Programme Area: Nuclear

Project: Natural Hazards Phase 3

Title: Volume 3: Extreme Wind

Abstract:

This technical volume addresses:

- Introduction
- Description of the main phenomena; key influences on UK weather and climate, extreme winds, tornadoes
- Observations, measurements techniques and modelling tools
- Methodologies
- Related phenomena including sandstorms
- Regulation
- Emerging trends

Context:

The Natural Hazards Review project will develop a framework and best practice approach to characterise natural hazards and seek to improve methodologies where current approaches are inefficient. This is to improve energy system infrastructure design and the project is intended to share knowledge of natural hazards across sectors. The project will be completed in three stages. Phase one will focus on a gap analysis. Phase two will look at developing a series of improved methodologies from the gaps identified in phase one, and phase three will demonstrate how to apply these methodologies. Finally, phase 3 will develop a "how to" guide for use by project engineers.

Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies

Volume 3:

Extreme Wind

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Legal Statement

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Version	Date	Details
0.1	05/03/18	Submitted for IPR
0.2	23/03/18	IPR comments addressed and submitted to CTO
1.0	18/04/18	CTO comments addressed and submitted to ETI
2.0	25/06/18	ETI and NHP3 Steering Committee comments addressed

This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Volume 1 – Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Case Study 1 – Trawsfynydd. IMechE, IChemE.

Contents

Volume 3: Extreme Wind

Several different definitions and criteria are used to categorise wind events. Meteorologically, the Beaufort scale can be used to define the extremes in wind speed, but this is primarily used for describing wind intensity based on observed sea conditions, which the Met Office only uses in marine forecasts. On the Beaufort scale, a 'gale' is defined as a surface wind of mean speed 34 to 40 knots averaged over a period of ten minutes (where a knot or nautical mile per hour = 0.51 m/s = 1.15 mph = 1.853 km/hr = 1.689 ft/s), whilst a 'severe gale' or 'storm' is used to describe winds of 41 knots or greater averaged over a period of ten minutes (*Met Office, 2018a*). There is no such defined categorisation for land-based surface winds. For tropical cyclones, the Saffir-Simpson Hurricane Wind Scale is used to define wind speed and impacts (*Met Office, 2018b*).

Wind warnings issued by the Met Office are based on their combined likelihood and impact. In addition to wind speed, knowledge of the wind direction and shear is also essential for the energy industry to ensure that infrastructure can withstand extreme events and prepare for variations in energy transmission, particularly in the wind power sector. Wind speeds at a particular location depend on the altitude, surface roughness (or friction), wind direction and positioning in the UK, such as proximity of the site to the coast. Typically, higher wind speeds are found at higher altitudes and in open country or water, where the effects of surface roughness are greatly reduced compared to an urban environment with high-rise buildings and trees. Wind direction can also define the impact that the wind speed has on physical infrastructure. Typically, the prevailing wind in the UK is from the south west, so on average the west side of the UK, especially parts of Northern Ireland, tend to have higher annual mean wind speeds than eastern parts of the country. Autumn and winter storms tend to originate from the Atlantic, which when combined with predominantly prevailing south-westerly winds, means the western side of the country also experiences more of the impact from individual storms. Northern areas, such as northern Scotland, are much closer to Atlantic storm tracks than southern areas, so the type of storm that is classified as a 1 in 200 year windstorm in England may actually occur more frequently in Scotland. Hence, in relative terms, the definition of 'extreme' winds may vary regionally.

Wind gusts are sudden, brief increases in wind speed caused either by turbulence due to friction, *wind shear** or solar heating of the ground. They are measured as the maximum value of a three-second running average wind speed. *Table 1* provides a list, by region, of the most extreme wind gusts recorded at low-level sites in the UK.

*All technical terms marked in blue can be found in the Glossary section.

Table 1. Highest gust speeds recorded from low-level sites (excluding stations above 500 metres above sea level). Gust speeds were calculated from 10-minute averages. Met Office, (2018c); © Crown copyright Met Office 2018.

District	Speed	Date	Location
East Scotland	123 knots/142 mph/ 63.5 m/s	13th February 1989	Fraserburgh (Aberdeenshire)
North Scotland	118 knots/136 mph/ 60.8 m/s	7th February 1969	Kirkwall (Orkney)
South Wales	108 knots/ 24 mph/ 60.8 m/s	28th October 1989	Rhoose (Vale of Glamorgan)
South West England	103 knots/118 mph/ 52.8 m/s	15th December 1979	Gwennap Head (Cornwall)
South East England & South Central	100 knots/115 mph/ 51.4 m/s	4th January 1998	Needles Old Battery (Isle of Wight)
South East England & South Central	100 knots/115 mph/ 51.4 m/s	16th October 1987	Shoreham-by-Sea (West Sussex)
Midlands	99 knots/114 mph/ 51.0 m/s	13th January 1984	High Bradfield (South Yorkshire)
North Wales	97 knots/112 mph/ 50.1 m/s	24th December 1997	Aberdaron (Gwynedd)
East & North East England	95 knots/109 mph/ 48.7 m/s	2nd June 1975	South Gare (North Yorkshire)
West Scotland	95 knots/109 mph/ 48.7 m/s	26th December 1998	Salsburgh (Lanarkshire)
North West England	88 knots/101 mph/ 45.2 m/s	16th January 1984	Sellafield (Cumbria)
North West England	88 knots/101 mph/ 45.2 m/s	8th January 2005	St Bees Head (Cumbria)
North West England	88 knots/101 mph/ 45.2 m/s	13th January 1984	Sellafield (Cumbria)
East Anglia	87 knots/100 mph/ 44.7 m/s	16th October 1987	Shoeburyness (Essex)

Extremes in wind speed can affect the generation of energy, energy transmission, distribution, demand and price, and can have health and safety implications for energy businesses. The impacts of extreme high and low wind speeds on the energy industry are briefly outlined below:

- injury or death from debris and fallen trees;
- damage to power lines or energy infrastructure from debris and fallen trees, causing power cuts;
- structural damage to buildings, e.g. tiles blowing off roofs or the impact on roofs of wind-blown debris;

- disruption to transport, e.g. through the closure of roads and bridges, and delays and cancellations to trains and aircraft;
- low wind speeds can lead to a reduction in wind power and therefore the amount of energy produced (*Met Office, 2018d*);
- the impact of wind speed during lower temperature periods amplifies the effects of wind chill, which can be dangerous to people working outside who could be exposed to hypothermia and frostbite if poorly equipped.

Examples of how extreme wind speeds have historically affected the UK and its energy infrastructure are described below (*Met Office, 2018d*). Typically, areas of low atmospheric pressure coming in from the Atlantic have caused a lot of disruption; for instance, the storm on 11th to12th November 2010 brought gale-force winds to Wales, Northern Ireland, northern England and southern Scotland which caused 6000 homes to lose power. Gusts reached up to 36.2 m/s (81 mph or 70 knots) in Aberdaron in Wales, which is over twice the daily maximum gust speed in the UK measured between 1980 and 2005 (10 to 20 m/s = ~22 to 45 mph = ~19 to 39 mph) (*Hewston and Dorling, 2011*). This storm was similar in intensity to one on 18th January 2007, which brought damaging gusts to much of England and Wales during the day and caused significant damage to energy infrastructure leaving many people facing prolonged power cuts, as well as disruption to rail, road and aircraft transport. Finally, one of the most notorious storms was the Great Storm on 15th to 16th October 1987 which, unlike the majority of storms in the UK, tracked up from the south and then north and east over very populated areas. It has since been described as a 1 in 200 year event (*Met Office, 2018e*), caused 18 deaths and felled 15 million trees. In addition, it left the whole of South East England without power between 03:00 and 09:30 on 16th October 1987, due to the destruction of power lines or disruption of safety mechanisms (*Prichard, 2012*). The strongest gusts were 51.4 m/s (115 mph or 100 knots), in context with the daily maximum gust speed of 10 to 20 m/s in the UK (*Hewston and Dorling, 2011*), and annual mean wind speed of 5.1 to 7.7 m/s (11.5 to 17.3 mph or 10 to 15 knots) over much of western England.

The windiest weather in the UK is normally associated with Atlantic low-pressure systems that can cause hurricane-force winds, particularly on the western side of the UK. Historical examples of these damaging storms, and how they would have been rated according to the Met Office's impact-based weather warning system (which has been in use since 2011), are shown in *Figure 1*.

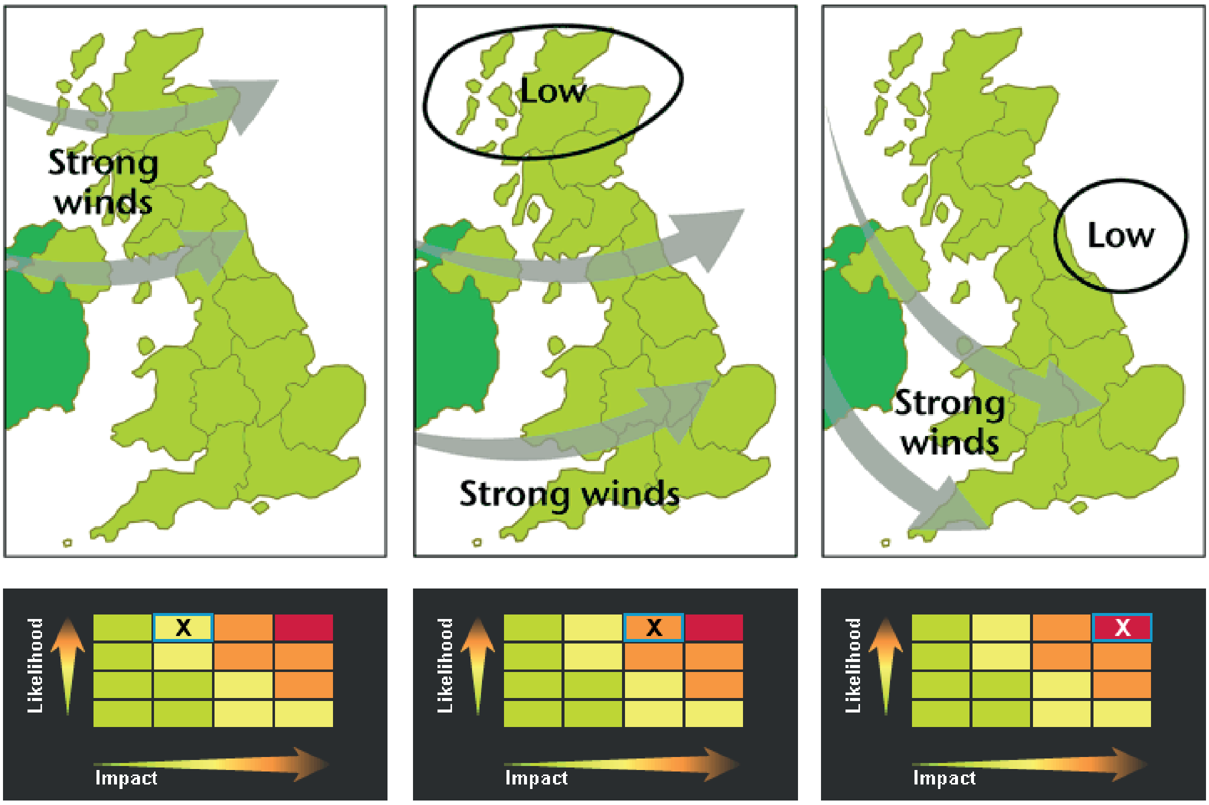

Figure 1. Schematics of the weather situation in three historical examples of impactful wind events (left to right: 3rd October 2009; 11th and 12th November 2010; 18th January 2007), and matrices showing the likelihood/impact ratings these events would have received under the Met Office National Severe Weather Warning Service's impact-based warning system. Met Office, 2018d. (© Crown Copyright Met Office 2018)

2.1 Key influences on UK weather and climate

The UK lies at latitudes of approximately 50 to 60°N, which means that it can be influenced by air masses originating from a variety of locations (*Figure 2*). The weather experienced by the UK essentially depends on the dominant air mass at a particular time.

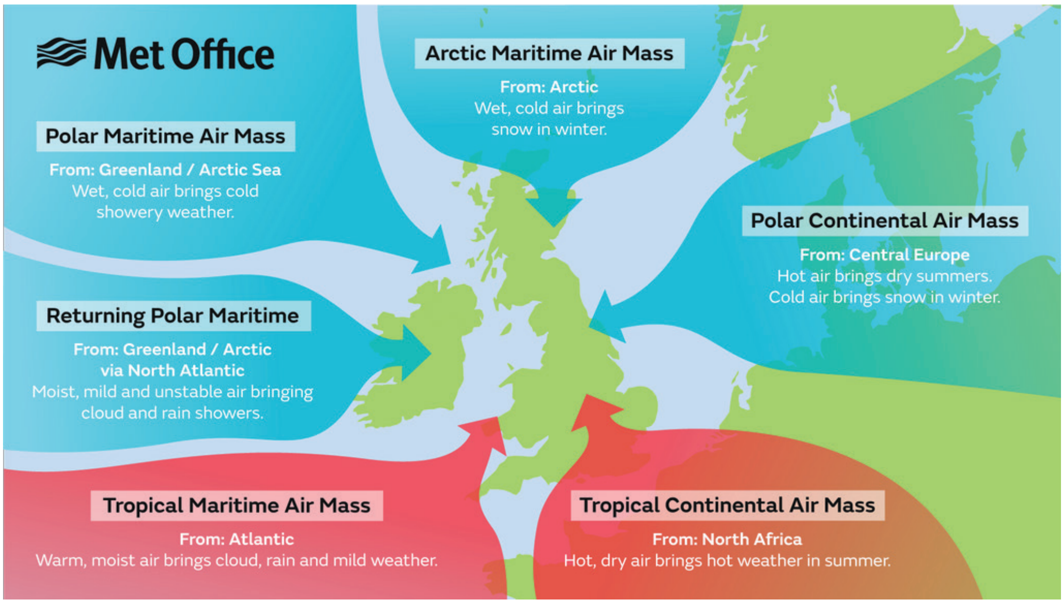

Figure 2. Air masses affecting the UK and their likely impacts in particular seasons. (© Crown Copyright Met Office 2018)

Large-scale climatic factors called ***modes of variability*** affect the global climate. The interaction between these modes of variability causes many complex feedbacks, leading to cycles of natural variation in our climate that operate over many timescales, extending even to multiple decades. Two of these naturally-occurring, low-frequency quasi-oscillations are the *El Niño Southern Oscillation (ENSO)*, a coupled ocean-atmosphere variation in the Pacific Ocean region, and the *North Atlantic Oscillation (NAO)*, a pattern of pressure variability over the North Atlantic, usually described as a pressure difference between the pressure over Iceland (usually low) and the pressure over the Azores (usually high). The NAO, in particular, influences the winter climate of the UK. It moves between positive and negative phases (*Figure 3*). In the positive phase, the Iceland/Azores pressure difference is larger, and this is usually associated with stormier, stronger winds and milder winters due to an intensified jet stream bringing westerly flow across the UK. In the negative phase, the pressure difference is smaller (below average), and this is usually associated with calmer, weaker winds and colder winters due to a weaker and more disrupted jet stream which may allow flow from other directions to dominate.

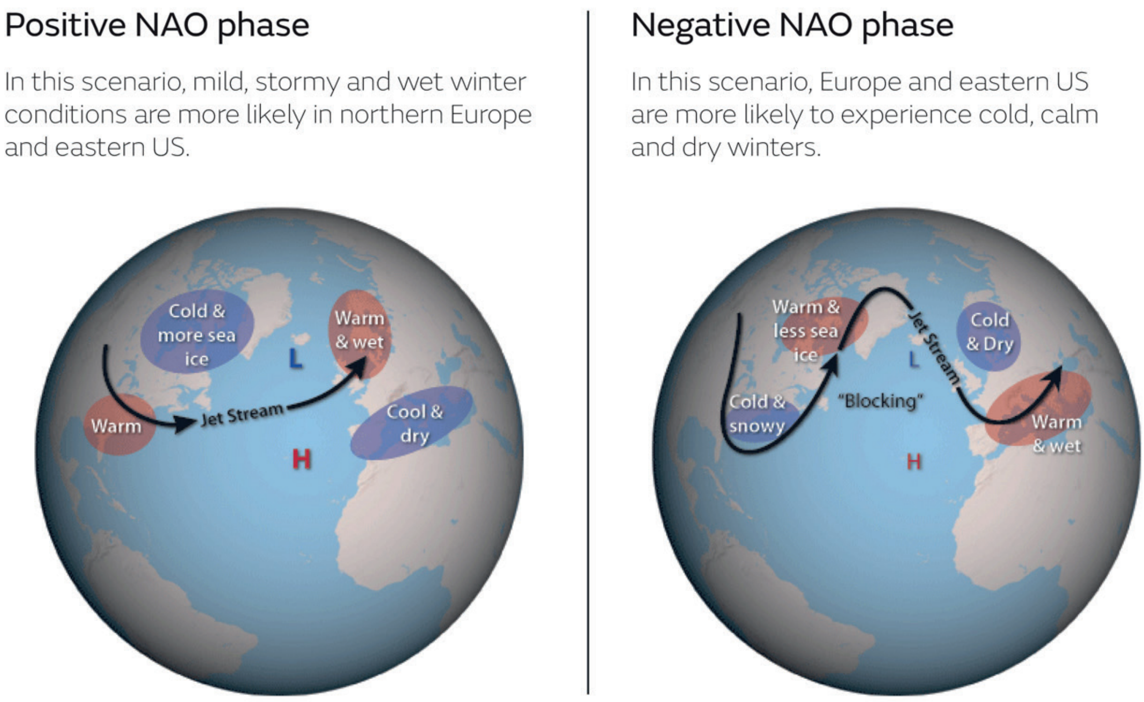

Figure 3. The NAO in its positive (left) and negative (right) phases, showing the influence on the storminess of winter weather over the UK. (© Crown Copyright Met Office 2018)

2.2 Extreme winds

Winds are caused by differences in atmospheric pressure. Globally, there are large-scale wind circulations made up of three circulation cells operating at different latitudes driven by warm, moist air rising from the tropics and moving to the poles (*Figure 4*). The effect of these three circulation 'cells', named the *Hadley, Ferrel and Polar cells*, combined with the *Coriolis force* (caused by the rotation of the earth) results in global circulation deflecting winds to the right in the northern hemisphere and causing prevailing south-westerly winds in the UK, which generally manifests as greater wind speeds on the western side of the UK (*Figure 5*). The UK falls on the same latitude as the polar front: the area of ascending air between the Ferrel and Polar cells where warm moist air meets cold polar air, which often leads to low pressure and unsettled weather. The polar front jet stream drives areas of low pressure across the Northern Atlantic, regularly bringing rain and changeable conditions. The jet stream varies on a seasonal basis. In the summer, the jet stream tends to positioned to the north of the UK, moving the weather systems away and bringing generally more settled weather. During the winter, the jet stream often lies west to east across the Northern Atlantic, driving low depression weather systems through quickly. Occasionally, the jet stream meanders further north or south which can cause areas of low pressure to become stuck over the UK leading to prolonged periods of rain and strong winds.

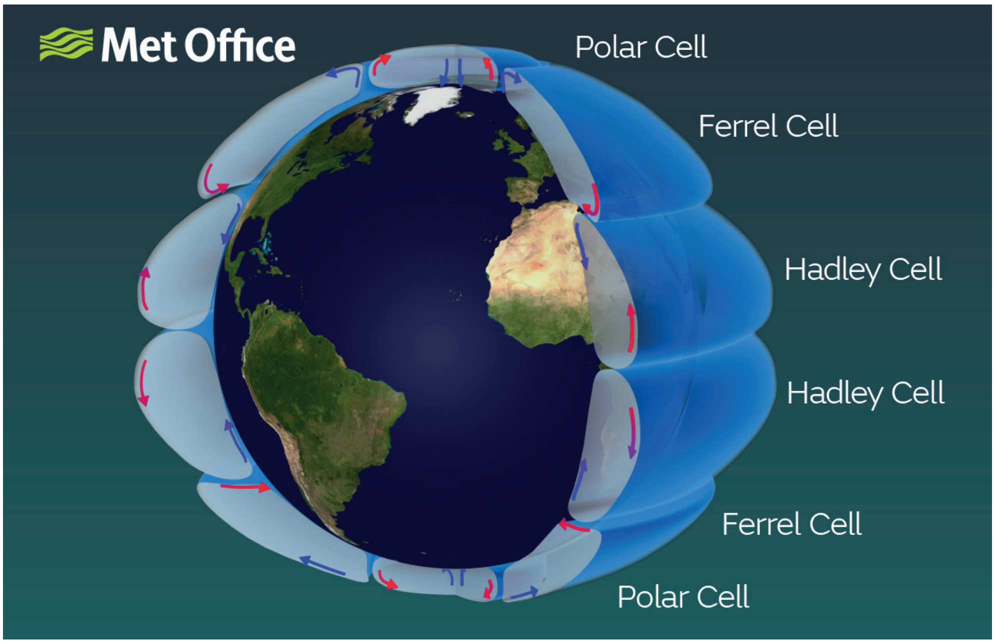

Figure 4. Global circulation patterns and their constituent 'cells' at different latitudes. Met Office, 2018f. (© Crown Copyright Met Office 2018)

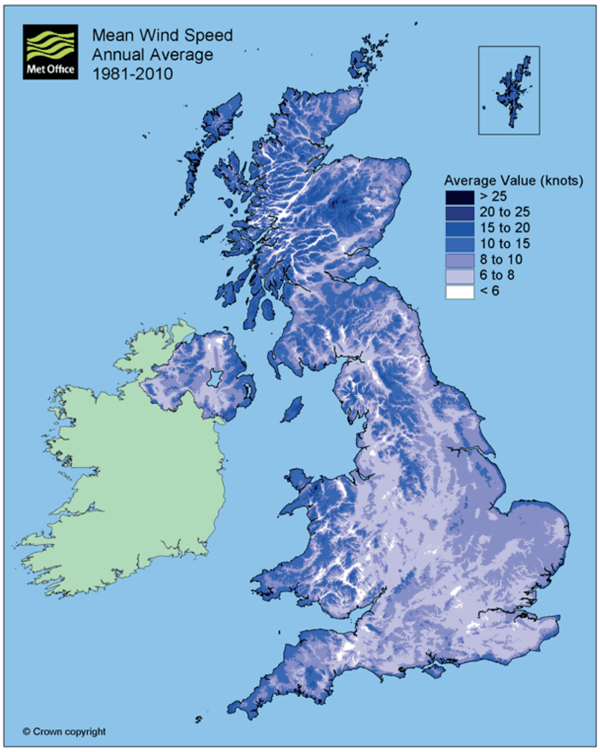

Figure 5. Mean annual wind speeds across the UK. Source: National Climate Information Centre; Met Office, 2018g. (© Crown Copyright Met Office 2018)

One potentially damaging effect of extreme wind storms is termed a 'sting-jet'. It is a phenomenon that can generate particularly damaging winds, such as occurred in the Great Storm of 1987. Sting-jets occur at the tail-end of a cloud which wraps around the area of low pressure and descend from high in the atmosphere in a few hours (*Met Office, 2018h*). As snow and rain fall into the descending air, it accelerates the wind to even higher speeds and they reach the ground within four to five hours. Small concentrated areas (approximately 48 to 80 km across) experience wind gusts of up to 51.4 m/s (115 mph, or 99.9 knots) associated with a 'sting-jet' for short periods of time (e.g. the Great Storm of 1987). Estimates suggest approximately 30% of North Atlantic storms have a sting-jet (*Hart et al. 2017*).

2.3 Tornadoes

Tornadoes are a type of extreme wind formed by the upward movement of warm, moist air which rotates due to the action of winds from different directions. Tornadoes are officially defined when the vortex of air is in contact with the ground and the cloud base (*Storm Prediction Center, 2018*). Tornadoes typically form when there is a large pressure gradient between the top and bottom of the atmosphere, creating a strong current of ascending air (updraught) and a deep cumulonimbus cloud (thunder cloud) (*Figure 6, stage 1*). When there is a strong gradient between wind speed at the top and bottom of the cumulonimbus cloud, i.e. a large vertical wind shear, then the thunderstorm begins to rotate horizontally, and can be tilted into a vertical spin by strong updraughts of wind (*Figure 6, stage 2*).

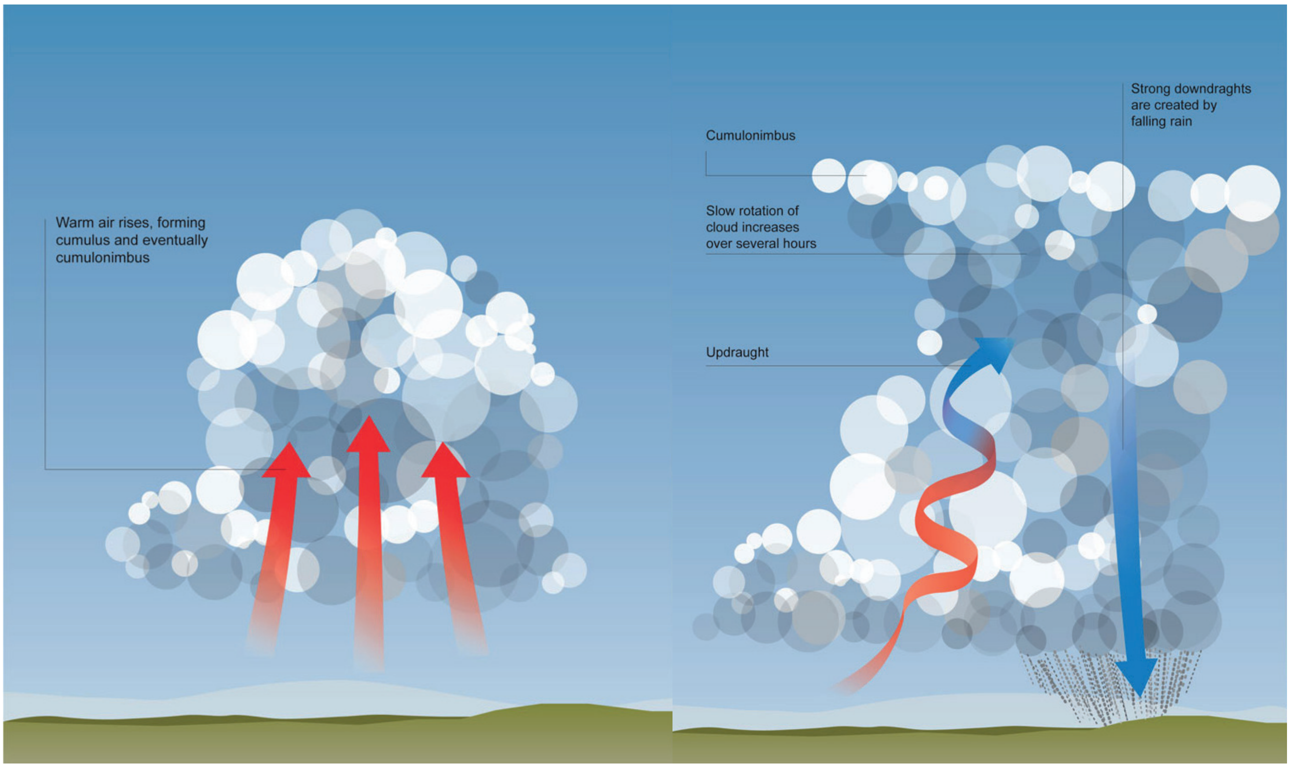

Figure 6. The beginnings of a tornado; storm development (stage 1) and storm organisation (stage 2). Met Office, 2018i. Supplied by Met Office, reproduced with permissions.

Downdraughts created by falling rain within cumulonimbus cloud help extend the rotation down to lower levels. This spiralling column of air is often visible because of the presence of a column of water (if over a body of water), and dust and debris which are picked up (*Figure 7, stage 3*). Eventually the tornado dissipates due to the downdraughts wrapping around the tornado and cutting off the supply of warm air (*Figure 7, stage 4*).

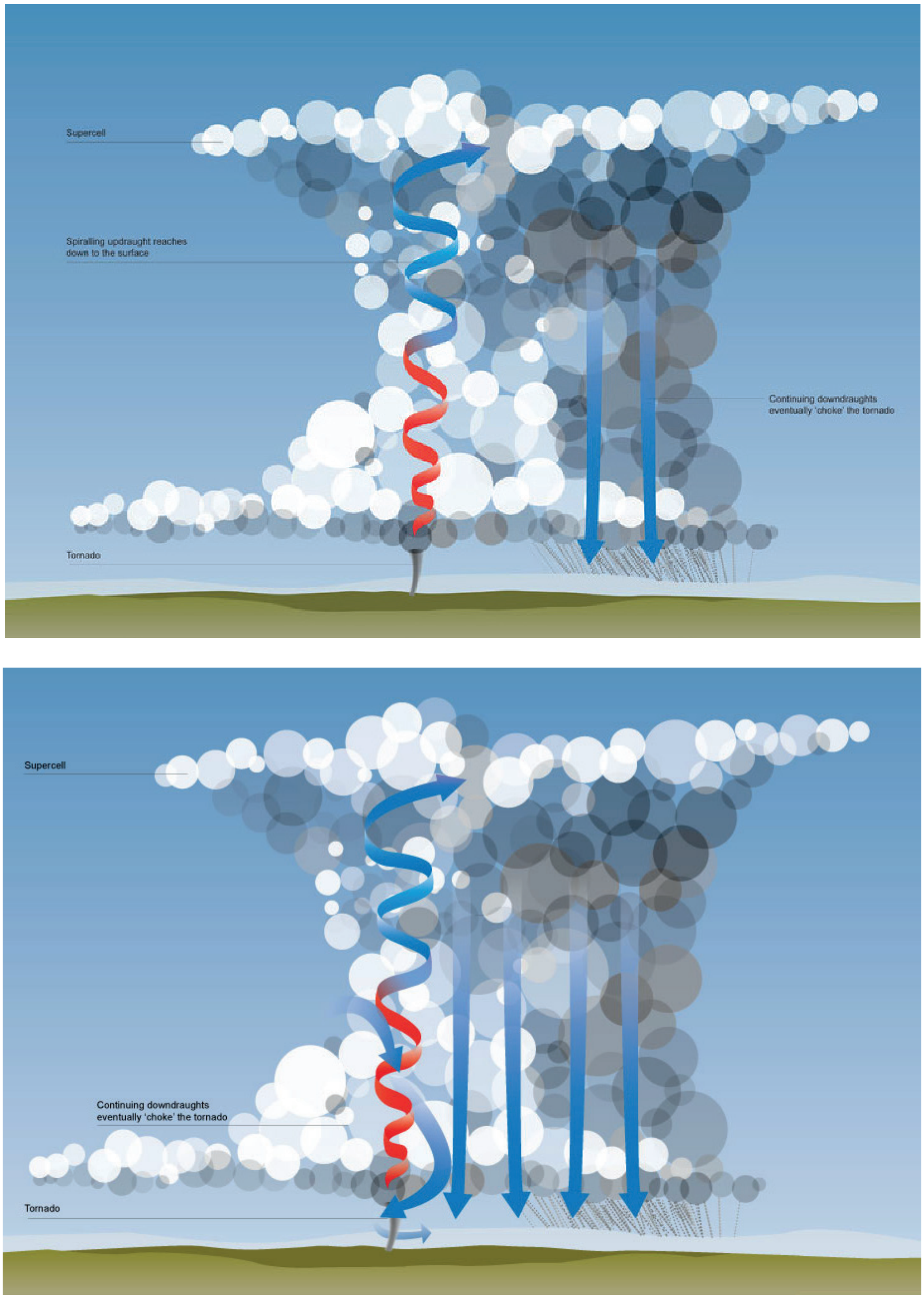

Figure 7. Stages of tornado formation (stage 3) and dissipation (stage 4). Met Office, 2018i. Supplied by Met Office, reproduced with permissions.

Tornado reports from the Tornado and Storm Research Organisation (also known as TORRO) revealed that over the last 33 years, the UK has experienced an annual mean of 34.3 tornadoes with the majority of these occurring in England (78%) (*Mulder and Schultz, 2015*). A wealth of information about UK tornadoes, including notable historical occurrences, frequency and spatial distribution, and the weather conditions that produce them, can be found in *Doe (2016)*. The intensity of tornadoes is measured using the the Tornado and Storm Research Organisation scale which ranges from 0 to 10 (*Table 2*). In the UK, tornadoes typically range from T0 to T2 categories which encompass wind speeds of 17 to 51 m/s (38 to 114 mph, 33 to 99 knots) and occur during the months of September to November, usually across southern and eastern parts of England as well as in the vicinity of the Channel Islands (*Kirk, 2014*). Funnel clouds (a rotating funnel-shaped cloud forming the core of a tornado, before it touches the ground) can occasionally be seen at more unusual times of year when conditions are right.

Table 2. The International Tornado Intensity Scale. Source: The Tornado and Storm Research Organisation (2018a) according to Meaden (1985).

Tornado intensity	Description of tornado and wind speeds	Description of damage
T0	Light Tornado 17 to 24 m/s (39 to 54 mph)	Loose light litter raised from ground level in spirals. Tents, marquees seriously disturbed; most exposed tiles, slates on roofs dislodged. Twigs snapped; trail visible through crops.
T1	Mild Tornado 25 to 32 m/s (55 to 72 mph)	Deckchairs, small plants, heavy litter becomes airborne; minor damage to sheds. More serious dislodging of tiles, slates, chimney pots. Wooden fences flattened. Slight damage to hedges and trees.
T2	Moderate Tornado 33 to 41 m/s (73 to 92 mph)	Heavy mobile homes displaced, light caravans blown over, garden sheds destroyed, garage roofs torn away, much damage to tiled roofs and chimney stacks. General damage to trees, some big branches twisted or snapped off, small trees uprooted.
T3	Strong Tornado 42 to 51 m/s (93 to 114 mph)	Mobile homes overturned/badly damaged; light caravans destroyed; garages and weak outbuildings destroyed; house roof timbers considerably exposed. Some of the bigger trees snapped or uprooted.
T4	Severe Tornado 52 to 61 m/s (115 to 136 mph)	Motor cars levitated. Mobile homes airborne/destroyed; sheds airborne for considerable distances; entire roofs removed from some houses; roof timbers of stronger brick or stone houses completely exposed; gable ends torn away. Numerous trees uprooted or snapped.
T5	Intense Tornado 62 to 72 m/s (137 to 160 mph)	Heavy motor vehicles levitated; more serious building damage than for T4, yet house walls usually remaining; the oldest, weakest buildings may collapse completely.
T6	Moderately-Devastating Tornado 73 to 83 m/s (161 to 186 mph)	Strongly-built houses lose entire roofs and perhaps also a wall; more of the less-strong buildings collapse.
T7	Strongly-Devastating Tornado 84 to 95 m/s (187 to 212 mph)	Wooden-frame houses wholly demolished; some walls of stone or brick houses beaten down or collapsed; steel-framed warehouse-type constructions may buckle slightly. Locomotives thrown over. Noticeable de-barking of trees by flying debris.
T8	Severely-Devastating Tornado 96 to 107 m/s (213 to 240 mph)	Motor cars hurled great distances. Wooden-framed houses and their contents dispersed over long distances; stone or brick houses irreparably damaged; steel-framed buildings buckled.
T9	Intensely-Devastating Tornado 108 to 120 m/s (241 to 269 mph)	Many steel-framed buildings badly damaged; locomotives or trains hurled some distances. Complete debarking of any standing tree-trunks.
T10	Super Tornado 121 to 134 m/s (270 to 299 mph)	Entire frame houses and similar buildings lifted bodily from foundations and carried some distances. Steel-reinforced concrete buildings may be severely damaged.

The strongest tornado recorded in the UK reached an intensity of T5 to T6 on 28th July 2005 in Birmingham, where wind speeds averaged between 41.6 m/s and 58.1 m/s (93 and 130 mph, or 81 and 113 knots). The estimated damage caused by this tornado cost £40 million (*Elkes, 2005*).

Tornadoes can also pose risks through intense bursts of heavy rainfall which can cause flash flooding, e.g. rainfall rates which exceed 100 mm/hr are not uncommon in association with southern, eastern and central England tornadoes. The majority of UK tornadoes, however, fall into category T0 to T2 (39 to 92 mph). As tornadoes are typically less than 1 km across, they are difficult to resolve on weather forecasting models and are not formally predicted or recorded by the Met Office.

A number of weather phenomena can contribute to tornado formation. These include:

Active cold front

A boundary between warm, moist, tropical air generally to the east/south east of the front and much colder, drier air to the west. If the cold front is powerful enough, it can generate a line of intense precipitation which can bring a multiple tornado outbreak, with each tornado lasting for a few minutes. This occurred in the UK during a cold front on 23rd November 1981, when there were 105 tornadoes across England and Wales over the course of a few hours (*Rowe and Meaden, 1985*).

Zone of shear wind

Winds of both different speed and direction which lie next to each other generate sufficient low level spin to generate a tornado. The tornado which occurred in Birmingham on 28th July 2005 was caused by a west-east warm front where winds to the north were strong and easterly and winds to the south were lighter. This created a huge gradient in wind speed and direction which caused the cloud to spin and generate a large tornado.

Severe surface-based thunderstorms

Strong surface heating occurs during spring, summer and early autumn. Convergence of lower level winds, e.g. sea breeze fronts or outflow from other thunderstorms, can create enhanced updraughts into the storm which can spin and generate a tornado. These tornadoes tend to be weak and will collapse when that part of the cloud begins to rain out.

Slack area of low pressure in summer

Occasionally areas of low pressure become slow-moving over the UK in summer. These are characterised by cool, showery conditions with high humidity. Showers and weak thunderstorms develop quickly within the slack pressure system which often have very low cloud bases. Outflow from these showers can often interact with frictional effects from the ground, generating funnel clouds which are highly visible but rarely do tangible damage.

Topography

In general, undulating topography will inhibit tornado development but certain landforms can also propagate vortices which are then picked up by passing thunderstorms. For instance, the Selsey tornado which occurred on 7th January 2008 was exacerbated by the combination of wind shear and a vortex formed around the south-eastern shore of the Isle of Wight. The Birmingham tornado which occurred on 28th July 2005 was aided by the fact that Birmingham is on a plateau, which forced air upwards.

3.1 UK datasets and sources of information

A non-exhaustive list of wind data over land and sea (both commercially and publicly available), as well as information and capability, is provided in *Table 3*. The main types of data available for the characterisation of extreme wind speeds using the methods described in this section are:

- Observations – *Sections 3.2* and *3.3* describe how wind speed and direction is measured at Met Office meteorological observing stations and buoys. These data may be:
  - point observations, i.e. values observed at a particular location;
  - gridded observations, i.e. derived from point observations by interpolating them onto a grid.
- Modelled data, including:
  - reanalysis data, derived via a technique that combines observations with numerical weather model runs to provide estimates over a grid covering the UK (*Section 3.5.1*);
  - projections of future climate, created using climate models (*Section 3.5.2*).

Table 3. A non-exhaustive list of wind and tornado datasets. [1]*The Tornado and Storm Research Organisation (2018b).*

		Dataset	Type	Domain		Time		Parameters	
				Region	Resolution	Period	Time step	Wind (land)	Wind (sea)
Historical	Observations	Marine observations	Site	Global	Best cover around Europe	From 1854, waves. Good confidence from 1990s	Up to half hourly	x	x
		UK observations	Site	UK	~200 to 300 sites for most parameters	From 1850, good coverage from 1960s	Up to 1 minute, good coverage at 1 hourly	x	
		Global observations	Site	Global	Good coverage over Europe, USA and parts of Asia	Good coverage from 1960s	Good coverage at 3 hourly	x	
		NCIC	Gridded	UK	5 km	From 1910, but good coverage from 1960s until 2014	Mostly monthly	x	
		The Tornado and Storm Research Organisation	Site	UK	Site specific	From 1950 to present	Coverage based on observed tornadoes mainly on land	n/a	n/a
	Archived forecast	UKV	Gridded	UK	1.5 km	2012 onwards	Up to 1 hour out to 36 hours	x	
		Euro4	Gridded	Europe	4 km	January 2009 onwards	Up to 1 hour to 57 hours, 3 hourly out to 120 hours	x	
	Hindcast	VMM&VMMplus (Virtual Met Mast) (tool for assisting with analysis, evaluation and selection of onshore and offshore wind farm sites)	Gridded	Europe	Site specific	1979 to near present (3 months in arrears)	1 hour	x	
		Euro4 (UK)	Gridded	UK	1.5 km	1979 to near present (4 months in arrears)	1 hour	x	
		Euro4	Gridded	Europe	4 km	1979 to near present (3 months in arrears)	1 hour	x	
		SWI(HiRes) & SWPlus (Site Wind Index) (derived from datasets)	Gridded	Global	Site specific	1979 to near present (1 month in arrears)	1 hour	x	
		Wind maps (derived from datasets)	Gridded	UK/ Europe	1.5 km	1979 to near present (3 months in arrears)	Decadal, monthly, annual	x	
	Reanalysis	ERA-Interim	Gridded	Global	~80 km	1979 to near present (3 months in arrears)	3 hours	x	
		MERRA	Gridded	Global	~40 km	1979 to near present (1 month in arrears)	1 hour	x	
Future	Projections	Seasonal	Gridded	Global	50 km		Up to daily	x	
		Met Office Hadley Centre + other IPCC models	Gridded	Global	~100 to 200 km	Preindustrial to 2099	Various	x	
		UKCP09 (WAM)	Gridded	UK	12 km, 25 km	2010 to 2099	Daily		x

3.2 Measuring wind variables over land and sea

Observations of wind from the Met Office observing sites on land are made using either a cup anemometer, which has moving parts used to measure wind speed and direction, or a sonic anemometer, which is used to measure wind speeds in locations prone to icing, e.g. on top of mountains or at sea (*Figure 8*). Observations of wind speed/direction/gust over the sea are measured using voluntary observing ships, shipborne automatic weather stations, and marine automatic weather stations, e.g. moored buoys, light vessels, offshore installations and marine platforms around the UK and within UK waters (*Met Office, 2018j*). It is important to note that observations collected from moving ships can be biased by the presence of the ship's hull, the relative wind direction and the angle of the ship to the wind.

Ideally, wind measured at the land surface should be done at a height of 10 m above the ground on top of a supporting structure, to lessen local influences on the air flow. The wind direction is measured relative to true north and is reported from where the wind is blowing. As wind speed is dependent on height above the earth's surface and surface roughness, e.g. presence of buildings, trees and other obstacles, then ideally the measurement site selected would be surrounded by level ground (no obstacles within 300 m) and have a uniform surface roughness from all wind directions.

In a sonic anemometer, the speed of acoustic signals transmitted between two transducers (a piece of equipment that converts signals into wind speed) can be combined to estimate wind speed and direction. Any interference from distortion of air flow caused by the transducers themselves can be corrected for.

Figure 8. A cup anemometer with a wind vane on the adjoining arm of the mast. Measurements made by transducers in a heated sonic anemometer (not shown) can be combined to give an estimate of wind speed and direction in more extreme weather conditions. (© Crown Copyright Met Office 2018)

Wind intensity and gusts can vary rapidly over short periods of time, and it is often the short burst of very high speed that causes the greatest damage in storms. Consequently, to sample wind speeds accurately, repeated measurements are required, typically every 0.25 seconds. The gust speed is defined as the maximum three-second average wind speed occurring during any period. Wind intensity is then defined by the average speed and direction over the ten-minute period prior to the reporting time (*Met Office, 2018k*). For instance, a gale is defined as a surface wind of mean speed of 34 to 40 knots averaged over a period of ten minutes (*Met Office, 2018a*).

The density of the UK Met Office land surface recording system is shown in *Figure 9*. These weather stations are typically 40 km apart to capture weather associated with low pressure and frontal systems. Over 200 predominantly automated stations produce data at minute intervals which are summarised into hourly data by the Met Office. In addition to this, citizen science platforms such as the Weather Observations Website (WOW) (*WOW, 2018*) and Weather Underground Wundermaps (*Weather Underground, 2018*) allow users to search for and provide observations from all over the globe at varying frequencies and resolution. However, it is important to note that observations collated through WOW do not undergo quality assurance and the sites are not regulated in terms of their location or height, as official Met Office observation stations are. The star rating given to the observation station on the WOW website reflects the quality of a site's observations, such that sites with a higher star rating may be useful for verification of nearby observations. Weather Underground provides a list of compatible weather stations available for purchase as well as guidelines about the siting of the station to ensure standardisation.

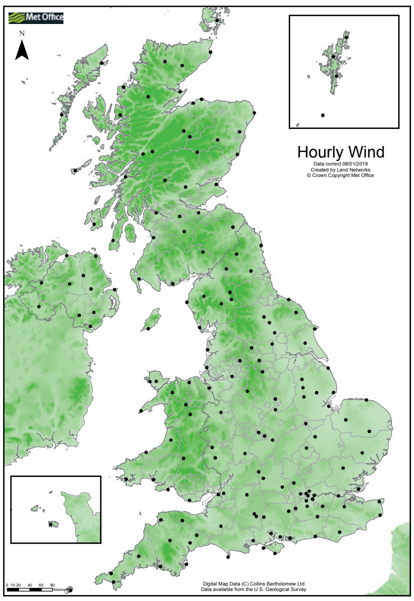

Figure 9. The density of observing stations over the UK (dots), recording wind observations such as mean wind speed, mean wind direction and maximum gust at 10 m above the ground. (© Crown Copyright Met Office 2018)

3.3 Remotely sensed wind speed observations

The UK observing network uses either cup or sonic anemometers to measure wind speed (*Figure 9*). However, wind energy sites are increasingly choosing to use remote sensing techniques which are able to accurately determine the wind speed and direction at several heights. Given that wind turbines have continued to grow in size, masts for mounting cup anemometers have also become taller and more expensive (*Lang and McKeogh, 2011*). Instead, two remote sensing tools have become more popular in the industry:

- Light Detection and Ranging (LIDAR), e.g. Windcube; and
- Sound Detection and Ranging (SONAR), which can be used over hundreds of metres, and for the tallest turbines (Windcube can be used 200+ m).

Both techniques use the Doppler effect (electromagnetic radiation in LIDAR, and pulses of sound in SONAR) to sense the movement of air in the atmospheric boundary layer to infer wind speed and direction. Employment of LIDAR and SONAR techniques allows for detailed mapping of wind fields, especially the differences in wind speed and shear across the rotor disc of a large modern turbine, which would not be possible with anemometers measuring a much smaller volume of wind (*Lang and McKeogh, 2011*).

3.4 Measuring and recording tornadoes

The Tornado and Storm Research Organisation is a privately supported research organisation set up in 1974, which enlists the support of approximately 300 to 400 volunteer amateur and professional meteorologists residing in the UK. Volunteers can collect and collate observations of tornadoes and waterspouts. As the data collection is dependent on the number of visible accounts made by volunteers, there is a high probability that observations will be biased towards more populated areas, such as South East England.

Currently, the Tornado and Storm Research Organisation remains the only centralised database of tornado observations in the UK. The Met Office has no formal means of measuring tornadoes unless they occur at manned weather stations. Measuring tornado wind speeds using conventional anemometry is usually not possible due to damage inflicted on the anemometer in wind speeds exceeding 45 m/s (100 mph, or 87 knots). As such, the Met Office accepts reports of tornadoes from the general public, which it passes on to the Tornado and Storm Research Organisation for further investigation and processing. The Tornado and Storm Research Organisation also collates observations of land/water/fire devils, very heavy showers, damaging hailstorms and ball lightning.

3.5 Modelling tools

3.5.1 Reanalysis

Available reanalysis datasets are summarised in *Table 3*. Reanalysis essentially involves using historical observations, retrospectively, to drive a numerical weather prediction (NWP) model, i.e. a model that is normally used for forecasting the weather in real time. Rather than being allowed to evolve freely, the model is systematically constrained at intervals (say, 12 hours) by the assimilation of further historical observations. The advantage of this process is that it produces a gridded dataset of many variables, spanning several decades and large geographical areas (even global). There are some limitations; mainly these relate to the limitations of the chosen NWP model (i.e. how well it performs in terms of modelling key weather parameters) and to any deficiencies in the quality of the observations ingested into the process.

3.5.2 Climate modelling

Future projections of UK climate can be obtained from climate modelling studies. Climate models often have similar configurations to NWP models, but as climate projections span decades rather than hours to days ahead, they are run slightly differently (e.g. with lower spatial resolutions and longer time steps). Projecting future climate involves several assumptions and uncertainties, some of which are discussed below:

Resolution uncertainty

The weather and climate system is very complex and no NWP or climate model can capture all of the processes within it. For example, some processes may occur at a spatial resolution lower than that of the model grid and hence may not be captured.

Emissions uncertainty

Running a climate model requires the provision of various inputs. For modelling the future climate, one of these inputs is an estimate of future greenhouse gas emissions. The latest version of climate modelling use representative concentration pathways (RCPs) (*van Vuuren et al., 2011*), which characterise the atmospheric concentrations of greenhouse gases, rather than the level of emissions.

Structural uncertainty

Understanding of the full climate system is incomplete, and what is known has to be represented in a climate model in an approximate way, owing to restrictions on computing power. Different climate models are based on a set of different choices, assumptions and approximations. Consequently, a set of climate models project different amounts of warming and other changes in the climate system in response to the same emissions of greenhouse gases.

The current main source of UK climate projections, for both land and marine regions of the UK, is the United Kingdom Climate Projections 2009 (*UKCP Project, 2009*). As an example, the land projections provide data at up to 25 km resolution for the whole UK, for a range of parameters relevant to energy (including daily surface wind speed), spanning out to the 2080s. Note that an updated set of climate projections for the UK, called UKCP18, is due to be released from September 2018 (*UKCP Project, 2018*). Details about the interpretation and use of surface wind speed projections can be found in the UK Climate Projections 2009 (UKCP09) technical documentation (*Brown et al., 2010*).

There are also coordinated global and regional climate modelling activities under the Coupled Model Intercomparison Project (CMIP) and Coordinated Regional Climate Downscaling Experiment (CORDEX) programmes. CORDEX (*Giorgi and Gutowski, 2015*) is coordinated by the World Climate Research Programme. One of its aims is to produce coordinated sets of regional downscaled climate projections worldwide. Some of the data produced under CORDEX are available for commercial use. Both CMIP and CORDEX programmes involve collaborative working between multiple climate modelling centres around the world, to build and develop climate models, evaluate their performance, and produce global future projections. The most recent of these activities is CMIP5 (*Taylor et al., 2012*), under which projections from 24 global climate models have been produced; most of these are available for commercial use. These projections were used to inform the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report (*IPCC, 2013*). While global projections are necessarily made at lower resolution than regional projections like UKCP09, their global context makes them useful in, for example, evaluating external (non-UK) risks to the UK energy sector.

There are also newer initiatives in global, high-resolution climate modelling. In order to understand the role of resolution in climate variability and change processes, the HighResMIP project (as part of CMIP6, *Eyring et al. 2016*) will produce global simulations at multi-resolutions from up to 22 different climate models. The Horizon 2020-funded project PRIMAVERA (*PRIMAVERA, 2018*) includes seven modelling groups that have already completed most of these computationally intensive, and technically challenging simulations, with ongoing analysis to assess the impact on processes affecting European climate. Such simulations can potentially add value to the methods currently available for undertaking climate risk assessments. PRIMAVERA data will be published to the Earth System Grid Federation (ESGF) CMIP6 nodes during the latter part of 2018.

New regional modelling capability in the shape of the H2020 European Climate Prediction System (EUCP) project is also beginning. This will enable much improved simulation of high impact climate extremes. It will assess uncertainty in different methods of prediction, and support improved climate risk and adaptation strategies. Updates on this can be found on the Barcelona Supercomputing Center website (*BSC, 2018*).

This section outlines a range of methodologies which can be used to characterise extreme winds in the UK. Extreme value analysis (EVA) is applied to wind data in *Section 4.1*. Further extreme wind methodology used within Eurocodes is discussed in *Section 4.2*, and finally tornado methodologies are discussed in *Section 4.4*. Additional methods used to characterise extreme wind such as the probabilistic Monte Carlo technique are outlined in *Appendix A*, which also looks at how numerical and climate models can be used. Finally, any knowledge gaps and recommended methodologies are discussed in *Section 4.5*. Further information about EVA can be found in the EVA Primer provided in Volume 1 — Introduction to the Technical Volumes and Case Studies.

4.1 Extreme value analysis

Extreme value analysis (EVA) is a statistical methodology which aims to estimate the probability of events that are more extreme than those previously observed at both extremely large or small levels. EVA is a methodology that is commonly used within the energy industry for different variables, but here it is demonstrated for wind. For example, a 20-year observation record can be used to estimate what might occur in the next 200 years given the historical record. EVA provides a framework that enables extrapolation of this type (*Coles, 2001*). The level of uncertainty in the projected extreme events will increase as the return period exceeds the length of the data series.

Climate change causes certain variables, especially temperature, to experience long-term changes. This long-term change is not necessarily reflected in some EVA techniques which assume that observations are independent of one another and data are 'stationary', i.e. the statistical properties of the variables such as temperature, rainfall or wind speed are consistent over the duration of the time series. Long-term changes can be accounted for by inclusion of 'co-variates', i.e. other independent variables which could contribute to the outcome of the model. Co-variates are further described in *Section 4.1.4*.

4.1.1 The generalised extreme value distribution

The generalised extreme value (GEV) distribution is usually fitted to a set of extreme events, where the extreme events are defined as the most extreme event that occurred within a fixed time period such as seasons or years. For instance, GEV models have been used to assess the seasonal wind energy potential (*Arreyndip and Joseph, 2016*). The process of selecting the most extreme observation in a fixed time period is also called a block maxima approach. A GEV distribution is described by three parameters: location, scale and shape.

The location parameter is analogous to the mean of a normal distribution in that an increase in the location parameter results in the entire distribution shifting to higher values while the form of the distribution remains unchanged.

The scale and the shape parameters together determine the rate at which the magnitudes of the extremes (the return level) alter with lengthening return period. This is illustrated in *Figure 10*, which shows the effect of the scale and shape parameters on the return-level curves. The shape parameter increases from left to right, from –0.2 through zero to 0.4, whilst the scale parameter increases from 1 at the top, 4 in the centre to 8 at the bottom.

The scale parameter is always positive, and broadly measures the variability in the source data: the larger the scale parameter, the greater the spread. The shape parameter controls whether the return-level curve is bounded, reaches a limit, or not. The left-most column in *Figure 10* shows return-level curves for a shape parameter of –0.2 with different scale parameters; a close inspection shows that the curve is levelling off as the return period increases. In other words, the return-level curves are approaching an asymptotic limit — a boundary that cannot be exceeded.

Plots in the central column have a shape parameter of zero; the return-level points would appear broadly to lie on a straight line which increases linearly as the return period increases on the log scale. Plots in the right-most column have a shape parameter of 0.4; here the return-level curves are increasing exponentially as the return period increases.

Considering all plots in *Figure 10* together, the return-level curves show that, for a specified return period and for increasing values of the shape and scale parameters, the associated return-level value increases.

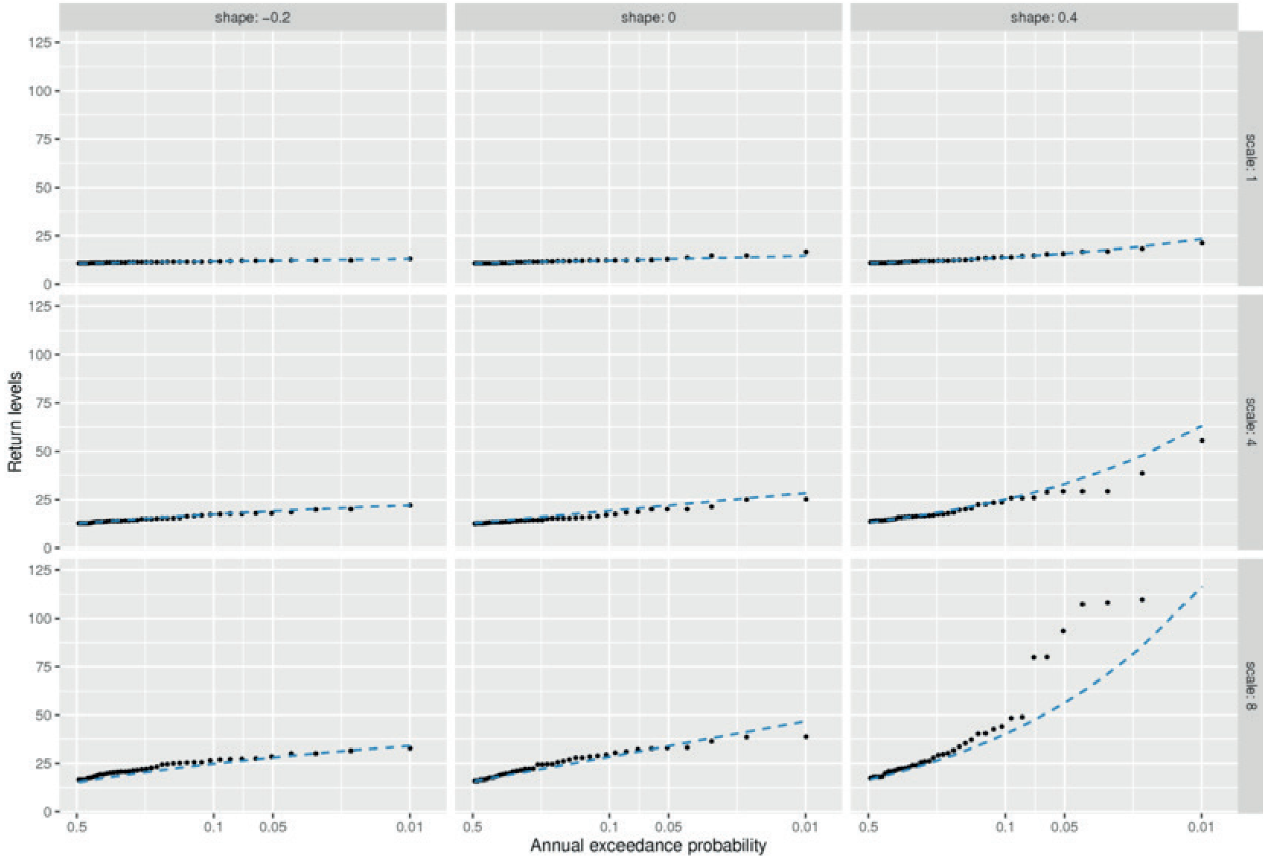

Figure 10. An illustration of how the scale and shape parameters in a GEV model affect the associated return-level curves. Columns, left to right: shape parameter values of –0.2, 0 and 0.4. Rows, top to bottom: scale parameter values of 1, 4 and 8. The location parameter is the same in all panels and all panels are plotted on the same scale for ease of comparison. Observations are represented by black dots and fitted GEV model is represented by blue dashed lines. Note the logarithmic scale on the x-axis.

Note that the 'generalised' part of the GEV distribution refers to the fact that it is a generalised form of three slightly different distributions: the Gumbel, Fréchet and Weibull distributions. These are associated with particular values and ranges of the shape parameter (see *Table 4*). An advantage to using the GEV distribution is that no decision is required before the analysis as to whether the shape parameter is less than zero, zero or greater than zero. Wind speeds at extra-tropical latitudes, such as the UK, have been shown to be approximately Weibull distributed (*Perrin et al. 2006*) which, unlike the Gumbel and Fréchet distributions, is a bounded distribution and reflects that there is a definitive upper and lower limit to extreme winds. However, there is uncertainty around how well extreme wind speeds are fitted by the Weibull distribution. *Galambos and Macri (1999)* found that the assumption of bounded wind speeds led to contradictions and the Gumbel distribution is better for modelling extreme wind speeds. *Perrin et al. (2006)* also found that the Weibull distribution did not accurately represent the tails of the wind distributions or the distribution of yearly maximum wind speed. This lack of consistency between which distribution is most suitable to fit to extreme wind speeds is likely to be because there is no differentiation between the meteorological causes behind extreme winds caused by e.g. convective storms versus cold fronts. *Simiu (2002)* suggested that statistics on wind storms caused by different meteorological phenomena should be developed separately and then combined in mixed distributions. The GEV is one such mixed distribution that has been used to estimate extreme wind speeds (*Kollu et al., 2012*), but even this method has some drawbacks which are discussed below.

Table 4. Characteristics of specific forms of the GEV distribution.

Distribution	Shape parameter can take values…	Asymptotically, this distribution is…
Negative Weibull	Less than zero	Bounded
Gumbel	Zero	Unbounded
Fréchet	Greater than zero	Unbounded

As mentioned previously, extremes for a GEV are selected using the block maxima approach. One criticism of fitting an extreme value distribution (EVD) using a block maxima approach is that it limits the number of extreme events available. This can be a problem especially if the time series of observations has a comparatively short length, compared to the inverse of the desired annual exceedance probability (AEP). Volume 1 — Introduction to the Technical Volumes and Case Studies defines the term 'annual exceedance probability', or AEP, as the annual probability of exceeding a specific level and it is the inverse of the return period for stationary data. Smaller samples of extreme events will generally result in the parameters of the EVD having larger uncertainties and in an increase in the variability associated with any return levels generated from the fitted GEV distribution. Another disadvantage of the block maxima approach is that it discards multiple extreme events that fall within the same block (e.g. year), even if some of those events are amongst the largest extreme events in the record. These issues have, in the past, motivated research into approaches that use more of the extreme events within the observation record.

4.1.2 Threshold exceedance approaches

Some authors have argued (*Coles, 2001*; *Katz et al., 2005*; *Brown et al., 2008*) that if an entire time series of daily observations is available, then it is better to avoid the block maxima approach. An alternative approach is to define a threshold and then define values that exceed this threshold as extreme events. This is called the 'points over threshold' approach. The choice of threshold is analogous to choosing the block size in a GEV analysis (e.g. blocks of a year, season, month, etc.), in that the choice of threshold (or block size for a GEV analysis) can have significant consequences on the subsequent EVA.

Too low a threshold could include too many observations, some of which may not originate from an EVD. This can ultimately lead to biases in the estimation of the parameters of the EVD and return values, which may be too high or too low.

Too high a threshold can have the opposite effect in that not enough observations are included which can lead to parameter estimates with high variance. Whilst this may have little effect on the return levels themselves (provided there are sufficient blocks or observations to ensure an appropriate fit), the associated confidence intervals may become large, possibly to the extent that they may be of no practical use for the application under consideration.

Good practice endeavours to choose a threshold that is as low as possible, so that the uncertainty associated with the extreme value parameters can be better quantified, yet still satisfies the assumption that the data come from an EVD.

4.1.3 The generalised Pareto distribution

The generalised Pareto distribution (GPD) and the Poisson-GPD are typically fitted to data that have been defined as extreme using a threshold exceedance approach. A GPD is used to model the intensity of an extreme event, i.e. by how much is the defined threshold exceeded. A GPD, like the GEV, is defined by location, scale and shape parameters.

The Poisson-GPD model, also known as the Marked Point Process (MPP) model or a point process GPD, as its name implies, has two components: a Poisson process which models how many times an extreme threshold is exceeded, and a generalised Pareto distribution which models by how much the threshold set for the Poisson distribution is exceeded. A Poisson-GPD model is also defined by location, scale and shape parameters.

There are many similarities between the parameters of the GEV and the parameters of the Poisson-GPD. Indeed, given a suitably large threshold, the shape parameters of the Poisson-GPD tend towards the GEV parameters (*Coles, 2001*).

The generalised Pareto distribution (GPD) has been widely used to represent extreme geophysical phenomena such as floods and extreme windstorms (*Lechner et al., 1992*; *Holmes and Moriarty, 1999*).

The correlation between wind speed and direction is useful to account for when conducting EVA because knowing which direction extreme wind speeds travel from will be essential when planning energy infrastructure. If different meteorological mechanisms are responsible for extremes from different directions or in different seasons, then partitioning into wind direction or time of year could be very useful. This can be done using a number of methods, one of which is the Method of Independent Storms (MIS) that analyses wind speed extremes by direction (*Cook, 1983*; *Palutikof et al., 1999*). This method of EVA was originally applied independently to the wind series in each direction, whereas *Coles and Walshaw (1994)* include direction as a 'covariate' in the EVA model, i.e. an additional variable which influences extreme wind speed and as such, could improve the fit of the model. They also converted the wind speed series into components, which allowed the full data series to be used for each direction, and extreme wind speeds from adjacent directions to influence the results. This model resulted in shape and scale parameters that varied smoothly across the directions, removing most local inconsistencies whilst still retaining the main features.

4.1.4 Factors to be considered when conducting extreme value analysis

Aside from considering the choice of method (block maxima vs threshold exceedance approach) and the type of EVD, there are some assumptions made when conducting an EVA which are considered briefly below:

Autocorrelation and independence of extreme events

Extreme value theory assumes that extreme events are independent and sampled from the same parent distribution, i.e. all extreme windstorms are assumed to be caused by the same meteorological phenomenon. Approaches to compensate for autocorrelation, such as 'declustering', can subset the time series in order to ensure independent observations (*Coles, 2001*).

Covariates

So far in this discussion, it has been assumed that the data being used to conduct the EVA are stationary, i.e. the statistical properties of the distribution (the EVD parameters) do not change in a systematic way with time. As discussed in *Section 2.1*, the NAO has been shown to influence the wind speeds over Europe and should therefore be included as a covariate where possible (*Ely et* *al, 2013*). As a result, the ability to include and assess possible covariates in the EVA is desirable. This is easy to achieve if the statistical models are fitted using the method of maximum likelihood (see *Coles, 2001* for more details). *Katz et al. (2002)* illustrated an approach that allowed the parameters of the EVD (the location, scale and shape) to depend linearly on such covariates. Any covariates included in an EVD should be assessed for statistical significance (i.e. does the inclusion of the covariate improve the fit of the EVD to the data, does it explain more of the ***noise***?) using likelihood ratio tests (*Coles, 2001*) or Akaike information criterion (AIC).

Length of dataset

For accurate EVA, the length of the dataset must be sufficient in order to maximise the number of extreme events captured. There are techniques available to lengthen datasets, such as combining a number of weather station data together. For example, *Peterka (1992)* did this with 29 individual stations in the US forming 924 station-years of record. When pooling station data, it is important to consider space/time equivalence issues, e.g. the difference between selecting a long time-series of data from one weather station vs selecting a short time-series of data from many different weather stations. It is also important to note when doing this that respective weather stations must be climatologically consistent.

Confidence intervals

These help to quantify the uncertainty associated with deriving the desired statistic, such as the return level, from the fitted extreme value distribution. There are different ways of calculating confidence intervals on return levels. Two commonly used approaches are the delta and profile-likelihood approaches. The delta approach relies on the approximate normal of the estimates of the EVD to obtain confidence intervals. It is easier to derive and is more readily available as standard output from EVA computer packages, but is considered less accurate than the profile-likelihood approach (*Coles, 2001*).

Fit diagnostics

Once the parameters of an EVD have been estimated, the quality of the fit of the distribution to the data should be assessed using either goodness-of-fit tests or diagnostic plots. Examples of goodness-of-fit tests include the Kolmogorov-Smirnov, Anderson-Darling and Cramer-von Mises tests (*Arnold and Emerson, 2011*). These tests assume that the data are from the desired EVD and then assess the probability that this is true. For standard statistical tests, such as the t-test, this is often done by comparing the t-statistic to a critical value. Diagnostic plots are also available and aid in the interpretation of the fit of the EVD and in the selection of the suitable thresholds for distributions fitted to points over thresholds datasets.

4.2 Methodology used within Eurocodes

Eurocodes are a set of standards developed (in part) to incorporate meteorological limits into the construction industry by specifying how structural design should be conducted in the European Union. Eurocodes outline a methodology which allows for extreme weather such as wind speed to be accounted for when building infrastructure. Eurocodes estimate extremes in wind speed using the method of independent storms (*Palutikof et al. 1999*) which identifies independent storms using a lull or period of wind speeds below a selected threshold to separate storms. The highest wind speed reached during each storm event is then fitted using a Gumbel distribution. When calculating the impacts of extreme winds on infrastructure for a specific site, it is important to note that the altitude, orography and surface roughness will naturally vary, as will the wind velocity in each part of the UK. It is possible to adjust these variables in the Eurocode calculation to compensate for site-specific differences. For instance, the Eurocode methodology assumes default mean return period of 50 years, i.e. the probability of encountering a 50-year wind in any one year, at a height of 10 m in open country, but if the annual probability of a 1 in 100 year event is required, the code can be adjusted appropriately.

Further adjustments can be made through changing inputs of pressure caused by extreme wind speeds (based on wind velocity, turbulence, and friction caused by the 'roughness' of the surrounding terrain), as well as wind pressures, e.g. for cladding, fixings and structural parts, both externally and internally. Finally, adjustments can be made for wind forces on structures such as facades/roofs and chimneys. Therefore, the number of adjustments made can vary depending on whether the building is made from concrete or steel for instance. The Eurocodes method is designed to predict wind actions on land-based structures, with their components and appendages, but does not cover torsional vibrations (i.e. tall buildings with a central core), bridge deck vibrations from transverse wind turbulence, and wind actions on cable-supported bridges. Calculation of the effect of wind pressures on cladding, fixtures and structural parts makes the method very applicable to contractors and engineers.

The method used to identify the impacts of wind on structures is outlined in the UK National Annex to Eurocode BS EN 1991-1-3:2003, *Eurocode 1 — Actions on structures (Part 1 to 4: General actions — wind actions)* which is designed for contractors and public authorities.

4.3 Additional methods for extreme wind characterisation

Additional methods for extreme wind characterisation are discussed in *Appendix A*. These include the probabilistic Monte Carlo simulation which uses a large number of random samples to characterise extreme wind speeds and also the probability of these wind speeds occurring. Numeric and climate modelling methodologies can also be used to extend wind datasets when the record of site observations is not sufficiently long. These longer datasets can then be analysed using EVA techniques discussed in *Section 4.1*.

4.4 The Tornado and Storm Research Organisation and linear methods

As mentioned in *Section 3.4*, the Tornado and Storm Research Organisation documents the frequency and intensity of tornadoes and waterspouts in the UK through voluntary observations (*TORRO, 2018b*). The spatial distribution of tornadoes across the UK in 25 km x 25 km gridboxes can be purchased from the Tornado and Storm Research Organisation, and resembles the initial maps originally produced by *Meaden (1985)*. They show that the greatest number of tornadoes occur within a triangle extending from Greater Manchester to Brighton and Norwich, with much lower frequencies in Scotland, Wales, Cornwall and counties in northern England according to the International Tornado Intensity Scale shown in *Table 2*. Damaging tornadoes can be classified as having a T-scale value of >T4, e.g. the Birmingham tornado in 2005. *Kirk (2014)* shows that for the period of 1981 to 2010, 38.2% of tornadoes were T2, 26.2% were T1 and 21.4% were T3.

Typically, when estimating the risk of a tornado occurring, EVA methods are not used because the length of the dataset for tornadoes in the UK is limited, and the count rate of tornadoes is too low. Instead, the probability of a location being affected by a tornado, and the ratio of damage area to total area, are used. No allowance is made for local geographical factors due to a lack of data and clear evidence concerning the impact on tornado risk.

To estimate the annual exceedance probability (AEP) of a damaging tornado in the UK (T4), it is assumed that tornadoes within the UK are uniformly distributed. To obtain a first approximation of the total land area of the UK affected by tornadoes, is necessary to first know the following:

- average number of tornadoes in the UK per annum;
- average diameter of a tornado (available from *Meaden, 1985*);
- average track length of a tornado (available from *Meaden, 1985*).

Following this, it can be shown that:

Probability of any location being affected by a tornado = $A_T \div A_{UK}$

Where A_T is equal to total land area of the UK affected by tornadoes, and A_{UK} is equal to the total land area of the UK.

To refine this first approximation, the average area of the UK covered by tornado tracks weighted by their frequency can be used to determine the probability for any location in the UK experiencing tornado damage. This can be done if the following variables are known:

- damage area of tornadoes (available from *Meaden, 1985*);
- percentage frequencies of tornadoes (available from *Meaden, 1985* and *Kirk, 2014*).

Site-specific probabilities can be estimated from the counts of tornadoes in 25 km x 25 km grid squares per 50-year period (provided by the Tornado and Storm Research Organisation), surrounding the site of interest. This can be done in one of two ways, either by (i) using the ratio of the damage area to total area to define probabilities (i.e. the finite damage area approach), or by (ii) assuming the tornado damage areas are small (i.e. working with tornado counts, rather than damage area), and the energy sites have finite size. In the latter, the AEP (inverse of the return period) is inversely proportional to the size of the site.

Some of the known caveats/assumptions associated with estimating the AEPs of tornadoes are as follows:

Limited observations of track length, width and damage area

There has been little formal research into tornado intensity and damage area, but the most extensive research was done by *Meaden (1985)* for the 1950 to 1984 period where a sample of 144 tornadoes were subsampled from a total of 974.

Distance to the sea

Kirk (2007) showed that for 1980 to 2004, there were approximately three times more tornadoes over land than over sea in the UK with significant interannual variation. Therefore, distance from the sea could affect the number of tornadoes experienced. There is some evidence to suggest tornadoes may be more prevalent in coastal areas (*Meaden, 1985*), but as this is difficult to quantify, it is not accounted for in this methodology outline.

Under-reporting and biased reporting

Fewer tornadoes are reported in areas with lower populations, and more observations are recorded in cities. Events occurring at sea are generally only reported in daylight hours when people are looking out to sea, and no damage track remains. Lower intensity events are also less likely to be reported than events which have a higher impact.

Double-counting

This can occur from event to event, especially in clustered tornado outbreaks. For instance, *Meaden (1985)* double counts tornadoes which cross grid boundaries. This double-counting is not accounted for in this methodology outline.

Funnel clouds

These have previously been misreported as tornadoes leading to an overestimate of T0 tornadoes.

The frequency of tornadoes in each grid box is uniform

The maps of tornado frequencies produced by the Tornado and Storm Research Organisation and originally *Meaden (1985)* assume that the frequency of tornadoes within each grid box is uniform.

Population impacts

In previous grid box counts compiled by *Meaden (1985)*, there was a weak correlation between population density and tornado counts. However, his later work using data up until 2010 demonstrated that this bias disappeared.

4.5 Knowledge gaps and recommended methodology

In order to outline the recommended methodology for estimating the recurrence of extreme windstorms and tornadoes, any known knowledge gaps must first be identified. The implications of not addressing these knowledge gaps may be an under-estimation of extreme winds and hence extreme wind pressure loads, which could undermine protection around energy infrastructure, e.g. loss of cladding, impacts of windblown missiles, partial collapse of buildings. The following should be considered:

- The extent of the effect of the North Atlantic Oscillation (NAO) and jet stream strength, which operate at a height of 10 to 16 km in the atmosphere, on extreme surface winds (for the mechanism, refer to *Section 2.1*). Although there is evidence to suggest that a positive NAO phase can exacerbate winter storms in the UK (*Section 2.1*) only 11% of

UK weather stations which recorded extreme wind speed display a correlation with the NAO (*Burningham and French, 2013*). Extremes in winter wind speeds in the UK, particularly during 2013 and 2014, were linked to the strength of the North Atlantic jet stream (*Met Office, 2014*). Understanding the relationship between these complex, overlapping atmospheric processes is an ongoing area of research.

- The effects of climate change on extreme winds and tornadoes (see *Section 7* for more description).
- Is there a theoretical limit to extreme wind speeds due to atmospheric characteristics?
- How applicable are EVA results compared to results from Eurocodes for extreme wind speeds? Current Met Office research suggests that EVA estimates and Eurocode estimates for 1 in 10,000 year events are comparable for hourly mean wind speed. However, there is greater dissimilarity between 1 in 10,000 year gust estimates between EVA and Eurocodes due to the different techniques used to derive gust speeds in the Eurocode.
- Uncertainty around the formation of tornadoes.
- What are the consequences of under-reporting tornadoes to current estimates of their prevalence?

Trends for analysing extreme wind speeds are moving towards using numerical/physical-based modelling, due to an increase in computer power, rather than statistical-based modelling, e.g. as described in *Appendix A*, *Section A.2*. High resolution model data can be used to adjust lower resolution, long-term sources of wind data to produce a high resolution climatological dataset, specific to the site area, or region of interest. Verification of these models can be done through site observations measured at different heights either through LIDAR or SONAR. If site-specific observations are not available, other nearby sites which experience a similar climatology may be needed to verify the model data output. It is also possible that regional frequency analysis which has previously been used for extreme storm surges (*Bardet et al., 2011*) and rainfall (*Goudenhoofdt et al., 2017*), could be applied to extreme wind speeds (*Hong and Ye, 2014*).

Due to the relatively few (and potentially biased) observations for tornadoes, extrapolating linear trends appears to be the current method of choice, as detailed in *Section 4.4*. However, as there is still some uncertainty around how a tornado is formed, research is trending towards dynamical modelling of tornadoes using computational fluid dynamics (*Rotunno, 2013*). This will also help to better simulate tornadoes in numerical weather prediction models, especially with the move towards more convective-permitting models. Current research is also investigating the use of numerical methods for vulnerability analysis, but most of this research is conducted in the United States where tornadoes are more prolific and damaging than the UK (*Dixon and Moore, 2012*).

5.1 Sandstorms

Sandstorms are not a phenomenon that has a direct effect on the UK and the energy industry. Sand and dust storms are common meteorological hazards in arid and semi-arid regions. They are usually caused by thunderstorms — or strong pressure gradients associated with cyclones — which increase wind speed over a wide area (*WMO, 2018*). The clouds of dust that are whipped up by strong winds can reach very high altitudes in the atmosphere and can be transported worldwide. When it rains, the dust is washed out to the surface; this leaves a layer of dust when the water evaporates.

The UK normally witnesses this phenomenon several times a year when large dust storms in the Sahara coincide with southerly winds that transport dust towards the UK. In certain weather scenarios, Saharan dust can also affect air pollution levels. In 2014, air pollution in combination with Saharan dust reached record levels in London and the South East.

Dust from sandstorms, when deposited across the UK, rarely causes anything more noticeable than a vivid sunset or dust deposits on cars known as 'blood-rain'; dust is a much more significant issue in arid and semi-arid regions of the world. Residue Saharan sand could have some very minor impacts on the energy sector:

- blockage of air filters, and the joint effects with air pollution could be a health hazard for personnel with ailments such as asthma;
- dust can also leave a residue on solar panels that can have some minor impacts on power output if not properly cleaned.

Characterising sand storms can be done through atmospheric modelling which can provide information in terms of dust and its dispersion. Atmospheric dispersion models act as guidance as they cannot accurately predict the precise location, magnitude and timing of ground-level concentrations to high levels of accuracy.

In this section, specific guidance on regulatory instruments, codes and standards applicable to extreme wind speed is considered. For more information on general regulatory considerations, please see Volume 1 — Introduction to the Technical Volumes and Case Studies.

The general approach of the nuclear industry to natural hazards is also described in Volume 1. Under the ONR Safety Assessment Principles (SAPs) (*ONR, 2014*), simple compliance with codes and standards may not necessarily comprise a robust safety substantiation for nuclear plants. For critical nuclear safety functions, a design basis should be defined that conservatively corresponds to an AEP of 10^{-4}. In addition, industry practice is to consider safety margins for events that are less frequent than the design basis.

However, it is also recognised that nuclear safety standards may not need to be applied to other energy infrastructure installations. As described in earlier sections of this technical volume, the appropriate return period to consider for risk assessment of 'extreme' events in design, operation or protection of such installations can be in the region of 1 in 50 or 100 years. Events occurring more frequently than that could be considered 'business as usual'.

Building regulations control how buildings are to be designed or modified on the public grounds of safety and sustainability. The latest and current version are the Building Regulations 2010 although the accompanying Approved Documents have been revised separately on occasions since then. A complete revision of the regulations has already been through a consultation stage and is expected in 2018. It is also worth noting that building regulations/standards are heading towards a devolved framework (i.e. each country in the UK will have its own variation of the regulations).

Most extreme weather hazards have the potential to cause structural stresses due to increased loading and/or impacts, and design against such hazards is addressed by code-compliance as a minimum. Currently the point of reference is *Eurocode 1* (BS EN 1991-1-1:2002, *Actions on structures. General actions. Densities, self-weight, imposed loads for buildings*). The part of the Eurocode relating to methods used to identify the impacts of wind loading on structures is EN 1991-1-4.

Some energy infrastructure installations will be registered Control of Major Accident Hazards (COMAH) sites and site-specific defences against, and responses to, extreme weather hazards will need to be incorporated into the COMAH safety case and emergency plans/procedures. Again, using the nuclear industry as a leading example with respect to extreme weather hazards, ONR guidance in the form of Technical Assessment Guide 13 (TAG-13) is for external hazards including natural hazards (*ONR, 2017*). TAG-13 expects that design basis events should take account of reasonable combinations of extreme weather conditions that may be expected to occur, and of consequential hazards from adjacent facilities arising from the extreme weather. For users, it is noted that (as of publication in 2018) TAG-13 is undergoing a significant revision.

7.1 Climate change and tornadoes

The uncertainties associated with the observations outlined in *Section 3.4* mean that it is not possible to attribute climate change to tornado frequency or intensity over the observational period of tornadoes (reliably from 1950 to present day). There is also no evidence to suggest that the number of severe tornadoes has changed over the duration of the observational record. However, tornadoes are associated with specific meteorological phenomena, the prevalence of which could plausibly be altered by physical changes in climate. For instance, under a warmer, wetter climate, latent heat release in storms which drive updraughts would be expected to increase (*Seeley and Romps, 2015*). However, a smaller temperature gradient between the pole and equator may be expected to reduce the intensity of depressions and associated cold fronts as well as the vertical wind shear necessary for many tornadoes to form (*Brooks, 2013*). The impact of climate change on small-scale systems that spawn tornadoes, such as active cold fronts and severe convective activity, is not well understood. Although the resolution of climate models is continuously improving, they cannot yet explicitly model the small scales associated with convective and active cold fronts and therefore cannot give an accurate indication of the physical conditions required to form a tornado. Overall, climate change could alter the frequency and intensity of tornadoes in the future, but there is currently no evidence to suggest that their trends have changed in the past.

7.2 Climate change and extreme windstorms

It is reported in the IPCC Fifth Assessment Report (AR5) that small increases in extreme wind speed are projected from Central and Northern Europe (medium confidence) connected to changes in storm tracks (*IPCC, 2013*). Interpreting trends in the UK storminess using current wind speed observations is not straightforward due to the changes in instrument type, station network size, exposure and the type of metric used for measurement (*Kendon et al., 2017*). However, some studies suggest that there has been a long-term decline in damaging European windstorms over the 21st century (defined as the speed of wind gusts exceeding 20 m/s caused by extratropical cyclones) (*Dawkins et al., 2016*).

Recent advances in climate modelling have indicated that there could be a small but significant increase in the number of windstorms affecting the UK (*Zappa et al., 2013; Sansom et al., 2013*) and that the frequency and intensity of these windstorms will increase during the winter months (*Zappa et al., 2013; Mizuta, 2012*). Assessment of the impacts of high-end climate change scenarios on various climate hazards including windstorms also supports this projection (*UKCP Project, 2009*). According to this report, which was written to inform the UK Climate Change Risk Assessment Evidence Report, "a plausible H++ [i.e. high emission] windstorm scenario suggests a 50 to 80% increase in the number of windstorms over the UK by 2070 to 2100 compared to 1975 to 2005". However, the caveat is that this scenario is based on CMIP5 climate model simulations, which contain known biases in the position of the North Atlantic storm track and systematically underrepresent the number of intense cyclones. Therefore, it is best to use H++ scenarios alongside estimates of the more likely range of future outcomes, e.g. the 10th or 90th percentile range on the UK Climate Projections 2009 or the CMIP5 models.

7.3 Climate change and sandstorms

Future changes in sand and dust storms are very dependent on climate change scenarios for precipitation, winds and temperature. Changes will also be dependent on future land use, for example vegetation degradation.

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Coriolis force

An invisible force caused by the rotation of the Earth, which deflects global wind patterns.

El Niño Southern Oscillation (ENSO)

A climatic event driven by changes in sea surface temperature which determines interannual changes in atmospheric pressure between the east and west tropical Pacific. These pressure changes can influence atmospheric circulation which, in turn, influences wind and pressure patterns.

Hadley, Ferrel and Polar cells

Large-scale wind circulations which transport heat from tropical to polar latitudes.

Modes of variability

A climate pattern that has a set pattern of spatial and temporal behaviour, typically affecting specific regions and over seasonal or longer timescales. This behaviour occurs on a quasi-regular basis. Examples of modes of variability include the North Atlantic Oscillation, El Niño Southern Oscillation and the Atlantic Multi-decadal Oscillation.

Noise (statistical)

The unexplained variability present within a sample of data.

North Atlantic Oscillation (NAO)

A large-scale surface pressure gradient between the 'Azores high' and 'Icelandic low'. A positive NAO represents a large pressure difference with stronger westerly winds whereas a negative NAO represents a smaller pressure difference and therefore weaker westerly winds.

Wind shear

The difference in wind speed and/or direction over a relatively short distance in the atmosphere.

AEP	Annual exceedance probability
CMIP	Coupled Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX	Coordinated Regional Climate Downscaling Experiment
ENSO	El Niño Southern Oscillation
ERA	European Reanalysis
ESGF	Earth System Grid Federation
EUCP	European Climate Prediction System
EVA	Extreme value analysis
EVD	Extreme value distribution
GEV	Generalised extreme value
GPD	Generalised Pareto distribution
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
H++ scenario	High emission scenario
LIDAR	Light Detection and Ranging
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MIS	Method of Independent Storms
MPP	Marked Point Process
NAO	North Atlantic Oscillation
NCIC	National Climate Information Centre
NWP	Numerical weather prediction
RCP	Representative concentration pathway
SAPs	Safety Assessment Principles
SONAR	Sound Detection and Ranging
SWI	Site Wind Index
TAG-13	Technical Assessment Guide 13
TORRO	Tornado and Storm Research Organisation
UKCP09	United Kingdom Climate Projections 2009
UKCP18	United Kingdom Climate Projections 2018
UKV	Met Office's high-resolution weather forecasting model for the UK
UM	Unified Model
VMM	Virtual Met Mast
WOW	Weather Observations Website

A.1 Probabilistic Monte Carlo simulation

Monte Carlo is a simulation technique that uses a large number of random samples to find solutions to physical problems that cannot otherwise be easily solved (*Nathan and Weinmann, 2013*). At the heart of a Monte Carlo simulation is a known mathematical relationship which relates input variables, e.g. wind speed at time *i*, to an output variable of interest, e.g. wind speed at time *i*+1 (as described below in *Section A.1.1*). For instance, in an EVA of wind speed, the Monte Carlo simulation can be used to build models of possible results by substituting a range of values — a probability distribution — which can then be used to describe uncertainty of the input variables. These probability distributions help to demonstrate the range of outcomes that could occur, and can aid in reducing the uncertainty around extreme wind observations. The Monte Carlo simulation will then calculate numerous results through repeatedly using this mathematical relationship with a different set of random values from the probability distributions of the input variables. Depending upon the number of input variables and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete.

To summarise, the benefits of using a Monte Carlo simulation approaches over deterministic or single-point estimate analysis are as follows:

- probabilistic results — results show not only what could happen, but how likely each outcome is;
- correlation of inputs — in Monte Carlo simulation, it is possible to model interdependent relationships between input variables.

The main limitation of this approach is that it is unbounded, so there is a potential that unrealistic wind data could be generated leading to an under or overestimation of wind speed data.

A.1.1 Generation of synthetic weather

The Monte Carlo simulation technique is best applied to observational records of adequate length but in the absence of records of suitable length, a synthetic time series can be produced. For instance, *Dukes and Palutikof (1995)* used at least six years of hourly data from four UK-based observation stations, which they considered to be an absolute minimum for their analysis. However, *Hrafnkelsson et al. (2016)* suggested using a minimum of ten years of data when they estimated annual energy production using Monte Carlo wind speed simulation. If a longer time series is available, fitting an EVD is still the recommended option *(Palutikof, 1999)*. This method has been reproduced for extreme wind many times (*Zwiers, 1987; Lechner et al., 1992; 1993*) as it reduces the size of the confidence intervals and reduces uncertainty. Generation of synthetic weather data is based on a Markov process where observed wind speed data are converted into a time series of wind speed 'states', i.e. winds between certain values such as <2 m/s, between 2 and 3 m/s and any winds above a defined upper limit (*Palutikof et al., 1999*). This time series of wind speed data assumes stationarity, i.e. the statistical properties are consistent over a duration of a time series so would not compensate for the effects of long-term climatic changes, and may not account for naturally occurring oscillations such as the NAO if the original time series is short. If desired, these wind states can be converted to synthetic wind speeds by adding suitable noise to the wind states, which approximates the original wind speed distribution within each category. Further details on how this was done can be found in *Dukes and Palutikof (1995)*.

Once a synthetic time series has been generated, there are several approaches that can be used to analyse the extreme values (*Palutikof et al., 1999*). *Dukes and Palutikof (1995)* used a Monte Carlo type approach by repeating each simulation 1000 times for the exact length of the required return period (e.g. 100 years, which is equivalent to an AEP of 1/100). From this, they extracted the maximum value and took the mean of the 1000 maxima as the simulated 100-year return period extreme. The advantages of this method are that it is computationally efficient and the standard errors of the quantiles can be directly calculated from the distribution of the quantile extremes generated by different simulation runs (*Palutikof et al., 1999*).

A.2 Numerical and climate models

NWP and climate models represent the climate system using mathematical equations that are discretised onto a grid. Within the climatological community, climate models are used to investigate the possible effects that anthropogenic greenhouse gas emissions may have on the future climate system. In an operational sense, in the meteorological community NWP models are used for nowcasting, i.e. a very detailed description of current weather alongside forecasts extrapolated for a period of 0 to 6 hours ahead, as well as forecasting the weather. An example of the grid box resolution and 'domain size', i.e. the regional extent of different primary Met Office forecast models, is shown in *Figure 11*.

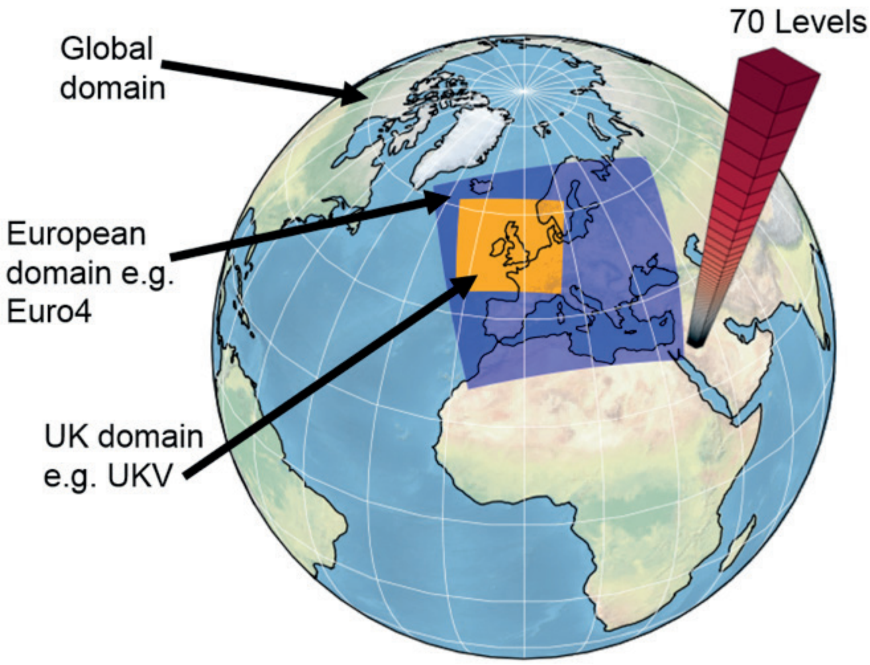

Figure 11. The different resolutions of primary Met Office forecast models, on global, European and UK resolutions. Data are discretised onto a grid. The number of grid boxes within a model 'domain' defines the spatial resolution and the number of 'levels' defines the vertical resolution either through the atmosphere, or depths in ocean models. Different coloured boxes on the globe represent different models and model domain sizes: UKV is represented by the smaller, orange box and Euro4 by the larger, blue box. (© Crown copyright Met Office 2018)

When applied to extreme wind speeds, numerical and climate models can be used to extend wind datasets when the record of site observations is not long enough to provide an accurate picture of the wind climatology. Computer simulations can produce long climate datasets in short time periods, but high-resolution modelling of airflow over long periods of time is computationally very demanding and expensive to resource.

One solution is to use a dynamical downscaling approach where high resolution regional simulations are created through dynamical extrapolation of large-scale climate processes. This can be done over the region of interest by using a nested suite of models, i.e. a set of models decreasing in domain size, but increasing in model resolution, for a period of time that is short enough to be cost effective, but long enough to provide a representation of variability due to regional weather and large-scale global circulations. These short-term but high-resolution model data can be used to adjust lower resolution long-term sources of wind data already available to produce a high resolution climatological dataset.

The Met Office numerical weather prediction models are run as part of the Unified Model (UM); a numerical model of the atmosphere used for both weather and climate applications. The UM is unique in that it runs a seamless forecast modelling system in which largely the same model is used to simulate the atmosphere across all spatial and temporal timescales. The UM nested suite of models can then be configured to dynamically simulate the atmosphere at high resolution (e.g. 4 km, 1 km, 333 m and 100 m) at various heights, (e.g. 10, 40 and 70 m above ground level) for e.g. one year over the region of interest. Concurrently, a longer-term time series of wind speeds at the heights of interest can be extracted over the region of interest at a coarser resolution from e.g. the European 4.4 km hindcast and archived forecast European 4.4 km dataset. The higher-resolution data can then be used to correct the 4.4 km long-term dataset using directional dependent linear regression to produce long-term, high-resolution wind time series at the sites and heights of interest.

The resulting time series can then be analysed using EVA (*see Section 4.1*), by selecting extreme wind speed events occurring above a wind speed threshold with successive events separated by a chosen maximum event duration. Events may be drawn from any of the modelled locations and heights, although the threshold is not necessarily the same for each. Each identified event then identifies the appropriate wind speed sample for each of the sites and heights. A GPD is then fitted to the selected sample set of data. This set of extreme wind speed events (for each site and height) is then partitioned into directional sectors, such that each event (for each site and height) is considered only in one direction sector. This produces AEPs (i.e. the inverse of return period) of wind speed events for specified wind directions.

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