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

Volume 4:

Extreme Precipitation

LC 0064_18V4

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	17/04/18	CTO comments addressed and submitted to ETI
2.0	26/06/18	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

Meteorologists use the term 'precipitation' to mean rain, snow, sleet or hail that falls to or condenses on the ground, and the term 'rainfall' as the liquid water equivalent of any type of precipitation, expressed as a depth in millimetres. There is no specific definition of what constitutes 'extreme' rainfall within the UK, either in the energy sector or meteorological community. Instead, the definition of rare and extreme events depends on the particular part of the energy sector being considered, as well as the physical location. Rainfall intensity differs from location to location and season to season, and the potential impacts of differing rainfall amounts over different time periods will differ across the energy sector. The definition of an extreme event for the energy sector and its given threshold will differ depending on the vulnerability and exposure of the asset. For example it would be expected that the robustness of a hydropower dam would have very different extreme rainfall thresholds compared to the energy utilities transmission network.

A rainfall event is considered to be extreme when it relates to one of these two contexts (*WMO, 2015*):

- When a rainfall event exceeds a certain threshold that has a certain impact, for example the joint Met Office/Environment Agency Flood Forecasting Centre use an accumulation threshold of 30 mm per hour as guidance to indicate flash flooding criteria (*Kendon, 2014*), or
- A rainfall event is considered to be extreme due to its rarity. The rarity of occurrence tends to take the form of upper 90th, 95th and 99th percentile. These percentile-based thresholds are usually derived from a statistical cumulative density function or some extreme value distribution. The percentile-based approach for extreme levels allows users to define a very rare event, e.g. the 99th percentile.

Pluvial (surface water), fluvial (river) and groundwater flooding events caused by extreme rainfall give rise to serious impacts on life and infrastructure. River flooding occurs as a result of water overflowing from river channels and pluvial flooding occurs when natural and man-made drainage systems cannot deal with the volume of rainfall. The latter is particularly hazardous in urban environments as sudden and intense rainfall cannot drain away easily (*Pitt, 2008*). Groundwater flooding lasts longer relative to pluvial or fluvial flooding and is defined by the emergence of groundwater at the ground surface away from perennial river channels, or the rising of groundwater into man-made ground under conditions where the 'normal' range of groundwater levels and groundwater flow is exceeded (*BGS, 2018*). Groundwater flooding is likely to affect low-lying areas, basements, buried services or assets stored below ground level

(*BGS, 2018*). Flooding events are often outcomes of four main contributory factors (*Collier et al., 2002*):

- intensity of precipitation;
- duration of precipitation;
- the wetness of the ground; and
- the response of the rainfall catchment.

Intensity and duration of precipitation are meteorological contributors, whilst the other two are hydrological. This guide concentrates on the meteorological factors — intensity and duration of precipitation. Each part of the energy sector will have different application purposes and will select a relevant duration of rainfall. In meteorology, common duration periods include 1, 3, 6, 12, 24 and 48 hours. If observation data exist, sub-hourly durations may be analysed.

A 'wet spell' is commonly used to describe 'a period of a number of consecutive days in which precipitation exceeding a specific minimum amount has occurred' (WMO-182). For example, in November 2009 heavy rainfall and flooding occurred in the Lake District, Cumbria, where some areas of high ground received more than 400 mm of rainfall in a 72-hour period (*Met Office, 2012*), and Seathwaite, Cumbria, recorded the highest UK 4-day rainfall total of 495 mm.

Tables 1 to 3 provide a list of the most extreme rainfall events that have occurred within the UK, both geographically and temporally. The highest 24-hour rainfall totals on record for countries within the UK are shown in *Table 1*. In the UK, daily rainfall totals are defined as any rainfall observed between 09:00 to 09:00 Greenwich Mean Time (GMT) on the next consecutive day. Whereas the 24-hour rainfall amount relates to any 24-hour period of rainfall in hourly denominations, 00:00 to 00:00 GMT. The highest 24-hour total recorded for any 24-hour period in the UK is 341.4 mm from 18:00 GMT on 4th December to 18:00 GMT on 5th December 2015 at Honister Pass, Cumbria. The UK rainfall records for consecutive rainfall days (09:00 to 09:00 GMT) are shown in *Table 2*. The UK rainfall records for short durations are shown in *Table 3*. These tables show the national weather records and are only for stations with standard instruments and exposure. Rain gauges and their setup are discussed in *Section 3.2*.

Table 1. Highest 24-hour rainfall totals for a rainfall day (09:00 to 09:00 GMT) on record in countries of the UK. (Source: Met Office (2018a); © Crown copyright Met Office 2018)

Country	Rainfall (mm)	Date	Location
England	279	18th July 1955	Martinstown (Dorset)
Scotland	238	17th January 1974	Slow Main Adit (Argyll & Bute)
Wales	211	11th November 1929	Lluest Wen Reservoir (Mid Glamorgan)
Northern Ireland	159	31st October 1968	Tollymore Forest (County Down)

Table 2.UK rainfall records for consecutive rainfall days (09:00 to 09:00 GMT). (Source: Met Office (2018a); © Crown copyright Met Office 2018)

Days	Rainfall (mm)	Date	Location
Highest 2-day total	405.0	4th to 5th December 2015	Thirlmere (Cumbria)
Highest 3-day total	456.4	17th to 19th November 2009	Seathwaite (Cumbria)
Highest 4-day total	495.0	16th to 19th November 2009	Seathwaite (Cumbria)
Highest monthly total	1396.4	1st to 31st December 2015	Crib Goch (Snowdon)

Table 3. UK rainfall records for short durations. (Source: Met Office (2018a); © Crown copyright Met Office 2018)

Minutes	Rainfall (mm)	Date	Location
Highest 5-min total	32	10th August 1893	Preston (Lancashire)
Highest 30-min total	80	26th June 1953	Eskdalemuir (Dumfries & Galloway)
Highest 60-min total	92	12th July 1901	Maidenhead (Berkshire)
Highest 90-min total	117	8th August 1967	Dunsop Valley (Lancashire)
Highest 120-min total	193	19th May 1989	Walshaw Dean Lodge (West Yorkshire)
Highest 120-min total	155	11th June 1956	Hewenden Reservoir (West Yorkshire)
Highest 155-min total	169	14th August 1975	Hampstead (Greater London)
Highest 180-min total	178	7th October 1960	Horncastle (Lincolnshire)

Extreme rainfall events can lead to river (fluvial) and surface (pluvial) water flooding. The UK Climate Change Risk Assessment (CCRA) 2017 identifies these as potential risks to UK infrastructure. It is the intensity, or prolonged nature of rainfall, which can lead to an increase in the risk of flooding. Examples of flooding impacts on the energy sector were documented in *Pitt 2008*. In May, June and July 2007 unprecedented levels of rainfall were recorded which led to severe flooding across England and Wales. The exceptionally heavy rainfall on 19th to 20th July resulted in electricity transmission and distribution networks being affected by flooding, where 40,000 customers in Gloucestershire were cut off for up to 24 hours and 9000 customers were on rota disconnection for several days in south Yorkshire and Humberside. There were also several near misses, e.g. temporary defences were raised at Walham electricity substation protecting power supply to 500,000 people in Gloucestershire and South Wales. These near misses raised the profile of the vulnerability of infrastructure assets; this included the potentially catastrophic near miss near Rotherham at the Ulley Reservoir. The dam was at high risk of breaching after heavy rainfall on 24th to 25th June, potentially putting lives in danger, as well as infrastructure assets including the M1 motorway.

For energy utilities there are broadly two main types of costs as a result of flooding: direct costs incurred by flooding of assets; and welfare costs to customers as a result of service disruption. In the flooding events of winter 2013/2014, it is estimated that power outages cost customers between £580,000 and £970,000 (*EA, 2016*). Estimated damages to energy infrastructure during the 2013 to 2014 winter floods are in the order of £44,000 to £54,000. This estimate was based on information from a single power company, however consultation with energy companies suggested that costs were similarly small.

Extreme rainfall and flooding can also have indirect impacts on the energy sector. Flooding will also affect other infrastructure not necessarily owned or maintained by the energy sector, e.g. access roads, which can affect safe access by key personnel and the ongoing operability of an asset.

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 1*). The weather experienced by the UK essentially depends on which air mass is dominant at a particular time.

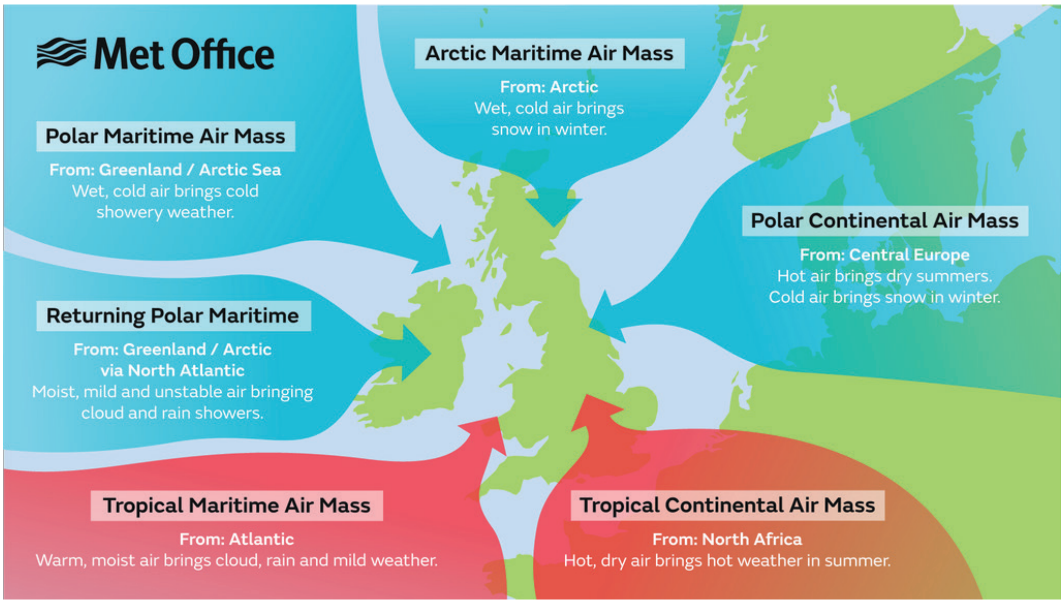

Figure 1. Air masses affecting the UK and their likely impacts in particular seasons. (© Crown Copyright Met Office 2018)

More generally, the natural variability of the global climate is influenced by large-scale climatic factors called *modes of variability**. The interaction of these modes of variability with one another 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, usually described as a sea surface temperature anomaly by the Oceanic Niño index in the central Pacific Niño 3.4 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 influences the winter climate of the UK in particular. It moves between positive and negative phases (*Figure 2*). In the positive phase, the Iceland/Azores pressure difference is larger, and this is usually associated with stormier, milder and wetter winters due to an intensified jet stream bringing westerly flow across the UK. In the negative phase, the pressure difference is smaller or reversed, and this is

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

usually associated with calmer, colder and drier winters, due to a weaker and more disrupted jet stream which may allow flow from other directions to dominate.

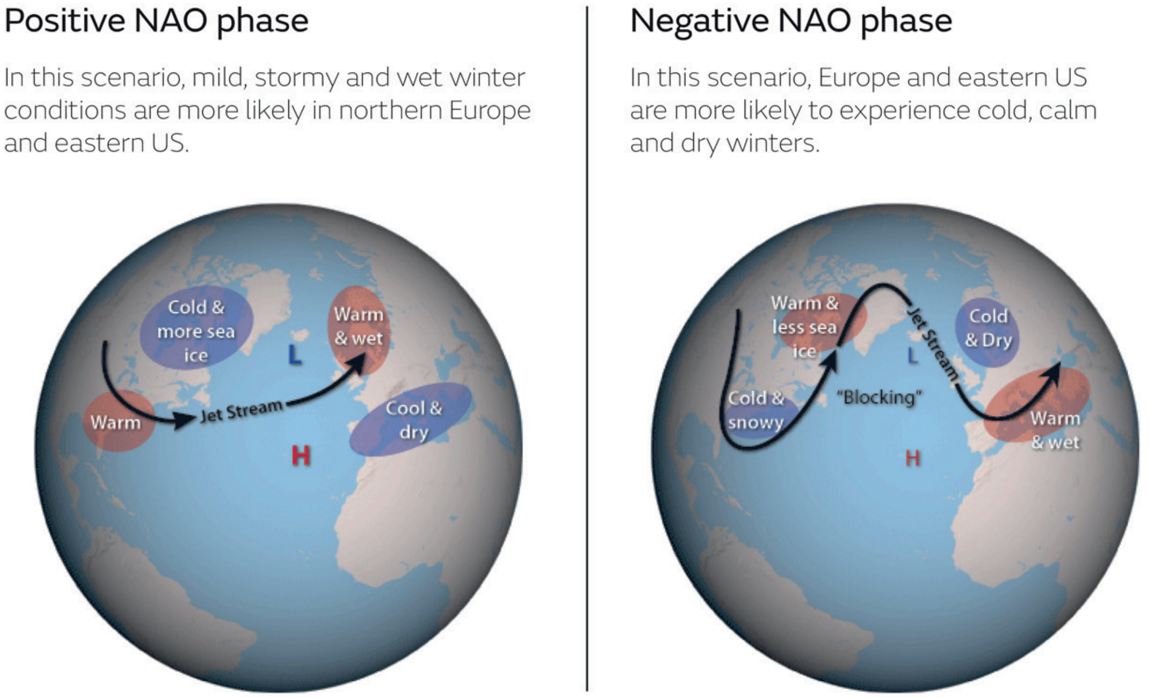

Figure 2. The NAO in its positive (left) and negative (right) phases, showing the influence on the winter climate of the North Atlantic region. (© Crown Copyright Met Office 2018)

2.2 UK rainfall mechanisms and extremes

As defined by the Met Office (*Met Office, 2018b*), there are three main rainfall mechanisms in the UK:

Frontal rain

Frontal rain occurs when two air masses meet. When a warm air mass meets a cold air mass, the warm, less dense air is pushed up over the cold dense air creating the 'front'. As the warm, less dense air rises it cools, and the water vapour condenses into very small water droplets which are very light. The droplets in the cloud collide and in time some grow larger and start to fall. As they coalesce with more droplets they fall faster and eventually fall as raindrops to the Earth's surface. This type of rain can occur anywhere in the UK.

Orographic rain

Orographic rain is rainfall produced as a result of clouds formed from the topography — or shape — of the land. Where there is high ground, moist air is forced upwards and cools and, as with frontal rain, it produces cloud and potentially precipitation. Mountainous areas that are to the west of the UK are more likely to experience this type of rainfall as the UK's prevailing wind direction is from the west. The geography of the UK means that this type of rainfall is most common in the north and west of the UK where warm, moist air from the Atlantic cools as it is forced upwards over high altitudes. Orographic effects can give rise to several days of persistent rainfall, leading to substantial accumulations.

Convective rain

Convective rain is produced by convective clouds. Convective clouds are those that form as a result of atmospheric thermal instability. One way that the atmosphere can become unstable is by heating from the sun. The ground warms up, causing both the moisture in the ground to evaporate and rise, and the air above the ground to warm. As the water vapour rises, it cools and condenses into clouds and eventually rain. If the clouds are able to develop strongly in the vertical direction, they may give rise to locally heavy rain, exceeding several tens of millimetres per hour. This type of rainfall is most common in the south and east of the UK, where it is typically warmer.

The list of rainfall mechanisms is not exhaustive; these are predominately the three rainfall types experienced in the UK. Extreme rainfall and associated hazards such as flooding events are normally caused either by prolonged orographically-enhanced rainfall, intense convective rainfall or a combination of all three rainfall types.

As can be seen in *Figure 3*, rainfall amounts vary per season as well as geographically. The rainfall maps in *Figure 3* are spatially and seasonally (spring — top left, summer — top right, autumn — bottom left, winter — bottom right) averaged across the UK. The 'wettest' rainfall seasons on average are autumn and winter. The wettest parts of the UK are concentrated in the more hilly and mountainous regions: Dartmoor, Wales, the Lake District, the Pennines and the Scottish Highlands. The maps also show a clear divide between the north-west and south east of the UK. The prevailing warm, moist, westerly winds mean that the west of the UK is likely to receive more rainfall from Atlantic weather systems in the form of previously described frontal rain. The mountains of the northern and western parts of the UK act to orographically enhance frontal rainfall and this mechanism led to the highest recorded UK 4-day rainfall total of 495 mm at Seathwaite, Cumbria and the flooding at Cockermouth in November 2009. Convective rainfall predominately occurs in the south and east of the UK. The largest rainfall showers or thunderstorms typically take place from April to October, as convection is constrained by a lack of surface heating during the winter months. The convective rainfall events are averaged spatially and seasonally in *Figure 3*.

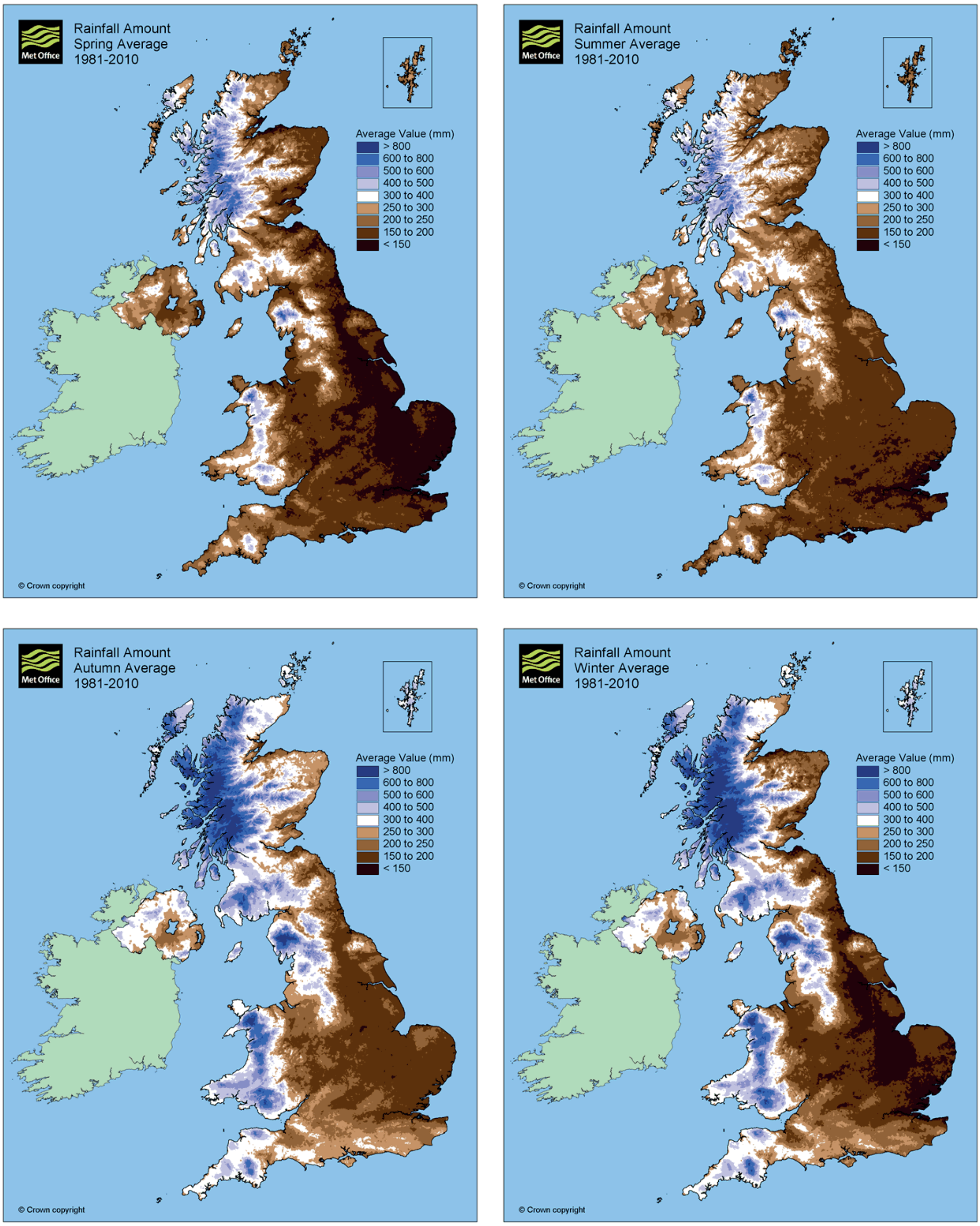

Figure 3. Maps of seasonal rainfall averages for the period 1981 to 2010, for spring (top left), summer (top right), autumn (bottom left) and winter (bottom right). Source: National Climate Information Centre. (© Crown Copyright Met Office 2018)

2.3 Potential interactions with other natural hazards

Potential interactions of extreme rainfall with other natural hazards, and how they may affect the energy sector in terms of infrastructure and operations, are considered:

- For the energy utilities' transmission and distribution networks the combination of rain, strong winds and lightning can have a significant impact on overhead lines, potentially causing disruption to power supplies.
- UK estuaries are at risk from a combination of flooding including the interactions of surge, waves, tides and rivers that could have a direct impact on energy infrastructure and operations across the UK, e.g. nuclear power stations. The Combination Hazard of Extreme rainfall, storm Surge & high Tide on estuarine infrastructure (CHEST) project (*NERC, 2018*) is assessing the management of combined river-surge-wave-tide flooding in UK estuaries, especially in light of sea-level rise and changing climates.
- Extreme rainfall events can be triggers for landslides that involve the movement of a mass of soil and/or rock down a slope. This can have implications for infrastructure in regions susceptible to landslides.
- Extreme rainfall events can also trigger groundwater flooding which can occur before water levels reach the ground surface, causing flooding of basements, buried services, e.g. transport links and underground installations, and assets below ground level (*BGS, 2018*). The areas most at risk from this are unconfined major aquifers, shallow unconsolidated sedimentary aquifers and groundwater rebound in urban centres (*BGS, 2018*).
- Extreme rainfall and freezing temperatures can cause freezing rain and ice build-ups. Large build-ups of ice from freezing rain can bring down major power transmission lines, leaving wide areas without electricity. Freezing rain can also affect the operability and efficiency of wind turbines.

For further information about hazard combinations please refer to Volume 12 — Hazard Combinations.

3.1 Types of data available for rainfall hazard characterisation

A non-exhaustive list of rainfall datasets (both commercially and publicly available) is provided in *Table 4*. The main types of data that may be useful for the characterisation of extreme rainfall by the methods described in this section are:

- Observations – *Section 3.2* describes how rainfall is measured at Met Office meteorological observing stations and *Section 3.3* describes how the Met Office UK Radar network measures rainfall. 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; or
  - obtained by combining observations from different sources, e.g. point observations and radar for rainfall data.
- Modelled data, including:
  - reanalysis data, derived via a technique that combines observations with numerical weather model runs to provide estimates of all locations within the UK (*Section 3.4.1*); and
  - projections of future climate, created using climate models (*Section 3.4.2*).

Table 4. Non-exhaustive list of rainfall datasets.

		Dataset name	Domain			Resolution			
			UK	Europe	Global	Temporal		Spatial e.g. 5 km	Parameter rainfall
						Time period	Time step		
Historical	Observations	Rainfall rates radar composites	X				12 images per hour	1 km and 500 m	X
		UK observations	X			From 1850, good coverage from 1960s	Up to 1 minute, good coverage at 1-hourly	~3000 daily gauges and 300 hourly gauges	X
		Global observations			X	Good coverage from 1960s	Good coverage at 3-hourly, but poorly defined leading to ambiguity in the rainfall accumulation period	Good coverage over Europe, USA and parts of Asia	X
		NCIC	X			Monthly from 1901, daily coverage from 1960s to present	Mostly monthly, temp and precipitation daily	5 km grid	X
	Archived forecast	UKV	X			July 2007 onwards	Up to 1 hour, out to 36 hours	1.5 km	X
		Euro4		X		January 2009 onwards	Up to 1 hour to 57 hours, 3-hourly out to 120 hours	4 km	X
		Global			X	From 1994 ~60 km, 17 km since 2014	Up to 1 hour, out to 168 hours	17 km	X
	Reanalysis	ERA-Interim			X	1979 to near present (3 months in arrears)	3 hours	~80 km	X
		MERRA			X	1979 to near present (1 month in arrears)	1 hour	~40 km	X
Future	Projections	Seasonal			X		Up to daily	~50 km	X
		Met Office Hadley Centre + other IPCC models			X	Pre-industrial to 2099		25 km	X
		UKCP09 (Probabilistic projections)	X			1961 to 2099	Annual averages	25 km	X

3.2 Observing rainfall

By convention, all meteorological observing stations that record daily rainfall measure it over the period 09:00 to 09:00 GMT. Tipping bucket rain gauges also record rainfall at shorter durations at a number of locations across the UK.

Observations of rainfall from Met Office observing sites are mostly automated using the tipping bucket rain gauge as shown in *Figure 4*. Rain collected by a funnel is channelled into a small bucket. When full, the bucket tips registering a fall of 0.2 mm of rain. Rainfall amount in mm is normally reported over periods of 1, 12 or 24 hours.

Figure 4. A tipping bucket rain gauge. (© Crown Copyright Met Office 2018)

The sites of rain gauge stations are selected to ensure observations are as representative as possible of the wider area around the station, and not unduly influenced by local effects. Ideally, the design and exposure of the rain gauge should prevent loss by evaporation and by the effects of wind either driving rain into or away from the funnel, and splashing from the ground or nearby objects into the funnel.

Rain gauges can rapidly become blocked in snow and any readings at the time, and during thawing events when melted snow gradually trickles into the gauge, should be treated with caution. Where an observer is present, the water equivalent of freshly fallen snow is reported.

Met Office observing sites are not fixed. New stations are opened, existing stations may close, and some stations may move within their sites, e.g. at airports. There is reasonable coverage across the UK of Met Office observing stations that report rainfall, as shown on *Figure 5*. In addition, there are many rain gauge-only sites providing daily rainfall measurements.

Rain gauge observations are widely used to check and adjust the outputs from weather radar and satellite-based systems, as well as being a primary source of observations (*Sene, 2013*).

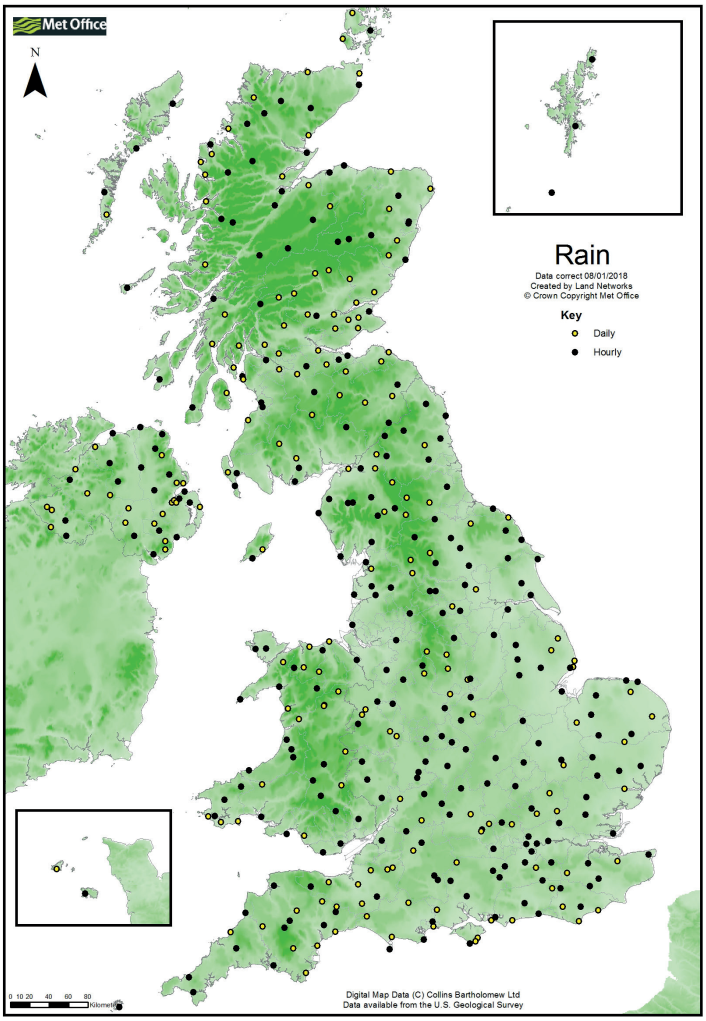

Figure 5. Met Office observing station rain gauge network. (© Crown Copyright Met Office 2018)

3.3 Radar network

The Met Office UK Weather Radar Network is designed to provide continuous, real-time rainfall data over almost the whole of the UK land area and inshore waters as shown in *Figure 6*. For real-time operational use, radar provides a unique means of obtaining widespread, spatially continuous measurements of precipitation location and intensity at scales of hundreds of metres (*Met Office, 2018c*).

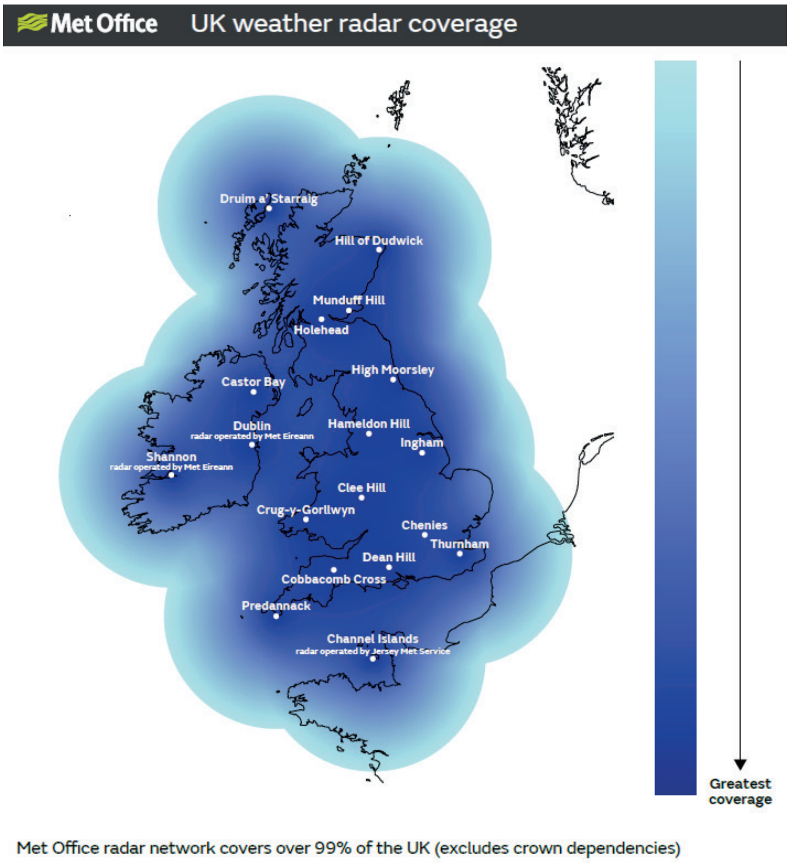

Figure 6. The UK radar network coverage. (© Crown Copyright Met Office 2018)

Data from all 18 radars (16 in the UK and 2 in the Republic of Ireland) with coverage in the UK are sent to the Met Office at Exeter for immediate processing. The resulting composite picture provides estimates of rainfall intensity over the whole of the British Isles and the surrounding sea areas at a resolution of up to 1 km. Processing at the Met Office normally removes:

- permanent echoes or reflections from hills and buildings, known as 'clutter';
- anomalous echoes from a radar beam reflected from the ground after being bent downwards by the atmosphere (typically in anticyclonic conditions);
- the strong echoes produced when falling snowflakes start to melt (appearing to the radar like giant raindrops).

The radar beam is readily reflected off rain, hail and snow particles, but drizzle can be more difficult to detect because the droplets are so small. To improve the accuracy of radar estimates, values are compared with rainfall amounts measured by rain gauges and appropriate adjustments are made. The radars have Doppler capability, enabling them to track the movement of precipitation particles and provide an estimate of the wind. Additional dual-polarisation capability gives information about the particle shapes and hence distinguishes between precipitation type, e.g. rain and snow.

The benefits of radar include the ability to observe rainfall and high intensity short-duration convective rainfall over an extensive area, including areas that have no rain gauges (*Sene, 2013*). However, there are also a number of limitations; for each scan angle rainfall values are recorded above the surface, therefore the radar may miss some forms of precipitation such as low altitude (*Sene, 2013*). Other issues include ground clutter and blockages from buildings, wind farms, and mountains.

3.4 Model data

3.4.1 Reanalysis

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 reasonable intervals (say, 12 hours) by the assimilation of further historical observations at each such interval. The advantage of this process is that it is capable of producing a gridded dataset of many variables, spanning several decades and large geographical areas (even global). There are some limitations; mainly these relate to 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.

3.4.2 Climate modelling

Future projections of UK climate can be obtained from climate modelling studies. Climate models often have similar configurations to NWP models, but because 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; see *Section 4.3* for discussion of some of these.

The United Kingdom Climate Projections 2009 (UKCP09) is currently the main source of climate information for the UK, including land and marine regions (*UKCP Project, 2009*). For example the land projections provide data at 25 km resolution for the whole UK, for a range of parameters relevant to energy (including temperature and rainfall), spanning time periods 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.

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. These 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 are 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 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, e.g. evaluating external (non-UK) risks to the UK energy sector. 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.

This section outlines a range of methodologies that can be used to characterise extreme rainfall for several different applications in the UK. Probable maximum precipitation is discussed in *Section 4.1*. Stationary extreme value analysis (EVA) and block maxima and threshold models are discussed in *Section 4.2*. Climate and NWP models are discussed in *Section 4.3*. Monte Carlo approaches are discussed in *Section 4.4*. Regional frequency analysis is discussed in *Section 4.5* and intensity-duration-frequency (IDF) curves in *Section 4.6*. Further information about EVA can be found in the EVA primer provided in Volume 1 — Introduction to the Technical Volumes and Case Studies. Finally, recommended methodologies are discussed in *Section 4.7*.

4.1 Probable maximum precipitation

The WMO method of estimating probable maximum precipitation (PMP) is an international standard and fully documented in the manual, WMO No. 1045 (*WMO, 2009*). The manual defines PMP as 'the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given size storm area at a particular location at a particular time of year, with no allowance for long-term trends'. A PMP estimate can be used to calculate the probable maximum flood (PMF) used in the design of a given project at a particular geographical location in a given watershed. *WMO (2009)* states that six methods of PMP estimation are currently used:

- the local method (local storm maximisation or local model);
- the transposition method (storm transposition or transposition model);
- the combination method (temporal and spatial maximisation of storm combination or combination model);
- the inferential method (theoretical model or ratiocination model);
- the generalised method (generalised estimation); and
- the statistical method (statistical estimation).

The Flood Studies Report (FSR) method, which has not been changed by later editions of the Flood Estimation Handbook (FEH), is similar to the WMO method in that it is based on estimates of precipitable water. The process of calculation is made using graphs and tables in Chapter 4 of FSR Vol II (*NERC, 1975*). The starting point is the 1 in 5-year estimate of precipitable water (M5 to 6hr), based on 6-hour persistent dew point temperature. This statistic for the UK is presented as a map of iso-lines in Figure 3.8 of FSR, Vol II (*NERC, 1975*).

The Herschfield Method, described in the *Guide to Hydrological Practices* (*WMO, 1994; WMO, 2009*) is a general statistical method, which is useful to check the validity of other estimates of PMP. It is specifically intended to be used to estimate PMP for point locations or small areas, and uses long-term annual maximum data.

The theoretical and practical limitations include:

- the accuracy and reliability of an estimate depend on the amount and quality of the data available for use in the estimating procedure;
- PMP methods do not account for climatic trends or climate change.

4.2 Extreme value analysis

Extreme value analysis (EVA) is a statistical methodology where the objective is to quantify the random behaviour of a process at unusually large or small levels (*Coles, 2001*). EVA is a methodology that is commonly used within the energy industry. EVA is discussed in the following sections, but the reader should consult Volume 1 — Introduction to the Technical Volumes and Case Studies for a broader discussion of the technique.

EVA can be used to estimate the probability and severity of events that are more extreme than any that have been observed in a given data series. For example a 20-year observation record could be used to estimate the annual probability of exceeding a predefined threshold value, which may be larger than any value within the observed record length. Similarly, if the annual probability of exceeding a predefined threshold is required (Volume 1 defines the term 'annual exceedance probability', or AEP, as the annual probability of exceeding a specific level), EVA could be used to estimate the magnitude of this event associated with that probability.

However, it is important to remember that the uncertainty in the projected extreme events will increase as the inverse of the AEP (which equates to a period of time that is measured in years, e.g. T-years, the return period) approaches the length of the data series. The uncertainty increases still further as the inverse of the AEP exceeds the length of the data series.

4.2.1 The generalised extreme value distribution

The statistical behaviour of the annual maximum daily rainfall has been the cornerstone of statistical hydrology, as it is directly related to the design of hydraulic infrastructures and to extreme floods (*Papalexiou and Koutsoyiannis, 2013*).

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, e.g. annual maximum daily rainfall. 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 7*, where the effect of the scale and shape parameter on the return-level curves is shown. 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 as it measures the amount of spread in the data: the larger the scale parameter, the greater the spread. In the return level plots, as the scale parameter increases so does the range of return levels.

The shape parameter controls whether the return-level curve is bounded, reaches a limit, or not. The left-most column in *Figure 7* 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 7* 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.

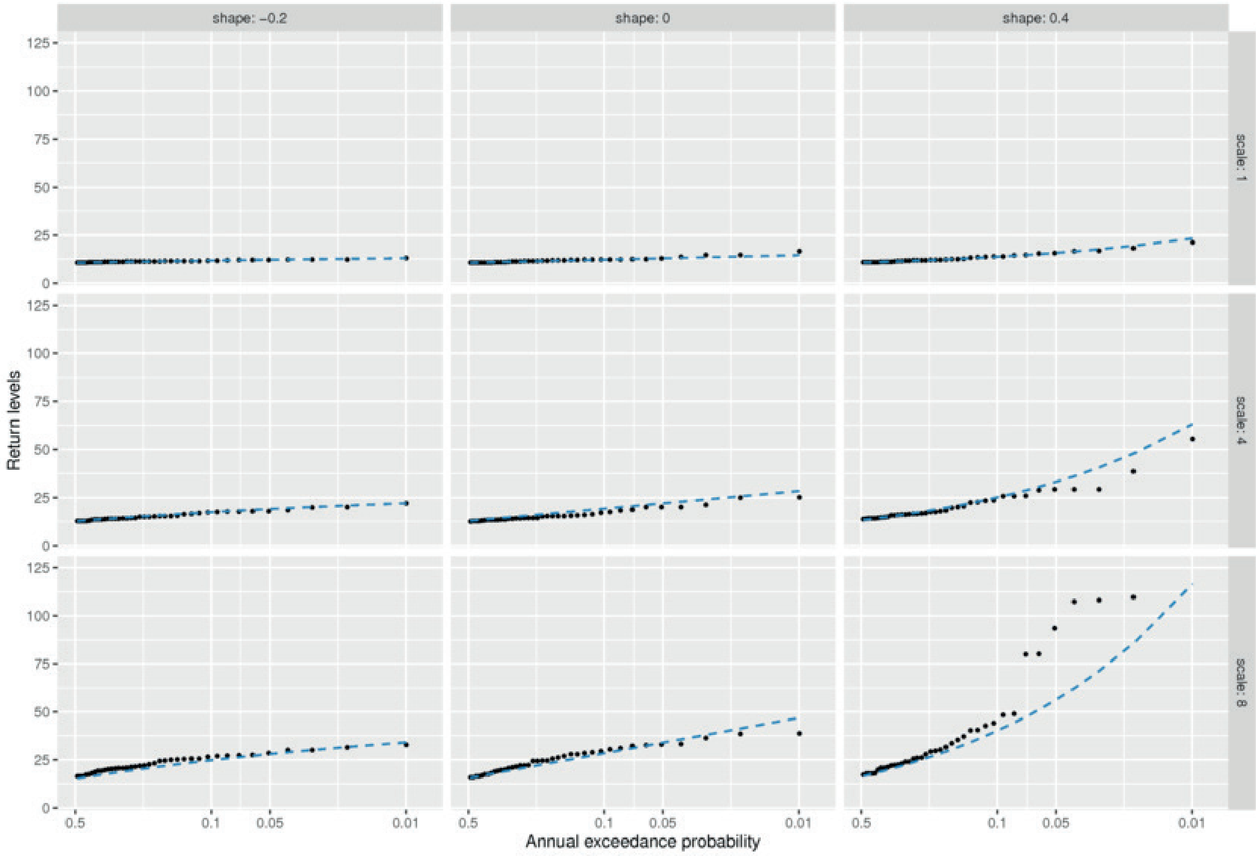

Figure 7. An illustration of how the scale and shape parameters in a GEV model affect the associated return-level curves. Columns, left to right: shape parameter values of –0.2, 0 and 0.4. Rows, top to bottom: scale parameter values of 1, 4 and 8. The location parameter is the same in all panels and 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, *Table 5*. A practicality about 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.

Table 5. Characteristics of specific forms of the GEV distribution.

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

As mentioned above, when using a GEV model, extremes 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 AEP. 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.

4.2.2 Threshold exceedance approaches

Coles (2001), *Katz et al. (2005*) and *Brown et al. (2008*) have argued 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 (creating multiple blocks containing only a few observations) can violate the assumption that the selected values come 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.

On the other hand, too high a threshold (creating few blocks with a large number of observations for a GEV analysis) 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.

4.2.3 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 the defined threshold is 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*).

4.2.4 Factors to be considered in conducting extreme value analysis

Aside from considering the choice of method (block maxima vs threshold exceedance approach) and the ensuing choice of EVD, there are other considerations when conducting an EVA such as those described 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 rainfalls are assumed to be caused by the same meteorological phenomenon. There are approaches available that compensate for autocorrelation, such as 'declustering' which subsets 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 — that is, the statistical properties of the distribution (the EVD parameters) do not change in a systematic way with time. As discussed in *Section 2.1*, rainfall is heavily influenced by the season and large-scale atmospheric circulation patterns like the NAO. As a result, the ability to include and assess possible covariates into 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). 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*).

Length of dataset

For accurate EVA, time series sequences must be sufficiently long in order to maximise the number of extreme events captured. There are techniques available which can be used to increase the robustness of the EVA, such as combining a number of weather station data together. 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 distribution 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 to 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.

A further consideration is that there needs to be an allowance for different characteristics of the site location compared to the nearest rain gauge station, e.g. different levels of elevation or coastal effects, to name a few.

4.3 Coupled global circulation and numerical weather prediction models

Climate and NWP models represent the climate system using mathematical equations that are discretized 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, NWP models in the meteorological community 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, e.g. severe convective rainfall events. NWP models can provide estimates of short-duration rainfall that are of use to the energy industry.

4.3.1 Unprecedented simulated extremes using ensembles method

It is assumed that an observed sample of data is representative of the local climate. However, given the rarity of extreme events and the nature of natural variability, this assumption is difficult to verify without a long time series of observations of the order of several hundred years.

Recent work is investigating ways to reduce this uncertainty. A simulated 1400-year model archive of many possible realisations of the current UK climate was produced as part of the National Flood Resilience Review (*HM Government, 2016*), the so-called 'UNSEEN' method (*Thompson et al., 2017*). These simulated years are created using data from a particular type of climate model (the Met Office's decadal prediction system; *Dunstone et al., 2016*) combined with actual observations for each year. The climate model is driven with observed levels of greenhouse gases, atmospheric aerosols and solar radiation. A large number of simulated years are created by taking advantage of the sensitivity of weather to small perturbations (also known as the 'butterfly effect') to create many different realisations of the atmospheric state. In these many realisations of current UK climate, there may be extreme values produced which are outside the realms of those in the observational record, but still consistent with the current climate; so called 'black swan' events. This approach can therefore potentially provide a more realistic estimate of the risk of extremes than statistical methods alone. This dataset may not fully sample the range of all possible near-future atmospheric conditions; however, it will sample a broader range of atmospheric states than have been observed within the recent period.

Using the 'UNSEEN' methodology, *Thompson et al. (2017)* found that for monthly rainfall totals:

- in the current climate there remains a high chance of exceeding the observed record monthly rainfall totals in many regions of the UK;

- in south-east England, there is a 7% chance of exceeding the current rainfall record in at least one month in any given winter;
- across other regions of England and Wales the risk increases to a 34% chance of breaking a regional record somewhere each winter.

4.3.2 Model uncertainty

The different types of uncertainty are:

Resolution uncertainty

The weather and climate system are very complex and no NWP or climate model can capture all of the processes within. 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 versions of climate modelling use 'representative concentration pathways' (RCPs) (*van Vuuren et al., 2011*), which instead 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.

4.3.3 Summary considerations and forward look

Bearing in mind the above uncertainties, it is advised that any projection of future extreme events should ideally also quantify sources of uncertainty; examples include the uncertainty associated with anthropogenic and natural greenhouse gas emissions and with population growth, and also the structural and internal model uncertainty.

All three sources of uncertainty were considered in the creation of a set of climate model projections for the UK, UKCP09 (*Murphy et al., 2009*). These official projections for the UK have been in use for almost a decade; the next release of official UK climate projections, UKCP18, is scheduled from September 2018. These projections will provide an update to UKCP09 and a range of different tools and data for use in assessing climate impacts on the UK. Some initial guidance has been issued by the project, including a Q&A (*UKCP Project, 2016*), a discussion of whether UKCP09 is still an appropriate tool for adaptation planning, covering projections for both land and marine environments (*UKCP Project, 2017*), and a UKCP18 project overview (*UKCP Project, 2018*). Other outputs will become available in due course.

4.4 Monte Carlo approaches

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*). The Monte Carlo simulation method can generally be defined as 'representing the solution of a problem as a parameter of a hypothetical population, and using a random sequence of numbers to construct a sample of the population, from which statistical estimates can be obtained' (*Halton, 1970*). A synthetic series of precipitation of a desired length is first generated from a probability distribution of the precipitation amounts; this distribution can be fitted using empirical or parametric methods. Depending upon the number of uncertainties and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete.

The benefits of Monte Carlo simulation approaches over deterministic, or single point estimate analysis for rainfall 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. It is important for accuracy to represent how, in reality, when some factors go up, others go up or down accordingly.

Multiple locations

Monte Carlo simulation is particularly suitable in cases where design flood characteristics need to be determined at multiple locations within a system (*Nathan and Weinmann, 2013*).

Combination of factors

Heavy precipitation events vary widely, depending on season, geography, topography, and other factors. It is not at all clear how to incorporate these factors, along with the very uneven spatial distribution of stations, into a theoretical treatment. For this reason, Monte Carlo approaches are used to assess uncertainties related to spatial sampling changes and missing data (*Kunkel et al., 2007*).

The main limitation of this approach is that it is not bounded by physical reality, unlike the UNSEEN methodology described in *Section 4.3.1*. Therefore, unrealistic rainfall data could be generated, leading to underestimation or overestimation of design rainfall criteria.

4.5 Regional frequency analysis

Regional frequency analysis (RFA) is described as the estimation of how often a specified event will occur within a defined region (*Hosking and Wallis, 1997*). Procedures for statistical frequency analysis of a single set of data are well established; however, it is often the case that there are many related samples of data available for analysis. In environmental approaches this is known as RFA, because the data samples analysed are typically observations of the same variable, in this case rainfall, at many measuring sites within a suitably defined region (*Hosking and Wallis, 1997*).

RFA pools the data from the site of interest with other sites that have similar frequency distributions from a homogeneous region (*Hosking and Wallis, 1997*). For example rain gauge stations can be pooled together that have similar daily rainfall frequency distributions and are characterised by similar topography.

Independence (i.e., no correlation) in the data series is a main assumption in frequency analysis (*Hailegeorgis et al., 2013*) and can refer to the correlation either at the spatial scale between neighbouring grid points or the temporal scale. High inter-site correlation can occur for low rainfall intensity (longer duration) storms, which cover larger areas; e.g. frontal rain. Low inter-site correlation occurs for localised, high-intensity (short duration) convective rainstorms (*Hailegeorgis et al., 2013*).

To remove correlation at the spatial and temporal scale the following methodology is suggested by *Hosking and Wallis (1997)*:

(1) Screening of the data — a close inspection of the data, checking for spurious errors and data-homogeneity (stationary) over time.

(2) Identification of homogeneous regions — assign sites to a region, based on a set of sites whose frequency distributions are approximately the same.
(3) Selection of the appropriate probability distribution.
(4) Choice of a frequency distribution — having identified suitable homogeneous regions, the final stage is the choice of an appropriate regional frequency distribution.

Theoretical and practical limitations include:

- the assessment of regional homogeneity is a critical point in RFA. There are many homogeneity tests, and the most commonly used test is based on L-moments ratios;
- the results of the frequency analysis depends on the length of the data available, although RFA should overcome this through sufficient pooling of homogeneous data.

4.6 Intensity-duration-frequency curves

An intensity-duration-frequency (IDF) curve gives the expected rainfall intensity for a given duration of storm with a desired frequency of occurrence. Frequency analysis of extreme precipitation events of different durations have long been used for the estimation of extreme quantiles corresponding to an annual probability of interest (*Hailegeorgis et al., 2013*). Estimated quantiles are summarised in the form of IDF curves from which design storm hyetographs can be derived. A hyetograph is a chart showing the distribution of rainfall for a particular area, usually throughout the year. The information is then useful for the design and management of urban drainage infrastructure, bridges, spillways, risk analysis for landslide hazards, etc.

Theoretical and practical limitations include:

- suitability of fit;
- data availability, stationarity, length, independence;
- limited short duration rainfall.

Suitable data for constructing IDF curves could be combined radar and rain gauge data, subject to the record length of the radar data. This would allow for short duration estimates to be produced due to the temporal resolution of the radar data. In the Netherlands, *Overeem et al. (2009)* used 11 years of rainfall radar data and the GEV distribution to produce rainfall depth-duration-frequency curves for durations of 15 mins to 24 hours. *Overeem et al. (2009)* compared their uncertainties with those based on rain gauge data and uncertainties were found to become large for long durations; however, it was shown that radar data are suitable for this purpose.

4.7 Recommended methodology

Section 4 has outlined several different methodologies that can be used to characterise the extreme rainfall hazard. There is no 'best' approach that is recommended in all situations. Each of the approaches has specific benefits and drawbacks given the situation; a brief summary on this aspect is provided below.

PMP is a mature methodology that is frequently used to assess extreme rainfall for hydrology purposes, e.g. when combined with a rainfall-runoff model it can be used to predict the timing, volume, and peak flow associated with extreme flood events at a dam. With PMP there are associated uncertainties as described in *Section 4.1* and estimates should always be characterised as a range of values recognising the significant uncertainties involved (*Micovic et al., 2015*). Other methodologies for characterising the intensity and frequency of precipitation for use in hydraulic design of urban drainage infrastructure purposes are RFA and IDF curves, as described in *Sections 4.5 and 4.6* respectively. The RFA methodology provides estimates of rainfall intensity and frequency across a homogeneous region, and IDF curves are site specific.

As described in *Section 4.2*, EVA is an industry-recognised methodology that is also frequently used and can work well given a reasonably long data series. However there can be large uncertainties if there is a small amount of data at the local scale, and there is a need to allow for different characteristics of the site location compared to the nearest rain gauge station. One way to resolve this is to follow a RFA methodology as described in *Section 4.5*; this involves pooling a number of observations that have similar regional characteristics. The EVA methodologies are not based on physical reality, and one way to combat this is to use a numerical modelling approach such as the UNSEEN method described in *Section 4.3.*

5.1 Description of phenomena

5.1.1 Snow

Precipitation can fall as snow when the air temperature is below 2 °C. In the UK the heaviest snowfalls tend to occur when the air temperature is between 0 and 2 °C. If the temperature is above 2 °C then the snowflakes will start to melt and fall as sleet rather than snow, and when warmer still the precipitation will be rain. The air temperature determines not only the number of ice crystals in a snowflake but also how they group together, which ultimately affects the size of a snowflake. When snow falls through dry, cold air (e.g. a polar continental air mass), the flakes will be small and powdery and will not stick together. This type of powdery snow is likely to drift. When the air temperature is warmer than 0 °C the flakes will melt around the edges and stick together to become larger heavy flakes known as 'wet snow'.

Very cold air masses during the winter are associated with northerly and easterly winds bringing with them snow to the UK. As shown in Figure 8, the snowiest regions in the UK are found in the upland areas of the east and north-east of the UK. On average (over the period 1981 to 2010) the UK gets 23.7 days of snowfall or sleet per year. The snowiest place in the UK is the Cairngorms in Scotland, with 76.2 days of snow or sleet falling on average (*Met Office, 2016*). Cornwall is the least likely to get snow, with an average of only 7.4 days of snow or sleet falling a year (*Met Office, 2016*). Much of the snow that falls does not settle and consequently the number of days with lying snow are fewer.

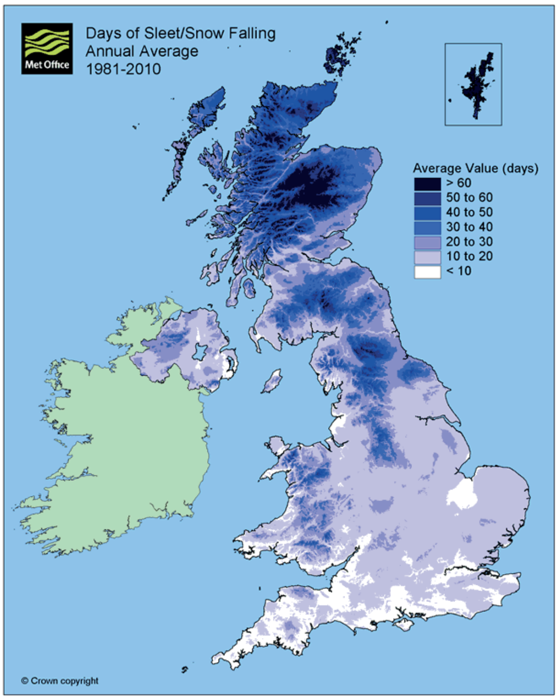

Figure 8. The annual average of the number of days of sleet/snow falling in the UK. Source: National Climate Information Centre, (© Crown Copyright Met Office 2018)

5.1.2 Snowpack and avalanches

Snowpack is defined as the total snow and ice on the ground, including both new snow and the previous snow and ice that has not melted. An avalanche is a rapid flow of snow down a hill or mountainside. Information on snowpack stability is critical for assessing avalanche risk (*Schweizer and Jamieson, 2010*). In the hills and mountains of the UK, most notably the Scottish Highlands, avalanches are potential hazards. Constantly changing weather factors including temperature, snowfall, wind speed and direction can affect the strength and stability of the snowpack. In an operational context the Scottish Avalanche Information Service (SAIS) provides daily reports of observed and forecast avalanche, snow, and mountain conditions (*SAIS, 2018*).

5.1.3 Ice

Ice occurs in the atmosphere and on the Earth's surface and can take many forms such as ice pellets, snow, hoar frost, rime, glaze and hail. Ice is not a directly observed variable. Many different ice types form at the surface in the UK including:

- Glaze (clear ice): a smooth, transparent type of ice that forms when drizzle or rain hits a cold surface. It forms when supercooled water comes into contact with the ground, or non-supercooled water comes into contact with a surface that is well below 0 °C. Supercooling is the process of lowering the temperature of a liquid below its freezing point without it becoming solid. The extra weight of glaze accumulations can have a significant impact on power lines and overhead cables.
- Rime: a rough white ice deposit that forms on surfaces exposed to the wind. Lattice structures, such as pylons, are particularly susceptible. It is formed by supercooled water droplets of drifting fog freezing on contact with a surface.

5.1.4 Impacts of extreme snowfall and ice on the energy sector

There are many associated impacts on the energy sector:

- Very heavy snow and ice on solar panels can have an adverse effect on the output of energy by obstructing light reaching the cells. The snow cover can stop the production of electricity and lead to faster deterioration (*Jelle et al., 2016*).
- The mass of the snowpack and its effect on the structural integrity of assets, e.g. the roof of a nuclear power plant.
- Snow melt and its potential to cause flooding, e.g. to a pumping station on a river.
- Glaze ice accumulations and rime on overhead power lines put a lot of stress on the cables and damage equipment. Ice can also affect the operability and efficiency of wind turbines.

Snow and ice can have indirect impacts on the energy sector. They will also affect other infrastructure not necessarily owned or maintained by the energy sector, e.g. access roads, which can affect safe access by key personnel and the ongoing operability of an asset.

An example of the impacts of extreme snowfall and ice includes the winter (December to January) of 2009/2010 which was characterised by prolonged cold spells, hard frosts, and frequent snowfalls across the UK and particularly in northern areas (*Prior and Kendon, 2011*). That winter brought travel delays, accidents on icy roads and pavements, and several large-scale avalanches across the Scottish mountains. It also had notable impacts on electricity and water supplies, e.g. on 25th February some 40,000 homes were affected across central northern Scotland by snow and ice bringing down power lines. The spells of snow in winter 2010 were the most widespread and significant across the UK since the mid-1980s, and the winter of 2010 was one of the snowiest in the last 100 years.

5.1.5 Humidity

Humidity describes the amount of water vapour in the air, i.e. in gas form. Warmer air can carry more water vapour than cooler air. This is because it has more energy to evaporate water into vapour, and keep it in this state. The amount of water vapour in the air can be quantified in various ways, three of which are (*Met Office, 2018d*):

Relative humidity

This describes how much water vapour there is in the air compared to how much there could be at that temperature. Relative humidity is a function of the dry bulb and wet bulb thermometer temperatures (*Huang et al., 2013*). The *dry bulb temperature* is the air temperature read from an ordinary thermometer in a ventilated Stephenson's screen 1.2 m above ground level. The *wet bulb temperature* is measured by allowing the air to cool a thermometer that has its bulb exposed to water by evaporation.

Specific humidity and mixing ratio

These measure the actual amount of water vapour in the air as a weight in grams. Specific humidity is the weight of water vapour for every kilogram of air. The mixing ratio is the weight of water vapour for every kilogram of dry air.

Thermal humidity

Dew point and wet bulb temperatures are both measures of humidity. The dew point temperature is measured by cooling a surface to the point at which water vapour starts to condense out of the air, but it is usually calculated from the wet and dry bulb temperatures.

5.1.6 Fog and mist

Fog and mist form when the atmosphere cools and water vapour condenses as the air's capacity to hold water vapour is decreased. In the atmosphere, water vapour condenses onto solid particles, which may be natural or manmade; they are called cloud condensation nuclei. In meteorology, there are three categories for fog: aviation fog for visibility less than 1000 m, thick fog for visibility less than 180 m, and dense fog when it falls below 50 m. If visibility is more than 1000 m it is called mist. The main types of fog are: radiation, valley, advection, upslope, evaporation, freezing (*Met Office, 2018e*).

5.1.7 Impacts of humidity and fog on the energy sector

The primary impact of humidity and fog on the energy sector is when they reduce visibility. This in turn affects safe operations on land and at sea; e.g. the disruption of helicopter flight plans to offshore wind farms, as they have strict aviation guidelines to follow. A specific impact of freezing fog is that it can affect vertical surfaces such as overhead wires, pylons and transmitting masts, by causing a build-up of rime. Rime is described in *Section 5.1.3*.

5.2 Observations

5.2.1 Snow

Automatic weather stations operated by the Met Office use a sensor to measure snow depth. An ultrasonic transducer transmits pulses and measures the returning echoes from the surface. An independent measure of temperature is required to compensate for the variation of the speed of sound in air. Artificial grass is used to avoid spurious readings associated with grass growth. At manned weather stations the snow depth is manually recorded using a measuring rod at many representative stations.

Operational radar sends out pulses of microwave radiation and detects the return signals reflected by different particles of precipitation, including hail, rain, sleet, snow and drizzle. The Met Office operates and maintains 18 radar stations providing coverage across the UK. Although not explicitly used, radar data could be used to provide estimates of snowfall rates similar to rainfall (e.g. *Boucher and Wieler, 1985*; *Hassan et al., 2017*). Careful quality checks would be needed to calibrate against snow depth weather station data.

Satellites can be used to provide information about the extent and duration of snow cover. No quantitative snowfall intensity determination has been found to date (*Levizzani et al., 2011*).

5.2.2 Humidity

Relative humidity or wet bulb temperature are measured at all Met Office weather stations. Screen psychrometers form part of the UK's long-term monitoring network (*Harrison and Wood, 2012*). Screen psychrometers are comprised of wet bulb and dry bulb thermometers within a standard Stephenson's screen. There are also gridded products available for land surface humidity; e.g. the HadISDH (*Willett et al., 2014*; *Smith et al., 2011*) dataset provides global gridded records from 1973 to present-day for a wide range of humidity-related variables, and the National Climate Information Centre UK (5 km x 5 km) gridded records from 1961 to present-day for relative humidity.

Visibility is measured in metres at automatic weather stations sensors across the UK.

In this section, specific guidance on regulatory instruments, codes and standards applicable to extreme rainfall 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).

6.1 Rainfall

For natural hazards that have the potential to cause flooding (e.g. rain), there are specific statutory considerations related to environmental protection and in particular the need for a flood risk strategy and thus assessment. The Flood and Water Management Act 2010 covers both flood and coastal erosion: for flooding, it aims to reduce the flood risk associated with extreme weather and calls for flood risk management to prevent flooding and reduce the impacts of flooding. The Act also contains a requirement for new developments to have sustainable drainage systems (SuDS). Standards for SuDS are undergoing a development programme. In Scotland, the Flood Risk Management (Scotland) Act 2009 sets out the requirements for Flood Risk Management Strategies and Local Flood Risk Management Plans. Northern Ireland currently has no legislative equivalent: flood risk management is the responsibility of the Northern Ireland Executive.

The Department for Environment, Food & Rural Affairs (Defra) has issued guidance for asset owners focused on ensuring that owners do not inadvertently alter structures and other features and potentially increase flood risk to themselves, their neighbours and the wider community.

The UK Government's National Planning Policy Framework aims to protect people and property from flooding. It forms part of the planning consent process for new development (as implemented at a local authority level). The main steps to be followed involve avoidance, management and mitigation of flood risk.

The Land Drainage Act 1991 sets out the powers of land drainage boards and their and local authorities' functions in relation to land drainage, including under flood conditions.

Due to the increased focus on flood risks in recent years, general and industry-specific guidance on the impacts of flooding due to natural hazards is abundant. 'An overview of the legislative framework relating to critical infrastructure (not energy-specific) is provided in *CIRIA (2009)*.

Precipitation (or the accumulation thereof) also has the potential to cause structural stresses due to increased loading, and design against such hazards is addressed by code-compliance as a minimum. 'Currently the point of reference is Eurocode 1 (*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 snow loading on structures is *EN 1991-1-3 (2003)*.

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.

6.2 Snow

The nuclear energy industry specifically addresses snowpack in *IAEA (2011)*. Regions are assessed for hazards including whether significant snowfall is likely to occur. Annual extreme values of snowpack associated with the annual frequencies of exceedance are assessed for design loads for structures, systems and components important to safety. The load on a structure due to the snowpack will depend on both snow depth and packing density. The guidelines stipulate, "the results of a hazard assessment for extreme snowpack should include the determination of the water equivalent and the annual frequency of exceedance". As an example, for plant design, "the appropriate extreme snowpack for each time period should be characterised by the annual frequency of exceedance of given thresholds with an associated confidence interval". Methodologies for stationary EVA are described further in the guidelines for extreme precipitation.

EN 1991-1-3 (2003) provides guidance on the characterisation of snow loads to be used for the structural design of buildings and civil engineering works. The guidelines cover snow load on the ground, snow loads on roofs, and local effects, e.g. drifting and obstructions. The guidelines provide the following definitions for these terms:

- *Characteristic value of snow load on the ground:* Snow load on the ground is based on the annual probability of exceedance of 0.02 kNm^{-1}, excluding exceptional snow loads.
- *Exceptional snow load on the ground:* The load of the snow layer on the ground resulting from a snowfall which has an exceptionally infrequent occurrence probability. The UK and Ireland National Annex of Eurocode 1 states that exceptional snow load on the ground should be treated as an accidental action.
- *Characteristic value of snow load on the roof:* A product of the characteristic snow load on the ground and appropriate coefficients. The coefficients are chosen so that the probability of the calculated snow load on the roof does not exceed the probability of the characteristic value of the snow load on the ground.
- *Drifted snow load on the roof:* A load arrangement that describes the load distribution resulting from snow having been moved from one location to another on a roof, e.g. by the wind.

The National Annex to Eurocode 1 provides a characteristic ground snow load map for the UK and Ireland. The map characterises zones of ground snow load at 100 m above mean sea level. Unusual local effects may not have been accounted for and these include local shelter from the wind, which can result in no drifting, and increased snow loads and local configurations in mountainous areas, which may funnel the snow and give increased local loading. For coastal sites below 100 m, the map value should be used without the altitude modification. Annex D of Eurocode 1 provides guidance on the adjustment of the ground snow load according to return period.

6.3 Humidity

A preliminary way to characterise extreme wet bulb temperatures is to obtain an initial order-of-magnitude estimate by examining observed extreme values (events) in the historical record. Stationary and non-stationary EVA methods could be used in this situation; EVA methodologies are discussed further in Volume 1 — Introduction to the Technical Volumes and Case Studies. Note that it is not appropriate to combine the output from a univariate extreme dry bulb temperature with the output from a univariate extreme wet bulb analysis. This is because dry bulb and wet bulb temperatures cannot be considered independent variables. Joint probabilities cannot be found by multiplying together two individual return periods.

CIBSE (2015) provides basic weather data for manual calculation of heating and cooling loads in the UK and Europe. For 14 locations across the UK, *CIBSE (2015)* provides tables of:

- percentage frequency for which the hourly dry bulb temperature exceeds a stated temperature;
- percentage frequency for which the hourly wet bulb temperature exceeds a stated temperature;
- percentage frequency of combinations of hourly dry bulb and wet bulb temperatures for June to September.

Using the dry bulb and wet bulb temperature frequency data, *CIBSE (2015)* has produced plots of percentage frequencies of combinations of hourly dry bulb and wet bulb temperatures on a psychrometric chart. Psychrometric charts provide an estimation of the moisture content of air. *CIBSE (2015)* states that "This enables the frequency with which the specific enthalpy exceeds given values to be determined, from which summer design conditions can be established". Enthalpy is described in Volume 1 — Introduction to the Technical Volumes and Case Studies.

7.1 Extreme rainfall

It was reported in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) that since 1950 there are likely ('likely' means that the probability of this outcome can range from ≥66% to 100%) to be more increases than decreases in the frequency, intensity and amount of heavy precipitation events on a global scale (*IPCC, 2013*). The severity of the heaviest rainfall events is only limited by the total amount of water vapour available in the air flowing into the weather system causing the rain. Global temperatures are warmer than in the pre-industrial era, which increases the amount of water vapour the atmosphere can hold and therefore affects the severity of the heaviest rainfall events.

As discussed in *Section 2.1*, rainfall across the UK is influenced by the seasons, air masses and longer term naturally occurring phenomena such as the NAO. A regional frequency analysis was performed to assess changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009 (*Jones et al., 2013*). They found that the magnitude of these changes depends on the location: in northern and western parts of the UK, the natural variability of large-scale climatic factors (such as the NAO) dominates; and in the southern and eastern parts of the UK, seasonality is the greatest influence. *Jones et al. (2013)* stated that:

- There were continued increases in spring and autumn extreme rainfall events.
- Longer duration winter events continued to increase in intensity, with a decrease in annual probability estimate from a 25-year to around a 5-year event over the full 50 years of record in parts of Scotland and south-west England.
- Short-duration summer rainfall events have continued to decline in intensity, whereas longer duration events appear to be increasing in intensity.

By the late 21st century (2081 to 2100) the *IPCC (2013)* reports that globally it is very likely over most mid-latitude land masses that there will be an increase in the frequency, intensity and amount of heavy precipitation. Projections of future UK climate change indicate that, when viewed over long-term averages, the frequency of wetter winters and drier summers is projected to increase over time. However, this does not mean that a very dry winter or very wet summer will not happen. It is likely the UK will continue to experience wet summers periodically due to natural variability. *Sanderson (2010)* assessed changes in the frequency of extreme rainfall events for selected towns and cities in the UK using an 11-member ensemble of regional climate projections released alongside the UKCP09 climate projections. *Sanderson (2010)* stated that during winter (December to February):

- The biggest increases in frequency of 5- and 10-year events are projected to occur over Essex, Sussex and Kent.

- For the 20-, 30-, 50- and 100-year events, the biggest increases occur over Suffolk.
- For 5- and 10-year events, the smallest changes occur in South Yorkshire.
- For the 20-, 30-, 50- and 100-year events, the smallest changes occur over Herefordshire and Worcestershire.

Sanderson (2010) stated that during summer (June to August):

- The biggest increases in frequency of 5- and 10-year events are projected to occur over central southern England (Berkshire, Hampshire and Surrey).
- For the 20-, 30-, 50- and 100-year events, the biggest increases are projected to occur over both Dorset and north-west England (Cumbria and Lancashire).
- The smallest changes (where the frequency of summer rainfall events does not change or decreases slightly) occur over Norfolk.

Projected changes in extreme rainfall is an active area of research; it is at the bounds of what is currently capable in terms of scientific understanding and climate modelling. Numerical weather prediction models operate at a higher spatial resolution than climate models and can model convective processes and clouds at smaller scales. The Met Office ran the world's first very high-resolution climate change experiments, looking at changes in hourly rainfall (*Kendon et al, 2014*). These were conducted using the Met Office's weather forecasting model, which simulates weather across the British Isles with a spatial resolution of 1.5 km. This high-resolution model was applied on climate change timescales that covered the present-day (1996 to 2009) and a second one that encompassed another 13-year period, starting from the year 2100. It was found that the model simulated realistic hourly rainfall characteristics, including extremes, unlike coarser resolution climate models. *Kendon et al. (2014)* stated that:

- The 1.5 km model showed increases in hourly rainfall intensities in winter that are consistent with projections from a coarser 12 km resolution model and previous studies at the daily duration. This is because predominantly winter rain is produced by large-scale frontal rain which can be resolved by both models.
- The 1.5 km model also showed an intensification of short-duration rainfall in summer, with significantly more events exceeding the high thresholds indicative of serious flash flooding.

This is an active area of research for climate science and, as supercomputing power increases, higher resolution climate models can be run multiple times to provide an understanding of the level of uncertainty in these future changes. Other current trends in research include stochastic approaches, e.g. developing stochastic rainfall models conditioned by weather types for the water resource region of Yorkshire (*Fowler et al., 2005*), and weather type approaches such as linking El Niño Southern Oscillation with heavy rainfall (*Brigode et al., 2013*).

7.2 Extreme snow

Across the globe and the UK there have been decreases in snow (*Kay, 2016*). To identify historical trends, there needs to be a reliable and sufficient time series beyond that of natural climate variability. Historically at Met Office sites, observers measured and reported the water equivalent of fresh snow at some stations, and point observations of snow depth from the network of weather stations at others (as discussed in *Section 5.2.1*). These data sources have been combined to provide a 5 km gridded dataset of the depth of falling and lying snow (*Perry and Hollis, 2005*); it should be noted that most sites are low-lying so interpolation for higher altitudes is likely to be less reliable (*Kay, 2016*).

A set of official climate projections for the UK known as UKCP09 (*Murphy et al., 2009*) have been in use for almost a decade; the next release of official climate projections, UKCP18, is scheduled from September 2018. The UKCP09 probabilistic projections of future changes in snow were found to produce unrealistic large uncertainties in future changes, and large biases were found between the historical record and the regional climate model historical period (*Brown et al., 2010*). No clear statements were made on changes in UK snow.

The modelling of snow is moving towards being physically replicated, as opposed to statistically represented, in NWP models. These NWP models are constrained by the laws of atmospheric physics, and physical modelling is being pursued alongside statistical methods due to the greater computational power that is becoming available. This will have numerous benefits; this will allow the modelling of combined parameters and hazards such as those associated with snow drift and avalanches.

7.3 Humidity and fog

To determine long-term trends in humidity, a long-term, consistent series of reliable and characterised measurements are required. As discussed in *Section 5.2.2* the UK has a land network of screen psychrometers measuring relative humidity. Between 1961 and 2006 the UKCP09 results suggest a relative humidity reduction of up to 5% for England, Scotland and Wales (*Murphy et al., 2009*; as cited in *Harrison and Wood, 2012*).

The UKCP09 climate projections provide estimates for future changes in relative humidity at the 90% probability level. The units of change for relative humidity (% of a %) between a future and baseline period are best illustrated by an example. If the relative humidity changes from 50% in the baseline climate to 60% in the future climate, then the change in relative humidity represents a proportional increase of 20% (60/50 x 100) (*Murphy et al., 2009*). For the UK as a whole, by the 2080s in winter there could be a 6% increase, and in summer a 4% increase (*Murphy et al., 2009*). Alongside projected changes in temperature, this indicates an increase in the amount of water vapour in the air.

In the main UKCP09 report, projected changes in fog were not directly provided due to a high level of uncertainty in the model output. A technical note was provided by *Boorman et al. (2010)* on future changes in fog frequency stating that by the 2080s:

- In winter, when fog days are most numerous, the general picture shows that reductions of 50% or more are projected in many areas of northern Britain and north Wales, with increases (in the range 0 to 30%) over southern and midland areas of England.
- In spring the pattern is similar to that in winter, but reductions tend to be greater.
- In summer, large reductions are projected in most parts of England; however the original frequencies were already small. In Scotland and Northern Ireland changes are much smaller.
- In autumn, reductions over most of the UK are generally 10 to 30%, but much greater than this over the Scottish Highlands.

Fog is routinely difficult to forecast and is an active area of research. For aviation, the Met Office is currently running high resolution models down to a few hundred metres over London to improve forecasting of fog and its associated visibility (*Met Office, 2018f*).

Arnold TB, Emerson JW. 2011. Nonparametric goodness-of-fit tests for discrete null distributions. *The R Journal,* 3, 34–39.

BGS. 2018. Groundwater flooding research overview. *http://www.bgs.ac.uk/research/groundwater/flooding/groundwater_flooding.html* (accessed on 17th April 2018).

Boorman P, Jenkins G, Murphy J. 2010. *Future changes in fog frequency from the UKCP09 ensemble of regional climate model projections.* Available at: *http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87948&filetype=pdf* (accessed on 17th April 2018).

Boucher RJ, Wieler JG. 1985. Radar determination of snowfall rate and accumulation. *Journal of Climate and Applied Meteorology,* 24, 68–73.
doi: 10.1175/1520-0450(1985)024<0068:RDOSRA>2.0.CO;2

Brigode P, Mićović Z, Bernardara P, Paquet E, Garavaglia F, Gailhard J, Ribstein P. 2013. Linking ENSO and heavy rainfall events over Coastal British Columbia through a weather pattern classification. *Hydrology and Earth System Sciences,* 17, 1455–1473.
doi: 10.5194/hess-17-1455-2013

Brown SJ, Caesar J, Ferro CAT. 2008. Global changes in extreme daily temperature since 1950. *Journal of Geophysical Research: Atmospheres*, 113, D05115.
doi: 10.1029/2006JD008091

Brown SJ, Boorman P, Murphy J. 2010. *Interpretation and use of future snow projections from the 11-member Met Office Regional Climate Model ensemble.* Available at: *http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87949&filetype=pdf* (accessed on 17th April 2018).

CIBSE. 2015. *CIBSE Guide A: Environmental Design.* The Chartered Institution of Building Service Engineers, London, UK.

CIRIA. 2009. *Flood resilience and resistance for critical infrastructure.* Available at: *https://www.ciria.org/Resources/Free_publications/Flood_resilience.aspx* (accessed on 10th September 2018).

Coles S. 2001. *An Introduction to Statistical Modelling of Extreme Values.* Springer, London, UK.

Collier CG, Fox NI, Hand WH. 2002. *Extreme Rainfall and Flood Event Recognition. R&D Technical Report FD2201.* DEFRA/Environment Agency, UK Available at: *http://science-search.defra.gov.uk/Document.aspx?Document=FD2201_708_TRP.pdf* (accessed on 17th April 2018).

Dunstone N, Smith D, Scaife A, Hermanson L, Eade R, Robinson N, Andrews M, Knight J. 2016. Skilful predictions of the winter North Atlantic Oscillation one year ahead. *Nature Geoscience,* 9, 809–814. *doi: 10.1038/NGEO2824*

EA. 2016. *The costs and impacts of the winter 2013 to 2014 floods. Report – SC140025/R1. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/501784/The_costs_and_impacts_of_the_winter_2013_to_2014_floods_-_report.pdf* (accessed on 17th April 2018).

EN 1991-1-1. 2002. Eurocode 1: *Actions on structures — Part 1-1: General actions — Densities, self-weight, imposed loads for buildings.* Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC.

EN 1991-1-3. 2003. Eurocode 1: *Actions on structures — Part 1-3: General actions — Snow loads.* Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC.

Fowler HJ, Kilsby CG, O'Connell PE, Burton A. 2005. A weather-type conditioned multi-site stochastic rainfall model for the generation of scenarios of climatic variability and change. *Journal of Hydrology,* 308, 50–66. *doi: 10.1016/j.jhydrol.2004.10.021*

Giorgi F, Gutowski Jr WJ. 2015. Regional dynamical downscaling and the CORDEX Initiative. *Annual Review of Environment and Resources,* 40, 467–490. *doi: 10.1146/annurev-environ-102014-021217*

Grunewald T, Lehning M. 2015. Are flat-field snow depth measurements representative? A comparison of selected index sites with areal snow depth measurements at the small catchment scale. *Hydrological Processes,* 29, 1717–1728. *doi: 10.1002/hyp.10295*

Halton JH. 1970. A retrospective and prospective survey of the Monte Carlo method. *SIAM Review,* 12, 1–63. doi: 10.1137/1012001

Hailegeorgis TT, Thorolfsson ST, Alfredsen, K. 2013. Regional frequency analysis of extreme precipitation with consideration of uncertainties to update IDF curves for the city of Trondheim. *Journal of Hydrology,* 498, 305–318. doi: 10.1016/j.jhydrol.2013.06.019

Harrison RG, Wood CR. 2012. Ventilation effects on humidity measurements in thermometer screens. *Quarterly Journal of the Royal Meteorological Society,* 138, 1114–1120. doi: 10.1002/qj.985

Hassan D, Taylor PA, Issac GA. 2017. Snowfall rate estimation using C-band polarimetric radars. *Meteorological Applications,* 24, 142–156. doi: 10.1002/met.1613

HM Government. 2016. *National Flood Resilience Review.* Available at: https://www.gov.uk/government/publications/national-flood-resilience-review (accessed on 17th April 2018).

Huang Y, Zhang K, Yang S, Jin Y. 2013. A method to measure humidity based on dry bulb and wet bulb temperatures. *Research Journal of Applied Sciences, Engineering and Technology,* 6, 2984–2987.

Hosking JRM, Wallis JR. 1997. *Regional Frequency Analysis.* Cambridge University Press, Cambridge, UK.

IAEA. 2011. *Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations: Specific Safety Guide No. SSG-18.* Available at: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1506_web.pdf (accessed on 17th April 2018).

IPCC. 2013. *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jelle BP, Gao T, Mofid SA, Kolås T, Stenstad PM, Ng S. 2016. Avoiding snow and ice formation on exterior solar cell surfaces — a review of research pathways and opportunities. *Procedia Engineering,* 145, 699–706. doi: 10.1016/j.proeng.2016.04.084

Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. 2013. An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology,* 33, 1178–1194. doi: 10.1002/joc.3503

Katz RW, Brush GS, Parlange MB. 2005. Statistics of extremes: modelling ecological disturbances. *Ecology,* 86, 1124–1134. doi: 10.1890/04-0606

Kay AL. 2016. A review of snow in Britain: The historical picture and future projections. *Progress in Physical Geography: Earth and Environment,* 40, 676–698. doi: 10.1177/0309133316650617

Kendon EJ, Roberts NM, Fowler HJ, Roberts MJ, Chan SC, Senior CA. 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change,* 4, 570–576. doi: 10.1038/nclimate2258

Kunkel KE, Karl TR, Easterling DR. 2007. A Monte Carlo assessment of uncertainties in heavy precipitation frequency variations. *Journal of Hydrometeorology,* 8, 1152–1160. doi: 10.1175/JHM632.1

Levizzani V, Laviola S, Cattani E. 2011. Detection and measurement of snowfall from space. *Remote Sensing,* 3, 145–166. doi: 10.3390/rs3010145

Met Office. 2012. Heavy rainfall/flooding in the Lake District, Cumbria — November 2009. https://www.metoffice.gov.uk/climate/uk/interesting/nov2009 (accessed on 17th April 2018).

Met Office. 2016. UK snow and facts. https://www.metoffice.gov.uk/learning/snow/snow-in-the-uk (accessed on 17th April 2018).

Met Office. 2018a. UK climate — extremes. https://www.metoffice.gov.uk/public/weather/climate-extremes/#?tab=climateExtremes (accessed on 17th April 2018).

Met Office. 2018b. Why does it rain? https://www.metoffice.gov.uk/learning/precipitation/rain/why-does-it-rain (accessed on 17th April 2018).

Met Office. 2018c. Rainfall radar. *https://www.metoffice.gov.uk/learning/making-a-forecast/first-steps/making-observations/rainfall-radar* (accessed on 17th April 2018).

Met Office. 2018d. Humidity. *https://www.metoffice.gov.uk/learning/learn-about-the-weather/weather-phenomena/humidity* (accessed on 17th April 2018).

Met Office. 2018e. What is fog? *https://www.metoffice.gov.uk/learning/fog* (accessed on 17th April 2018).

Met Office. 2018f. The London Model: forecasting fog at 333m resolution. *https://www.metoffice.gov.uk/research/news/2015/london-model* (accessed on 17th April 2018).

Micovic Z, Schaefer MG, Taylor GH. 2015. Uncertainty analysis for Probable Maximum Precipitation estimates. *Journal of Hydrology,* 521, 360–373. *doi: 10.1016/j.jhydrol.2014.12.033*

Murphy JM, Sexton DMH, Jenkins GJ, Boorman PM, Booth BBB, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Howard TP, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA. 2009. *UK Climate Projections Science Report: Climate change projections.* Met Office Hadley Centre, Exeter, UK. Available at: *http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87893* (accessed on 17th April 2018).

Nathan R, Weinmann E. 2013. *Australian Rainfall and Runoff. Discussion Paper: Monte Carlo Simulation Techniques.* Engineers Australia Water Engineering. Available at: *http://arr.ga.gov.au/__data/assets/pdf_file/0017/40562/ARR_DiscussionPaper_MonteCarlo.pdf* (accessed on 17th April 2018).

NERC. 1975. *Flood Studies Report, Vol II, Meteorological Studies.* Natural Environment Research Council, UK.

NERC. 2018. Combination Hazard of Extreme rainfall, storm Surge & high Tide on estuarine infrastructure (CHEST). *http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FR009007%2F1&cookieConsent=A* (accessed on 17th April 2018).

ONR. 2014. *Safety Assessment Principles for Nuclear Facilities* (Revision 0). *http://www.onr.org.uk/saps/* (accessed on 17th April 2018).

ONR. 2017. *Nuclear Safety Technical Assessment Guide: External Hazards*, NS-TAST-GD-013 (Revision 6). *http://www.onr.org.uk/operational/tech_asst_guides/* (accessed on 17th April 2018).

Overeem A, Buishand TA, Holleman I. 2009. Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar. *Water Resources Research*, 45, W10424. *doi: 10.1029/2009WR007869*

Papalexiou SM, Koutsoyiannis D. 2013. Battle of extreme value distributions: A global survey on extreme daily rainfall. *Water Resources Research*, 49, 187–201. *doi: 10.1029/2012WR012557*

Perry M, Hollis D. 2005. The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology*, 25, 1041–1054. *doi: 10.1002/joc.1161*

Prior J, Kendon M. 2011. The UK winter of 2009/2010 compared with severe winters of the last 100 years. *Weather*, 66, 4–10. *doi: 10.1002/wea.735*

Pitt M. 2008. *The Pitt Review: Learning Lessons from the 2007 Floods*. Cabinet Office, London, UK. Available at: *http://webarchive.nationalarchives.gov.uk/20100702215619/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html* (accessed on 17th April 2018).

SAIS. 2018. Scottish Avalanche Information Service. *https://www.sais.gov.uk/* (accessed on 17th April 2018).

Sanderson M. 2010. *Changes in the frequency of extreme rainfall events for selected towns and cities*. Available at: *https://www.ofwat.gov.uk/wp-content/uploads/2015/11/rpt_com_met_rainfall.pdf* (accessed on 17th April 2018).

Schweizer J, Jamieson B. 2010. Snowpack tests for assessing snow-slope instability. *Annals of Glaciology*, 54, 187–194. *doi: 10.3189/172756410791386652*

Sene K. 2013. Precipitation Measurement. In *Flash Floods.* Springer, Dordrecht, Netherlands. *doi: 10.1007/978-94-007-5164-4_2*

Smith A, Lott N, Vose R. 2011. The Integrated Surface Database: recent developments and partnerships. *Bulletin of the American Meteorological Society,* 92, 704–708. *doi: 10.1175/2011BAMS3015.1*

Taylor KE, Stouffer RJ, Meehl GA. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society,* 93, 485–493. *doi: 10.1175/BAMS-D-11-00094.1*

Thompson V, Dunstone NJ, Scaife A, Smith DM, Slingo JM, Brown SJ, Belcher S. 2017. High risk of unprecedented UK rainfall in the current climate. *Nature Communications,* 8, 107. *doi: 10.1038/s41467-017-00275-3*

UKCP Project. 2009. About UKCP09. *http://ukclimateprojections.metoffice.gov.uk/21684* (accessed on 17th April 2018).

UKCP Project. 2016. UKCP18 Project Q&A. *http://ukclimateprojections.metoffice.gov.uk/24126* (accessed on 17th April 2018).

UKCP Project. 2017. Is UKCP09 still an appropriate tool for adaptation planning? *http://ukclimateprojections.metoffice.gov.uk/24127* (accessed on 17th April 2018).

UKCP Project. 2018. UKCP18 Project. *http://ukclimateprojections.metoffice.gov.uk/24125* (accessed on 17th April 2018).

van Vuuren DP, Edmonds J, Kainuma M. 2011. The representative concentration pathways: an overview. *Climatic Change,* 109, 5–31. *doi: 10.1007/s10584-011-0148-z*

Willett KM, Dunn RJH, Thorne PW, Bell S, de Podesta M, Parker DE, Jones PD, Williams Jr. CN. 2014. HadISDH land surface multi-variable humidity and temperature record for climate monitoring. *Climate of the Past,* 10, 1983–2006. *doi: 10.5194/cp-10-1983-2014*

WMO. 1994. *Guide to Hydrological Practices.* WMO no. 168, 5th Edition. World Meteorological Organization (WMO), Geneva, Switzerland. *http://www.wmo.int/pages/prog/hwrp/publications/guide/english/168_Vol_I_en.pdf* (accessed on 17th April 2018).

WMO. 2009. *Manual on Estimation of Probable Maximum Precipitation (PMP).* WMO no. 1045. World Meteorological Organization (WMO), Geneva, Switzerland. *http://www.wmo.int/pages/prog/hwrp/publications/PMP/WMO%201045%20en.pdf* (accessed on 17th April 2018).

WMO. 2015. *Guidelines on the Definition and Monitoring of Extreme Weather and Climate Events.* Draft version — first revision by TT-DEWCE December 2015. Available at: *https://www.wmo.int/pages/prog/wcp/ccl/opace/opace2/documents/DraftversionoftheGuidelinesontheDefinitionandMonitoringofExtremeWeatherandClimateEvents.pdf* (accessed on 17th April 2018).

Dry bulb temperature

The temperature of air as measured by a thermometer freely exposed to the air, but shielded from moisture and radiation typically by a Stevenson screen.

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.

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.

Wet bulb temperature

The temperature of air measured using a thermometer wrapped in wet muslin; it represents the adiabatic saturation temperature.

Abbreviations

AEP	Annual exceedance probability
CCRA	Climate Change Risk Assessment
CHEST	Combination Hazard of Extreme rainfall, storm Surge & high Tide on estuarine infrastructure
CIBSE	Chartered Institution of Building Services Engineers
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
EVA	Extreme value analysis
EVD	Extreme value distribution
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
GEV	Generalised extreme value
GMT	Greenwich Mean Time
GPD	Generalised Pareto distribution
HadISDH	Gridded Global Land Surface Humidity Dataset
IAEA	International Atomic Energy Agency
IDF	Intensity-duration-frequency
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
NAO	North Atlantic Oscillation
NCIC	National Climate Information Centre
NERC	Natural Environment Research Council
NWP	Numerical weather prediction
MERRA	Modern-Era Retrospective analysis of Research and Applications
PMF	Probable Maximum Flood
PMP	Probable maximum precipitation
RCP	Representative concentration pathway
RFA	Regional frequency analysis
SAIS	Scottish Avalanche Information Service
SAPs	Safety Assessment Principles
TAG-13	Technical Assessment Guide 13
UNSEEN	Unprecedented Simulated Extremes using Ensembles
UKCP09	United Kingdom Climate Projections 2009
UKCP18	United Kingdom Climate Projections 2018
UKV	The Met Office's high-resolution weather forecasting model for the UK
WMO	World Meteorological Organization

LC 0064_18V4