Computation of Windstorm Catalogues and Windstorm Severity Indices 1969-2013 for the UK and 11 UK Regions

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Summary: This document outlines the methodology employed by the Climate Extremes Group in the Department of Space and Climate Physics at University College London (UCL) to identify and severity rank UK windstorms for the 45-year period from 1969 to 2013. The UCL methodology is underpinned by a robust UK windstorm definition that is applied to cleaned and homogenised continuous gust observations from 262 low-level station sites spread evenly around the UK. Windstorm catalogues and event severity rankings are provided for the whole UK and, uniquely, for each of 11 UK regions. The product's background, input data, creation methods and output form are summarised under eight headings. References and appendix figures provide additional information.

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1. Introduction. UK windstorms are a substantive peril for the (re)insurance industry and a significant hazard for UK transport and UK infrastructure (including rail and road travel, construction projects, and power networks). UK windstorms also have financial impacts in other sectors and markets including forestry and mortgage lending. Windstorm catalogues provide quantitative information about the intensity, frequency and location of these extreme weather events. This information is crucial to quantifying the risks that different markets experience from windstorms, and to improving our understanding of the occurrence and predictability of these damaging events. To our knowledge four catalogues relating to UK windstorms exist currently. These are: (a) The pioneering catalogue by *Lamb* [1991] which documented all windstorms with serious effects on the UK and northwest Europe between 1509 and 1989; (b) The catalogue made by *Palutikof and Skellern* [1991] which documented 47 severe UK windstorms between 1920 and 1990; (c) The XWS open access catalogue of extreme European windstorms which includes 30 UK windstorms between 1979 and 2013 [*Roberts et al*., 2014; *XWS*, 2015]; (d) The Met Office Euro Windstorm Historical Catalogue [*Met Office*, 2015] comprising 6,110 events between 1979 and 2014 of which an unknown number affected the UK. Table 1 compares the characteristics of these four catalogues to those of the new UCL UK windstorm catalogue.

2. UK Windstorm Definition. The UCL catalogue defines a UK windstorm as a strong extra-tropical cyclone where at least one weather station records a 3-second gust with a return level of at least 2 years and at least one further weather station records a gust with a return level of at least 1 year. The second station must be separated from the first station by at least 30 km. This robust definition uses firm thresholds for gust speed and storm size exceedance thereby ensuring that all identified events are strong extra-tropical cyclones. The UCL UK windstorm definition is underpinned by continuous gust observations from 262 stations spread uniformly across the UK. The definition leads to the identification and cataloguing of 394 UK windstorms 1969-2013. This total corresponds to an annual UK windstorm rate of 8.76. It should be noted that 95 windstorms (24.1% of the 394 UK windstorm total) had a 2-year return level gust recorded at just one station, this mostly at a UK periphery.

Table 1: Catalogues Relating to UK Windstorms					
	Lamb [1991] catalogue: Historic storms of the North Sea, British Isles and NW Europe	*Palutikof and Skellern* [1991] catalogue: Storm severity over Britain	XWS catalogue of extreme European windstorms [*Roberts et al.*, 2014]	Met Office Euro windstorm historical catalogue [*Met Office*, 2015]	UCL windstorm catalogues and windstorm severity indices for the UK and 11 UK regions
Period covered	1500 to 1989	1920 to 1990	1979 to 2013	1979 to 2014	1969 to 2013
Number of UK windstorms in catalogue	166 windstorms in catalogue but not all affected the UK.	47	30	Unknown (6,110 events in European catalogue).	394
Threshold for windstorm event selection	Events selected based on their perceived historical impact and severity.	Events selected from *Lamb* [1991] and *Hammond* [1990] studies.	Events selected based on insured loss and a meteorological storm severity index.	Events selected using vorticity maxima identified using the approach of *Hoskins and Hodges* [2002] based on the *Hodges* [1995] tracking algorithm.	Events selected based on gust exceedance above a spatially varying 2-year return level for windstorm peak gust, and on storm size exceeding 30 km.
Underpinning data	Many historical documents and other sources.	Met Office monthly weather reports.	ERA-Interim reanalysis data, Met Office Unified Model output for downscaling to surface, and recalibration using MIDAS weather station observations.	ERA-Interim reanalysis data, and Met Office Unified Model output for downscaling to surface.	Met Office MIDAS continuous hourly gust observations combined with data cleaning, data homogeneity corrections, and extreme value analysis.
Windstorm Severity Indices (WSIs)	Yes	Yes	Yes	No	Yes
UK-regional catalogues and WSIs	No	No	No	Subset windstorm catalogues available.	Yes (available separately for 11 UK regions).

3. Windstorm Severity Grading. The severity grading of UK windstorms allows the potential wind impacts of different windstorms to be compared in a quantifiable manner. Windstorm severity rankings were initiated by *Lamb* [1991] and are gaining increasing use [*Haylock*, 2011; *Roberts et al*., 2014]. In insurance they are used to quantify the windstorm severity in catastrophe models [e. g. *Waisman*, 2015]. *Lamb* [1991] introduced the term Storm Severity Index (*SSI*) to grade windstorms in terms of their wind power. We follow Lamb's idea to grade UK windstorms in terms of their windpower but choose to use the more appropriate term Windstorm Severity Index (WSI), rather than SSI, to grade windstorm severity. This is because high windspeed alone properly categorises the severity of a windstorm, whereas a 'storm' may be severe in terms of multiple hazards including high windspeed, high rainfall and storm surge. If using *SSI* to define a storm's severity one should, robustly, also include the storm's severity in terms of rainfall and/or storm surge.

4. UK Regions. Windstorm catalogues are prepared for the whole UK and, separately, for 11 UK regions. The chosen UK regions from north to south are: Northern Scotland, Eastern Scotland, Western Scotland, Northern Ireland, North West England, North East England, Wales, Midlands, Eastern England, South West England and South East England. These 11 UK regions are selected because they correspond well to the 11 regions defined by the Met Office for UK regional climate (http://www.metoffice.gov.uk/climate/uk/regional-climates) and because they each contain at least 20 anemometer stations with continuous hourly gust data 1969-2013. Figure 1 (Appendix) geographically defines the 11 UK regions. Figure 2 (Appendix) maps the names and locations of the anemometer stations whose data underpin the windstorm catalogues and windstorm severity indices for the whole UK and for each UK region. These figures show that the 262 stations are spread uniformly both across the UK and within each region.

5. Input Data. Three main input data sets are used. These are: (**A**) Cleaned and homogenised hourly and daily peak 3-sec gust recordings from 262 UK weather stations within the Met Office Integrated Data

Archive System (MIDAS) [*Met Office, 2012*]. These data span the 45 year period 1969-2013. The data cleaning procedures and data homogeneity corrections are described in *Saunders and Lea* [2017]. The homogeneity corrections include the application of data imputation to give nearly complete 45-year time series of daily maximum 3-sec gusts at all 262 stations. This correction has resulted in only 13 windstorms (out of the 394 total) having less than 260 stations with maximum gust data, and only five windstorms having less than 256 stations with maximum gusts. The 262 station total excludes UK stations located at elevations above 300 m (with one exception, Sennybridge in Wales, located at 307 m elevation, which is included to ensure that Wales has 20 stations), and stations located on remote and largely uninhabited islands off the north Scottish coast. These exclusions are to ensure that such remote stations do not exert undue influence on storm severity rankings. **(B)** Peak 3-sec gust return levels for each of the 262 stations in §5(A), these computed from the cleaned and homogenised station data by using the method of independent storms combined with a robust peak-over-threshold analysis [*Saunders and Lea,* 2017]. **(C)** Six-hourly sea level pressure data and zonal (east-west) wind data at 10 m altitude at 2.5 degree spatial resolution from the NCEP/NCAR global climate reanalysis 1969-2013 [*Kalnay et al.,* 1996; *NCEP,* 2016]. Our use of the MIDAS data for commercial value-added products is permitted via a perpetual licence with the Met Office. The NCEP/NCAR reanalysis data are available free of charge.

6. Method for Selecting Windstorms

Our method to select UK windstorms has seven steps:

(A) Use the cleaned and homogenised daily maximum 3-sec gust values from all 262 UK stations (§5A) combined with the independent storm peak 3-sec gust return levels (§5B) to identify all days between 1st January 1969 and 31st December 2013 when at least one station recorded a windstorm-related daily maximum gust with a return level of at least 2 years. The locations and hourly times of all these peak gusts are documented.

(B) Examine the NCEP/NCAR 6-hourly sea level pressure data for the days, times and locations identified in 6(A) to confirm whether the high gust speed event was likely due to a strong extra-tropical cyclone or to a localised mesoscale or microscale storm event. The criteria for the event to be a strong extra-tropical cyclone are the nearby passage of a deep low pressure storm system in the NCEP/NCAR reanalysis data, and for the station peak gust direction to approximately match the wind direction deduced from the NCEP/NCAR pressure data. 98.9% of the cleaned and homogenised daily maximum 3-sec gusts with a return level of at least 2 years recorded at all 262 stations between 1969 and 2013 were thereby confirmed as corresponding to a UK windstorm.

(C) Use the NCEP/NCAR 6-hourly sea level pressure data, NCEP/NCAR 6-hourly zonal and meridional windspeed data at 10 m height, and hourly gust data from anemometer stations at the UK extremities to estimate the start time and duration of each UK windstorm output from 6(B). The deduced windstorm durations range from 12 to 84 hours with 93.7% of events having a UK duration of 36 hours or less.

(D) For each UK windstorm output from 6(C) use the hourly gust data from §5A to obtain the peak 3-second windstorm gust at each of the 262 stations.

(E) For each UK windstorm combine the output from 6(D) with the windstorm peak 3-sec gust return levels for each station (input data §5B) to compute how many of the 262 stations have a peak gust which is (a) ≥ 1 yr return level; (b) ≥ 2 yr return level; (c) ≥ 5 yr return level; (d) ≥ 10 yr return level; (e) ≥ 20 yr return level.

(F) Combine the output from 6(E) with knowledge of station separation distances to deduce which of the UK windstorm events meet the robust 'windstorm' definition given in §2. A total of 394 UK windstorms 1969-2013 are thereby identified for the final catalogue.

(G) Obtain regional windstorm catalogues by repeating steps 6(E) and 6(F) but using only those stations which lie in the relevant UK region. The UK regions and the stations used for each region are shown in the Appendix Figures 1 and 2.

7. Method for Computing Windstorm Severity Indices

We compute two Windstorm Severity Indices (WSIs) for each UK windstorm, and call these *WSI 1* and *WSI 2*. *WSI 1* is the mean windstorm severity index per station predicated on the cubed gust exceedance above a spatially constant 25 ms^{-1} (55.92 mph) gust threshold [cf *Roberts et al*., 2014; *Waisman*, 2015].

WSI 2 is the mean windstorm severity index per station predicated on the cubed gust exceedance above a spatially varying 1-year return level for windstorm peak gust. The formulas for *WSI 1* and *WSI 2* are as follows:

$$WSI\ 1 = \frac{1}{N}\sum_{n=1}^{N}\left(U_g - 55.92\right)^3 \qquad (U_g > 55.92)$$

$$WSI\ 2 = \frac{1}{N}\sum_{n=1}^{N}\left(U_g - U_{grl1}\right)^3 \qquad (U_g > U_{grl1})$$

where N is the number of stations (either for the whole UK or for a particular UK region), U_g is the station peak gust (mph) for the windstorm, and U_{grl1} is the station 1-year return level for windstorm peak gust (mph). These formulas also appear in the windstorm catalogue and windstorm ranking files for each UK region.

The *WSI 2* index should be linked better to loss than the *WSI 1* index because the vulnerability of buildings to windspeed will vary spatially in accord with spatial changes in extreme wind climate. The *WSI 2* index incorporates such spatial variability whereas the *WSI 1* index assumes (for the purposes of loss) that vulnerability is spatially constant. In common with other efforts to estimate WSIs we assume that windstorm severity is proportional to the cube of the gust speed. Gust speed cubed is a measure of windstorm kinetic energy and thus of wind power [*Lamb*, 1991; *Roberts et al*., 2014]. WSI values for a particular UK region are computed by using only the stations in that region.

8. Description of Windstorm Data Files

Our windstorm catalogues and windstorm severity indices 1969-2013 are presented in excel files called *"xxx Windstorm Catalogue and WSI Rankings 1969-2013.xlsx"*, where *xxx* is the UK region. There are twelve excel files comprising a data file for the whole UK, and data files for each of the 11 UK regions. Each excel file consists of three data sheets. The first data sheet gives the windstorm catalogue and associated information. The second data sheet ranks the 40 most severe windstorms in terms of *WSI 1* and *WSI 2*. The third data sheet lists the anemometer stations, together with their positions and elevations, used for each UK region.

8.1 Windstorm Catalogues 1969-2013 for the UK and for 11 UK Regions

The windstorm catalogues comprise the first sheet in each excel file. The windstorms in these sheets are listed chronologically and contain the following information, characteristics and severity grades for each event:

Column A: Windstorm number.
Columns B to E: Windstorm start date (year, month, day, hour).
Column F: Windstorm duration (hours).
Column G: Number of anemometer stations which record a peak gust ≥ 1 year return level.
Column H: Number of anemometer stations which record a peak gust ≥ 2 year return level.
Column I: Number of anemometer stations which record a peak gust ≥ 5 year return level.
Column J: Number of anemometer stations which record a peak gust ≥ 10 year return level.
Column K: Number of anemometer stations which record a peak gust ≥ 20 year return level.
Column L: Number of anemometer stations which record a peak gust ≥ 50 year return level.
Column M: Number of anemometer stations with maximum gust data for windstorm.
Column N: Windstorm Severity Index *WSI 1*.
Column O: Windstorm Severity Index *WSI 2*.
Column P: Windstorm name.

The windstorm names in column P are mostly those issued by the Frei University of Berlin for the windstorm-originating low pressure system (see http://www.met.fu-berlin.de/adopt-a-vortex/historie and http://www.met.fu-berlin.de/adopt-a-vortex/archiv). However, in a few cases, the better-known UK windstorm name is used. The UK Met Office names for windstorms are not used because these names commenced in 2015 and thus postdate the catalogue period. The windstorms with no names are cases

where either the event was relatively weak or where an unambiguous identification of the Frei University low pressure name was not possible. The catalogues contain the following number of windstorms by region: UK whole 394; Northern Scotland 106; Eastern Scotland 88; Western Scotland 83; Northern Ireland 79; North West England 91; North East England 79; Wales 90; Midlands 79; Eastern England 85; South West England 95; South East England 93. The excel data format allows for event filtering and sorting. For example, users may select and rank windstorms based on the number of stations which record gusts of a given return level or in terms of two different windstorm severity indices.

8.2 Windstorms Ranked by Severity for the UK and for 11 UK Regions

The 40 most severe windstorms 1969-2013, ranked separately by *WSI 1* and *WSI 2*, comprise the second sheet in each excel file. These windstorm severity rankings contains the following information:

Windstorm ranking by *WSI* (numbers 1 to 40).
Windstorm start date (year, month, day, hour).
Windstorm duration (hours).
WSI value.
Windstorm name
Definitions and formulae for *WSI 1* and *WSI 2*.

Table 2 shows an example of these rankings, their presentation format and the types of information thereby provided. The table displays the 25 most severe windstorms for South East England 1969-2013 as ranked by *WSI 1* (left set) and by *WSI 2* (right set). It is clear from Table 2 that: (a) The Great Storm of 1987 and the Daria (Burns' Day) windstorm both had a windstorm power ~5 times higher (*WSI 1*) and ~13 times higher (*WSI 2*) than any other South East England windstorm during the 45-year period; (b) Windstorms can have different severity rankings depending upon which WSI is used. For example, Kyrill is ranked 12th for *WSI 1* but rises to 3rd for *WSI 2*, Fanny is ranked 4th for *WSI 1* but falls to 17th for *WSI 2*, and Gisela changes from rank 11 for *WSI 1* to rank 23 for *WSI 2*.

Windstorm Ranking by WSI 1	Windstorm start date				Windstorm duration (hrs)	WSI 1	Windstorm Name
	Year	Month	Day	Hour			
1	1987	10	15	18	24	49775	Great storm of 1987
2	1990	1	25	3	24	37870	Daria (Burns' Day storm)
3	1974	1	16	6	24	8379	
4	1998	1	4	3	24	7562	Fanny
5	1976	1	2	12	24	7268	Capella storm
6	1993	1	13	0	24	7022	Verena
7	1987	3	26	21	36	6957	
8	1990	2	25	21	24	6780	Vivian
9	1972	11	12	16	24	6503	Quimburga
10	2002	10	26	21	19	6503	Jeanette
11	1997	2	24	14	24	6404	Gisela
12	2007	1	18	0	24	6328	Kyrill
13	1974	2	10	3	48	6316	
14	2000	10	28	12	72	6069	Oratia (Tora)
15	2008	3	10	0	24	5781	Johanna
16	1990	2	28	12	24	5759	Wiebke
17	1998	1	3	0	24	5560	
18	1996	10	28	7	24	5308	
19	2013	10	28	0	24	5307	Christian (St Jude)
20	1997	2	19	6	34	5216	
21	1990	2	7	7	24	4934	Judith
22	1993	12	8	9	24	4815	Quena
23	1977	1	25	4	24	4107	
24	1994	3	31	3	33	3543	
25	2009	11	13	16	24	3533	Hans

Windstorm Ranking by WSI 2	Windstorm start date				Windstorm duration (hrs)	WSI 2	Windstorm Name
	Year	Month	Day	Hour			
1	1987	10	15	18	24	19503	Great storm of 1987
2	1990	1	25	3	24	17303	Daria (Burns' Day storm)
3	2007	1	18	0	24	1409	Kyrill
4	1976	1	2	12	24	1215	Capella storm
5	1974	1	16	6	24	1057	
6	1987	3	26	21	36	1036	
7	2002	10	26	21	19	999	Jeanette
8	1995	3	17	1	29	944	
9	2000	10	28	12	72	934	Oratia (Tora)
10	1990	2	25	21	24	896	Vivian
11	1993	1	13	0	24	802	Verena
12	2008	3	10	0	24	739	Johanna
13	1993	12	8	9	24	707	Quena
14	1994	3	31	3	33	668	
15	1974	2	10	3	48	539	
16	2013	10	28	0	24	529	Christian (St Jude)
17	1998	1	4	3	24	491	Fanny
18	1990	2	28	12	24	487	Wiebke
19	1978	1	11	11	24	484	
20	1972	11	12	16	24	377	Quimburga
21	1977	12	23	10	27	294	
22	1990	2	7	7	24	277	Judith
23	1997	2	24	14	24	270	Gisela
24	1996	10	28	7	24	195	
25	2012	1	3	0	24	186	Ulli

Table 2. The 25 most severe SE England windstorms 1969-2013 ranked by *WSI 1* (left) and *WSI 2* (right).

9. Application to Further UCL UK Windstorm Products

The catalogue of UK windstorms 1969-2013 described herein informs and supports two further UCL UK windstorm products. These are: (a) The *UK windstorm gust return levels on a high spatial resolution (110 m) grid* product [*Saunders and Lea*, 2017], and (b) The *UK windstorm gust footprints at high (100 m) spatial resolution* product (to be released in March 2017). UK windstorms in the UCL catalogue account for 98.9% of the cleaned and homogenised daily maximum 3-sec gusts with a return level of at least 2 years that underpin the former product. Event selections for the latter product is made based on the windstorm severity rankings provided with the UCL UK windstorm catalogues.

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11. Appendix

The Appendix displays two figures which define geographically the 11 UK regions, and which show the locations of the anemometer stations in these 11 regions.

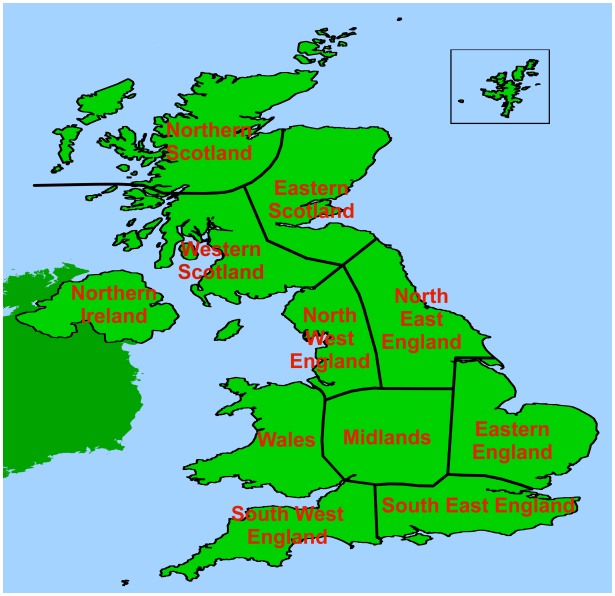

Figure 1: The locations of the 11 UK regions for which separate windstorm catalogues and windstorm severity indices 1969-2013 are provided. The Isle of Man is included with North West England, and the Shetland Isles is part of Northern Scotland.

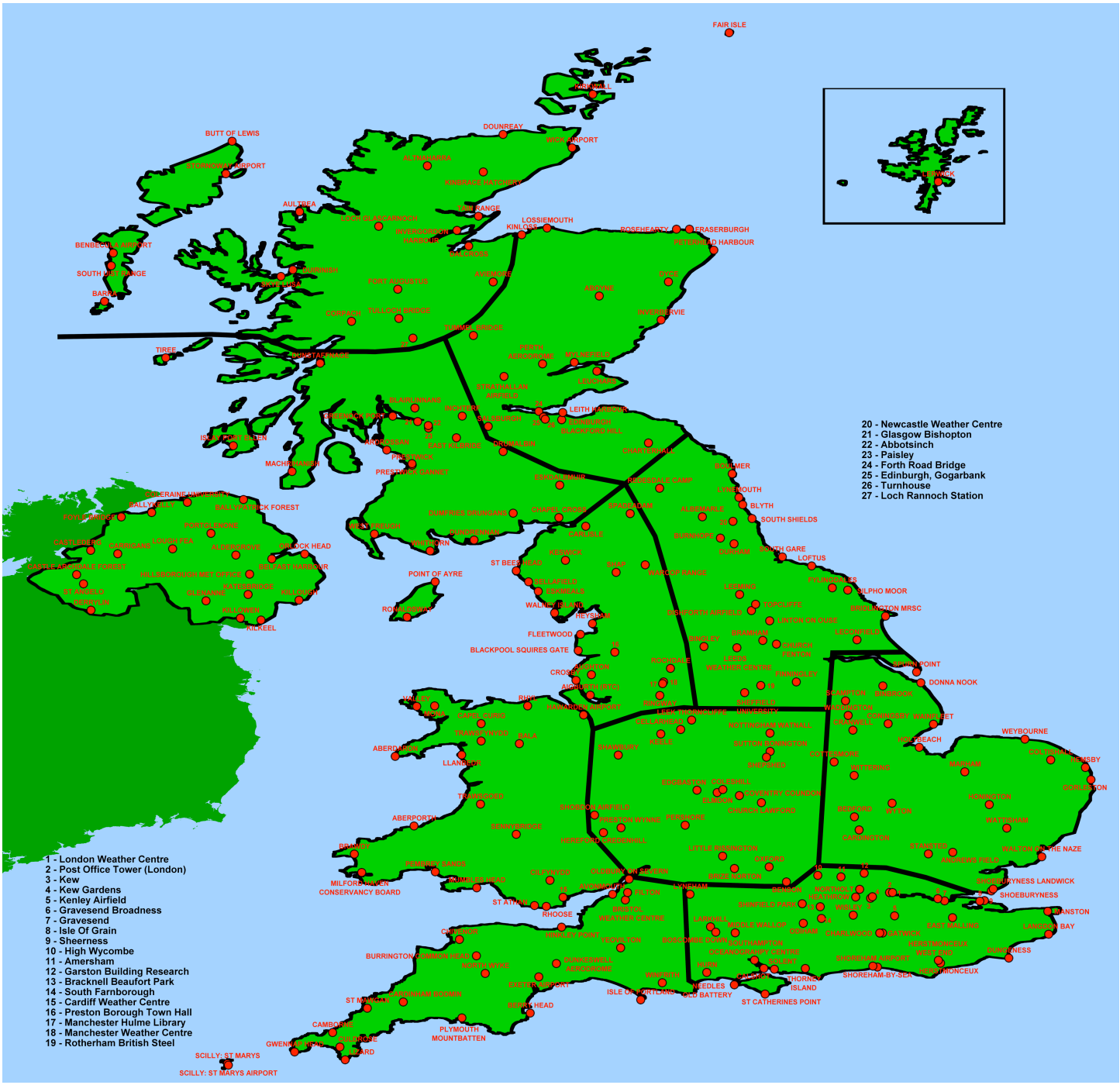

Figure 2: The locations and names of the anemometer stations included within each of the UK regions defined in Figure 1. The number of stations by region are as follows: UK: 262; Northern Scotland: 24; Eastern Scotland: 20; Western Scotland: 21; Northern Ireland: 20; North West England: 23; North East England: 24; Wales: 20; Midlands: 20; Eastern England: 27; South West England: 23; South East England: 40. The two Isle of Man stations are included with North West England