An analysis of observed daily maximum wind gusts in the UK

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Abstract

Greatest attention to the UK wind climatology has focused upon mean windspeeds, despite a knowledge of gust speeds being essential to a variety of users. This paper goes some way to redressing this imbalance by analysing observed daily maximum gust speeds from a 43-station network over the period 1980-2005. Complementing these data are dynamically downscaled reanalysis data, generated using the PRECIS Regional Climate Modelling system, for the period 1959-2001. Inter-annual variations in both the observed and downscaled reanalysis gust speeds are presented, with a statistically significant (at the 95% confidence interval) 5% increase across the network in daily maximum gust speeds between 1959 and the early 1990s, followed by an apparent decrease. The benefit of incorporating dynamically downscaled reanalysis data is revealed by the fact that the decrease in gust speeds since 1993 may be placed in the context of a very slight increase displayed over the longer 1959-2001 period. Furthermore, the severity of individual windstorm events is considered, with high profile recent events placed into the context of the long term record. A daily cycle is identified from the station observations in the timing of the daily maximum gust speeds, with an afternoon peak occurring between 12:00-15:00, exhibiting spatial and intra-annual variations.

Keywords

Wind gusts, PRECIS, dynamical downscaling, climate variability

1. Introduction

While the surface mean wind regime of the UK is reasonably well documented (Barrow and

Hulme, 1997; Palutikof et al., 1997; Sinden, 2005), literature regarding observed gust speeds is rather sparse. It is desirable to first establish the difference between mean windspeed and gust speeds. The World Meteorological Organisation refers to mean windspeeds as the average windspeed recorded over a 10- to 60-minute period, while gust speeds are typically measured over 2-3 seconds (WMO, 2008). Long, continuous, homogeneous records of both mean windspeeds and gust speeds in Europe, though highly desirable, are largely unavailable (Rockel and Woth, 2007). A knowledge of the local characteristics of gust speeds is directly relevant, for example, to those involved in the design of structures (Ambrose and Vergun, 1995), sailing activities (Spark and Connor, 2004; Strefford, 2002), wind energy (Pryor et al., 2005; Sinden, 2007), the insurance sector (Klawa and Ulbrich, 2003; Leckebusch et al., 2007), aviation (Manasseh and Middleton, 1999), the forestry industry (Usbeck et al., 2010) and those considering the effects of wind driven rain (Choi, 1997).

The Association of British Insurers estimates that average annual insured losses from wind-related domestic property damage in the UK are in excess of £340m (ABI, 2005), with over 200,000 properties suffering damage each year (Blackmore and Tsokri, 2004). The impact of windstorms on the UK is significant, with record economic losses in the region of £5bn (in 2011 values) for the 16th October 1987 event (Munich Re, 1999). Wind damage, and subsequently insured loss, is disproportionately related to the peak gust speed of a storm (Munich Re, 2002; Spence et al., 1998), with Hawker (2007) reporting that a 25% increase in peak gust speed can result in a 650% increase in damage. Compounding this is the increase in the number of people living in areas at risk from windstorm damage (ABI, 2005; IPCC, 2007).

The effect of wind gusts on structures (gust loading) has traditionally been assessed by multiplying the mean wind force by a Gust Loading Factor (Kareem and Zhou, 2003). Wind loading effects over the course of a lifetime of a structure have long been a subject of research and design codes (e.g. the Eurocode for wind loading BSEN 1991-1-4). The majority of research into the effects of extreme wind and gust speeds on structures utilise statistical methods (Bierbooms and Cheng, 2002; Cook, 1982; Pandy et al., 2001; Bierbooms et al., 2001), in order to establish values with return periods in excess of several hundred years (which clearly exceed the length of any observational records).

Temporal trends in gust speeds may be of particular importance to several sectors, including those involved in the design and construction of structures. A limited number of studies consider the historic variability of the upper percentiles of observed (Hanson and Goodess, 2004) and modelled (Knippertz et al., 2000; Rockel and Woth, 2007) mean windspeeds but not gust speeds, nor do they consider any pattern to the time of the day when these high windspeeds tend to occur or the associated wind directions. The time of the day that the highest mean windspeeds and gust speeds are recorded can significantly influence the severity of their impact. For example, casualties during the 16th October 1987 windstorm in the UK would likely have been substantially greater had the peak windspeeds occurred during daylight hours, when more people would have been outside and/or travelling (Baxter et al., 2001). Preferred wind directions associated with the highest gust speeds may also have implications in the design of the built environment.

In order to remedy the lack of a documented gust speed database for the UK, a long, continuous record of gust speeds is presented here for a network of 43 stations. Unlike existing records, this paper focuses upon long-term measurements of wind gusts rather than mean windspeeds, which are of direct relevance to several sectors. In addition to observed gust speeds, dynamically downscaled data generated by a regional climate model are also considered, permitting an analysis of the UK wind gust regime back to 1959. Dynamical downscaling is a method of generating high-resolution climate information from relatively coarse-resolution global climate models (GCMs). Typical GCM spatial resolutions exceed 200 km, while many impact models require information at a scale of 50 km or less, thus necessitating an approach to estimate finer-scale information. Dynamical downscaling utilises a limited-area, high-resolution model (a regional climate model, or RCM) driven by boundary conditions from a GCM to derive more detailed finer-resolution information.

The following section describes the data and methodology, including a discussion of how the modelled windspeed data are generated. Inter- and intra-annual temporal and spatial variations in gust speeds are identified and quantified in section 3, in addition to several notable features of the wind gust regime. The final section summarises the outcomes, draws a number of conclusions, and highlights potential applications of the dataset established here.

2. Methods and Materials

2.1 Observed Wind Data

This study analyses hourly surface windspeed observations (measured at the standard 10-metre height) from 43 UK Met Office stations across the UK over the period 1980-2005. Wind data were extracted from two UK Met Office datasets: the Met Office Land Surface Data (UK Met Office, 2006b) and MIDAS (Met Office Integrated Data Archive System) Land Surface Observations Station data (UK Met Office, 2006a), stored at the British Atmospheric Data Centre. The daily maximum gust speed (DMGS), *i.e.* the highest gust speed observed in the period 00:00-23:59 UTC each day, is extracted for each station, along with the associated hour of occurrence and wind direction. The "gust speed" measurement is in fact a 3-second average windspeed, with the Met Office observing stations typically reporting the maximum value recorded in each hour. Given the nature of this discourse, it is important to differentiate between the gust speeds analysed here and "extreme windspeeds" discussed elsewhere in the literature (e.g. Hanson and Goodess (2004), Hanson et al. (2004), Leckebusch and Ulbrich (2004), Rockel and Woth (2007)). Extreme windspeeds generally refer to the upper percentiles (*e.g.* 95th or 98th) of *mean windspeeds* (usually a 10-minute average windspeed). Section 3 of this paper includes a discussion of extreme DMGS, hereby defined as the 98th percentile of DMGS, which by definition refers to the 190 days in the 1980-2005 record with the highest observed gust speeds. The 98th percentile threshold is specifically selected as it is of particular importance to those considering the various wind applications previously described. The 98th percentile value of DMGS has been shown to be related to wind damage and subsequent insured loss in Germany (Klawa and Ulbrich, 2003) and Great Britain (Hewston, 2008).

Due to changes in the UK Met Office monitoring network throughout the years, a small percentage of gust speeds are measured over 1.5 seconds (e.g. manually analysed anemographs and certain automatic weather stations). However, due to scaling errors (of approximately 5%) in some automatic weather stations the difference between the 3-second measurement and 1.5-second measurement may be offset (UK Met Office, 2007). Furthermore, calibration errors (likely in the region of 5%) in manually derived anemographs exist which again may offset the reduced measurement period (UK Met Office, 2007). A lack of meta-data prevents the identification of periods when these errors may have occurred. However, given that these errors are within the bounds of the maximum measurement error of 10% stipulated by the UK Met Office, in conjunction with the lack of meta-data, no data transformation is applied to account for these potential inhomogeneities.

Station moves are common within the UK Met Office network. Several stations with documented moves were excluded from this study following the discovery of inhomogeneities in the windspeed records. However, two stations with documented moves were retained since no statistically significant differences could be found in the windspeed data before and after their relocation. This is likely due to the short distance of the station displacement (less than 200 metres in both cases). A further source of inhomogeneity may lie in the changing instrumentation throughout the years. However, this is generally restricted to issues of anemometer start-up speeds, and therefore redundant when considering DMGS, as these are, by definition, at the high end of the gust speed distribution. The difficulties of establishing a long, homogeneous record of windspeed, briefly highlighted here, are well understood, and further detailed by Best et al. (2008), Usbeck et al. (2010) and Tuller (2004) amongst others. Overall, the errors in the data appear to be less than 10%, the upper UK Met Office limit of error, which should be borne in mind during the interpretation of the results.

Figure 1 shows the location of the UK Met Office stations utilised in this study, with Table 1 detailing their altitude and the number of days with missing data. Stations with greater than 5% of missing days were removed from the network. One exception, Durham, exceeds this threshold, but is retained due to the dearth of windspeed information in the north-east of England.

2.2 Regional climate model wind data

In order to extend the record provided by the observational data and to place this station data in a longer context, dynamically downscaled reanalysis data are utilised for the period 1959-2001. Reanalysis data provides a historical analysis of the atmosphere, land and sea surface conditions, and is generated from a variety of products such as past operational forecasts, land- and ship-based observations, radiosonde data and satellite observations. The European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis product, ERA40 (described in Uppala et al., 2005), were dynamically downscaled from a 1.875^o (east-west) by 1.250^o (north-south) spatial resolution to 0.22^o by 0.22^o (equivalent to approximately 25 km) using the Hadley Centre's PRECIS (Providing REgional Climates for Impact Studies) system. This dataset, henceforth known as PRECIS-Re, is kindly provided by the UK Met Office. PRECIS is configured from the Hadley Centre's third generation regional climate model HadRM3P, with Jones et al. (2004) providing a thorough description of the system and full technical details of the model. HadRM3P does not incorporate gust parameterisation, instead a daily maximum windspeed is output based on the 576 2.5-minute mean windspeeds simulated for each day. While the magnitude of daily maximum windspeeds simulated by regional climate models is underestimated in comparison to observations, they do provide a reasonable proxy when considering temporal trends (Jungo et al., 2002; Leckebusch et al., 2006).

It is instructive here to consider the relative strengths and weaknesses of the observed and PRECIS-Re datasets. Surface windspeeds in reanalysis data are largely governed by model physics and the observational data assimilated into the reanalysis model. Although downscaling results in a significant increase in resolution, the PRECIS model still simulates windspeeds at a spatial resolution (25 km) that does not completely resolve small scale features at the surface (e.g. convective turbulent effects, small scale eddies and channelling of flow in urban environments). Such features are more likely to be captured in the observed dataset. However, observed data may be subject to inhomogeneities due to instrumental changes, stations moves, land use changes, and missing data. With careful quality control by the UK Met Office and the authors the observational data utilised in this study may be considered as being largely free of such inhomogeneities.

The comparison of gridded climate model data to station observations carries with it its own limitations, described by Moberg and Jones (2004) and Osborn and Hulme (1997) amongst others. In order to directly compare gridded data with station observations, data are extracted from the grid cell whose centre has the nearest coordinates to the observation station. If that grid cell is "wet" (i.e. over the model sea) then data from the nearest "dry" (land) grid cell is utilised (but not one which is more than two moves north-south or east-west). PRECIS-Re is subsequently presented and discussed in terms of stations (directly comparable to the observation stations), although clearly the values represent those of whole grid-cells. It is not the intention here to thoroughly assess the reliability of the downscaling process, but merely to utilise the data in order to extend the gust speed record prior to 1980.

3. Results and discussion

3.1 Geographic variation of DMGS

The highest recorded gust speed in the 1980-2005 period in the monitoring network of 43 stations analysed here is the 50 ms^{-1} gust recorded at Kirkwall (*station 42*), Orkney on 29th January 2000. This figure may be compared with other station records (which are not considered here due to length of record discrepancies); the record low-altitude gust speed published by the UK Met Office is 63.3 ms^{-1} at Fraserburgh, Aberdeenshire, on 13th February 1989, while the record high-altitude value is 77.3 ms^{-1} at Cairngorm (1,245 m above sea level), on 20th March 1986 (UK Met Office, 2010). During the course of the study Aberporth (*14*), Lerwick (*43*), Salsburgh (*36*) and Stornoway Airport (*41*) all recorded gusts exceeding 45 ms^{-1}. Figure 2 presents a range of DMGS statistics for each of the stations in the network. The directions from which the DMGS originated at each station, a sample of which are presented in Figure 3, are dominated by the south-west sector of the compass, varying from 189^{o} to 216^{o} (DMGS wind roses show little difference to mean windspeed roses in this respect). If only extreme DMGS values (i.e. those exceeding the 98th percentile, and shown to be related to structural damage) are considered a similar pattern is revealed by the wind roses, although the prevalence of DMGSs in the south-west sector is even more pronounced.

Geographic variations of DMGS (and indeed extreme DMGS) are partly dictated by the proximity of stations to the coast, in particular the west coast (despite an east coast station, Kirkwall, recording the highest maximum gust speed); higher gust speeds are recorded at stations located on the south-west England peninsular and the Welsh and Scottish coasts, compared to those recorded further inland. These results are expected since reduced friction over the sea results in increased windspeeds on the coast, given an appropriate fetch. These results are in line with spatial variations of mean windspeeds across the UK described by Palutikof et al. (1997) and Wheeler and Mayes

(1997). This offers some validation to the quality of the dataset, and the network of stations, utilised here.

Inland, gust speeds are generally lowest in the south-east region of England, and increase with latitude. However, the prominence of coastal stations in Scotland (there are only two inland Scottish stations in the network considered here) acts to mask latitudinal variations. Stations located at higher latitudes tend to be exposed to a greater number of extratropical cyclones, and subsequently record higher DMGS values; baroclinic zones along the polar front promote cyclone development, which then track across the North Atlantic with their centres commonly following a path between Scotland and Iceland. This is not to say southern parts of the UK are exempt from damaging windspeeds, as testified by the October 1987 storm. However, return periods for high windspeeds tend to be lower with increasing latitude. For a more thorough description of the temporal and spatial variations of the North Atlantic storm track readers are directed to Rogers (1997) and Dacre and Gray (2009) and references therein.

3.2 Temporal variations of DMGS

It is common in the wind energy sector to use “wind indices” to assess long term wind variation (e.g. Garrad Hassan, 2010; Windmonitor, 2010). Such an index enables temporal variations across a number of stations to be assessed, without the inherent spatial variation in windspeeds unduly impacting the results. In order to assess the long-term variation in DMGS values across the network, annual means of DMGS are calculated for each station. In order that geographic variations in absolute DMGS values do not unduly bias the results, annual mean values are compared to the long-term average (1980-2001). These annual anomalies are subsequently averaged across the network, and presented in the form of percentages in Figure 4, and as such may be directly comparable to wind indices. Positive values indicate stronger than average gust speeds, and negative values imply below average gust speeds.

Trends in the annual anomalies of PRECIS-Re and observed gust speeds between 1980 and 2001, shown in Figure 4, correlate well ($R^2 = 0.83$), enhancing confidence in the PRECIS-Re values prior to 1980. A clear downturn can be seen since 1993, with observed values dropping more than

6% by 2005, compared to the long term average. This trend is in line with Atkinson et al. (2006) and Boccard (2009), who also identify a drop in windspeeds across Europe between the early 1990s and 2005. It is of interest to note that annual anomalies of extreme DMGS (not shown) (i.e. just the top 2% of DMGS) reveal a very similar pattern, with nearly a 15% decrease from 1993 to 2005 in the observed values, while the PRECIS-Re value drops 5% between 1993 and 2001. This peak in gust speeds in the early 1990s is in line with Usbeck et al. (2010) who, for the period 1931-2007, report a peak in the early 1990s in the number of days on which the highest maximum gust speeds occurred in Zurich.

Across the station network observed DMGS values display a slight, but statistically significant, decline of 5% (equivalent to 0.02 ms^{-1} per year) from 1980 to 2005 (statistical significance is considered at the 95% confidence interval throughout this paper). Observed DMGS trends downward at 35 stations (of which 12 exhibit statistically significant decreases), while significant upward trends are found at two stations. There appears to be no coherent spatial pattern in these trends with significant decreases seen at stations across the UK, while the two statistically significant increases occur at Culdrose (*1*) and Heathrow (*11*). For comparison, over a similar period (limited to 1980-2001 by data availability) PRECIS-Re data also suggest a similar decline in DMGS values. However, over the longer 1959-2001 period PRECIS-Re data reveal increasing values at all locations, with the network as a whole exhibiting a statistically significant 3% increase (equivalent to 0.01 ms^{-1} per year). The greatest increases are found at locations in northern England and in Scotland. The period over which inter-annual variations are considered is crucial with regard to the evidence and robustness of the trends identified here.

Long-term seasonal variations in DMGS values are also evident. Between 1980 and 2005, autumn (September-November) observed DMGS values decrease by 8% (0.04 ms^{-1} per year), with over a quarter of the stations displaying statistically significant decreases. The majority of these stations are located in Scotland, with two in Cornwall and three in central and northern England. Significant decreases are found at 8 stations in summer (June – August) and 7 stations in spring (March – May), with winter (December – February) exhibiting the weakest downward trend in DMGS values, with only 3 stations showing significant decreases and one showing a significant increase.

The stations exhibiting decreases in spring, summer and winter mean values generally correspond with those showing the decreasing trends in autumn described above. Meanwhile, long-term variation in winter and autumn values of DMGS in the PRECIS-Re data appear to be the drivers in the upward trend of annual values, with increases found at all stations in these seasons between 1959 and 2001.

If only extreme DMGS are considered observed values indicate a (statistically insignificant) decline of 8% (0.08 ms^{-1} per year) between 1980 and 2005. Of the 38 stations exhibiting downward trends 12 show significant decreases. Six of these stations are located in southern England, with five in northern England and southern Scotland. The greatest decreases in these stations are shown in southern England at Camborne (*2*) (0.21 ms^{-1} per year), St Mawgan (*4*) (0.10 ms^{-1} per year), East Malling (*9*) (0.14 ms^{-1} per year) and Manston (*10*) (0.19 ms^{-1} per year).

In the period 1980-2001 extreme DMGS values in the PRECIS-Re dataset suggest no spatially coherent long-term trend across the UK, with network annual mean value increasing less than 0.004 ms^{-1} per year. However between 1959 and 2001 a (statistically insignificant) decrease of 6% in extreme DMGS values is seen (equivalent to a decrease of 0.02 ms^{-1} per year).

Further examination of the inter-annual trends in observed and PRECIS-Re DMGS values reveal that they are largely driven by winter values. Winter is also the dominant season for the occurrence of extreme gusts, with 59% (63%) of observed (PRECIS-Re) extreme DMGSs occurring in this season. A major mode of atmospheric variability in the Northern Hemisphere is the North Atlantic Oscillation (NAO), which exhibits strong inter-decadal variability. The strength of the NAO is assessed using an index based on the difference between the normalised sea level pressure between Gibraltar and Southwest Iceland (Jones et al., 1997). Inter-annual variations in observed and PRECIS-Re DMGS are consistent with known NAO variations. Generally, a more positive NAO index coincides with higher DMGS values; logical given that during this phase the prevailing westerly winds are stronger. Although a thorough investigation of this relationship is beyond the scope of this paper the upward trend in the NAO index between the late 1960s and early 1990s, linked to increases in geostrophic windspeeds in that period (Alexandersson et al., 2000; Matulla et al., 2007), is likely driving the upward trend shown by the PRECIS-Re data.

Observed DMGS values are lowest in 1987, with the annual mean anomaly 1.5 ms^{-1}

(equivalent to 9.5%) below the long term average, while extreme values are nearly 3 ms^{-1} below average. The Great Storm of 16th October 1987 set records for insured loss in the UK, causing extensive structural damage across large swaths of the UK. Results presented here suggest gust speeds were markedly below average that year, and this may have contributed to the degree of damage experienced during the storm, with structures and trees not recently exposed to high windspeeds.

While the analysis of annual mean anomalies of DMGS provide valuable information, it is also informative to consider the interannual variability of the occurrence of extreme DMGSs. Figure 5 shows the number of days per year on which the extreme DMGSs (i.e. the highest 2%) occur. Yet again a maximum is reached in the early 1990s in both the observed and PRECIS-Re values. However, it is interesting to note that while several of the peaks in Figure 5 match those in Figure 4, (e.g. 1974, and 1990) there are several years when this is not the case (e.g. 1962 and 1993). It seems that in these years, despite having below average DMGS, an above average number of extreme DMGS occurred. To emphasise this the UK experienced a severe windstorm in January 1962 which caused extensive structural damage (Palutikof et al., 1997; Lamb and Frydendahl, 1991). This demonstrates that even in an "average" year in terms of wind gust speeds (the 1962 annual mean DMGS anomaly is +0.6%) the potential for structural damage resulting from high windspeeds is not necessarily reduced.

Figure 5 demonstrates that PRECIS-Re is skilful in accurately capturing inter-annual variations in the frequency of high-percentile gusts, with respect to observations. Nevertheless it should be noted that negative biases in the absolute magnitude of PRECIS-Re DMGS, arising largely from unresolved small-scale processes, are significant (approaching 40%) and are analysed and discussed in detail by Hewston (2008). As outlined in section 2.2, reliably modelling maximum gust speeds with RCMs presents a major challenge due to the length of the model timesteps involved. Methodologies to derive gust speeds from RCMs output, through gust parameterisation and, or in combination with, statistical methods, are largely based on the surface mean windspeed variable (Cvitan, 2003; Goyette et al., 2003; Pinto et al., 2009). Values of surface windpseed, and their variability, are generally reliably captured by RCMs, and therefore analyses of relative (rather than absolute) trends in model gust speed may be considered indicative of trends in observed gusts (Leckebusch et al., 2006).

3.3 Time of occurrence of DMGS

The hour in which the DGMS is recorded each day, at every station in the period 1980 to 2005, is shown in Figure 6. A clear and smooth diurnal cycle is evident, with prominent peaks at 13:00-15:00 and 23:00-01:00 UTC. The average DMGS recorded in each time band ranges from 11.8 ms^{-1} (at 15:00-15:59) to 14.6 ms^{-1} (04:00-04:59). If this analysis is limited to extreme DMGS, a similar pattern is revealed by the network as a whole, and also by individual stations (Figure 8). This pattern is still evident when the analyses are limited to DMGS exceeding absolute thresholds of 20, 25 and 30 ms^{-1}. These are significant thresholds since it is common practice for insurance companies to validate claims for wind-related damage when a nearby observation station measures a gust speed exceeding 20-25 ms^{-1}.

The peak in occurrence of the DMGS in the afternoon results from a greater likelihood of atmospheric instability since a positively driven lapse rate (temperature falling with height due to surface heating) facilitates mixing and downdrafts from the synoptically driven winds at a higher level; thermally driven vertical mixing leads to the transfer of momentum to the surface manifesting in the form of gusts. Since this process is dependent on solar radiation it follows that the afternoon peak in the timing of DMGS should vary seasonally, as demonstrated in Figure 7, with the afternoon maximum occurring 1-2 hours earlier in winter compared with summer.

The presence of a nocturnal peak may, in part, be an artefact of the method in which DMGS data are recorded. While more recent wind observations report the maximum gust speed in each hour, data extracted from anemographs only include the maximum gust speed observed in the 24-hour period 00:00-23:59 UTC. Hence, in order to maintain consistency the DMGS variable utilised here is calculated over this 24-hour period. However, if a storm, for example, passes over a station at 23:45 recording the DMGS, it is likely that the DMGS for the following day will be associated with the same storm, and would likely be recorded in the 00:00-00:59 time band. This may result in some double counting in the period 22:00–02:00, with the same weather feature registering twice in the

DMGS record, producing a misleading nocturnal peak. In order to quantify the degree to which this may impact results, a series of sensitivity tests were conducted. A ‘buffer’ period was introduced, whereby a DMGS on two consecutive days could not be recorded within 4, 6, 8, 10, and 12 hours of each other (i.e. if two successive DMGS are recorded in the period 22:00-01:59, 21:00-02:59, 20:00-03:59, 19:00-04:59 and 18:00-05:59 respectively, the lower value is discarded). As a result the frequency of DMGS in the 22:00-02:00 period was reduced by 9%, 13%, 16%, 19% and 22% respectively, demonstrating that the nocturnal peak is moderated but not entirely removed by this methodology. Results shown in Figures 6, 7 and 8 are those produced utilising a 12-hour buffer period, and further demonstrate the apparent robustness of the nocturnal maximum.

Figure 8 presents a selection of histograms displaying the diurnal variation in the timing of DMGSs at select individual stations. Coastal stations show a reduction in the afternoon peak compared with inland stations, epitomised by Aberporth (*14*), which recorded over 750 instances of the DMGS occurring between 23:00-23:59 UTC, while just over 400 were recorded between 12:00-12:59 UTC. Inland stations tend to produce histograms with a more emphasised maximum in the afternoon. Afternoon maxima likely result from surface heating and subsequent instability in surface layers through convection. Such a process will be damped at more temperate coastal stations, and hence the magnitudes of the afternoon peaks are reduced. In these locations the time of occurrence of DMGS is largely governed by the somewhat random passage of frontal systems.

The histograms produced at the inland stations Middle Wallop (*8*), Nottingham Watnall (*20*), Bingley (*27*) and Salsburgh (*36*), increasing consecutively in latitude, suggest that the afternoon peak occurs progressively later with latitude. This demonstrates the effect of longer day lengths at higher latitudes in summer months.

3.4 Storm Severity Index

Downscaled reanalysis data (PRECIS-Re) provides an opportunity to assess the severity of individual windstorm events occurring prior to observational record. In a similar vein to the ‘Storm Catalogue’ presented by Palutikof et al. (1997), who rank windstorms based on their maximum recorded windspeed, duration and area affected, the relative severities of individual windstorm events are estimated here using the DMGS and the number of affected properties. A proposed severity index is presented here, designed to reflect the potential destructiveness of the storm, as well as incorporating some measure of the socio-economic exposure to it. Therefore, a windstorm with exceptional gust speeds over northern Scotland (with a sparse property density), may result in a lower severity index than a storm with lower gust speeds centred over London.

The severity index is calculated in the following manner. Initially extreme DMGS values are scaled by the local 98th percentile value of DMGS at each station, producing values that can be considered representative of storm intensity independent of non-meteorological factors such as altitude and exposure. The local 98th percentile value is utilised as this has been shown to be a threshold for wind damage (Klawa and Ulbrich, 2003; Hewston, 2008). These values are then cubed (since the advection of kinetic energy is proportional to the cube of windspeed) and interpolated across the UK; a methodology consistent with Dorland et al. (2000) and Klawa and Ulbrich (2003). From the interpolated layer a value is extracted for each postcode sector in the UK, and scaled according to the number of properties in that sector. In order that storms may be directly comparable the property density from 2001 is utilised in all cases to calculate the storm severity. The severity index of each storm is reported as a percentage of the most severe storm in the record. Storm events with a severity index exceeding 10% are shown in Figure 9.

In addition to the peak in gust speeds in the early 1990s described above, the occurrence of severe storm events also peaks in that decade. The number of storms with a severity index exceeding 5% occurring in the 1990s is nearly double the number in any other decade in the record. While it is difficult to assess the accuracy of Figure 9 due to a lack of appropriate data (*e.g.* insured loss information), similarities do exist between this record and that suggested by Palutikof et al. (1997). Notable events occurring in both datasets include 16th February 1962, 9th February 1988 and 1st February 1983, which rank 1st, 2nd and 8th respectively in the Palutikof et al. (1997) catalogue in the period 1959-1990. This may prove a valuable tool in placing recent or future windstorms into a long-term context, especially as historical evidence may be somewhat limited for storms prior to 1980, as they were often under-reported.

4. Conclusions

The characteristics of UK wind gust regime are presented here, based on data from a 43-station observation network over a continuous 26-year period. Spatial variations have been identified, with stations located on the west coast shown to consistently record higher daily maximum gust speeds (DMGSs) than those on the east coast and inland. The prevalence of DMGSs from the south-west quadrant of the compass is even more emphasised when only extreme DMGSs (i.e. the highest 2% of DMGSs, which are those related structural damage) are considered.

Temporal trends in DMGS and extreme DMGS values may be summarised in the following manner;

(i) Observed DMGS values show a statistically significant decline between 1980 and 2005, dropping 5% (equivalent to 0.02 ms^{-1} per year) across the network. Negative trends are similarly found in the PRECIS-Re data between 1980 and 2001. However, if the longer (1959-2001) PRECIS-Re dataset is considered a slight, but statistically significant, increase of 3% (equivalent to 0.01 ms^{-1} per year) in DMGS values is suggested. This increase is driven by marked increases in DMGS values in northern England and Scotland. These trends are in line with those identified in mean windspeeds by Atkinson et al. (2006) and Boccard (2009).

(ii) Observed extreme DMGS exhibit a statistically significant decline of 8% (equivalent to 0.08 ms^{-1} per year) between 1980 and 2005. These decreases are greatest (up to 0.22 ms^{-1} per year) in stations in southern England. No statistically significant trend is shown by extreme DMGS values in the PRECIS-Re dataset in either the corresponding period (1980-2001), or in the longer 1959-2001 period.

By considering the observed data in conjunction with the PRECIS-Re data it appears that values of DMGS rose steadily from 1959, peaking in the early 1990s, and subsequently underwent a more rapid decline into the 21st century. Both DMGS and extreme DMGS wind indices peaked in 1993, a result in line with other wind indices calculated for various other regions in north-west Europe (Atkinson et al., 2006; Boccard, 2009). However, some caution must be exercised in the interpretation of the decline in values post-1993, due to the extent of data available after the peak (PRECIS-Re terminates in 2001, and the observed data in 2005). In addition to the peak in DMGS values in the early 1990s, the frequency of extreme DMGSs appear to peak at the same time, a result in line with (Usbeck et al., 2010). These variations are likely driven by decadal variations in the large scale atmospheric circulation, with temporal variations in the NAO index correlating well with the inter-annual variations in DMGS and extreme DMGS.

Various metrics calculated in this study suggest interannual variations in observed gust speeds are in general agreement with those derived from dynamically downscaled reanalysis data (i.e. PRECIS-Re). However, long term temporal variations in observed mean windspeeds and those derived from reanalyses have been shown to differ in other locations, such as in the Netherlands (Smits et al., 2005), the USA (Pryor et al., 2009) and Australia (McVicar et al., 2008). The reliability of the PRECIS-Re data is dependent upon the quality and reliability of data assimilation in the ERA40 project. This dataset is generated by employing historic observational data to constrain models producing information on the background state of the atmosphere. Biases in these analyses can therefore be reduced by incorporating more observational data. Greater reliability of reanalysis data has been demonstrated for the period following the introduction of meteorological observations from satellites (1979 onwards) (Bengtsson et al., 2004; Simmons et al., 2004), and should be borne in mind when considering the PRECIS-Re data for the period 1959-1979.

In addition to putting recent inter-annual variations in the observed record of DMGS in context, the PRECIS-Re data allows the impact of historic windstorms to be compared to those occurring in the more recent past, which tend to be better documented (*e.g.* windstorm Erwin (8th January 2005), the Burns' Day Storm (25th January 1990) and the Great Storm (16th October 1987)). A storm severity index is proposed here using DMGS data and the number of impacted properties. Several potentially high-impact storms are identified dating back to 1959, a timeseries likely to be of interest to those in a number of sectors, including building design and the insurance industry.

The presence of an afternoon maximum in the time of occurrence of DMGS, even for the highest gust speeds, has been identified at every station considered in this study. Spatial variations in this peak do exist, with the peaks at stations in the northern parts of the UK lagging up to 2 hours compared with stations in the south. While this peak is primarily of meteorological interest, the timing of maximum wind gusts does have some bearing on the vulnerability of people to during windstorms.

As identified at the outset, part of the structural design process includes estimating the gust loading on a building. Extreme gust speed values required in building design codes cannot be calculated directly from the wind gust record generated here as even the 42-year PRECIS-Re dataset is too short to be used to directly extract gust speeds with 100-250-year return periods. However, the dataset could be used in conjunction with statistcial methods (e.g. Payer and Küchenhoff, 2004) to improve estimates of extreme gust speeds with return periods in that range.

The ability of future generations to efficiently adapt to future climates is partially reliant on the current generation proactively and profitably managing climate change (e.g. alterations of building and urban design) (Roaf et al., 2009). Historic changes in the UK wind gust regime have been quantified in this paper, and provide a basis on which to assess the potential risk posed by future severe windstorms in a changed climate. It is highly likely that the frequency and intensity of extreme extratropical cyclones will vary in the future (IPCC, 2007). Yin (2005) and Knippertz et al. (2000) project a poleward shift in the extratropical cyclone track in the Northern Hemisphere over the course of this century. This likely explains the findings by Leckebusch et al. (2006), who project increases of up to 8% in winter extreme mean windspeeds over the UK in the period 2071-2100, with simultaneous decreases in the total number of extratropical cyclones. Future UK climate simulations reveal a reduced return period for extreme windspeeds (Della-Marta and Pinto, 2009) in conjunction with an increased number of extreme cyclones (Pinto et al., 2009). The link between the positive phase of the NAO and high gust speeds in the UK has been confirmed in this paper, with a similar relationship to high windspeeds in Europe shown by Gulev et al. (2001), Pinto et al. (2009) and Raible (2007). Increases in the frequency of future extreme windspeeds described in the above studies is likely a result of the tendency to a more positive phase of the NAO in future climates simulated by most GCMs (Stephenson et al., 2006).

Acknowledgements

Funding for this work was kindly provided by the Worshipful Company of Insurers, and was undertaken at the University of East Anglia. Thanks must go to the British Atmospheric Data Centre (BADC) and UK Met Office for providing the windspeed data, and to the UK Met Office for the PRECIS-Re dataset. Our thanks also to anonymous reviewers for their valuable suggestions of improvements to the paper. Interested parties wishing to access the observed windspeed data may, for research purposes, apply for access through the BADC. Current work undertaken by the authors

and Nick Earl, at the University of East Anglia, will lead to the publication online of updates to long term trends in both mean UK windspeeds and gust speeds.

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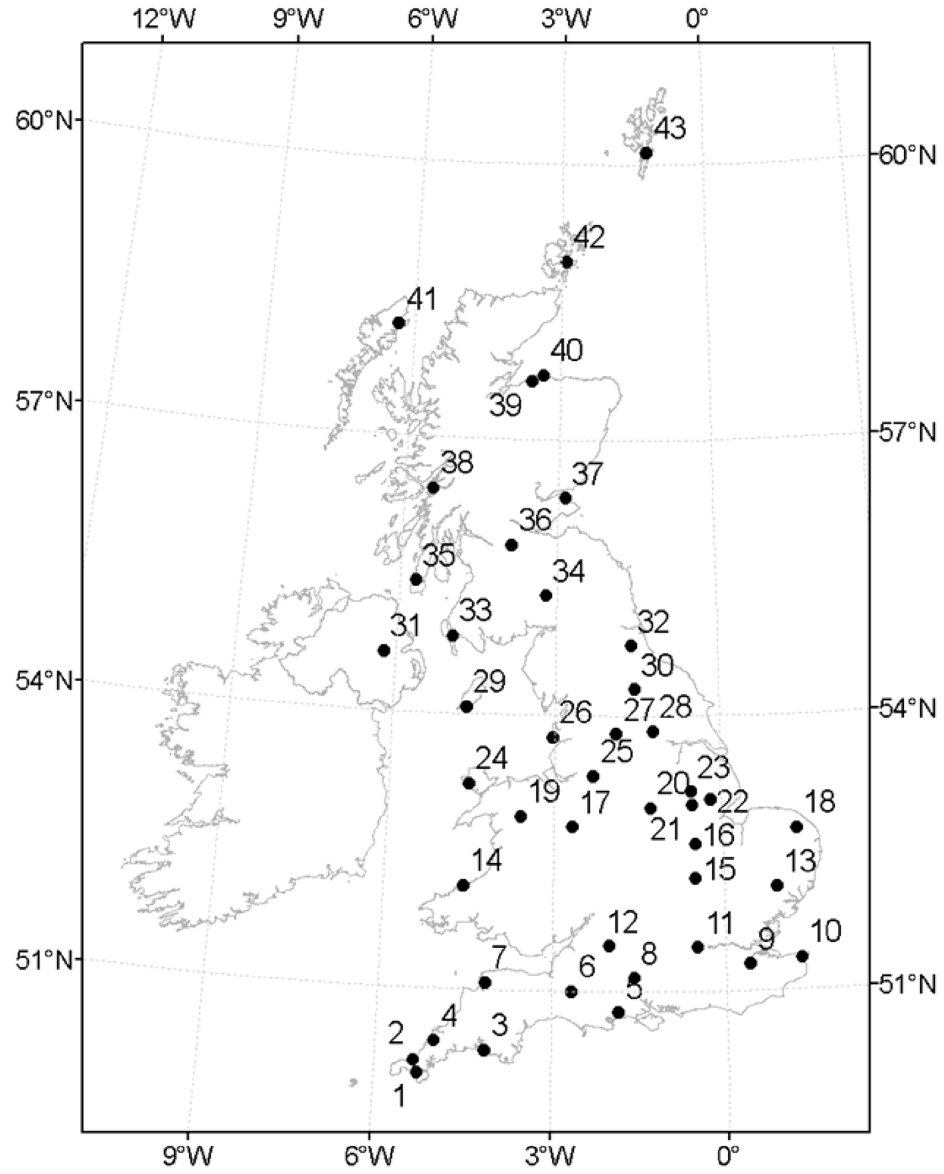

Figure 2 - Box plot of observed DMGS

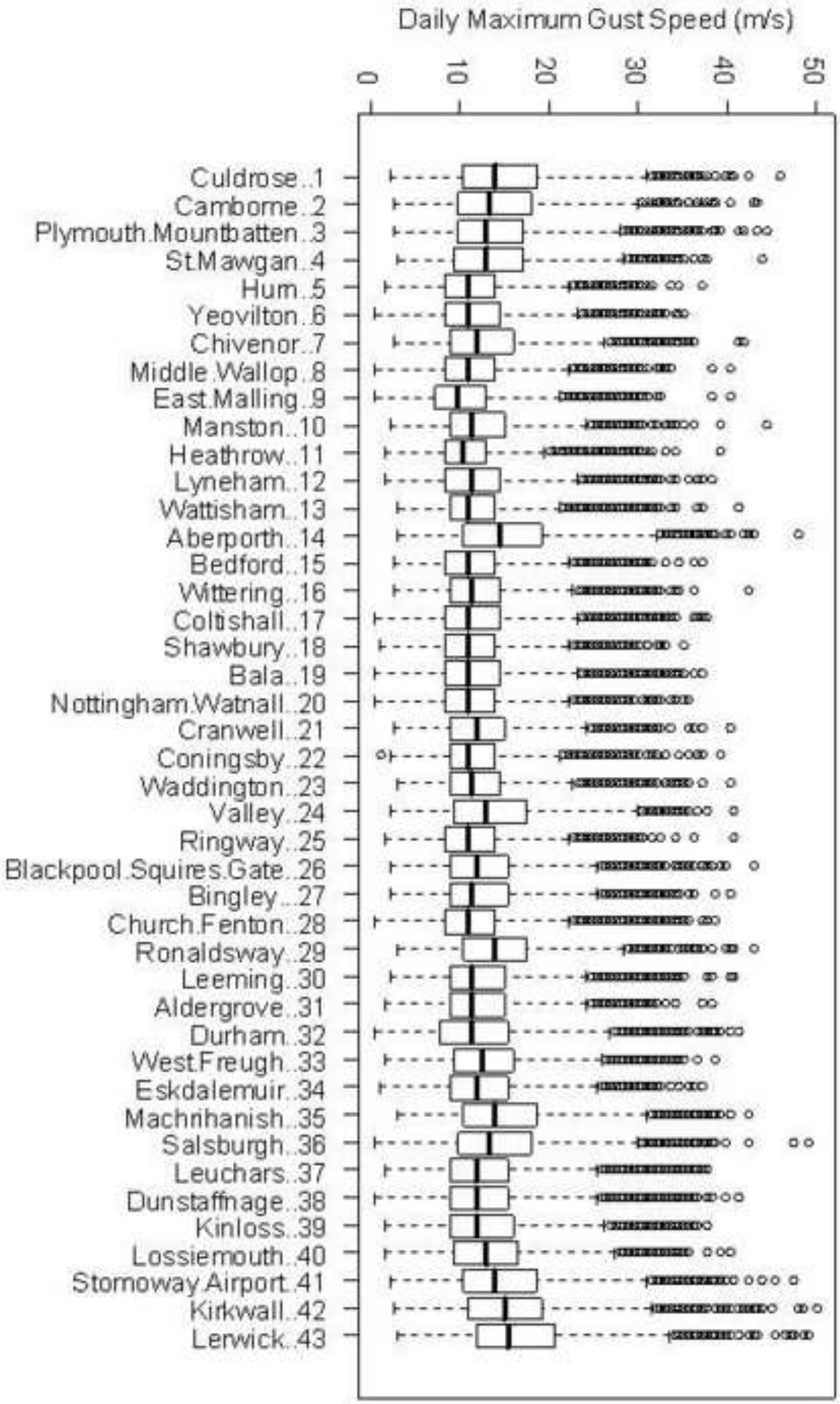

Figure 3 - Wind roses of DMGS at select stations

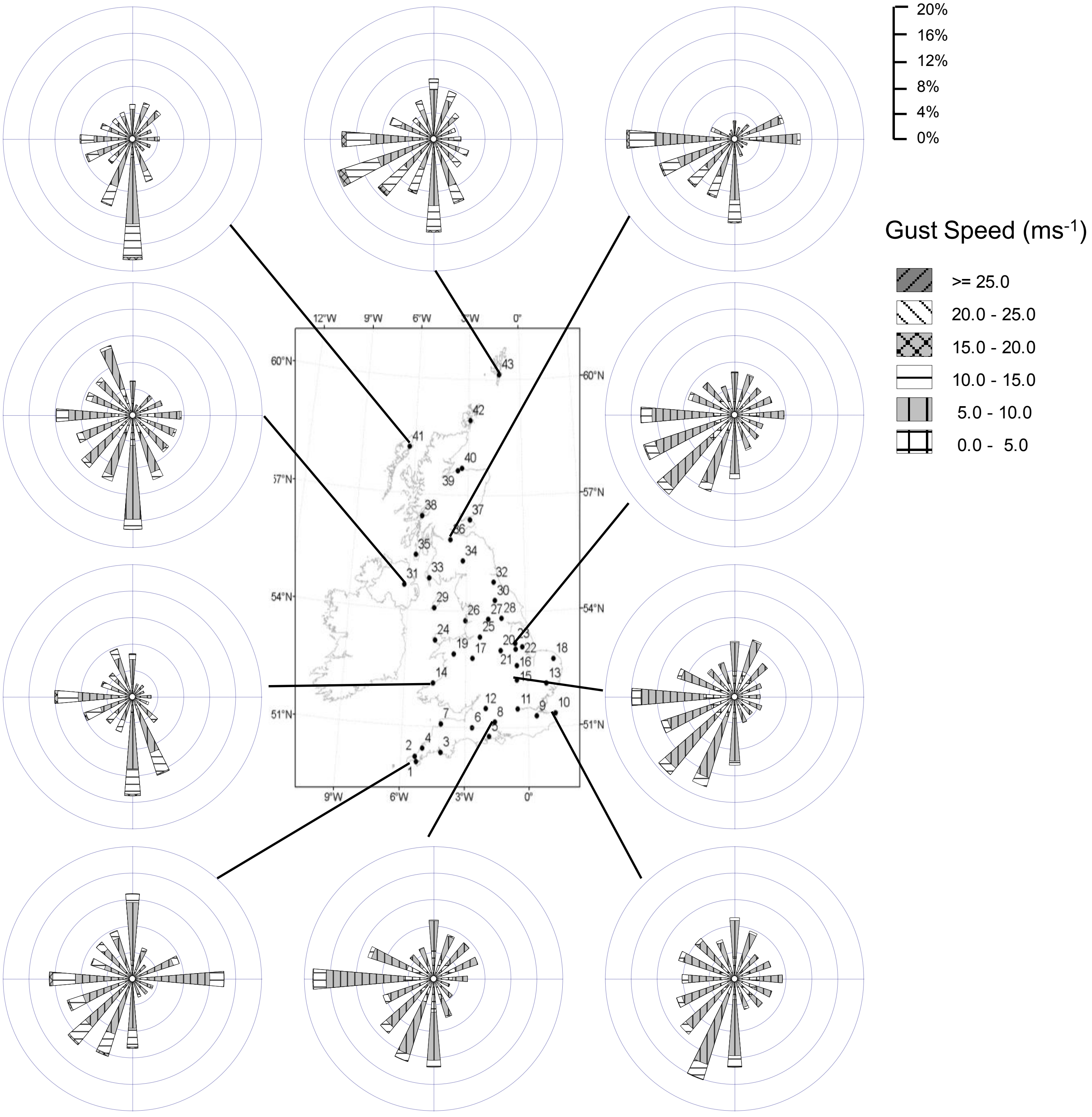

Figure 4 - Network average annual anomaly (%) of DMGS

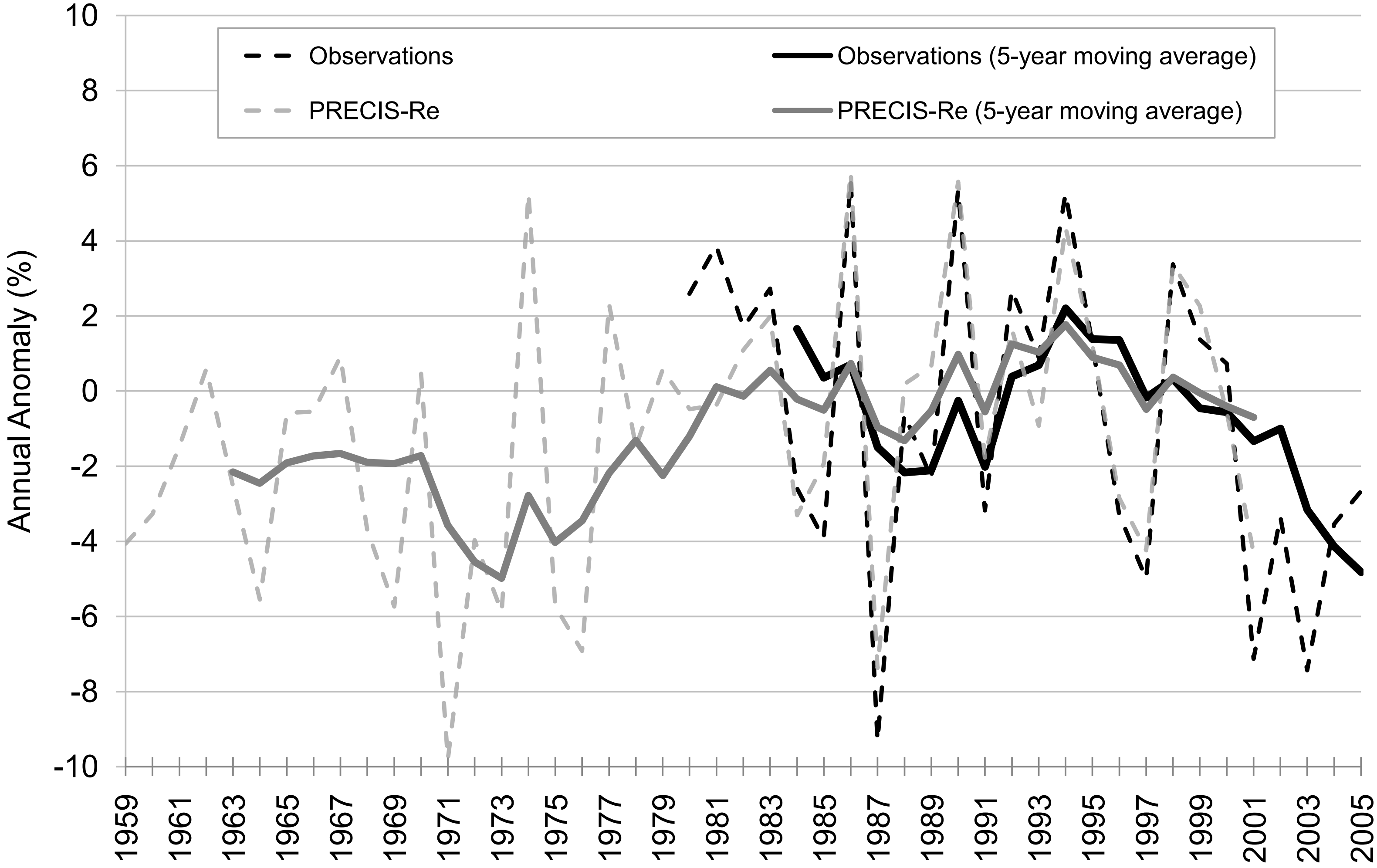

Figure 5 - . Number of days per year on which extreme DMGS (i.e.

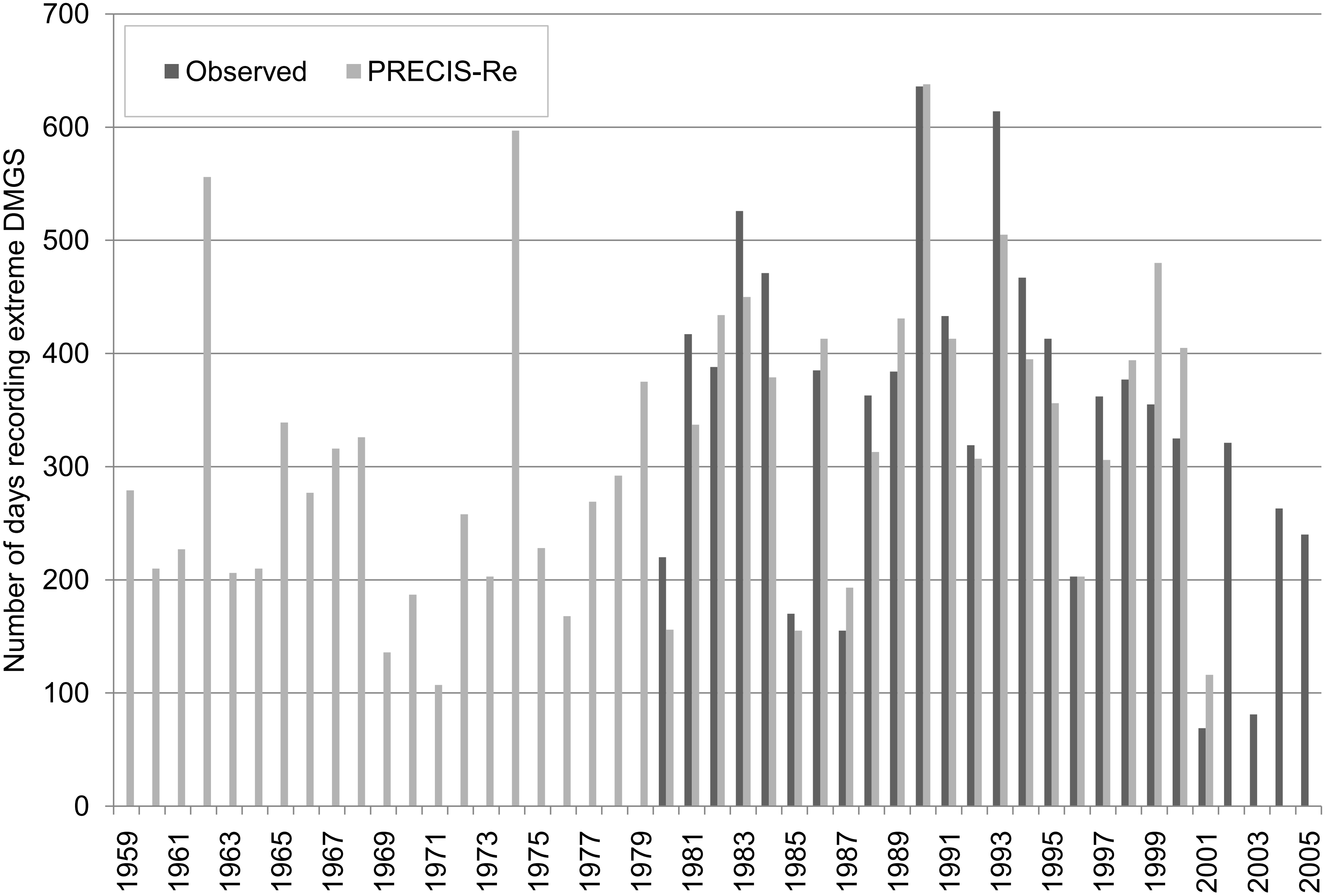

Figure 6 - Daily variation in occurence of DMGS

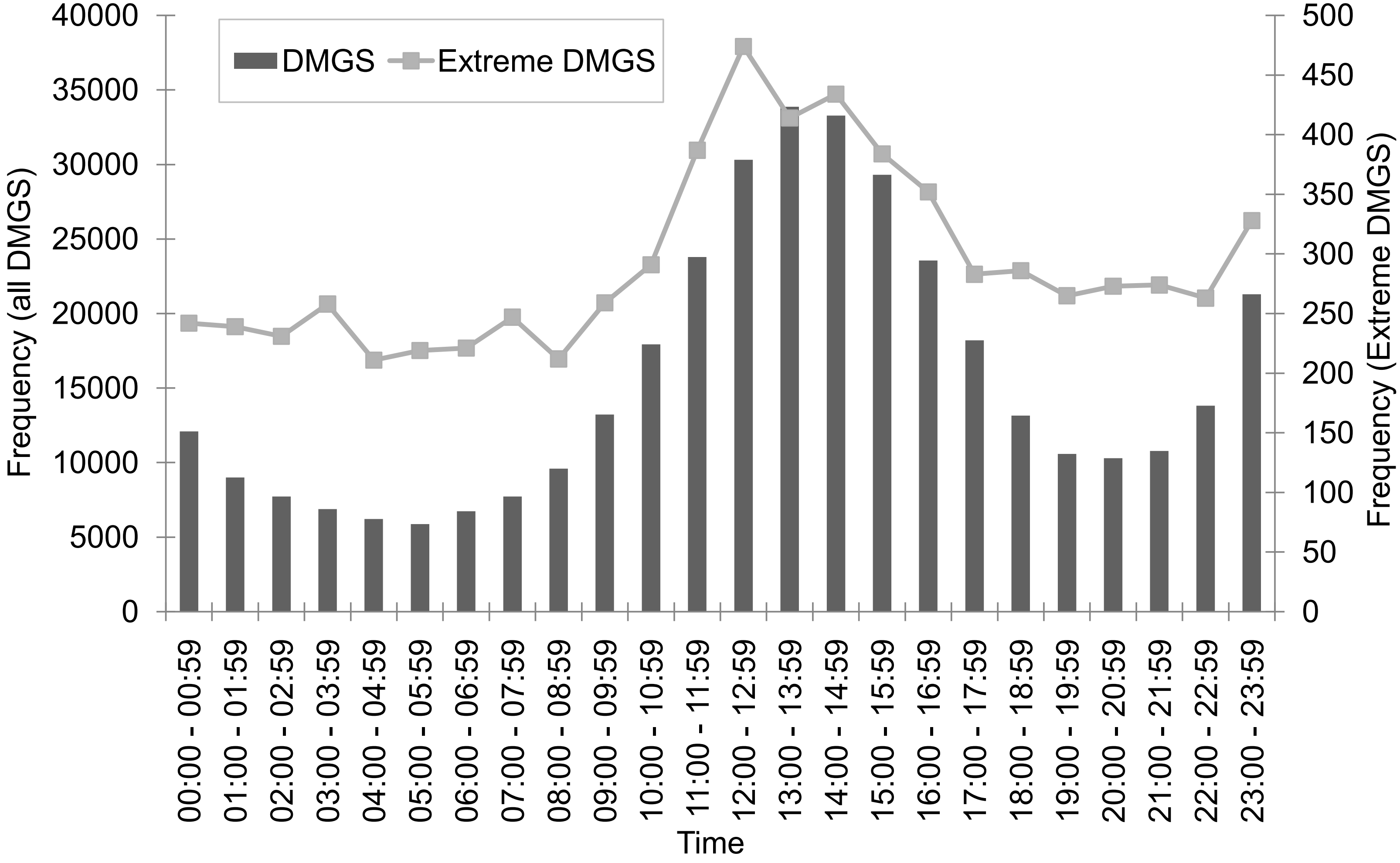

Figure 7 - Daily variation in occurence of DMGS (seasonal)

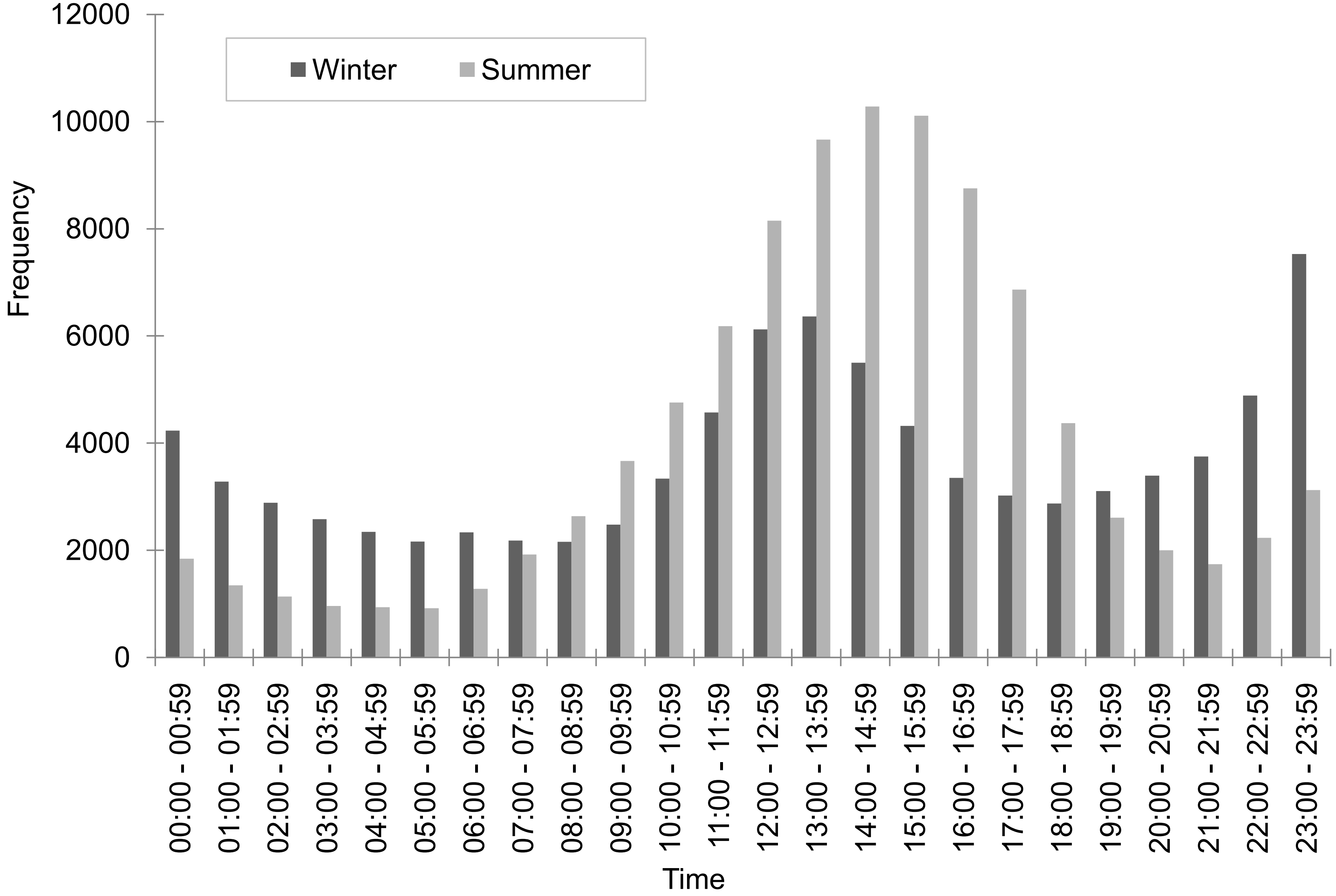

Figure 8 - DMGS timing histograms at various locations

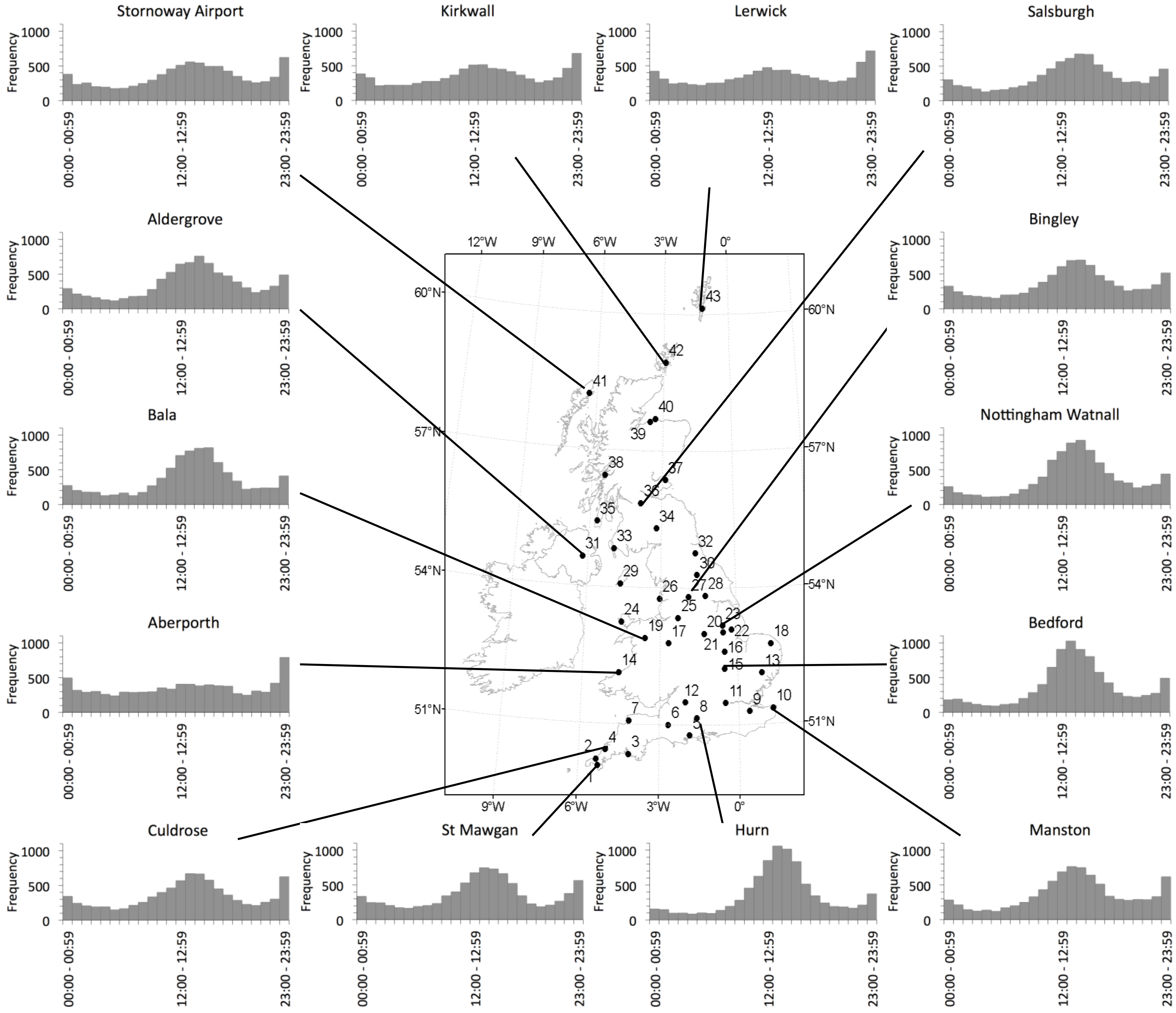

Figure 9 (top section) - Storm Severity Index

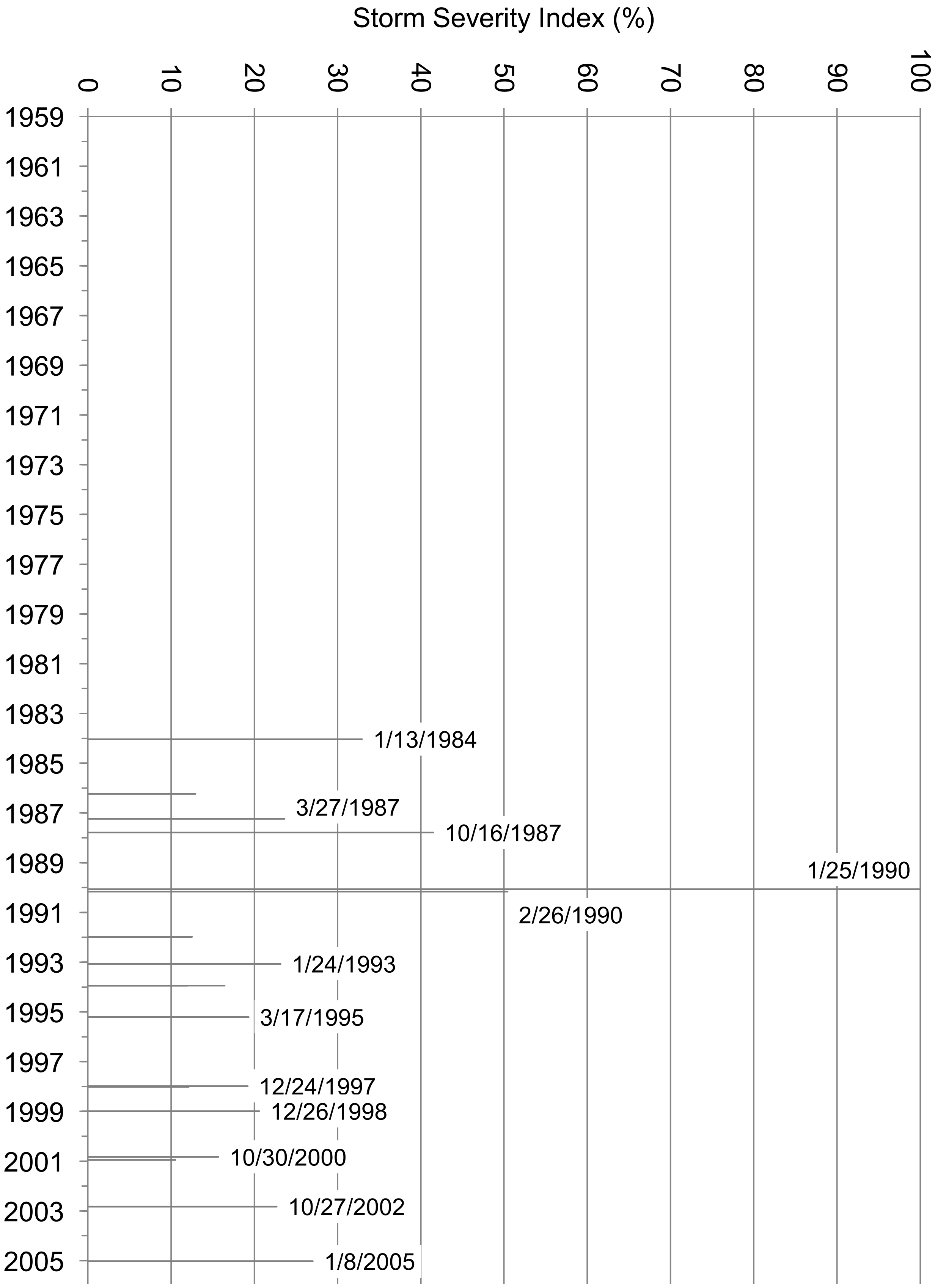

Figure 9 (bottom section) - Storm Severity Index

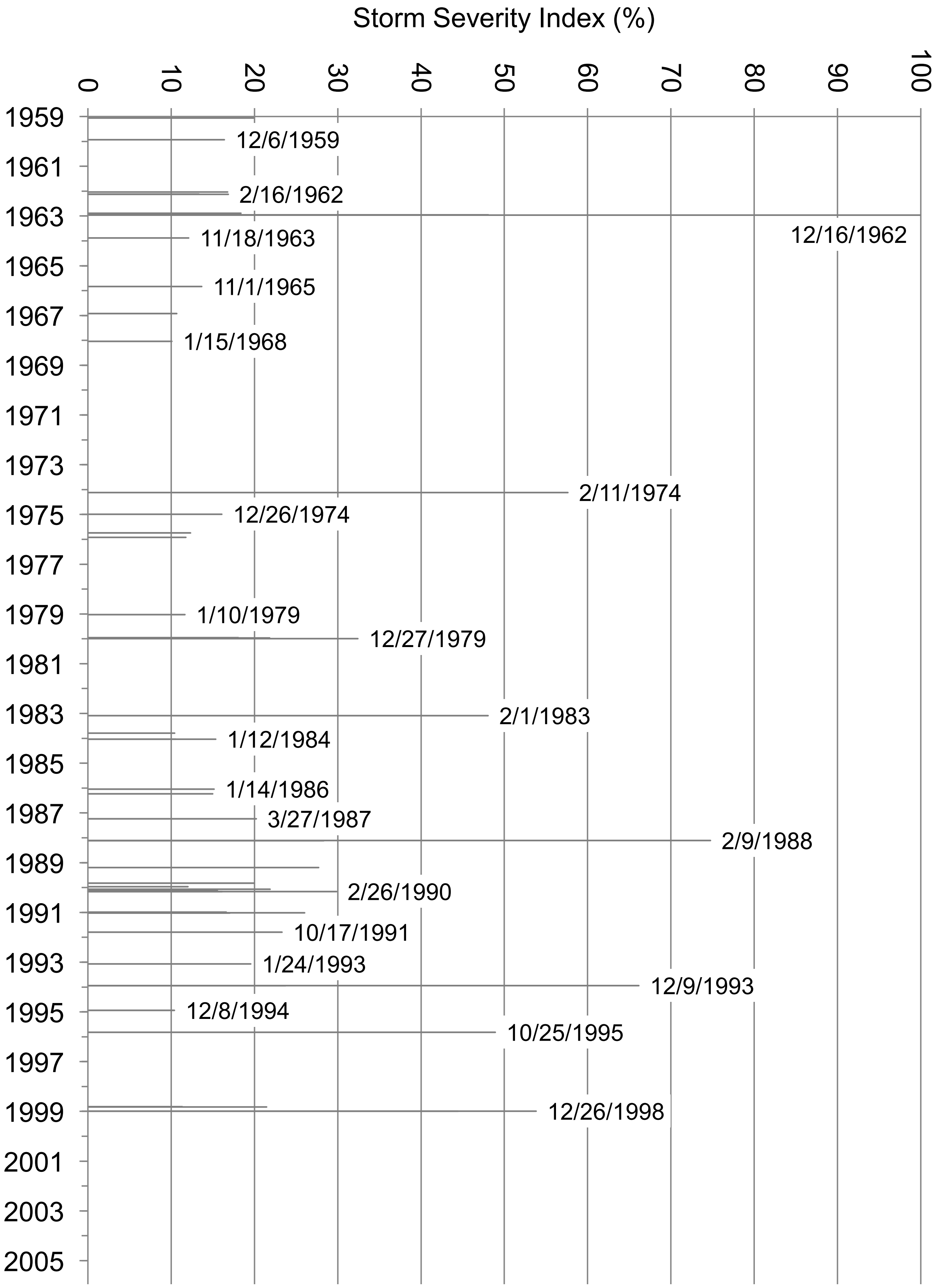

Table 1 - Elevation and data capture of wind monitoring network

No.	Station	Elevation (m above sea level)	% Missing Days
1	Culdrose	78	3.61
2	Camborne	87	0.04
3	Plymouth Mountbatten	50	1.33
4	St Mawgan	103	0.01
5	Hurn	10	3.71
6	Yeovilton	20	1.12
7	Chivenor	6	3.29
8	Middle Wallop	90	0.47
9	East Malling	33	2.32
10	Manston	44	0.51
11	Heathrow	25	0.28
12	Lyneham	145	1.95
13	Wattisham	89	0.01
14	Aberporth	115	0.14
15	Bedford	85	0.88
16	Wittering	73	0.49
17	Coltishall	17	0.19
18	Shawbury	72	3.39
19	Bala	163	2.83
20	Nottingham Watnall	117	0.22
21	Cranwell	62	0.36
22	Coningsby	6	1.21
23	Waddington	68	0.22
24	Valley	10	0.4
25	Ringway	69	1.18
26	Blackpool Squires Gate	10	1.39
27	Bingley	262	3.04
28	Church Fenton	8	0.52
29	Ronaldsway	16	0.18
30	Leeming	32	0.2
31	Aldergrove	68	0.41
32	Durham	102	7.57
33	West Freugh	11	0.06
34	Eskdalemuir	242	0.48
35	Machrihanish	10	0.2
36	Salsburgh	277	2.53
37	Leuchars	10	0.43
38	Dunstaffnage	3	1.76
39	Kinloss	5	3.78
40	Lossiemouth	6	0.03
41	Stornoway Airport	15	0.28
42	Kirkwall	26	0.65
43	Lerwick	82	0.15