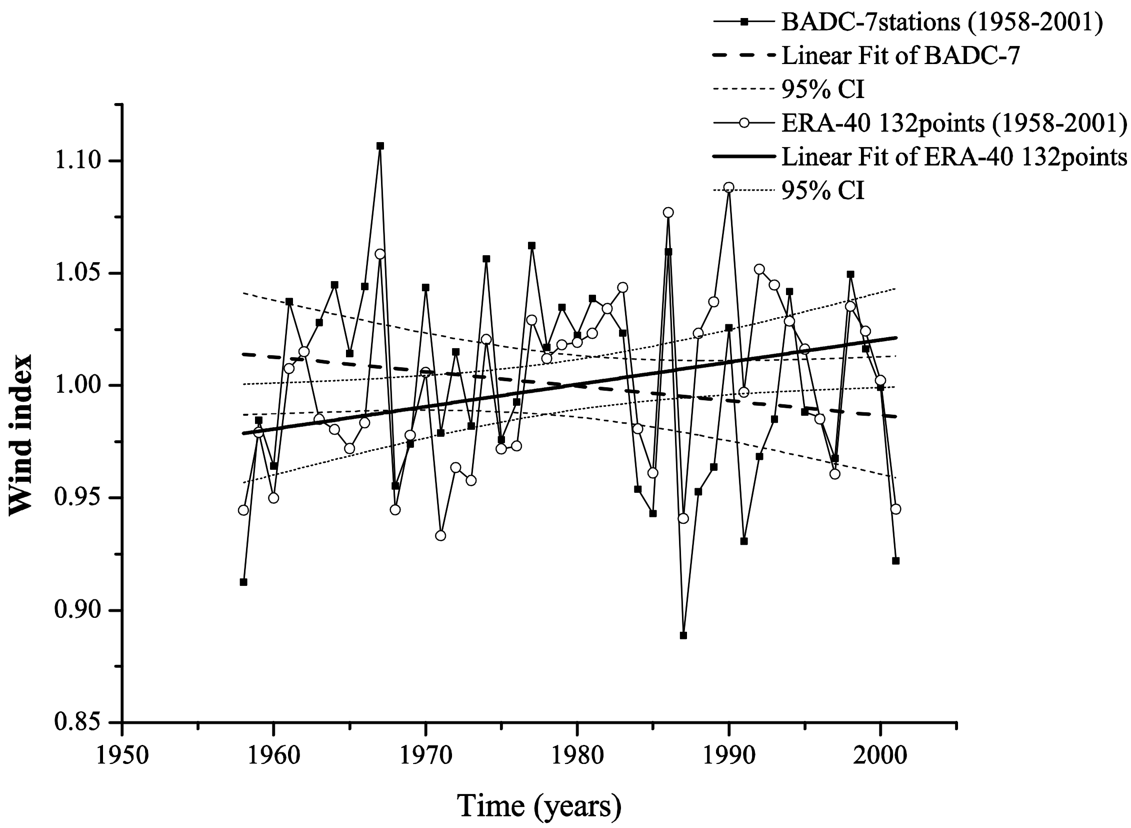

Figure 8: A comparison between a wind index calculated using the BADC-7 stations and ERA-40 averaged over the UK over the period 1958-2001.

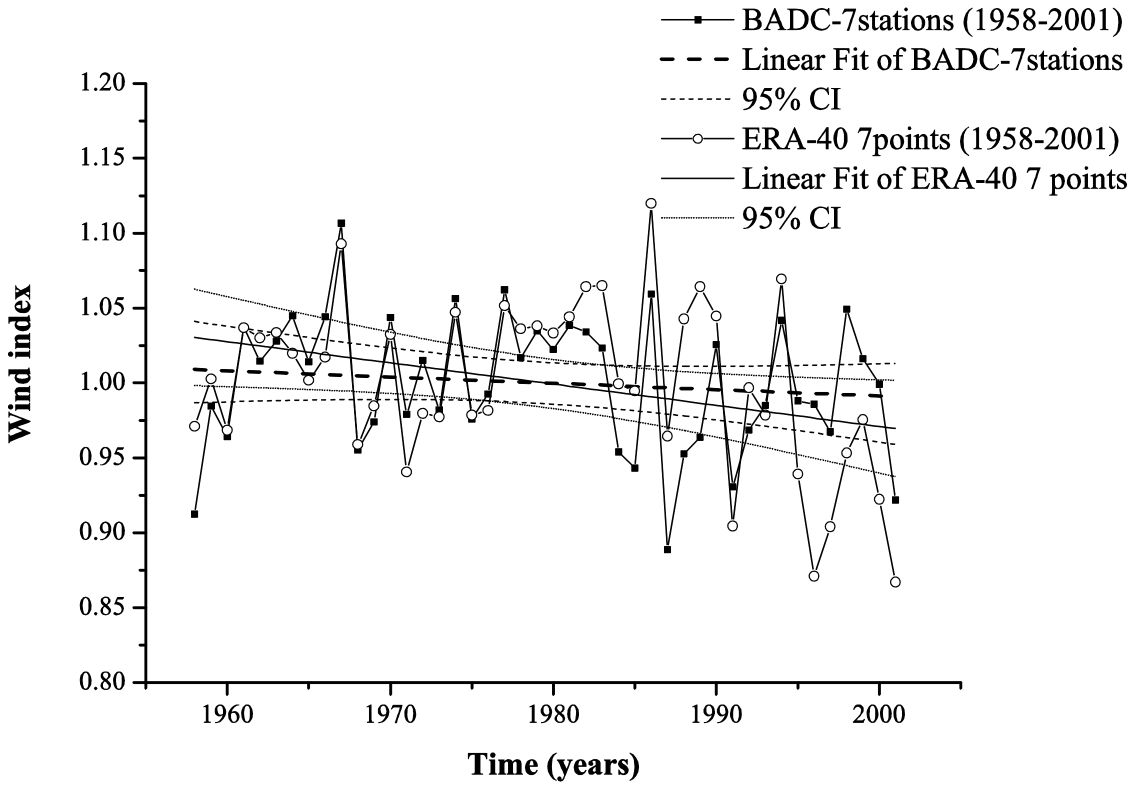

Figure 9: A comparison between a wind index calculated using the BADC-7 stations and ERA-40 data interpolated to the same sites over the period 1958-2001.

Figure 10 shows a comparison between the index calculated using the BADC-57 stations and one using the ERA-40 data averaged over the UK over the period 1983-2001. The trends are very similar over the period and the features also show relatively good agreement. Figure 11 shows a similar comparison, this time between the index calculated using the BADC-57 stations and one using the ERA-40 data interpolated to the locations of the 57 stations over the period 1983-2001. In this case, the difference in the trend over the period is more marked with the ERA-40 data showing a steeper decrease.

Figure 12 shows a comparison between the index calculated using the BADC-7 stations and the one generated using the UKCIP Meteorological Office gridded dataset for the period 1969-2006. The agreement is relatively good, as would be expected given that the UKCIP dataset was generated using observed surface station wind speed data, though there is a more steeply declining trend in the latter index. This also might be expected given that the UKCIP dataset includes data from a large number of stations including more urbanised stations whose exposure is likely to have changed over time with increasing shelter more likely.

Finally, Figure 13 shows a comparison between the index calculated using the BADC-57 stations and the Garrad Hassan index over the period 1995-2007. Here agreement is good but with a more sharply declining trend for the Garrad Hassan index.

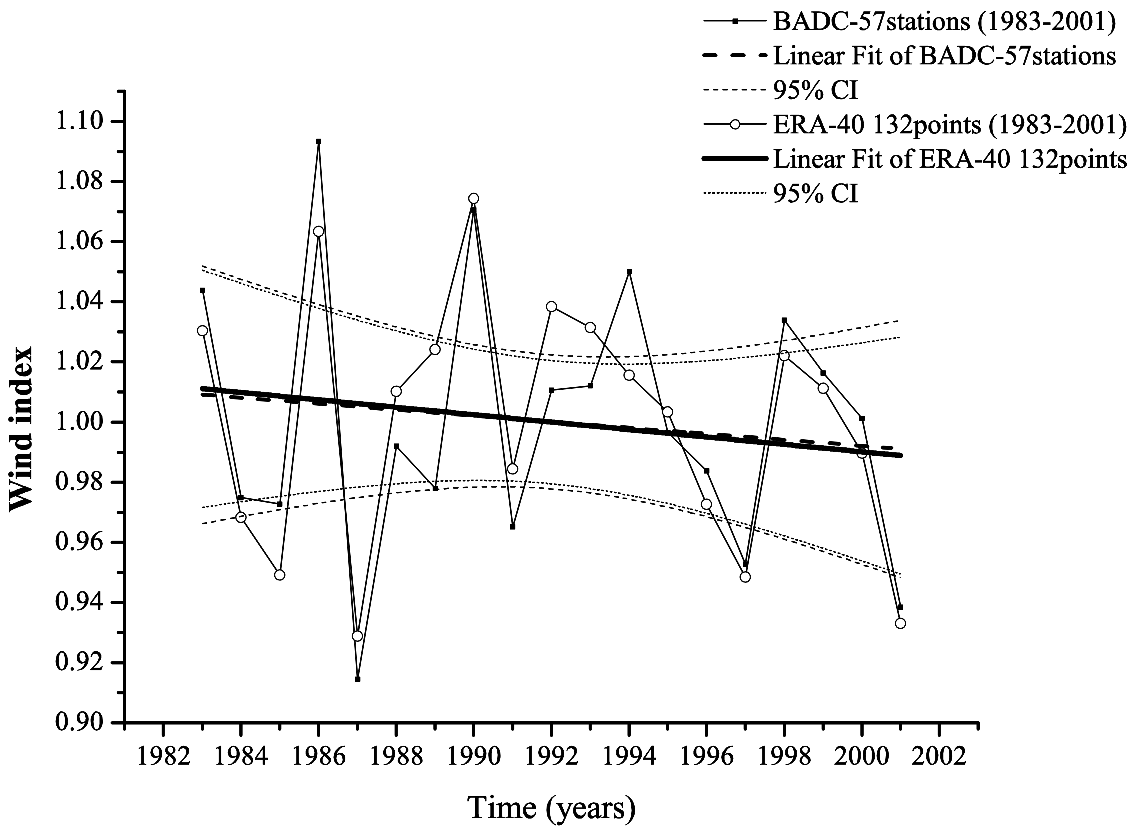

Figure 10: A comparison between a wind index calculated using the BADC-57 stations and ERA-40 data averaged over the UK over the period 1983-2001.

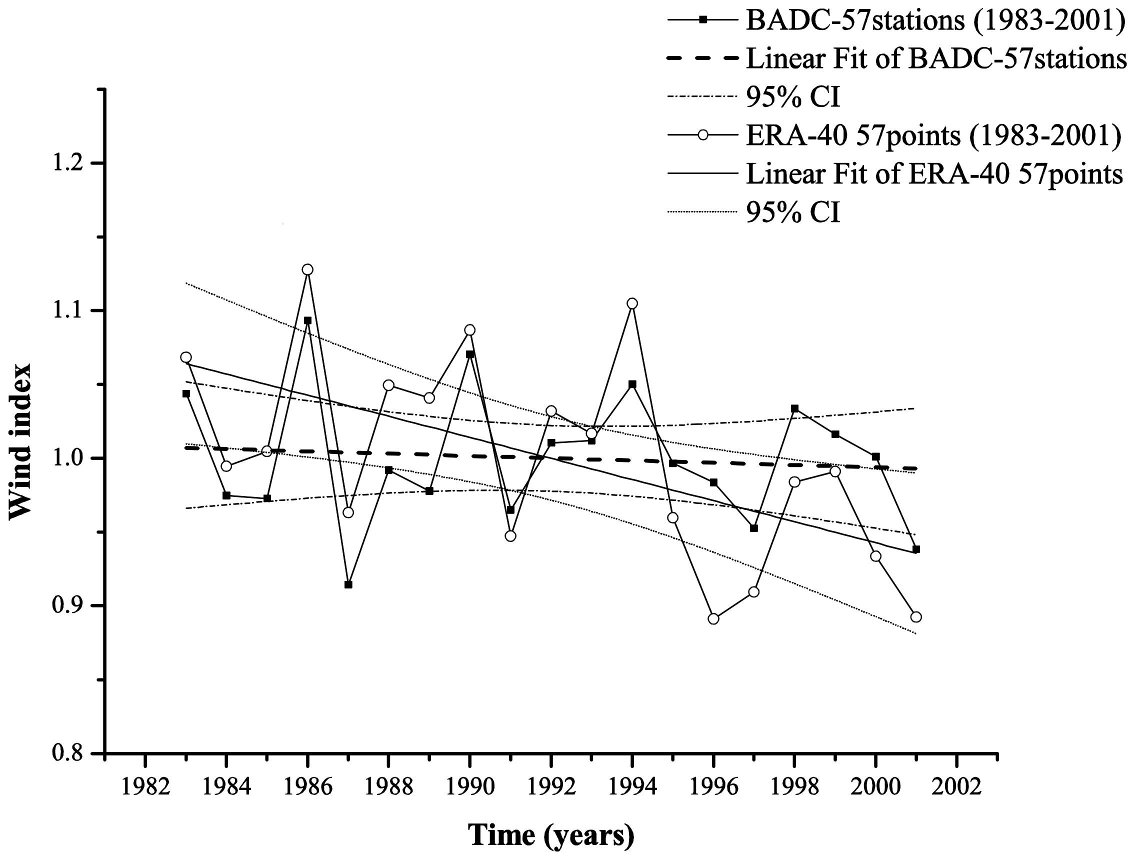

Figure 11: A comparison between a wind index calculated using the BADC-57 stations and ERA-40 data interpolated to the same sites over the period 1983-2001.

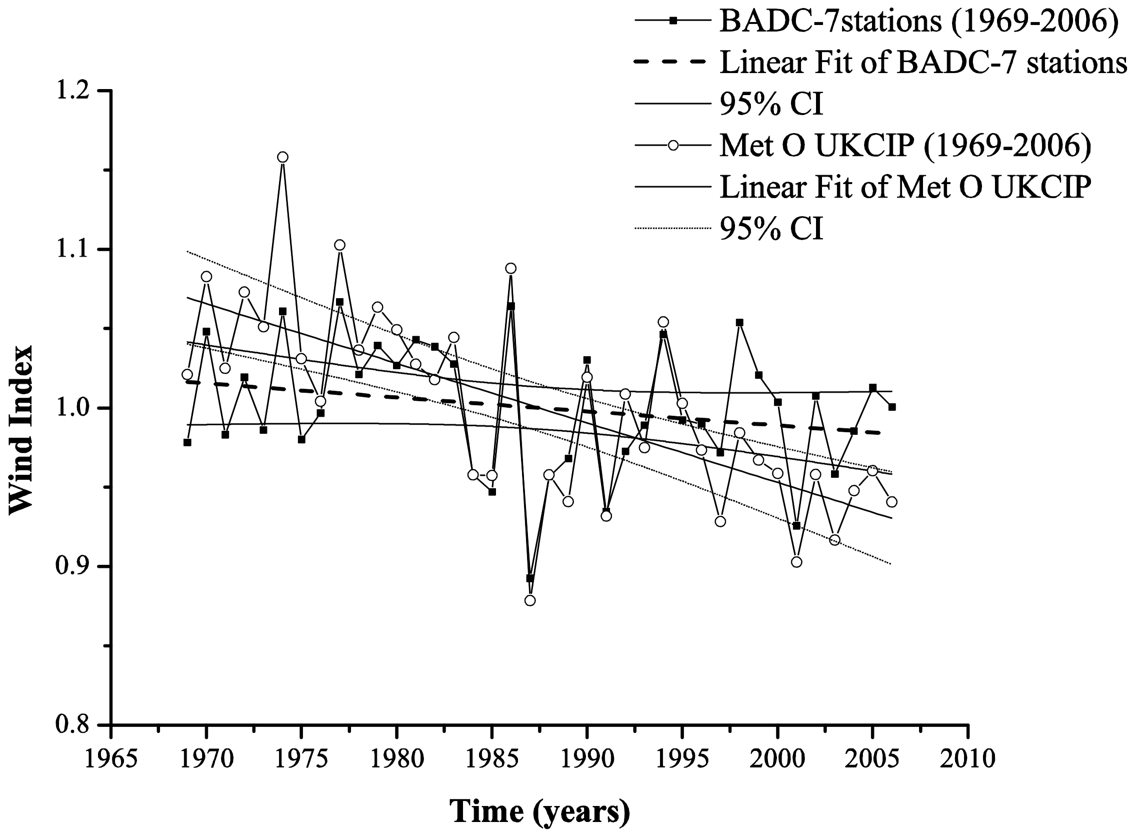

Figure 12: A comparison between a wind index calculated using the BADC-7 stations and the UKCIP Meteorological Office gridded dataset over the period 1969-2006.

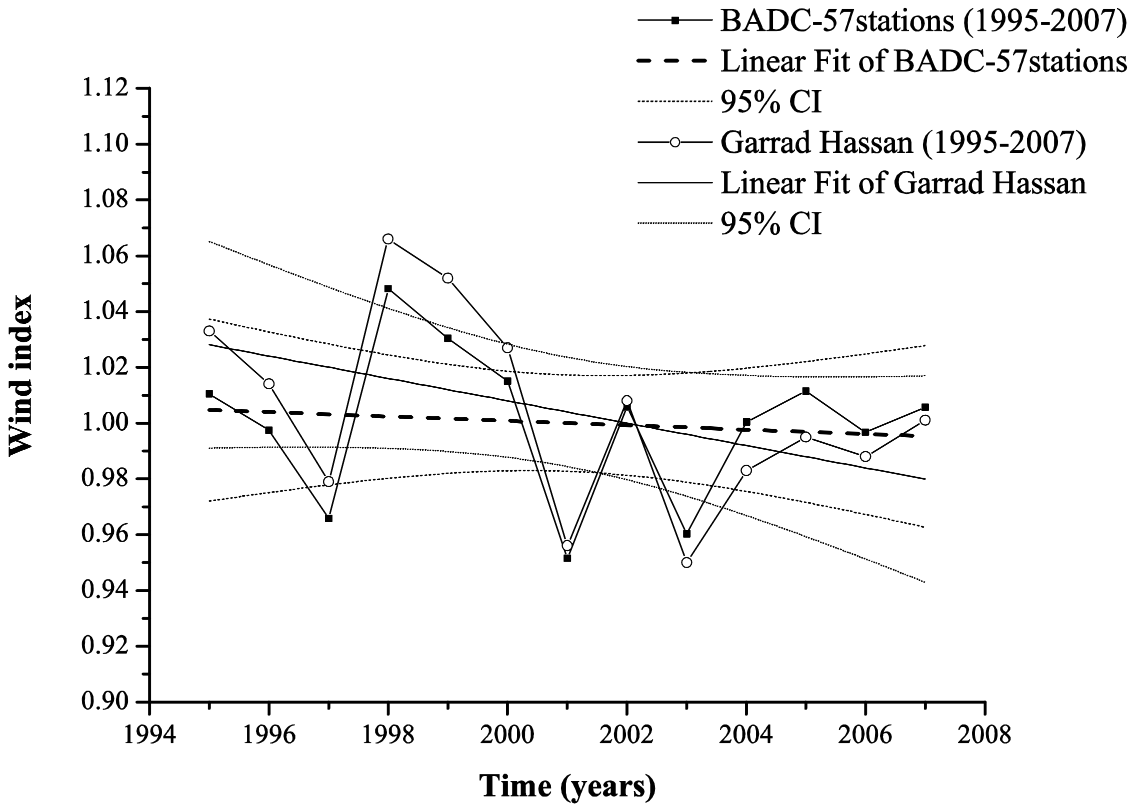

Figure 13: A comparison between a wind index calculated using the BADC-57 stations and the Garrad Hassan index over the period 1995-2007.

5.2. Trends of the Different Indices

An analysis was made of the long term trends of each of the indices for comparison and the result is shown in Table 5. All the indices show a declining trend (between -0.05% per year and -0.71% per year) with the exception of that derived for the whole UK using the ERA-40 reanalysis data (+0.1% per year). The significance of each trend has been assessed using the non-parametric Mann-Kendall test (Mann, 1945) and the associated F-statistic reported. The only trends which are seen to be significant at the 5% level are those for the indices derived from the ERA-40 reanalysis data for the UK, the ERA-40 reanalysis data interpolated to the BADC-57 sites and that derived from the UKCIP data. Table 5 also shows the standard deviation of each index over the relevant period with and without the trend removed. The BADC-7 and BADC-57 indices show a standard deviation of 4.3% (4.2% detrended). The largest level of variation is seen for the ERA-40 index interpolated to the BADC-57 sites with a standard deviation of 7.0% (5.7% detrended).

Strictly, the Mann-Kendall test assumes no autocorrelation in the data. To assess this, autocorrelations for the de-trended indices were assessed up to a lag of 10 and the results shown in Table 6. Those autocorrelations significant at the 5% level are marked in bold according to the formula: $1/N \pm 2/\sqrt{N}$, where N is the number of annual values in each series. It can be seen that there is little evidence of autocorrelation in any of the series. Although the Garrad Hassan index appears to show significant autocorrelations at high lags, the significance level is not valid for these lags for such a short time series (N=13).

The difference in trends and variability between the indices are partly due to the different periods over which they have been calculated. However, much of the difference will be due to the different levels of spatial averaging. The ERA-40 index averaged over the UK includes all grid cells in a square box over the UK, some of which will be over areas of sea as well as land in contrast to the other indices. The largest decreasing trends are seen for the ERA-40 index interpolated to the BADC-57 sites, the UKCIP index and the Garrad Hassan index. The ERA-40 index interpolated to the BADC-7 sites shows a steeper decline than the BADC-7 index (-0.14% per year compared with -0.05% per year) but neither trend is significant. This would suggest that local or large scale (mesoscale) changes in surface roughness do not appear to be significant, at least for the BADC-7 sites. The UKCIP index shows a steeper (significant) level of decline (-0.38% per year) than the BADC-7 index over a similar period of time. This suggests that changes in local surface roughness or instrument measurement height might be a factor.

The steepest rates of decline are seen in the ERA-40 index interpolated to the BADC-57 stations for the period 1983-2011 (-0.71% per year) and the Garrad Hassan index for the period 1995-2007 (-0.40% per year) which suggest a more significant decline in wind speeds in recent times, though the BADC-57 index over a similar period shows a much smaller decline (-0.10% per year) which is not seen to be significant. Again, as the ERA-40 index is not sensitive to changes in surface roughness, changes in surface roughness (which are likely to be positive) are not likely to be a factor. The fact that the ERA-40 index averaged over the UK shows a positive and significant trend (+0.10% per year) suggests either the coupling between surface and upper level winds has changed over time, or that wind speeds over the sea have increased over the period in contrast to that seen for the land-based grid points.

The Garrad Hassan index shows the lowest level of variability though this is likely due to the shorter period over which this index is calculated. The ERA-40 index averaged over the UK shows the least variability which may be due to the fact that this averaged over the largest area and includes some areas of sea where wind speeds are less variable. The ERA-40 index interpolated to the BADC-57 sites shows the greatest variability which would be consistent given the concentration of land-based sites upon which the index is based.

5.3. Correlation Between the Different Indices

In order to quantify the degree of agreement between the different indices, the Pearson correlation coefficient was calculated using selected combinations of the concurrent annual index values. The value was calculated before and after any long term linear trend was removed. The results of this analysis are shown in Table 7. There is a high degree of correlation between the indices calculated using the surface station data, i.e. the BADC-7, BADC-57 and GH indices. The correlation between the BADC-7 and ERA-40 index is somewhat lower. The BADC-7 index is calculated using a relatively small number of point observations whereas the ERA-40 index is more spatially homogeneous. In addition, the ERA-40 index is based on six-hourly rather than hourly data, though this should still capture the main features of diurnal variation and is unlikely to introduce bias. The correlation between the BADC-57 and ERA-40 index is better. This is consistent with the previous observation in that 57 stations will provide a higher degree of spatial smoothing. The correlation between the BADC-7 and the UK Met. Office gridded dataset lies somewhere in between. Both are generated with surface observations, though the latter would be expected to exhibit a greater degree of spatial smoothing given the much larger number of stations used to generate the 5km × 5km grid.

In order to analyse the degree of spatial smoothing of the BADC-7 stations, the Pearson correlation coefficient was calculated between each combination of the seven sites using the annual mean wind speeds at each site. The results of this are shown in Table 8. In addition, the correlation coefficient is plotted as a function of distance in Figure 14. The overall level of correlation even at relatively short distances is relatively low and shows significant scatter. It can be seen that the degree of correlation reduces with distance. The highest correlation is between Aldergrove and Tiree (0.731) which are ~200km apart. It is noticeable that beyond a separation of ~600km (in the predominantly north-south direction) that the sites show some weak anti-correlation. As it is unlikely that all of the sites have unusual climates, then it would seem that annual windiness is quite site-specific in general.

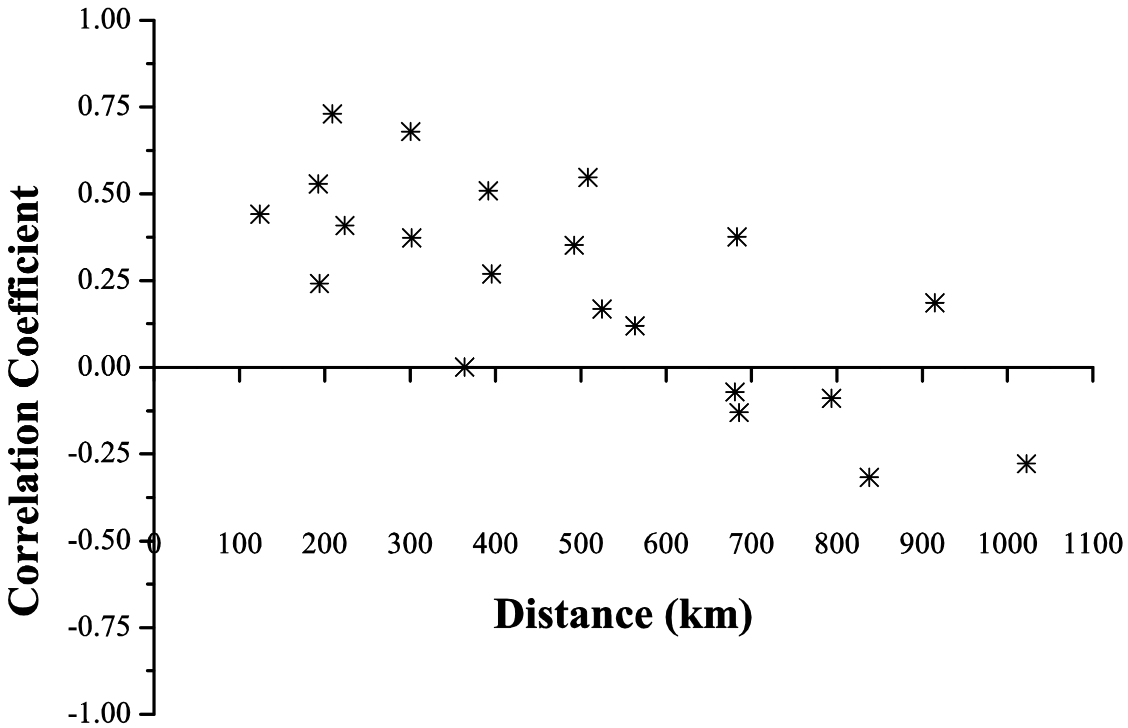

Figure 14: Pearson correlation coefficient calculated using the annual mean wind speeds at the BADC-7 sites as a function of the distance between the different site combinations.

5.4. UK Annual Regional Wind Index

Using the BADC-57 stations, a wind index was calculated by region for the period 1983-2011 using Equation 2 sub-setting the stations by the six regions as denoted in Table 2. The number of sites by region was: North-West: 6, North-East: 10, Central-

West: 9, Central-East: 10, South-West: 13, South-East: 9. Figure 15 shows this wind index for the six regions. It can be seen that there is a general trend to decreasing wind speeds in all regions except the south-east which shows a slightly increasing trend. The largest decreasing trend is in the north-west. When these trends were analysed in more detail, it was found that the greatest declines occurred in the winter months and the smallest in the summer, with the south-east region showing a significant increasing trend during the summer months. It should be stressed that these trends are tentative given the large degree of inter-annual variation.

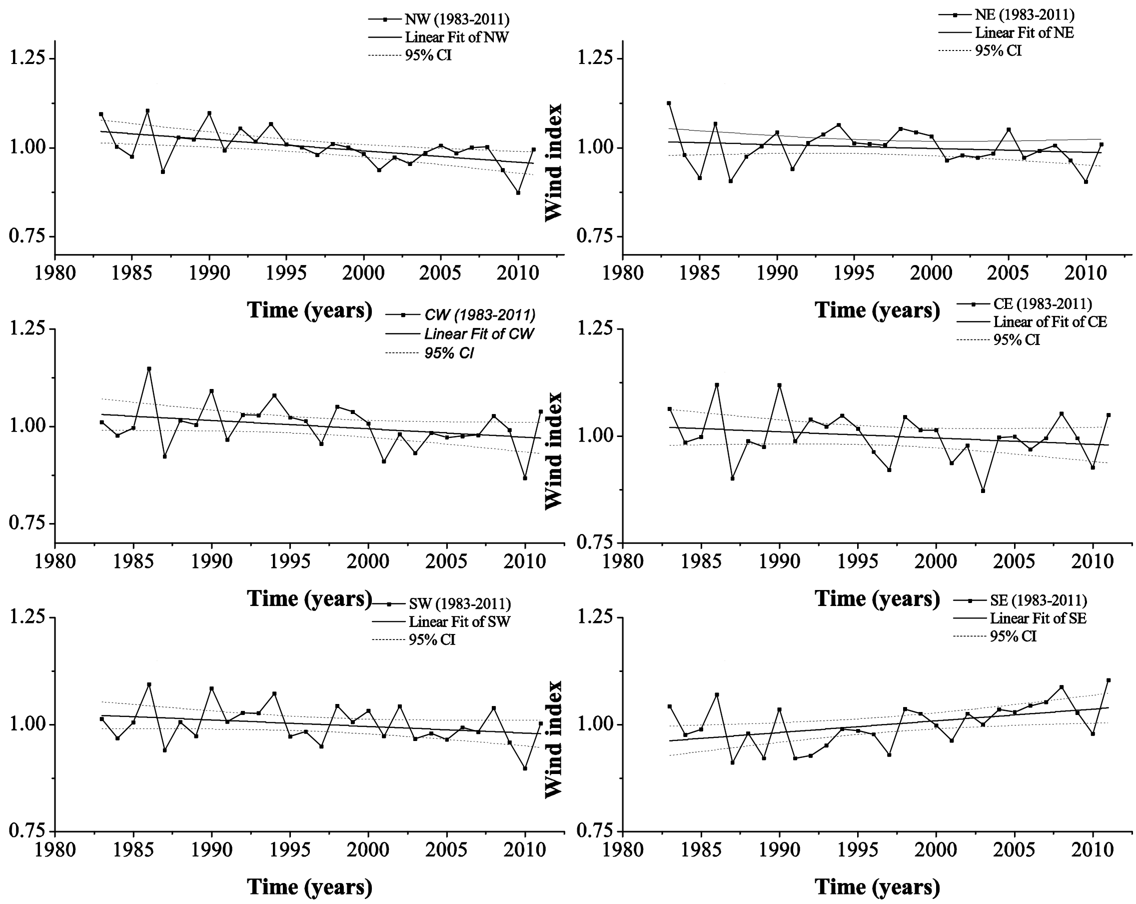

Figure 15: UK wind index by region generated using the BADC-57 stations over the period 1983-2011.

6. THE EFFECT OF WIND SPEED VARIABILITY ON WIND ENERGY

The theoretical power in the wind varies as the third power of the wind speed, so small changes in wind speed could be expected to translate to rather larger changes in wind power. In fact, a modern MW-sized wind turbine wind turbine will start to regulate above ~9m/s, so the change in annual energy yield from a turbine will not increase as rapidly as the third power of the wind speed. The capacity factor of a wind turbine is defined as the average energy produced by a turbine over a representative period, e.g. a year, divided by that which would have been produced had the turbine operated at full output during that entire period. Using the power curve from a Vestas V80 2MW wind turbine, it is possible to calculate the expected capacity factor assuming a given average wind speed at hub height. The capacity factor will also depend on the distribution of wind speeds. A two-parameter Weibull distribution is commonly used to describe the distribution of wind speeds at a site with its cumulative form given as (Burton *et al*, 2001):

$$p(U > V) = exp\left(-\left(\frac{V}{C}\right)^{k}\right) \qquad (3)$$

Where $p(U > V)$ denotes the probability that a wind speed U will exceed a value V, C is the scale parameter and k is the shape parameter. For most UK sites, a value of k close to 2 is common. In this case, the Weibull distribution becomes a Rayleigh distribution and:

$$C = \frac{2\bar{U}}{\sqrt{\pi}} \qquad (4)$$

Where $\bar{U}$ is the mean wind speed at the site. Using such a Rayleigh distribution, the capacity factor for a Vestas V80 2MW turbine is calculated and is shown as a function of mean wind speed in Figure 16. It can be seen that the capacity factor goes up fairly linearly with mean wind speed until around 9m/s and then reduces more slowly, flattening off near 14m/s. This is due to a combination of the turbine regulating at 9m/s, reaching rated wind speed at around 14m/s and shutting down at 25m/s.

If a mean wind speed of 7m/s is assumed at 80m hub height, then a 4% variation (one standard deviation) in wind speed, as seen for the BADC-7 and BADC-57 indices, represents a variation in capacity factor and associated annual energy yield of 7%. A 7% variation in wind speed, as seen for the ERA-40 index interpolated to the BADC-57 sites, would represent a variation in capacity factor and annual energy yield of 13%.

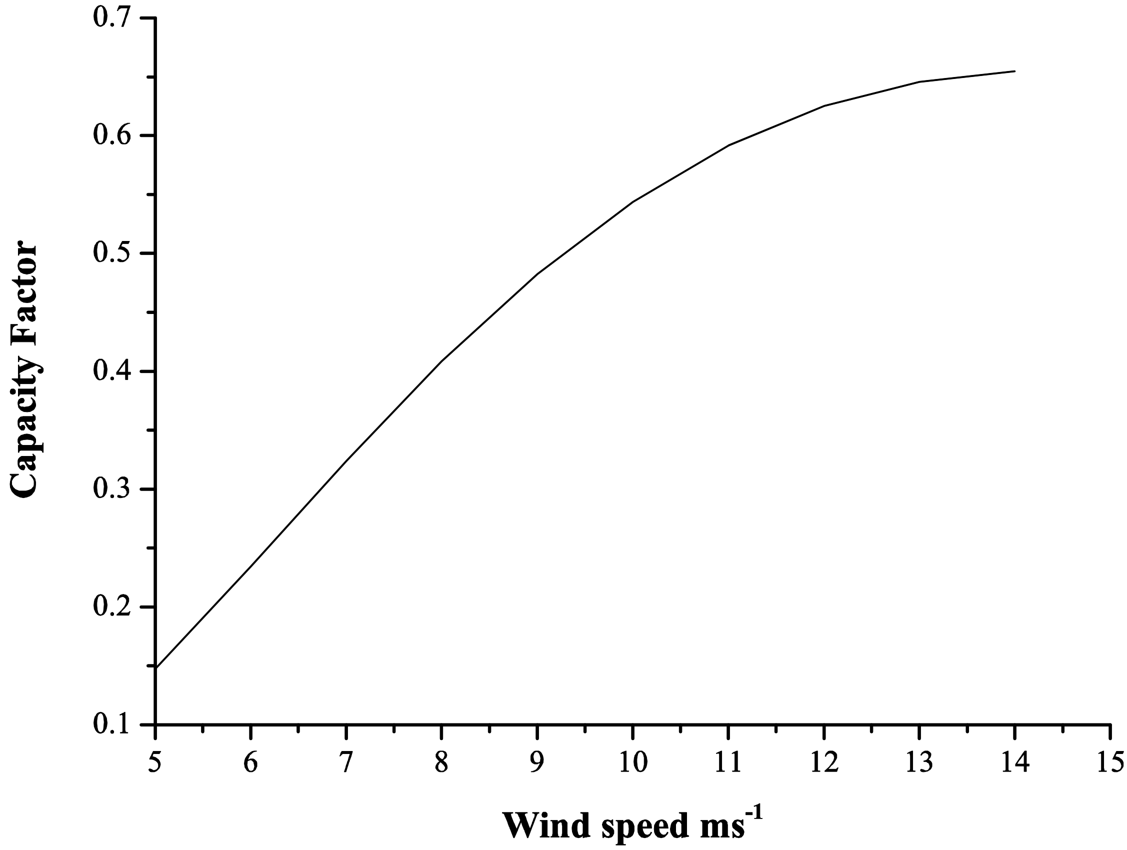

Figure 16: Capacity factor of a Vestas V80 2MW turbine as a function of mean wind speed.

7. CONCLUSIONS

This paper has presented two wind indices for the UK based on surface station observations of wind speed: one based on seven stations (BADC-7) over a 55-year period (1957-2011) and a second based on 57 stations (BADC-57) over a 29 year period (1983-2011). These indices have been compared with indices generated using a gridded dataset of values interpolated from UK stations, three indices calculated using the ERA-40 reanalysis dataset and another UK wind index. The directional wind speed at the BADC-7 stations was examined and there was found to be no obvious evidence of changes in site exposure or instrument location which could affect the continuity of wind speeds at these stations. There have, however, been notable changes in instrument height at many of the stations included in the two indices and, as a result, wind speed observations at all stations were corrected to 10m above ground level. An attempt been made to assess trends in long term wind speed values for each of the indices and to investigate the degree of correlation between them. These trends have been identified using linear regression and their significance assessed using a Mann-Kendall test.

The principal findings of this paper are that:

- The BADC-7 and BADC-57 indices agree reasonably well over the common 1983-2011 period with a correlation coefficient of 0.887 (0.917 when trends are removed);
- The inter-annual variation of the BADC-7 and BADC-57 indices was found to be 4%;
- This variation equates to a standard deviation in wind farm capacity factor of 7%;
- From the late 1950s until the late 1960s, there was an apparent increase in annual mean wind speeds followed by a rapid decrease and another increase throughout the 1970s into the early 1980s. Between the mid-1980s and 2011, there have been some notable low wind speed years including 1987, 2001 and 2010;
- When compared to the other indices, similar trends in wind variability are seen, though correlations vary between 0.60 and 0.92 (0.61 and 0.98 when trends are removed) reflecting the different levels of spatial smoothing, different averaging periods and site specific effects;
- All of the indices show declining trends (between -0.05% per year to -0.71% per year) with the exception of the ERA-40 index calculated over the UK which shows

an increase (+0.1% per year), though not all of these trends were found to be significant;

- The differences in trends do not suggest that increases in large area (mesoscale) roughness are a significant factor but there may be differences in trends between land and sea;
- Local changes in exposure and changes in measurement height may have had an influence, particularly for the UKCIP index;
- When the correlation between annual mean wind speeds at the BADC-7 sites is analysed, it is found to be relatively weak indicating that inter-annual variability is very localised;
- Similarly, when the BADC-57 index is broken down by region, differences in inter-annual variability are seen across the UK. In addition, there appears to be a general trend to decreasing wind speeds in all regions except the south-east and the largest decreasing trend is seen in the north-west. The greatest declines are seen in the winter months and least in the summer, where the south-east region shows an increasing trend. However, the uncertainty on these trends is large considering the large degree of inter-annual variation.

8. ACKNOWLEDGEMENTS

The authors would like to thank Dr Graham Parton of the British Atmospheric Data Centre (BADC) who offered some interesting insights with respect to UK wind fields. The authors would also like to thank the UK Met Office and the BADC for providing access to the UKCIP gridded dataset and the MIDAS data, respectively. The authors are grateful to the staff of the Met. Office archive in Exeter for providing access to records related to the meteorological stations used in this research.

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Table 1. Summary of the parameters used in Equation 2 for calculation of the different indices.

Index	i	j	k	l (years)	m_j
BADC-7	Hourly values	Year	7 (stations)	38, 44, 55	Hours in year
BADC-57	Hourly values	Year	57 (stations)	13, 19, 29	Hours in year
ERA-40	Six-hourly values	Year	Bilinear interpolation to either BADC-7 or BADC-57 sites; average of grid points over entire UK (8^0W to 2^0E, 50^0N to 61^0N)	44	Six-hourly values in year
UKCIP	Monthly values	Year	All grid points covering UK	38	Months in year

Table 2. List of stations used in the 29- and 55-year Wind Indices. Those stations used to generate the 55-year index (BADC-7) are shown in *italics*.

Identifier	Name	Region	Availability	
			29years	55years
9	*Lerwick*	North-East	99.7%	99.4%
10	Sella Ness	North-East	98.9%	
23	Kirkwall	North-East	98.7%	
32	Wick Airport	North-East	97.8%	
54	*Stornoway Airport*	North-West	99.0%	99.0%
113	Aviemore	North-East	97.8%	
132	Kinloss	North-East	99.9%	
137	Lossiemouth	North-East	99.7%	
161	Dyce	North-East	94.7%	
170	Peterhead Harbour	North-East	93.2%	
235	Leuchars	North-East	99.3%	
315	Boulmer	Central-East	99.5%	
346	Linton on Ouse	Central-East	98.4%	
384	Waddington	Central-East	99.9%	
386	Cranwell	Central-East	99.1%	
393	Coningsby	Central-East	99.8%	
409	Marham	South-East	99.5%	
432	Gorleston	South-East	94.9%	
440	Wattisham	South-East	99.7%	
461	Bedford	South-East	98.3%	
513	Bingley, No 2	Central-East	95.5%	
527	High Bradfield	Central-East	89.0%	
533	Church Fenton	Central-East	99.3%	
556	Nottingham, Watnall	Central-East	99.0%	
583	Wittering	South-East	99.2%	
605	Brize Norton	South-West	99.2%	
613	Benson	South-East	99.0%	
643	Shawbury	Central-West	99.4%	
674	Avonmouth	South-West	96.0%	
708	Heathrow	South-East	99.1%	
744	East Malling	South-East	94.0%	
775	Manston	South-East	98.5%	
842	Hurn	South-West	99.6%	
847	Middle Wallop	South-West	99.4%	
886	Lyneham	South-West	97.8%	
888	Larkhill	South-West	99.3%	
889	*Boscombe Down*	South-West	99.7%	99.2%
908	Machrihanish	North-West	98.4%	
918	Dunstaffnage	North-West	96.7%	
982	Salsburgh	North-West	96.1%	
1023	Eskdalemuir	Central-West	99.4%	
1039	West Freugh	Central-West	99.5%	
1046	Ronaldsway	Central-West	100.0%	
1090	Blackpool, Squires Gate	Central-West	98.4%	
1145	*Valley*	Central-West	99.5%	99.7%
1180	Bala	Central-West	97.5%	
1198	*Aberporth*	South-West	99.5%	99.7%
1215	Milford Haven Conservancy Road	South-West	99.1%	
1302	Yeovilton	South-West	98.8%	
1336	Plymouth, Mountbatten	South-West	96.4%	
1346	Chivenor	South-West	96.6%	
1395	Camborne	South-West	99.8%	
1450	*Aldergrove*	Central-West	99.6%	99.9%
1467	Ballypatrick Forest	North-West	95.6%	
1529	Orlock Head	Central-West	95.3%	
17414	Leeming	Central-East	99.8%	
18974	*Tiree*	North-West	98.5%	99.5%

Table 3. Instrument changes since 1957 for the seven stations (BADC-7) used in the 55-year wind index. The last time changes, in either type of instrument or its effective height, were checked was in December 2009. *Particular anemometer type not specified.

Site	Dates	Instrument Type	Effective Height (m)
Lerwick	1957-1960	Assman Mk2 anemometer	6
	1960-1984	Munro Mk 4 anemometer	10
	1984-1999	Munro Mk 4 anemometer	10
	1999-12/2009	Vector Mk 6 anemometer	10
Stornoway Airport	1957-1967	*Anemograph	14 (a)
	1967-1971	Munro Mk 4 anemometer	14
	1971-1974	Munro Mk 4 anemometer	10
	1974-2002	Munro Mk 5 anemometer	10
	2002-12/2009	Vector Mk 6 anemometer	10
Boscombe Down	1957-1964	*Anemograph	16
	1964-1972	Assman Mk2 anemometer	16
	1972-2009	Munro Mk 4 anemometer	10
	2009-12/2009	Vector Mk 6 anemometer	10
Valley	1957-1988	Munro Mk 4 anemometer	12
	1988-1995	Munro Mk 4 anemometer	10
	1995-2007	Munro Mk 5 anemometer	10
	2007-12/2009	Munro Mk 6 anemometer	10
Aberporth	1957-1966	*Anemograph	11
	1966-1969	*Anemograph	11
	1969-2000	Munro Mk 4 anemometer	10
	2000-12/2009	Vector Mk 6 anemometer	10
Aldergrove	1948-1963	Pressure tube	17
	1963-2003	Munro Mk 4 anemometer	10
	2003-12/2009	Vector Mk 6 anemometer	10
Tiree	1957-1970	Pressure tube	16
	1970-1980	Munro Mk 4 anemometer	12
	1980-2001	Munro Mk 4 anemometer	10
	2001-12/2009	Vector Mk 6 anemometer	10

Table 4. The BADC Surface Wind Speed Indices.

Time (years)	BADC-7 index normalised to 55-year period	BADC-7 index normalised to 29-year period	BADC-57 index normalised to 29-year period
1957	0.987	0.999	
1958	0.915	0.927	
1959	0.987	1.000	
1960	0.967	0.979	
1961	1.040	1.054	
1962	1.017	1.031	
1963	1.031	1.044	
1964	1.048	1.061	
1965	1.017	1.030	
1966	1.047	1.060	
1967	1.109	1.124	
1968	0.958	0.970	
1969	0.977	0.989	
1970	1.046	1.060	
1971	0.981	0.994	
1972	1.018	1.031	
1973	0.984	0.997	
1974	1.059	1.073	
1975	0.978	0.991	
1976	0.995	1.008	
1977	1.065	1.079	
1978	1.019	1.033	
1979	1.037	1.051	
1980	1.025	1.038	
1981	1.041	1.055	
1982	1.037	1.050	
1983	1.026	1.039	1.050
1984	0.956	0.969	0.981
1985	0.945	0.958	0.978
1986	1.062	1.076	1.100
1987	0.891	0.903	0.920
1988	0.955	0.968	0.998
1989	0.966	0.979	0.984
1990	1.028	1.042	1.077
1991	0.933	0.945	0.971
1992	0.971	0.984	1.016
1993	0.988	1.000	1.018
1994	1.044	1.058	1.056

1995	0.991	1.004	1.002
1996	0.988	1.001	0.989
1997	0.970	0.983	0.958
1998	1.052	1.066	1.040
1999	1.019	1.032	1.022
2000	1.002	1.015	1.007
2001	0.924	0.936	0.944
2002	1.006	1.019	0.998
2003	0.957	0.969	0.953
2004	0.984	0.997	0.992
2005	1.011	1.024	1.003
2006	0.999	1.012	0.989
2007	0.999	1.012	0.998
2008	1.025	1.038	1.035
2009	0.993	1.006	0.985
2010	0.931	0.944	0.907
2011	1.010	1.023	1.032

Table 5. Comparison of the trends of the different indices and standard deviation of each index (with and without tend removed). The F-statistic relates to the level of significance of the trend according to the non-parametric Mann-Kendall test.

Wind index	*Trend (% yr^{-1})*	*Period*	*F*	*St. dev (%)*	*St. dev (%) (Detrended)*
BADC-7	-0.05	1957-2011	0.14	4.3	4.2
BADC-57	-0.10	1983-2011	0.23	4.3	4.2
ERA-40 (UK)	+0.10	1958-2001	0.99	3.8	3.6
ERA-40 (7)	-0.14	1958-2001	0.09	5.6	5.3
ERA-40 (57)	-0.71	1983-2001	0.01	7.0	5.7
UKCIP Met O	-0.38	1969-2006	0.00	6.1	4.5
GH	-0.40	1995-2007	0.08	3.4	3.1

Table 6. Autocorrelations up to lag 10 for the de-trended indices. Those autocorrelations which are significant at the 5% level are marked in bold.

	Lag									
Wind index	1	2	3	4	5	6	7	8	9	10
BADC-7	0.00	0.05	0.07	0.18	-0.14	-0.16	-0.17	-0.10	-0.10	-0.07
BADC-57	-0.37	-0.09	-0.14	0.34	-0.29	0.05	-0.15	0.11	0.10	0.03
ERA-40 (UK)	-0.06	0.02	0.08	0.13	-0.09	-0.12	-0.13	-0.10	-0.08	-0.01
ERA-40 (7)	0.22	0.09	0.17	**0.38**	0.23	0.08	-0.13	0.01	-0.09	-0.13
ERA-40 (57)	-0.11	-0.23	-0.36	**0.42**	0.04	-0.01	-0.40	0.11	-0.03	-0.21
UKCIP Met O	-0.21	0.12	-0.01	0.20	-0.21	0.04	-0.24	-0.15	0.07	-0.28
GH	-0.01	-0.11	-0.36	-0.11	-0.33	0.10	**0.50**	0.22	**0.53**	**-0.88**

Table 7. Pearson correlation coefficients calculated using concurrent annual values for the different indices.

Wind index 1	*Wind index 2*	*Concurrent years*	*Corr. coeff.*	*Corr. coeff (detrended)*
BADC-7	BADC-57	29	0.887	0.917
BADC-7	ERA-40 (UK)	44	0.604	0.716
BADC-57	ERA-40 (UK)	44	0.876	0.850
BADC-7	ERA-40 (7)	44	0.629	0.611
BADC-57	ERA-40 (57)	19	0.755	0.843
BADC-7	UKCIP Met O	38	0.782	0.878
BADC-57	GH	13	0.919	0.979

Table 8. Pearson correlation coefficients calculated using annual mean wind speed values for combinations of the BADC-7 sites.

	Aldergrove	Boscombe Down	Lerwick	Stornoway	Tiree	Valley
Aberporth	0.373	0.409	0.186	-0.130	0.547	0.441
Aldergrove		0.351	-0.071	0.270	0.731	0.529
Boscombe Down			-0.277	-0.317	0.376	0.680
Lerwick				0.002	0.168	-0.089
Stornoway					0.241	0.119
Tiree						0.508