ONR Expert Panel on Natural Hazards

NS-TAST-GD-013 Annex 2 Reference Paper:

Analysis of Meteorological Hazards for Nuclear Sites

Expert Panel Paper No: GEN-MCFH-EP-2017-1

Sub-Panel on Meteorological & Coastal Flood Hazards

October 2018

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AOGCM	Atmosphere Ocean General Circulation Model
AMO	Atlantic Meridional Overturning
AO	Arctic Oscillation
AR	Atmospheric River
AR4	Fourth IPCC Assessment Report
AR5	Fifth IPCC Assessment Report
BSW	Blended Sea Winds
CCMP	Cross-Calibrated Multi-Platform
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
ECHAM	European Centre Hamburg (climate change) Models
ECS	Equilibrium Climate Sensitivity
EMIC	Earth System Model of Intermediate Complexity
ENSO	El Niño Southern Oscillation
ERA-40	Reanalysis of global atmosphere and surface data from European Centre for Medium Range Weather Forecasts
ESM	Earth System Model
FFA	Flood Frequency Analysis
GCM	Global Climate Model
H++	Plausible high-end climate change scenarios, typically more extreme climate change scenarios on the margins or outside of the 10th to 90th percentile range presented in the UKCP09 projections
HadRM3	Hadley Centre Regional Climate Model Version 3 (UKMO)
HadUKP	Hadley Centre UK Precipitation (UKMO)
HIRLAM	High Resolution Limited Area Model
IC	Initial Condition
IPCC	Intergovernmental Panel on Climate Change
IS92	IPCC Emissions Scenario 1992
Knot	Speed. One nautical mile per hour
LOVECLIM	Earth System Model created by coupling of five GCMs (Loch-Vecode-Ecbilt-CLIoaglsm-Mode)
MIDAS	Met. Office Integrated Data Archive System
mph	Speed. Miles per hour
MRI	Mean Recurrence Intervals
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NCEP1	National Centres for Environmental Prediction
NH	Northern Hemisphere

NOC	National Oceanographic Centre (UK)
NWP	Numerical Weather Prediction
OAFlux	Objectively Analysed air sea Fluxes
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SAM	Southern Annular Mode
SH	Southern Hemisphere
SNAO	Summer North Atlantic Oscillation
SRES	Special Report on Emissions Scenarios
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SST	Sea Surface Temperature
TAG	Technical Assessment Guide
u	Wind speed
UKCP	United Kingdom Climate Projections
UKMO	United Kingdom Meteorological Office
UNFCCC	United Nations Framework Convention on Climate Change
USNRC	US Nuclear Regulatory Commission
WG1	Working Group 1 of the IPCC

ACKNOWLEDGEMENTS

This document was drafted by members of the ONR Expert Panel on Natural Hazards – Sub-Panel on Meteorological and Coastal Flood Hazards (Alan Gadian of the University of Leeds, Stephan Harrison of Climate Change Risk Management and Kevin Horsburgh of the National Oceanography Centre). Significant assistance was also provided by the Environment Agency in the production of this document. The document was also reviewed and additional input provided by several staff members of the Office for Nuclear Regulation, by Alice B Walker, who serves as Technical Secretary to the ONR Expert Panel, and by Richard Washington, David Smith, Mark Macklin and Matt Wilson of Climate Change Risk Management.

Comments were also received from various external stakeholders through an organised stakeholder event. All these comments are gratefully acknowledged.

1 INTRODUCTION

1. A key element of developing a safety case for nuclear plant at a nuclear licensed site is the demonstration that the plant is adequately protected against external hazards, including those related to meteorological and geological processes. An indispensable component of this process is the characterisation and quantification of the external hazards that can credibly challenge nuclear safety at the site. Guidance for Inspectors on the assessment of site-specific studies to quantify the threat from external hazards at nuclear sites is provided in *Nuclear Safety Technical Assessment Guide NS-TAST-GD-013* (ONR, 2018a), generally referred to as TAG 13.

2. Annex 2 of TAG 13 (ONR, 2018b) is focused specifically on meteorological hazards and their analysis for nuclear sites in the UK. The purpose of this document is to provide additional detail on the analysis of meteorological hazards. Annex 2 of TAG 13 is specifically intended to provide guidance to Inspectors carrying out assessment of meteorological hazard studies for nuclear sites. The present document is intended to provide guidance to experts or consultants called upon to assist Inspectors with assessments of meteorological hazard studies for nuclear sites in the UK. It also provides an overview of the challenging area of climate change and the methods by which this is incorporated into the analysis process. The details of relevant climate scenarios, models and climate reports are presented in Tables 1-3.

2 OVERVIEW OF UK CLIMATE & WEATHER

3. The British Isles experiences one of the most variable weather and climate regimes in the world. Situated at the boundary between the Atlantic Ocean and the European/Asian continent, the weather is driven by the interplay of a variety of air masses, largely controlled by the jet stream, one or sometimes two fast moving currents of air in the extratropical middle to upper troposphere. The main systems are south westerly to north westerly air masses that originate over the Atlantic Ocean; easterly or northerly airstreams originating from the Eurasian continent and the Arctic and, less often, southerly or south easterly airstreams originating from Spain or North Africa. The dynamics of the system is dominated by proximity to the Atlantic Ocean, to the Eurasian continent and to Arctic influences. The interplay between these airstreams largely explains the weather and climate variability of the region.

4. The dominant wind direction over the British Isles is south westerly to westerly, associated with alternating relatively fast moving cyclonic and anticyclonic systems from the Atlantic Ocean. These systems bring to the region generally mild, often wet weather and strong winds. If the cyclones become slow moving, heavy and persistent rainfall and flooding may occur, especially in western areas where the rainfall is enhanced by hills and mountains. In contrast, northerly or easterly winds from the continent and Arctic generally produce dry weather. Northerly winds are generally cold at all times of the year, while easterly winds are cold or very cold in winter but can often be warm or very warm in summer, especially away from the immediate east coast. Periods of persistent anticyclonic weather associated with large, near stationary meanders in the jet stream, known as blocking, give quiet weather which can be very warm in summer and cold or very cold in winter.

5. The role of topography in affecting the climate and weather of the British Isles is profound, with a clear impact on general precipitation patterns; it plays a crucial role in the extreme precipitation associated with atmospheric rivers (ARs). Topographic variations strongly mediate the impact of large-scale weather systems that affect the British Isles in winter and may also play a role in affecting summer convective storms through buoyancy-driven atmospheric circulation. High ground is concentrated mainly in western regions of England and Wales (and to a lesser extent in Scotland) and interacts with prevailing wind systems to produce orographic rainfall, rising to over 3000 mm per year in some western mountains. Rising air over mountain slopes expands and cools (Roe, 2005). As the amount of water vapour that an air mass can contain is inversely related to air temperature (described by the Clausius-Clapeyron relation, Held and Soden, 2006), cooling results in air saturation and condensation, and eventually rainfall. As a result, precipitation totals over high ground are invariably higher than over surrounding lowlands. Rainshadow effects are marked in the lee of mountains where precipitation totals are reduced. Differences in atmospheric temperature lapse rates occur when rising air with high water vapour cools at the saturated adiabatic lapse rate on windward sides of mountain barriers and descends on lee sides at the dry adiabatic lapse. These are known as Fohn effects which are therefore common with strong westerly air flow over mountains.

6. Two major climate systems play an important role in the weather and climate of the region. The North Atlantic Oscillation (NAO) is one of the most important regional atmospheric systems on Earth. Together with a closely related atmospheric pattern known as the Arctic Oscillation (AO), it is responsible for much of the variability in weather in the mid and high latitudes of the Northern Hemisphere. The NAO can be defined in different ways that nevertheless create similar indices of its variability. A common method is to define the NAO as the difference between the standardized mean sea level pressure anomalies for the Azores and Iceland where the stations Ponta Delgada (Azores) and Stykkisholmur or Akureyri (Iceland) are often used (e.g. Rogers, 1984; Washington et al., 2000; Murphy and Washington, 2001). This definition can be usefully used from September to perhaps May. In summer (June-August) the NAO dipole pattern is rather different (Folland et al., 2009) with a centre over the eastern

North Atlantic extending over UK to Scandinavia and another over the Arctic centred over Greenland. We call this the summer NAO (SNAO).

7. The SNAO can also be defined in different ways that still create similar indices. One method is to define the SNAO as the difference between standardised mean sea level pressure anomalies between the northern North Sea and southern Greenland (e.g. the points [55N, 0E], [67N, 45W]).

8. The NAO or SNAO form a dipole pattern between the two negatively correlated pressure systems. During the positive phases of the NAO, the Icelandic low is deeper and the Azores high pressure system higher than normal. This is associated with an enhanced westerly air flow from the Atlantic over the British Isles. The positive phase is associated with high winter air temperatures over the British Isles and increased rainfall over most of the UK, though not always over the south east. There are particularly strong correlations between the NAO Index (NAOI) and autumn and early winter rainfalls (Wilby et al., 1997). Conversely, during the negative phase of the NAO the pressure gradient between the two systems is weaker or reversed and westerly airflow is largely replaced by easterly or northerly airflow.

9. Hurrell and Loon (1997) have demonstrated that the winter NAO is a very significant element of Northern Hemisphere (NH) climate and weather variability, accounting for about 31% of NH winter surface temperature variance north of latitude 20°N. In summer, the positive phase of the SNAO is associated with anticyclonic conditions over the UK, giving dry and warm weather. The negative phase of the SNAO is associated with cyclonic wet weather over the UK and cooler conditions, especially in the daytime. So, the SNAO is a strong controller of summer UK rainfall, explaining about 50% of its variability. The other half of the SNAO dipole pattern occurs in the Arctic, centred on Greenland, so that the positive phase has low sea level pressure over this region and the negative phase high sea level pressure.

10. The NAO drives variations in the pressure gradient of the North Atlantic and these strongly affect the strength of the North Atlantic westerlies. The NAO winter index has varied considerably over the 20th century, having a downward trend from the 1940s to the late 1960s, a rising trend from the late 1960s until the 1990s (Scaife et al., 2005) and varying since then with a weak negative phase peaking around 2010 followed by generally very positive indices since then. There are suggestions that interdecadal variability in the NAOI has increased since the 1950s, which recent research suggests largely represents a forced climate signal rather than mainly chaotic atmospheric variability. Indeed, variations in the NAO in winter from one winter to the next now appear to be forced to a considerable extent (Scaife et al., 2014).

11. There is research to show that the NAO is related to a hemispheric mode of variability known as the AO, also known as the Northern Annular Mode. Some researchers have suggested that this mode shows better correlation with European surface air temperatures in winter than the NAO. Many authors have studied the AO which, because of its larger spatial scale, not surprisingly accounts for a larger amount of Northern Hemisphere surface air temperature variance than the NAO, which is largely confined to the North Atlantic/European sector. The northern centre of the AO teleconnection pattern covers the whole Arctic while the southern centre covers the mid latitudes of the whole Northern Hemisphere.

12. Precipitation types in the British Isles are strongly seasonally dependent. In winter, about 70% of the precipitation in the British Isles is associated with the development of extra-tropical cyclones. Important contributors to extreme winter precipitation are ARs. These are narrow lower troposphere atmospheric structures, usually 10^2 km wide and 10^3 km in length (Dacre et al., 2015). They form a component of the warm conveyor belt found in mid-latitude storms and are characterised by a strong low level jet and produce filamentary bands of air transporting large amounts of water vapour (typically with vertically integrated water vapour of more than 2.5cm liquid equivalent) and with

maximum wind speeds higher than 10 m/s. They have been shown to be responsible for extreme winter flooding in the UK (Lavers et al., 2011; 2012) and associated with the 10 most extreme UK storms since the 1970s. All these floods developed from an AR plume oriented SW-NE.

13. Enhanced moisture transport occurs ahead of the cold front of an extratropical cyclone within the cyclone's warm sector. This gives a narrow band of enhanced water vapour transport that forms at the base of the warm conveyor belt ahead of the cold front. Heavy precipitation occurs when this system encounters significant orography (e.g. along the western coast of the British Isles) and produces 'seeder-feeder' precipitation where high level precipitation falls through low level mesoscale orographic stratus clouds (Browning, 1990), thereby enhancing precipitation intensity. Such prolonged winter precipitation is associated with lengthy, vigorous, quasi-stationary training cold fronts just to the west (some 10^3 km in length), and commonly lasts several days.

14. In contrast, there is little evidence to show that summer precipitation is dominated by ARs with fewer than 20% of summer extremes having associated ARs. Most summer rainfall is short-term in nature with extreme flood events produced by strong convection, often in combination with thunderstorms and, more rarely, supercell thunderstorms.

15. A better understanding of the future evolution of ARs would help in managing flood and snowfall risk to nuclear facilities. The success of future long-term projections of trends in ARs will depend on better modelling of the behaviour of baroclinic wave[1] activity in the Atlantic (Ulbrich et al., 2009) and better parameterisation of cloud properties. However, increased future flooding is very likely as continued atmospheric warming will lead to increased atmospheric water vapour content, which is governed by the Clausius-Clapeyron moisture-temperature relationship (Held and Soden, 2006).

16. Lavers et al. (2013) used CMIP5 models (latest versions from the Coupled Model Intercomparison Project) to project an increase in the frequency and magnitude of ARs in the North Atlantic, with a doubling of AR frequency by 2074-2099 under the RCP (Representative Concentration Pathway) emissions scenario RCP8.5[2]. Modelling at shorter timescales is undertaken using numerical weather prediction (NWP) models. Currently, these are not able to model the position and timing of the landfall of ARs well, although they show better skill at modelling the presence of ARs (Wick et al., 2013).

17. Some very significant rainfall totals associated with ARs may not have been captured by past meteorological records because they were not dense enough spatially. As a result, historical data has the potential to mislead analysts concerning the frequency of these events. Accordingly, large departures from mean conditions should be assumed to be likely to occur occasionally during the construction, operation and decommissioning of nuclear sites.

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[1] A baroclinic wave is generated when the density/temperature structure of the atmosphere is not aligned with the pressure pattern and is commonly associated with developing mid latitude weather systems and frontal rain bands.

2.1 Teleconnections

18. Teleconnections[2] involve the dominant modes of low-frequency variability in weather and climate systems. The NAO represents one such system and, in the NH a number of others have been identified such as the Scandinavia pattern, a primary circulation centred over Scandinavia (often associated with blocking highs) with weaker centres of opposite sign over Western Europe. NH extratropical climate and weather systems are also linked to a variety of phenomena elsewhere on the globe e.g. the El Niño Southern Oscillation (ENSO) atmospheric and oceanic coupled system in the Pacific, variations in tropical rainfall elsewhere (Scaife et al., 2016) and long term variations of North Atlantic sea surface temperatures (e.g. Sutton and Dong 2012; Shimura et al., 2013). Such teleconnections may evolve as ongoing global climate warming increases. So a global approach is needed to understanding regional weather and climate variations, such as those over the British Isles.

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[2] Teleconnections are when weather events and anomalies, many thousands of kilometres apart appear correlated. Some of these relations often correspond to long wavelength structures in the earth's (fluid) atmosphere.

3 DATA SOURCES FOR METEOROLOGICAL HAZARDS ANALYSIS

19. Site-specific meteorological hazard analyses need to draw upon all available information comprising of geological (where appropriate), historical and instrumental data sources. Where some of these data is not readily available (as might be the case for sediment cores which will provide proxy palaeoclimate data), then these may be sought. It should also be stressed that various data sources can be used in combination to complement each other or to provide long term context to understand natural and forced climate variability. For example, sedimentary records of past hurricanes have been used to reconstruct changes in hurricane strength and frequency (e.g. Liu and Fearn, 2000; Mann et al., 2009) to compare with current instrumental data and to assess recent patterns and trends in hurricanes against the palaeo-record.

20. In addition the use of synthetic data generated from climate models can add a theoretical basis to support projections. An overview of these areas is provided in this section.

3.1 Palaeoclimate Data

21. Data on past climate change can be used to better assess the significance of contemporary events (i.e. whether extreme events in the observational record are extreme in the context of longer time periods) and place future projections in context. Palaeoclimate data will also allow scientists and practitioners to understand natural (unforced) variability and, therefore, gain insight into the probable behaviour of climate and coupled earth systems over time. However, palaeoclimate data must be used with caution because the data being used to interpret past climate are only proxies for climate and interpretation of these can be misleading. Use of past proxy data to better understand the future behaviour of the climate system also makes the untested assumption that future system behaviour is as constrained as past behaviour. Clearly, non-stationarity in datasets makes this assumption invalid.

22. Palaeoclimate reconstructions for the British Isles are numerous and include work on peat bogs (e.g. Barber et al., 2000; Blundell and Barber, 2005; Barber et al., 2013), tree ring dating (Rydval et al., 2016) and lichen dating (e.g. Armstrong, 2006; Bradwell, 2010).

23. Observational datasets on relevant climate hazards are generally of short duration, are spatially variable and, therefore, only cover small regions of interest. As a result, developing hazard assessments for events with high magnitudes but very low frequencies is made very difficult by the nature of these datasets. Given this, the use of geological proxy data for climate events should be considered to provide information on potential climate hazards. Such geological data have been used extensively in the UK and elsewhere for assessments of the nature and timing of river flooding and other extreme climate and weather events.

24. For instance, various proxy data have been used to develop flood risk assessments and to extend the flood record. These include the use of:

- *Boulder berms*: These are depositional landforms in river valleys that record the timing and magnitude of past floods (e.g. Anderson et al., 2004). They have been dated using radiocarbon dating of included organic material dendrochronology (tree ring dating) and lichenometry (dating using lichen growth curves).

- *Floodplain sediments*: Analysis of flood plain sediments uses sediment cores to reconstruct the size of past floods and dating of these using radiocarbon dating and luminescence techniques (e.g. Macklin et al., 2010).

25. However, the relationship between a climate or weather event and a corresponding change in a climate proxy is rarely linear and uncomplicated. For instance, there are

temporal and spatial lags between climate events and the response of a proxy and the nature of these lags may themselves change. It is also difficult to isolate the climate signal in a proxy. For instance it may be difficult to distinguish between a storm surge and tsunami inundation in marine sediments. As a result, while climate proxies may be used to extend data series caution must be taken in their assessment.

26. As has been seen, geological records have been used to extend records of flood hazards (O'Connor et al., 2014). In fluvial systems these types of investigations have been termed palaeoflood hydrology (Kochel et al., 1982) and are defined as:

> "the reconstruction of the magnitude and frequency of past floods using geologic evidence" (Baker et al., 2002).

27. Palaeoflood studies were pioneered in the USA where they are now used routinely to provide reliable estimates of rare floods (potentially with annual exceedance probabilities of 10^{-6}) for critical structures such as dam spillways, nuclear power-plants and hazard waste repositories (O'Connor et al., 2014). In some cases, sedimentary deposits give the most complete geologic record of large floods, and they may be preserved for hundreds or thousands of years in suitable environments, thereby providing an archive of rare, high-magnitude events (Benito and O'Connor, 2013).

3.2 Historical Records/Accounts

28. Documentary records have been used to assess the size and extent of past climatic events although these records are often qualitatively described, are likely to have considerable epistemic uncertainty and are not generally used in hazard analysis. However, they have been used in tsunami and storm surge research (e.g. Bryant and Haslett 2007) to examine past wind storms (Dawson, 2004) and, routinely, for extending flood time series (e.g. Glaser et al., 2010; Kjeldsen et al., 2014). Here, historical records usually predate the installation of gauging stations and can provide indirect information on peak flood discharge, often in the form of a water-level marker, information that a specific location had been flooded, damaged or destroyed, or that a flood reached a level relative to a structure. Of particular interest is the Great Storm of 1703 (Wheeler, 2003). It caused widespread flooding in the Somerset Levels, with the loss of hundreds of lives, and caused one ship to be washed 15 miles inland. Lamb (1991) estimated that the wind speeds were 150 Knots (~165 mph).

29. There are, however, three well recognised limitations of documentary records in the UK, in terms of flood frequency and particularly flood magnitude analysis (Rumsby and Macklin, 1994). First, the accuracy and reliability of measurements deteriorates before AD 1700. Second, the record is biased towards populated areas. Third and most significant, changes in channel capacity resulting from river aggradation and incision (e.g. Macklin et al., 2013), floodplain morphology through sedimentation and wetland drainage (e.g. Lewin and Macklin, 2010) and construction of bridges, embankments and transport infrastructure, make it very difficult to convert a historical water level to a peak flood discharge.

30. Although peak discharges of major floods have been reconstructed using historical water level information, as a consequence of major channel and floodplain modifications such as changes in channel-margin sedimentation, they are likely to have large, unsystematic and presently unknown errors. Unfortunately in the UK instrumental documentary and palaeoflood records have rarely been investigated in an integrated manner (Macklin et al., 2012). This is in strong contrast to the USA (e.g. O'Connor et al., 2014) and mainland Europe (e.g. Glaser et al., 2010; Toonen, 2015) where combined studies of instrumental documentary and geologic records of major floods are becoming increasing routine and are being used by regulatory and environmental protection agencies to inform flood risk assessment. The UK lags significantly behind this rapidly developing field of water-resource risk assessment and planning.

31. Despite this, over recent years new methodologies have been developed to construct long-term assessments of flood frequencies and magnitudes, and these have used a range of geomorphological and sedimentological archives.

3.3 Instrumental Data

32. Rainfall and snow measurements are collected at weather stations. The UK Met Office (UKMO) operates an extensive network of (at the time of writing) 270 stations supplemented with an additional network of 162 stations for climate monitoring. The historical archive of station observations at the UKMO extends back to 1853 for a small number of sites. The UKMO also produces long term climate monitoring series such as the Met. Office Hadley Centre UK Precipitation (HadUKP) series (Alexander and Jones, 2001) including daily averages back to 1931, and a monthly series back to 1766. However, climate series such as HadUKP are designed for monitoring climate change over long timescales and are less suitable for extreme value analysis of rainfall from convective thunderstorm events; they are at an insufficient temporal resolution to allow for the assessment of pluvial flood risk. Hourly rainfall data is available from the UKMO Integrated Data Archive System (MIDAS) (UKMO 2012). Digital records exist for a small number of sites back to 1949. However, these data is currently restricted to approved Centre for Environmental Data Archival (CEDA) users. The MIDAS database also contains daily rainfall measurements from the full network of registered raingauges including several thousand additional sites managed for hydrological purposes by a number of government agencies and private authorities.

33. The Centre for Ecology and Hydrology Flood Estimation Handbook (2016) represents the most comprehensive collection of data from the Environment Agency, the UKMO and data from distributed Water Boards.

34. Automated measurements for snow depth are more sparse, augmented until 2007 by the Snow Survey of Great Britain (Kay, 2016). Snow depth by itself does not provide the necessary snow water equivalent (i.e. the volumetric quantity of liquid-equivalent water contained in the snow) since the density of the snow pack will vary depending on the conditions in which the snow fell. In addition, snow may be a significant source of error in precipitation measurements with few automated stations equipped with heated precipitation gauges to improve its measurement (Kay, 2016).

35. It should be noted that there is considerable spatial variability in both extreme precipitation and snow. Point-based measurements provided by gauges do not fully capture this variability and, in the worst cases, may entirely miss storm events. In order to reduce the uncertainty in assessments, analysts should utilise data from multiple sites.

3.4 Synthetic Data

36. Stochastic Weather Generators are a form of statistical model which have been used in impact studies to provide synthetic and realistic data of weather variables, including variables describing weather persistence and natural variability (Wilks and Wilby, 1999). They provide outputs that have similar statistical characteristics to observational datasets and are applied at short spatial scales. They are computationally more efficient than datasets derived from climate models. However, they are not able to reproduce extreme weather variables well, including long-term persistence (e.g. heat waves, large flood events).

37. Although not obtained from direct measurement, climate models (see Section 5.1) can also be used to create synthetic-datasets to supplement the observed data, and to assess the effects of future climate change. Numerical model integrations of the sort conducted as part of UK Climate Projections 2009 (UKCP09) using regional models, or UKCP18 (deliverable in late 2018) which is likely to employ higher resolution models compared with UKCP09, will provide an important data resource in the near future.

These are considered to be relevant good practice, even if the uncertainties make them problematic to use.

38. Synthetic datasets are required to assess the behaviour of climate and weather variables in situations where observational data is either lacking, of short duration, or of poor quality. For instance, information for nuclear sites is required on a number of wind characteristics, including wind magnitude and directionality. It may be possible to estimate wind magnitude impacts with large mean recurrence intervals (MRI) using probabilistic models of extreme wind speeds which have been calibrated with observational datasets of short length (e.g. Aksoy et al., 2004). In some cases however, with large MRI, the time series length may be exceeded by the MRI, and synthetic datasets have to be constructed to provide data against which design assessments can be measured. Synthetic wind speed datasets can be produced to provide wind data of specified lengths and statistical consistency with observational records and these then used to develop design bases for structural load analysis. A number of approaches have been used to develop these data. These include the use of probabilistic models for wind characteristics which can then be calibrated to observational data; these are then used to generate the synthetic data of interest. Markov chain models have also been employed to generate synthetic wind speed data (e.g. Shamshad et al., 2005; Sahin and Sen, 2001). Other approaches include using the Weibull function to estimate wind speed frequency distributions (e.g. Justus et al., 1978; Garcia et al., 1998) and the peaks over threshold approach (e.g. Lechner et al., 1993).

39. Many climate modelling groups use climate reanalysis products (e.g. NCEP1 and ERA-40 see Dee et al., 2011). These are a combination of past observational data assimilated by a climate model simulation. They were developed by weather forecasting groups to help standardise past datasets to aid model development and investigate historical climate change. Essentially they interpolate between data of various degrees of completeness (e.g. satellite observations versus sea level pressure measurements) using a physically consistent process to produce a more complete and gridded dataset than would otherwise be available. As a result, they are used to examine data consistency and quality as sudden changes in data series often reflect shifts in observational monitoring equipment, errors in station location etc. Reanalyses made after real time therefore reduce data uncertainties and allow a clearer exploration of model performance and climate trends. As an example of how sharp jumps in data series have been identified, reanalysis using residuals from the ERA-40 analysis of the radiosonde[3] temperature record, found problems caused by changes in data collection methods. Reanalysis can also generate the initial states of data (initial conditions) to enable NWP models to begin integrations.

40. While numerical climate models are used to assess future climate change, other types of numerical models have been developed to model flood risk.

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[3] A radiosonde is a battery-powered telemetry instrument package carried into the atmosphere usually by a weather balloon that measures various atmospheric parameters and transmits them by radio to a ground receiver.

4 USE OF STATISTICAL METHODS IN ANALYSIS OF METEOROLOGICAL HAZARDS ANALYSIS

41. A wide range of statistical techniques are used in the analysis of climate and weather systems and patterns. These include the statistics to test for significance of trends in data, correlation between multiple and single variables and tests for randomness. Problems arise when data is not available, of short duration, are incomplete or of poor quality, or are from sites at a distance from the study location and where spatial and/or temporal extrapolation is required.

42. For example, assessment of future wind characteristics has used Extreme Value Analysis to extrapolate data from time limited datasets to generate hazard values at 10^{-3}/yr and lower. A question arises as to which extreme value method to use for analysis of extreme wind (the most commonly used distribution in studies of wind extremes is the Generalised Extreme Value Type I (Gumbel), applied to a set of annual maxima). This decision will likely be influenced by the length of the available dataset(s). Rather than selecting one extreme value from an epoch, the analyst may choose to use alternative approaches to increase the number of values for analysis (e.g. r-largest, method of independent storms, peak-over-threshold). This has an attraction that for a given time series more points are selected for analysis, thus reducing the standard errors. Should the dataset be too short for application of standard methodologies, lengthening of the time series may be considered (e.g. comparison with neighbouring stations, simulation modelling, or parent distribution methods). However, the results can never be as reliable as those obtained from a long dataset. A short dataset implies large standard errors and may not capture the full range of extremes. The extreme value analysis should also aim to quantify the full range of uncertainty surrounding the results. In so doing the duty holder needs to proceed with care and give due attention to the epistemic uncertainty arising from the use of expert judgement.

43. Another example comes from the problems of estimating flood risk. In order to assess flood risk, it is necessary to:

    - define the annual exceedance probability (return period) for floods at different levels;
    - determine ‘design storms’ to convert flood levels with associated probability to storm hydrographs (e.g. using a defined unit hydrograph or other methods) which can be used to predict inundation;
    - assess the impact of these floods through use of a hydraulic flood model;
    - assess damage potential based on predicted flow depths and velocities allowing conversion of model output to a quantification of potential impact; and
    - convert each damage potential into an annualised damage likelihoods, based on the annual exceedance probability associated with each event.

    Similar techniques with similar limitations are used in the analysis of extreme sea levels (ONR Expert Panel on Natural Hazards, 2018).

44. The *annual exceedance probability* is the probability that a flood will exceed a given level in any year[4], and is the inverse of the *return period,* or frequency interval (i.e. an event with a 1 in 100 year return period has a 1/100 or 1% annual exceedance probability). These probabilities are usually determined using observations of river level or flow for past events. However, extreme events are rare, leading to few observations and meaning that there is considerable uncertainty in the estimation of the most extreme

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[4] The concept of annual exceedance probabilities can (and are) applied to many different natural hazards variables including earthquake ground motion severity, wind speed and sea level.

events. In the United Kingdom, flow records are available for around 100 or more years, but often the duration of the timeseries is considerably shorter. With a longer observational record, more reliable estimates of probability are possible, but, irrespective of the record length, the most extreme events will always have the most uncertainty associated with them. In order to estimate flood levels for very extreme events as required for nuclear sites, such as the 1 in 1,000 year or 1 in 10,000 year events (0.1% or 0.01% annual exceedance probability), extrapolation well beyond the length of the observational record is required. This is achieved through the fitting of a statistical model to the observed data, such as the Extreme Value Type I (Gumbel) or Log-Pearson Type III distributions (e.g. Frances et al., 1994). These models are then used to predict the value at each required level.

45. A major assumption with this is that observed flood events (and those that are likely to occur in future) occur under homogeneous conditions – in other words, that the floods occur under the same type of conditions within the catchment and climatically (i.e. the probability of flood events is assumed to be stationary or unchanging). However, anthropogenic basin alterations such as urbanisation or deforestation can change the likelihood of flooding, reducing the reliability of probability estimates, or shortening the usable length of the observational record. Importantly, changes in the climatic conditions that lead to floods (e.g. increases in the proportion of convective rainfall with high intensity) means that past observations of flooding may not provide reliable estimates of future flood probability.

5 CLIMATE MODELS & UK CLIMATE CHANGE PROJECTIONS

46. The only viable approach available for assessing future climate change is through the use of mathematical models, run on powerful computers, which simulate the climate over future decades. Climate models are based on fundamental physical laws (e.g. energy, mass, and momentum conservation) and subdivide the Earth surface, oceans and atmosphere into 3D grids. The processes within each grid square are computed and discretised and these form the future integrations.

47. This is the approach used by many research institutes, with results summarised by the Intergovernmental Panel on Climate Change (IPCC) from its initial First Report in 1990 to the Fifth Assessment Report (AR5) in 2013 and other national and international bodies (see Table 3 and 4).

48. From the late 1950s, attempts to model the global climate originally used General Circulation Models to examine the nature of atmospheric and oceanic circulation. By the 1980s models were relatively simple, portraying oceans with no currents and fixed atmospheric cloudiness (National Research Council, 2012). Over the past few decades the resolution of these models and the range of physical processes that are now included has increased significantly. In recent decades Global Climate Models (GCMs) have been developed by a number of modelling teams, and the outputs from these have been used extensively in IPCC reports since 1990. Much effort has also gone into developing the computer resources to run sophisticated climate models, especially as multiple simulations (ensembles) are now routinely run to evaluate model and initial condition uncertainty.

49. The size of grid squares defines the model resolution, and for the current range of models this is about 100 km for the land and ocean in the mid-latitudes. The oceans are typically subdivided into 30-60 vertical layers and the atmosphere into 30-40 vertical layers. IPCC AR5 (2013) GCMs have increased their resolution from about 50 to 25 km since IPCC AR4 (2007) with Regional Climate Models (RCMs) operating at 10 km or better resolution (see Tables 3 and 4 and e.g. Kendon et al., 2012)

50. In order for these models to run, information needs to be provided to them on future concentrations of greenhouse gases in the atmosphere. A scenario approach has been used to achieve this. In AR4 the scenarios used included A2, a scenario with relatively high future emissions through rapid development based on carbon-based energy generation, and A1B, in which technological advances help reduce emissions. For AR5 a different approach was used, referred to as RCPs, with emissions increasing successively through RCP2.6, RCP4.5, and RCP6.0 to RCP8.5. The number represents the radiative forcing[5] in Wm^{-2} at the top of the troposphere. A2 is roughly equivalent to RCP8.5 and RCP6.0 is about halfway between A1B and B1 (a relatively low emissions scenario). RCP2.6 ultimately leads to zero emissions after about 2070 and is the only one that, if followed, would offer a reasonable chance of reaching the United Nations Framework Convention on Climate Change (UNFCCC) target of restricting the average global temperature rise to below 2°C. Even this scenario, however, makes assumptions about climate sensitivity that probably will not be reflected in real-world responses. Recorded emissions to date have tended to follow approximately those of scenario A2 and of RCP8.5.

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[5] Radiative forcing is the difference between the incoming radiation energy and the outgoing radiation energy in a given climate system.

5.1 Types of Climate Models

51. There are three main types of climate models.

- **Atmosphere-Ocean Global Climate Models (AOGCMs):** These models have been developed from earlier GCMs and incorporate more sophisticated modelling treatments of atmosphere and ocean processes, AOGCMs were the main models used in IPCC AR4 (2007; Table 3). Despite this, they lacked detailed components concerning biogeochemical cycles, and representations of ice sheet processes.

- **Earth System Models (ESMs):** For IPCC AR5 (2013) these now form the current cutting edge in modelling with much better representation of elements of the carbon cycle, which enables the models to better characterise the feedbacks that are expected to develop when the carbon cycle is disrupted by climate change.

- **Earth System Models of Intermediate Complexity (EMICs):** In some instances more focused modelling schemes aim to answer specific scientific questions concerning long term climate change and climate sensitivity, or for developing large model ensembles, and for these projects lower resolution models called EMICs are used. For example the LOVECLIM model includes representations of the atmosphere, the ocean and sea ice, the land surface (including vegetation), ice sheets, icebergs and the carbon cycle (see Goosse et al., 2010).

5.2 Downscaling from Climate Models

52. AOGCMs and ESMs are applied at the largest scales (i.e. for climate projections at continental hemispheric or global resolutions). However, adaptation planners, risk managers, infrastructure developers and other end users (such as nuclear site Licensees) of climate services want climate projections at small spatial (and sometimes temporal) scales, and for this various techniques have been used to downscale information from GCMs to regional scales. As a result, RCMs have been developed to simplify climate processes and to provide detailed information on regional-scale climate change (e.g. Marioti et al., 2011; Jacob et al., 2014).

53. There are several ways in which RCMs can be used to provide these. The most commonly used RCMs in climate change downscaling studies include the UKMO Hadley Centre Regional Climate Model Version 3 (HadRM3) and the German HIRHAM (a combination of the dynamics of the High Resolution Limited Area Model (HIRLAM) and European Centre Hamburg (ECHAM) models (see Table 2). These downscaling schemes can be used globally and several schemes have been brought together. For example CORDEX (Coordinated Regional Climate Downscaling Experiment); Giorgi et al. (2009) provides a global coordination of Regional Climate Downscaling for improved regional climate change adaptation and impact assessment.

54. Three main types of RCMs are used: nested RCMs driven by data from GCMs and empirical/statistical and statistical/dynamic downscaling approaches. Despite their use, projections derived from nested RCMs may not provide more useful decision-relevant data than GCMs. Several issues exist:

- There will be systematic errors in the boundary values provided by GCMs which force the RCMs and these are not reduced during downscaling.

- Parameterisation of small-scale physical processes is often a subjective choice in model development and internal variability in climate processes not associated with boundary forcing will affect the model projections.

- Further difficulties are encountered when attempting to assimilate large-scale meteorological conditions.

- RCMs are also computationally demanding which restricts their use, the grid spacing and the time scales over which they are run, but are the topic of active current research and can provide useful data (Gadian et al., 2017).

55. Statistical downscaling assumes that the regional climate is driven by the state of the climate at large scale and the local topography, land-use and land cover (von Storch, 1999). Regional climate information is obtained by developing a statistical model which relates large-scale climate variables to regional and local variables. The large-scale variables are then derived from a GCM simulation and the local and regional climate characteristics are then estimated from the statistical model (IPCC AR4 2007; Table 3).

56. Such approaches do assume that any statistical relationships which obtain during the present climate will also hold in future under different forcings and assumes that changes in regional feedbacks or forcings will not change those relationships. In addition, such techniques are difficult in areas with complex terrain and where observational data is lacking.

5.3 Climate Model Uncertainty

57. Climate modelling has developed enormously in the computational power and resources available, complexity, model resolution and understanding of the physical process driving the climate and associated feedbacks. Climate models can be seen as one of the success stories of modern science, giving us unrivalled insight into the workings of the climate system. Despite this, huge uncertainties in the outputs from GCMs remain. There are several ways in which to assess model uncertainty (e.g. Stainforth et al., 2005; 2007a; 2007b; Hawkins and Sutton, 2009). Model uncertainty may be classified as: forcing uncertainty; microscopic initial condition (IC) uncertainty; macroscopic initial condition uncertainty; model uncertainty; and model inadequacy (see Stainforth et al., 2007a; 2007b). Different models may treat elements of the climate system or physical processes such as cloud physics, gravity wave drag over mountains or condensation processes in different ways. Some models may do this less successfully than others and this model inadequacy may affect projections if these are based on one or a small number of models. Figure 1 from Hawkins and Sutton (2009) demonstrates these points.

58. What is also important to recognise is that the climate system exhibits internal variability to an extent that, over timescales of years to perhaps a few decades, may mask longer term underlying trends. Internal variability is sometimes called unforced variability and is associated with stochastic processes that drive climate. Forced variability represents those climate processes that are driven by external or internal influences (such as changes in solar irradiance or changes in atmospheric greenhouse gas concentrations). As a result, long-term (and low frequency) climate is driven largely by the forced response; at short timescales internal variability may dominate and even produce climate change which runs counter to the long-term trends.

59. Finally, different models will produce different projections of the nature and patterns of climate change, even with the same ultimate level of warming. In other words, the climate projected for a warming of 3°C for the British Isles in one model would likely be different from that produced by another model, even though the warming level is the same.

60. While models are mathematical representations of the climate system, all handle the mathematics through different approaches, and not all models simulate all processes in the climate system. In addition certain physical processes operate at smaller scales than that of the model grid cells and these processes have to be parameterised and estimated values calculated. Projections produced by any model will change in response

to small changes in the state variables of the model. These small changes in input parameters are those that are used to produce climate model ensembles.

61. As a result of these differences in model design, parameterisation scheme and changes to the initial conditions and state variables, different models or different runs of the same model produce different projections, and relatively small changes to the structure of a model may have a disproportionately large impact on the projections produced.

62. Thus, with numerous climate models being used to produce an ensemble of individual projections the issue is one of optimal interpretation of the broad spread of information produced. Several approaches have been used:

- At the simplest level is the identification of a preferred model based on some approach: unfortunately there is no clear evidence to demonstrate that this selection can be achieved objectively.
- At the next level is the identification of a small number of preferred models from the complete ensemble. However, there is no more justification in predictability theory for selecting a subset of models than there is for selecting a single model; nevertheless numerous National Communications to the UNFCCC have taken this approach.
- Finally, there is creating the problem of as large an ensemble as is possible, yet ensuring that the results that flow from it can then be interpreted. The IPCC uses all available models from the various climate modelling centres. Other approaches have used large ensembles from a single GCM by varying some of the model parameters (often used in perturbed physics ensembles). This is the approach used in UKCP09. However, this approach does not deal well with the inherent model uncertainty and inadequacy attached to any single GCM, consequently different models have shown different ‘skill’ in simulating some aspects of current weather or climate (e.g. precipitation).

63. With the AR4 and AR5 ensembles running to 20 or 30 or more projections, various interpretive approaches have been used both by the IPCC and elsewhere.

64. The simplest approach is to take average values across all members, i.e. individual projections within an ensemble. This is a popular technique as it permits a straightforward deterministic interpretation to be provided and is commonly used throughout IPCC reports. According to this approach, taking an ensemble mean is an appropriate technique to use as it averages out those aspects that are ‘unpredictable’ leaving behind a summary of the predictable elements. However, two caveats underlie this theory:

- First, it is assumed that parameter distributions within the ensemble are Gaussian. However, climate and weather are inherently non-linear and therefore display non-Gaussian distributions. Developing projections using assimilations of such models means that employing statistical tools such as the Kalman filter for time series analysis may not be appropriate.
- The second caveat is that the ensemble is formed ‘properly’, which in effect means that the ensemble provides a complete distribution of all realistically possible future states with each given its correct probability of occurring. No tests have been made on the IPCC projections of this second caveat, for entirely pragmatic reasons, but experience with ensembles at shorter time scales indicate that the IPCC ensembles are unlikely to be ‘proper’. Use of the ensemble mean, therefore, although straightforward, is not recommended.

65. A next step is to provide a range of possible climate scenarios based on the ensemble, with the range typically expressed around the ensemble mean. This approach is also

used by the IPCC, and provides a degree of advice about the uncertainties involved. Nevertheless, the two caveats mentioned above remain an issue. In fact the caveats need to be broadened. Predictability theory indicates that a properly formed ensemble cannot, and should not encompass the entire probability distribution of future states – for a properly formed ensemble there is always a possibility of the ‘answer’ lying completely outside the range of the ensemble, with this possibility decreasing as the ensemble size increases. Any range that lies fully within the compass of the ensemble is (by definition) ignoring some possible future states, even though sometimes the ensemble are calculated to capture 95% or 99% of parameter uncertainty.

66. The only approach that provides all information inherent within an ensemble is to calculate probability distributions for each variable at each point and time of interest. Such probability distribution functions characterise the range of possible climate or weather outcomes by assigning relatively higher or lower probabilities to subintervals. They can also assess the range of probability by distributing this asymmetrically. Probability distributions are often not popular amongst users who may find them difficult to interpret. In addition, not all published probability distributions consider the fact that the ‘answer’ may lie outside the ensemble; none are able to consider that the ensemble may not be ‘proper’ in the sense discussed above. One major disadvantage of this approach is that the vast amount of information produced can readily overwhelm the user.

67. It should be noted that the natural variability seen in observed historic datasets is currently greater than predicted by this type of simulation. This is the case for modelling extreme Atlantic storminess for instance. Here projections from CMIP3 and more recent CMIP5 models and downscaled RCMs from these show a consistent pattern. This is, that natural variability is greater than either modelled changes in wind behaviour or inter-model differences. As a result, it is not possible to say that model projections of wind prediction are greater than observed natural variability (Nikulin et al., 2011; Pryor et al., 2012; Bakker et al., 2013; Sterl et al., 2015).

5.4 RCP versus SRES

68. Scenarios of different emissions pathways or trajectories are needed in climate change projections studies to enable inter-model comparisons and better communications of modelling results within and between modelling groups. Given model complexity and running costs, scenarios also provide the basis to enable modelling experiments to be streamlined. Finally, they are required to provide the basis for assessing climate risks associated with crossing physical and ecological climate thresholds and they indicate, as far as the modelling can, the consequences of certain socio-economic decisions (e.g. energy policy).

69. Given these requirements, the first IPCC report in 1990 published the first set of scenarios (IS92); these were replaced in 2000 by the Special Report on Emissions Scenarios (SRES) which were used until the 4th Assessment Report in 2007 (Table 3).

70. These have now been replaced by the RCPs used in IPCC AR5. IPCC describes them thus:

> “In climate change research, scenarios describe plausible trajectories of different aspects of the future that are constructed to investigate the potential consequences of anthropogenic climate change. Scenarios represent many of the major driving forces - including processes, impacts (physical ecological and socioeconomic), and potential responses that are important for informing climate change policy. They are used to hand off information from one area of research to another (e.g. from research on energy systems and greenhouse gas emissions to climate modelling). They are also used to explore the implications of climate change for decision making (e.g. exploring whether plans to develop water management infrastructure are robust to a range of uncertain future climate conditions). The goal of working with scenarios is not to predict the future

but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures".

A comparison between the RCP and SRES scenarios is shown in Table 4.

5.5 Climate Sensitivity

71. The amount of long-term warming that is expected depends on the emissions trajectory that is adopted and the sensitivity of the climate to increased forcings. If the climate is highly sensitive to changes in forcings then a future high temperature rise could be expected with modest changes in forcings. The term Equilibrium Climate Sensitivity (ECS) is therefore used to define the equilibrium change in global mean near-surface air temperature that would result from a sustained doubling of the atmospheric (equivalent) carbon dioxide concentration. IPCC AR5 reporting on the range of ECS stated:

"there is *high confidence* that ECS is *extremely unlikely* less than 1°C and *medium confidence* that the ECS is *likely* between 1.5°C and 4.5°C and *very unlikely* greater than 6°C."

There is a very vigorous scientific debate on the nature of ECS. Some estimates of future temperature increases based on palaeoclimate reconstructions are higher than those based on numerical climate models.

5.6 Climate Change Projections for the UK

72. Over the last 15 years two sets of climate model projections have been produced for the UK by the UKMO and partners. These are UKCIP02 (a development from UKCIP98) and UKCP09. UKCIP02 was a deterministic (rather than probabilistic as in UKCP09) projection of climate change that produced a single value for a specific climate variable at a location (see Table 3). The scenarios did not account for uncertainty in the projections. The emissions scenarios used by both UKCIP02 and UKCP09 are from the IPCC Special Report on Emissions Scenarios (SRES) used in AR4 (Table 3). UKCIP02 uses four different scenarios (A1FI, A2, B2 and B1) while the later UKCP09 uses three scenarios (A1FI, A1B and B1; see Table 1). The model projections come from the CMIP3 set of model experiments. These will be replaced by new UKCP18 projections, which will be a development from the UKCP09 projections in several ways:

- They will use the wider CMIP5 models and will increase the small-scale modelling of physical processes to allow for better resolution of convection.
- They will have a better modelling capability over the land and will provide new assessments of projection uncertainties. Most projection data will be provided at a resolution of around 60 km although there will also be downscaled numerical experiments run at a resolution of around 5 km to better simulate convection storms for adaptation planning (Gadian et. al., 2017). Warmer air temperatures provide more energy for vertical atmospheric motions and combined with the ability for hotter air to hold more water vapour, extreme precipitation events will likely become more common (Gadian et al., 2017).
- There will also be new assessments of future sea level rise (ONR Expert Panel on Natural Hazards, 2018).

73. Model projections outlined as part of the 5th Assessment Report from IPCC (AR5 2013; Table 3) show that annual average land temperatures over the UK and Europe are projected to increase over the rest of the 21st century by more than the global average. The highest temperature increases are projected over eastern and northern Europe in winter and over southern Europe in summer. Annual precipitation is generally projected to increase in northern Europe and to decrease in southern Europe, thereby enhancing the differences between currently wet regions and currently dry regions. The intensity

and frequency of extreme weather events is also projected to increase in many regions, and sea level rise is projected to accelerate significantly.

74. At local scales, extreme weather hazards may be affected by changes in land cover, land-use and urbanisation. At regional scales, trends are likely to relate to changes in atmospheric behaviour at regional and larger scales. For example, more intense storms might result from increased availability of thermal energy due to climate-change driven warming of the atmosphere and sea.

5.7 Analysis of Combination Events in Climate Change

75. Overall, specific analyses on combination effects of changes in earth systems in response to climate change are rare and represent a clear gap in climate change risk assessments. Combination events include events such as high sea levels associated with storm surges occurring at the same time as heavy inland rainfall. Such a combination would likely cause enhanced coastal flooding. While these combinations maybe more likely under conditions of future climate change, the assessment of these in the context of risk management for infrastructure development is not routinely done.

76. The focus of recent climate scientific research on combination effects has been on so-called ‘tipping points’ in the climate system. These are defined as:

“subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered” (Lenton et al., 2008).

77. The climate systems that may exhibit tipping point behaviour in the future include the Greenland and West Antarctic Ice Sheets, Amazon Rainforest, thermohaline circulation and the Southern Annular Mode (SAM). It is clear that perturbation of one system may impact another system such that the combined effects are magnified, although the precise details, timing and consequences of such sequences of events have not been analysed. An example comes from assessments of high latitude climate change. It is known that melting of Arctic sea ice has affected high latitude atmospheric circulation patterns and temperature (e.g. Overland et al., 2015), and is leading to increased negative mass balance of the Greenland Ice Sheet. Recent work (Liu et al., 2016) has demonstrated a close association between Arctic sea ice loss and ice sheet melt probably driven by anomalous changes in tropospheric pressure systems and wind fields.

78. The analysis of such combination effects can produce events that potentially lie within the probability set out by H++ scenarios (UKMO, 2015). These are very low probability (10^4 year exceedance probability) changes in the magnitude or frequency of a climate event, metric or hazard and are beyond the 10th and 90th percentile range as set out by UKCP09. They may not be tied to a specific time frame and (apart from cold snaps) are associated with high end emissions scenarios with no mitigation policy. They have been used by the Environment Agency to assess peak river flows (EA, 2011) and the first Climate Change Risk Assessment (Wade et al., 2012) discussed the scenarios in relation to sea level rise and tidal surges. The current UK Climate Change Risk Assessment Evidence Report (Wade et al., 2015) discusses H++ events in the context of heat waves, droughts, floods, windstorms and cold snaps.

5.8 Implications of Climate Change for Weather Extremes in the UK

79. High Impact Weather (HIWeather) is now a major programme of the World Weather Research Programme (WWRP) in the World Meteorological Organisation[6]. The research

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[6] https://www.wmo.int/pages/prog/arep/wwrp/new/high_impact_weather_project.html

programme is carrying out an ensemble of simulations at ~12 km resolution (Kotlanski et al., 2014). The UKMO, using its numerical prediction model at 2.2 km resolution, is examining the change in extreme weather following a pilot experiment that suggested increased summer precipitation over a limited area in Southern England (Kendon et al., 2014). The Weather Research/Forecasting model (Skamarock et al., 2008) is now being used to look for changes in extreme weather over the UK and Western Europe in the 2020s and 2030s (Gadian et al., 2017). Both the Kendon and Gadian simulations are at a resolution scale of less than 3 km, which permits the modelling of convective storms for the first time and is critical for the examination of future extreme weather. Hand et al. (2004) showed that more than 50% of flash flood events were caused by short lived extreme convective storms, which by their nature are currently difficult to predict. This mirrors similar weather simulation experiments being carried out over a US domain (Bruyere et al., 2014).

80. Preliminary results from both Gadian et al. (2017) and Kendon et al. (2014) suggest that there are now more summer extreme convective rainfall events that are not resolved in climate and weather prediction models, as these do not permit the resolution of convective storms. They also suggest that over the UK, models predict longer dry spells and shorter heavier periods of convective precipitation. Gadian et al. (2017) further suggests that this under-representation is by as much as a factor of 10 in terms of frequency. Furthermore, by the 2031-2036 period, in these events, the amount of precipitation increases up to 20% in terms of severity as the average precipitation per event increases. The trend is mirrored to a lesser extent for the 2021-25 dataset and is consistent with the work of Kendon et al. (2014), who examine precipitation in the next century.

81. Summer wind speeds are projected to reduce, corresponding to prolonged periods of high pressure. Work by Gadian (2018) argues that there is similar enhanced rainfall in embedded convection in winter synoptic storms, but this has not been confirmed in other work. Results from EURO-CORDEX (Kotlanski et al., 2014) support this intensification of extremes, although not at a resolution to replicate extreme convection storms. Current active research in this area is expected to deliver further results over the coming years.

6 ANALYSIS OF PLUVIAL & FLUVIAL FLOODING

6.1 Pluvial Flooding

82. *Extreme rainfall:* Intense rainfall is associated with events such as ARs (which occur largely in winter) and convective thunderstorms which occur during periods of high humidity and at the junction between cold and warm fronts. These are common in summer but can also occur throughout the year. Such convection events may only last a few hours and are usually spatially localised in nature. However, significant localised pluvial flood risk may result, particularly in low-lying areas with poor or insufficient drainage systems. In addition, some locations may be prone to flash flooding resulting from extreme rainfall in areas upstream, particularly if they are situated in small, steep or highly urbanised catchments, or if upstream soil infiltration capacity is reduced (e.g. due to antecedent rainfall leading to soil saturation). Consequently, any assessment of flood risk due to extreme rainfall should take account of both on-site heavy rainfall and upstream conditions within the catchment.

83. In the British Isles recent extreme rainfall events have occurred in late autumn and winter. Between 20-26th November 2012, four consecutive cyclonic systems produced one of the wettest weeks in the last 50 years in England (similar to a period in late 2000 (Marsh et al., 2012). In December 2015, exceptional rain totals fell in the Lake District, giving the highest rainfall measured for any 24 hour period (341.4 mm of rain fell at Honister Pass, Cumbria, in the 24-hours to 18:00 GMT on 5th December 2015) and the highest two consecutive rain-day total measured (405 mm at Thirlmere) (see Parry et al., 2016).

84. Analysis of rainfall data between 1868 and 1968 in the British Isles (Rodda et al., 2009) shows that the maximum number of extreme events of 100 mm and above in the record occurred in November. Rainfall totals above 150 mm per event occurred mainly in the summer months (associated with convective storms) with a secondary peak in November and December, probably associated with extreme cyclonic conditions. In summer 1989, the Halifax convective storm produced 193 mm in less than two hours (Acreman, 1989). This was associated with a combination of a strong urban heat island and sea breeze convergence (Thielen and Gadian, 1997) and could be taken as an indication of possible precipitation events in a warming climate.

85. *Snowfall: S*now forms in clouds with an air temperature that is below freezing, as a result of the uplift of moisture-laden air causing the condensation of water vapour to ice crystals and their subsequent aggregation into snow particles. Commonly, snow forms within regions of upward air movement associated with the warm-fronts of low-pressure extratropical cyclonic weather systems; the upward movement of air may also be caused by upland areas, leading to orographic precipitation and the heavy snowfall associated with mountain systems. When the atmosphere at ground-level is cold (less than around 2°C), snow will reach the ground without melting into rainfall and, if temperatures remain cold, accumulate into a snowpack.

86. A recent example of extreme snowfall accompanied by cold was the winter of 2009-10, which was the worst winter over the UK since 1978-79. From late November 2009, strong north-easterly winds from Northern Europe and Siberia blowing over the mild North Sea brought extreme cold and heavy snowfalls, especially for eastern Scotland and northeast England. Snow accumulations of 58 cm at Balmoral in Aberdeenshire and 55 cm in County Durham were measured on 2nd December and snow depths were comparable to the winter of 1965. Extreme low temperatures were recorded in November and December, including a new minimum record of -18.7°C in County Tyrone in Northern Ireland on 23rd December (see Prior and Kendon, 2011).

87. *Rain-on-snow:* Where a snow-pack has accumulated through a sustained period of below freezing weather, a rapid thaw may occur with a rise in air temperature. This is particularly the case when precipitation falls as rain onto a snowpack, leading to a rapid

melting and high runoff, increasing flood risk. This appears to have been one of the main drivers of large floods that occurred during the Little Ice Age of the 17th-19th centuries in the British Isles when the Polar Front moved to a more southwards location accompanied by a weakened AMO circulation and a probably low NAOI (e.g. Orme et al., 2015). The magnitude of these ‘rain on snow’ events was probably at least as high as the largest events seen in recent years.

88. *Climate Change:* Climate change will affect the weather events that cause extreme rainfall and snow, but considerable uncertainty is associated with the estimation of these processes. Under a warmer climate, the atmosphere is able to hold more water and more energy is available for the generation of convective thunderstorms, leading to an increase in the likelihood of extreme rainfall (e.g. Chan et al., 2014). Due to the resulting change in the nature of rainfall, past climate datasets on rainfall extremes may not provide a reliable indication of future trends. In addition, convective thunderstorms are extreme and localised events and consequently difficult to assess through the use of climate models which have insufficient spatial and temporal detail. However, the IPCC points to a trend towards more severe thunderstorms, although without a likelihood estimate (Collins et al., 2013).

89. Across Europe, despite projected decreases in the overall level of summertime precipitation, flood risk resulting from episodes of intense precipitation is projected to increase (Christensen and Christensen, 2003; Haarsma et al., 2013). For snow, increases in overall precipitation means that cold areas may see an increase in snowfall, even though the overall proportion of precipitation which falls as snow is likely to decrease. The IPCC indicates that it is very likely (high confidence) that the maximum seasonal snow-cover extent will decline for the northern hemisphere (Collins et al., 2013); however, the total amount of snowfall as represented by the snow water equivalent is less certain with the coldest regions projected to experience an increase. UK winters are set to become milder, on average, and the chances of a winter as cold as 2009-10 drop from 6% to 0.6% by 2100 (Sexton and Harris, 2015), although with the caveat that short term variability in climate may well mask long term trends (see Section 5.3).

6.2 Fluvial Flooding

90. Analysing river flood hazard involves:

- Collection of data.
- Flood frequency analysis, i.e. analysing the data to establish the probability with which flood events of a particular severity occur and/or are exceeded.
- Flood modelling to model deterministically how the river catchment responds to flood water, and then at a more local level to establish how the site or area of interest is affected.

91. *Potential climate change effects in recent flood events and short datasets*: The influence of climate change has been a topic of interest in relation to recent flooding events in the UK, with questions raised over whether such events are the result of human greenhouse gas emissions. But the lack of long term instrumental records makes it difficult to respond to such questions with confidence. The 2000 ‘Millennium’ floods in England and Wales damaged 10,000 properties and caused insured losses of around £1.3bn and occurred during probably the wettest autumn experienced in England and Wales up to that date since records began in 1766 (Pall et al., 2011). The authors used an ensemble of climate models to develop a probabilistic attribution framework to demonstrate that anthropogenic greenhouse gas emissions substantially increased the risk of flood occurrence by between 20-90%. Similar work using climate model ensembles to analyse the 2013/14 England floods showed that anthropogenic warming increased the number of January days with westerly flow, with the amount of water vapour in the atmosphere

increasing the likelihood of extreme precipitation (Huntingford et al., 2014; Schaller et al., 2016).

92. Other approaches have used documentary and historical evidence and proxy data on flood inundation to assess the magnitude of past floods. Using such techniques has allowed researchers (e.g. Glaser et al., 2010) to reconstruct large floods on central European rivers between the 16th to 19th centuries and show that these were caused by a number of hydroclimatic drivers. Overall, events causing local flooding affecting limited catchments were associated with convective rainstorms that were not large enough to impact large areas; those events involving multiple (four or more) catchments and widespread flooding were clustered in winter and the main triggers were ice-break on rivers and snow melt (and included the floods following the severe winter of 1784). Later parts of the flood record from Central European Rivers suggests that land-use changes have played an important role in affecting river flooding and have contributed to the non-stationarity observed in such datasets (e.g. Toonen, 2015). In contrast to the work using climate models, it appears that recent changes in flood frequency variability is not exceptional when compared with the flood behaviour of the past 500 years in Europe.

93. It is likely, therefore, that recent UK floods have not been caused by anthropogenic climate forcings, but this conclusion carries substantial uncertainty.

6.2.1 Fluvial Flooding and Flood Frequency Analysis

94. The impact of using short-term datasets for flood analysis is noted above. To assess the validity of using such data to reconstruct magnitude/frequency relationships requires access to long flood records. Flood frequency analysis (FFA) for engineering design, according to the Interagency Advisory Committee on Water Data 1982, is based upon two assumptions:

- “annual maximum peak flows may be considered a sample of random and independent events” and, if a sufficiently long record is available, a frequency distribution for a site can be precisely determined; and
- “flood flows are not affected by climatic trends or cycles”, which implies that climatic or environmental changes (e.g. catchment land cover or land-use) do not alter the statistical parameters of the frequency distribution – termed ‘stationarity’.

95. There is however growing realisation in the UK, and worldwide, that for assessment of flood risk associated with infrequent events down to 0.01% annual probability of exceedance, these two basic assumptions of traditional FFA cannot be met. The first assumption – annual maximum peak flows are a sample of random and independent events – has been shown not to be true in the UK by growing evidence that both the frequency and magnitude of 1% and lower probability floods have changed significantly over time, particularly when the flood series is extended beyond the second half of the 20th century (e.g. Macklin et al., 2012). The second assumption of stationarity of flood flow also cannot be met because of hydroclimatic variability linked to shifts in atmospheric circulation (e.g. Foulds and Macklin, 2016), and that the second half of the 20th century (when most instrumental flow records started in the UK) was itself a period characterised by relatively small floods.

96. As a consequence of quasi-cyclic multi-decadal climatic fluctuations (including the NAO and AMO), a single population of extreme flood events does not exist, nor is the probability of such extremes equal at any particular time. Traditional FFA based on instrumental flow records of usually less than 50 years in length are therefore at best unlikely to provide robust estimates of flood events with a 1% or lower annual probability of exceedance, and at worst result in a significant under-estimate of flood risk. These issues are exacerbated when such data is extrapolated in order to predict the magnitude of an extreme event with a 0.01% annual probability of exceedance.

97. Assessment of flood frequency and magnitude, therefore, highlights several linked methodological issues. First, extrapolation from short climate or flood datasets to produce low exceedance probability estimates fails to include the non-stationarity in such data and the likely non-linearity in climate forcing-response relationships. Second, it provides support for attempts to extend the event record using proxy data. In the UK, there are examples of extending the flood record using documentary, geomorphic and sedimentary evidence (e.g. Macklin et al., 2005; 2010).

6.2.2 Flood Modelling

98. There are two primary types of flood model: *hydrologic* and *hydraulic*. Hydrologic models represent river catchments and are used to determine how much runoff occurs after rainfall events. The main outputs of these models are predicted hydrographs of stream flow over time, which may then be used to assess inundation extent within a hydraulic model.

99. Hydraulic models simulate, in detail, the flow of water within rivers and across floodplains, incorporating complex hydraulic structures such as embankments, culverts, storm drainage and bridge constrictions. The main output of a hydraulic model, is a series of maps of surface water depths and flow rates throughout the flood event, which may then be assessed in relation to buildings and other infrastructure to determine the severity of flood hazard. A hydrologic model may be used to drive a hydraulic model, as is necessary for the assessment of the impact of basin-scale alterations on flood risk or to convert climate projections of rainfall to localised inundation risk. However, a hydraulic model may be used independently from a hydrologic model to assess flood hazard if observations of river stream flow are available.

100. A hydraulic flood model allows river flow to be related to inundation extent and depths. Given different river flow levels with known prior probabilities (derived from flood frequency analysis), a hydraulic model may be used to obtain a map of inundation risk which integrates each flow level and can be used to assess flood risk for infrastructure. Further, models may be used to test different flood risk mitigation schemes (e.g. embankments), or the assessment of changes in flood risk given changes to the probabilities for each flow level (e.g. as a result of basin alterations or due to climate change).

101. Before a hydraulic model is used as a tool for flood risk assessment and to provide a quantification of the level of confidence in model outputs, model calibration and accuracy assessment should be completed. In this process, a model is developed for a past event and assessed against observational data for that event. Ideally, these data would consist of airborne (e.g. Bates et al., 2006; Néelz et al., 2006) or satellite imagery (e.g. Brivio et al., 2002) of a flood event, to which predicted inundation extent is then compared (often using the percentage of correctly predicted inundation extent, excluding dry areas). However, such data is uncommon, particularly for short-duration events, and may not represent the peak of flood inundation extent. In the absence of these data, previous studies have utilised reconstructed flood areas from post-flood field mapping of flood trash lines (Neal et al., 2009) or river level measurements during the flood event which are internal to the model domain. An advantage of using these latter data is that they may more easily allow a temporal assessment of model accuracy, but only at one location meaning that this accuracy may not be representative of elsewhere in the study site. In model calibration, parameters (usually friction) are adjusted until model outputs match as closely as possible the observation data. Ideally, model verification is then completed using a second, independent event. In practice, however, the lack of data availability may preclude this.

102. Model accuracy assessment can, of course, only ever provide an estimate of model reliability for events within recent experience, and for areas in which observational data of flood inundation are available. For extreme floods (greater than 1 in 1,000 year events), areas which have not been observed to have experienced river flooding may be

at risk. With rare events the quantitative verification of extreme predictions is not possible. Rather, it is necessary to assume that the model performance calculated using smaller, observed events will be maintained at higher flood levels, and that the representation of critical hydraulic features within the expanded flood area (e.g. micro-topography, drainage) are represented appropriately.

6.2.3 Approaches for Hydraulic Flood Modelling

103. The structure and complexity of hydraulic flood models varies in terms of:

- dimensionality, with river and floodplain flow represented in one-, two- or three-dimensions;
- spatial representation, where the grid structures used may be regular or irregular in their spacing; and
- the level of detail in the representation in the physics of fluid flow, where simplifications can be made by assuming that various forces of momentum are negligible.

104. Spatially detailed, 3D approaches with complete handling of fluid physics are able to represent vertical movement and turbulence within the water column and may be used for applications where this is of particular importance (e.g. deep water, breaking waves, sediment transport, and bed scour). However, it is widely recognised that for the broad-scale simulation of flood inundation, such detail is not usually necessary and two-dimensional (2D) depth-averaged shallow water approximations are adequate, particularly within the constraints of available data for model construction and validation (Bates and De Roo, 2000; Hunter et al., 2005). One-dimensional (1D) approaches, which represent flow as a series of cross-sections placed along the river reach, have been used previously due to their high computational efficiency. Unlike 2D schemes, however, fully 1D approaches suffer from an inability to represent the lateral diffusion of the flood wave (Hunter et al., 2007) and cannot simulate accurately topographically complex floodplain environments where flow is inherently at least two-dimensional. Hybrid approaches have also been developed which represent channel flow in 1D and flow on the floodplain in 2D (e.g. Bates and De Roo, 2000; Bradbrook et al., 2004). Generally, hydraulic models represent the channel in the 1D domain and the floodplain in the 2D domain – this is the general modelling convention for studies of fluvial flood risk.

105. Within 2D approaches, the modelling grid represents the topographic land surface. Small topographic variations, on the floodplain will affect the flow of water during a flood event, particularly during floodplain wetting and drying. Airborne remote sensing using LiDAR now permits the routine collection of detailed topographic data that include these important features at spatial resolutions of around 1-2 m, with a vertical accuracy of around 15 cm (Habib, 2008), or even smaller. The level of detail in the representation of topographic features will likely affect the accuracy of predictions of flood inundation, although there is a trade-off between spatial resolution and computational expense. Néelz and Pender (2010), determined that models which solve the full shallow water equations are all suitable to support flood risk management in most scenarios, except where the models application area is large (>1000 km^2) or where multiple simulations are required (e.g. probabilistic assessments), due to the prohibitive length of computation time required. However, computational efficiency has improved through greater computing power and more intelligent 2D solutions. Where detailed simulation of super- to sub-critical flow transitions are required (e.g. the turbulent water close to a dam or embankment break), numerical schemes which are capable of capturing hydraulic shock waves were found to have superior performance.

7 ANALYSIS OF WIND

106. Understanding the future evolution of windstorms, their magnitude, frequency and tracks is important for assessing the risks of severe storms to nuclear facilities.

7.1 Wind Speed Trends

107. Trends in wind speeds are shown for 1988-2010 in Figure 2 (IPCC AR5). Surface wind speed data from ocean surface areas use satellite-based interpolated wind datasets blended from different satellites and atmospheric reanalyses. The latter, provide wind directions as in products such as Blended Sea Winds (BSW; Zhang et al., 2006), or background fields as in Cross-Calibrated Multi-Platform (CCMP) winds (Atlas et al., 2011), and OAFlux (Yu and Weller, 2007; OA Flux, 2018). Over Europe, Smits et al. (2005) found declining trends in extreme winds in 10 m anemometer data over the period 1962-2002. The results for this period for moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year), indicate a decrease in storminess over the Netherlands between 5% and 10%/decade. Vautard et al. (2010) also found mostly declining trends in surface wind observations across the continental northern mid-latitudes and a stronger decline in extreme winds compared to mean winds in surface wind measurements (see also Kumar et al., 2015). Gadian et al. (2017) model simulations, project a decrease in average wind of ½ m/s over summer months in Northern Europe between the 1990s and the 2030s, with an associated decrease of up to 100 hours per month of wind speeds below 3 m/s over much of the UK except over the South East region, where convective activity increases.

108. McVicar et al. (2012) have produced a global review of 148 studies looking at wind speeds and showed that near-surface terrestrial wind speeds are declining in the Tropics and the mid-latitudes of both hemispheres at a rate of −0.14 m/s per decade (see Figure 3). The analysis of these studies allowed the reporting of global patterns of terrestrial *u* (wind speed) trends (with uneven and incomplete spatial distribution and differing periods of measurement) and found that the average trend was −0.014 m/s per year for studies with more than 30 sites observing data for more than 30 years. This confirmed that atmospheric stilling (reductions in wind speeds) was widespread. Assuming a linear trend this constitutes a −0.7m/s change in *u* over 50 years. Vautard et al. (2010), analysing a global land surface wind dataset from 1979 to 2008, found negative trends in the order of –0.1m/s per decade over large portions of NH land areas. The wind speed trend pattern over land inferred from their data (1988–2010) has many points with magnitudes much larger than those in the reanalysis products, which appear to underestimate, systematically, the wind speed over land, as well as in coastal regions (Kent et al., 2012).

109. In summary, there is evidence that wind speeds globally are reducing but there is low confidence in changes to surface wind speed over the land and oceans owing to remaining uncertainties in datasets and measures used.

7.2 SREX Report

110. The 2012 IPCC report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), see Table 3, made a number of findings relevant to the nature of extratropical winds and the confidence that climate scientists can put on the trends of relevant datasets:

- First, they suggested that there has been a recent shift to higher latitudes for the hemispheric extratropical storm tracks.

- Second, they noted that there is currently low confidence in observed trends on tornadoes and hail storms and this is due to inhomogeneities and uncertainties in observational data.

- Third, given the few numbers of modelling studies that have addressed the issue of extreme wind projections, SREX have low confidence in these projections and simulations of extreme wind events. They identify tropical cyclones as the exception to this view and suggest that cyclone extreme winds will likely increase in future, but this is not a clear projection for all ocean basins. The frequency of such events will likely either decrease or remain unchanged.

- Fourth, projections of small-scale extreme events such as tornadoes are made uncertain because there are several ways in which future atmospheric trends might evolve, and the small-scale nature of such events means that the physical processes driving them have to be parameterised in climate models with the uncertainties that follow from this.

- Fifth, SREX argue that they have medium confidence that the number of mid-latitude cyclones in the future will reduce globally, but there is low confidence in the spatial detail of such trends and events.

- Finally, they support other studies by suggesting that mid-latitude storms should move poleward under future climate change, although see discussion that follows.

111. SREX also cautions that confidence in trends of surface wind speeds is low because of biases and gaps in observations and this is supported by IPCC AR5 (2013) (Table 3) by arguing that past methods of analysing and measuring winds (e.g. ship speed at sea, sails carried or using sea state as a proxy), or changes in measuring conventions (Beaufort phenomenological scale to measured winds) have introduced considerable biases that require corrections (e.g. Thomas et al., 2008). In addition, satellite measurements of winds, especially using passive radiometers, only provide data back to 1987 (Bourassa et al., 2010). As a result, assessing current trends in the context of past wind behaviour is difficult.

7.3 Wind Speeds Along European Coasts

112. Long term changes in prevailing wind direction and trends in wind speeds can cause changes in coastal sea levels (e.g. McInnes et al., 2009), wave climate and coastline stability because of the role that wind regimes play in affecting geomorphological erosion and deposition processes along coasts (Pirazzoli and Tomasin, 2003).

113. In the UK, and along northwest European coasts analysis of available data show that there has been considerable natural variability in wind behaviour over the 20th century. Although the precise reasons for this variability are not clear (Bakker et al., 2013), there are close correlations between wind strength and frequency and the nature of atmospheric systems such as the NAO. In addition, over sea areas empirical data on wind strength are of short duration and only relate to spatially localised regions. As a result, GCMs and RCMs have been used to assess future wind behaviour.

114. Projections from CMIP3 and more recent CMIP5 models and downscaled RCMs from these show a consistent pattern. This is, that natural variability, is greater than either modelled changes in wind behaviour or inter-model differences. As a result, it is not possible to say that model projections of wind predictions are greater than observed natural variability (Nikulin et al., 2011; Pryor et al., 2012; Bakker et al., 2013; Sterl et al., 2015).

7.4 European Wind Storms

115. The winter storms affecting the British Isles in 2013-14 and 2015-16 were unusually severe and associated with extreme rainfall and coastal flooding (UKMO and CEH 2014) and have served to focus renewed attention on these events in the context of infrastructure development. However, assessment of future European windstorms is

made difficult by current limitations in our ability to measure important physical processes in the atmosphere that drive baroclinicity and, therefore, cyclonic behaviour. Other factors that need to be better understood include changes in Arctic amplification, the expansion of sub-tropical cells and the influence of teleconnections between Northern Hemisphere wind regimes and multi-annual oscillations such as ENSO.

116. In IPCC AR4, the argument was made that increased greenhouse gases will result in

“a poleward shift of storm tracks in both hemispheres that is particularly evident in the Southern Hemisphere (SH), with greater storm activity at higher latitudes’’ (Meehl et al., 2007).

However, this simple picture may not capture the complexities of the response of storm tracks in future (Zappa et al., 2013). Climate model projections suggest that North Atlantic winter storm tracks will extend eastwards bringing enhanced storminess to the UK and parts of northern and central Europe (e.g. Pinto et al., 2009; Catto et al., 2011).

117. There are major uncertainties in assessing the future evolution and nature of European windstorms. Partly these reflect the complexities in modelling the future behaviour of the NAO (see Section 2), which explains about half of the interannual variability in winter atmospheric pressure in the North Atlantic (e.g. Ortega et al., 2015) and drives the storm tracks across the British Isles. Early attempts to model the NAO include that by Stephenson et al. (2003) who used 17 CMIP1 coupled GCMs. Out of these, 13 captured the surface temperature pattern and the northern dipole, although a number also overestimated the teleconnections between ENSO and NAO. More recent work (e.g. Davini and Cagnazzo, 2014), has shown that CMIP5 models misinterpret the dynamical behaviour of the NAO such that at least three series of jet stream and blocking behaviour are represented in the model projections incorrectly. As a result, caution must be employed in interpreting model simulations of NAO behaviour and using these to estimate future wind trends. Further, the location and, therefore, trajectory of storms is strongly influenced by the location of elevated sea surface temperatures (SSTs) and, therefore, the location of warm currents such as the Gulf Stream, and these are not currently accurately represented in many climate models (Keeley et al., 2012).

118. IPCC AR5 summarised the latest research findings on North Atlantic storms:

- Observations of winter storms suggest there has been an increase in the frequency and intensity of winter storms over Europe (e.g. IPCC AR5 2013; Donat et al., 2011); although this finding may also be obscured by differences between datasets (Krueger et al., 2013).
- CMIP5 produce two zonal storm tracks in the North Atlantic where only one is expected, and also underestimates cyclone intensity.
- Climate model resolution is key to assessing storm tracks and this is especially true when individual models are used; these tend to capture many of the general characteristics of wind storms.

7.5 Tornados

119. While there is no clear consensus whether tornados will become more frequent and more intense globally with climate change (Kunkel, 2013), there are published data that suggest the conditions for tornado development (such as increased capacity of the atmosphere to hold water vapour and changes in wind shear) may change in the future. Globally, there is an increasing trend in convective available potential energy which partly drives convective storms (e.g. Riemann-Campe et al., 2009).

120. Tornados are more common In the UK than in any comparably-sized land mass in the world (Reynolds, 1999; Mulder and Schultz, 2015), although the vast majority of these

are of low intensity and the data is of short duration. Using data from 1980-2012, Mulder and Schultz (2015) showed that most UK tornados (78%) occur in England, with the majority of these occurring in eastern, south-eastern and western England. Tornado intensity is measured using the F (Fujita) Tornado Damage Scale with F0 producing winds <73 mph; F1 producing winds between 73-112 mph and F2 with winds between 113-157 mph. In the UK dataset, >95% of tornados where wind speed could be measured or estimated were on the F0 or F1 scale, with the remainder reaching F2. No F3 tornados (with wind speeds between 158-206 mph) were observed in the dataset. F3 tornados are those where severe damage would occur including:

“Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown” (NOAA 2007).

8 ANALYSIS OF OTHER METEOROLOGICAL HAZARDS

121. This section provides information on a number of meteorological aspects, in addition to flooding and wind hazards that could be relevant to nuclear safety and are also the subject of active research.

122. *Heatwaves*: Heatwaves are associated with prolonged periods of extreme high temperature; in mid-latitudes they are commonly associated with quasi-stationary high pressure systems. There are numerous examples of note, including:

- The European heat wave of 2003, approximately 8 days in duration, was estimated to have killed more than 35,000 people[7]. In France, especially during this period, the maximum temperature was over 40°C. Normally the daily cycle of temperature provides significant cooling at night, but in this event, temperatures barely dropped below 30°C at night. Details of the causes and effects, focused on the UK can be found in Black et al. (2003).

- One of the most intense recorded heat waves in the UK occurred in 1976, with 15 consecutive days of temperatures reaching 32°C in central England.

- In 1972, a heatwave affected the Arctic Circle with temperatures reaching 32°C, leading to forest and peat fires in Russia.

123. These low frequency weather systems are often called ‘blocking’ patterns and some opinion argues that such systems are associated with sea surface temperature (SST) anomalies around the globe and particularly in the western Atlantic (Holton and Hakim, 2012). At the surface, quasi-stationary high pressure weather systems are observed to be several thousand km in diameter, and evidence suggests that in NH mid latitude regions, their longevity is enhanced when simultaneously associated with numerous smaller scale cyclonic systems (Holton and Hakim, 2012).

124. The formation and breakup of such low frequency weather systems cannot yet be accurately predicted by numerical methods and remains an area of active research. It is likely that they are caused by the large scale descent of dryer air from upper levels in the atmosphere, causing a more stable vertical temperature structure and inhibiting convection and vertical mixing. Such weather systems also exhibit low horizontal wind velocity, generally leading to the absence of significant cloud formation, high surface temperatures and poor air quality.

125. High resolution weather models, run for future climate scenarios, suggest that these events might become more common (Gadian et al., 2017). Current opinion is that hot summers leading to conditions that could support heatwaves, could become more frequent by 2050, UKMO[8]. These higher temperatures, with prolongation of dry spells, are also discussed in Section 5.

126. *High humidity - Fog*: In this modern society, fog (and low visibility generally) is one of the most costly weather events in terms of financial and human losses, in some situations comparable to the losses from tornadoes or even from hurricanes (Gultepe et al., 2007). Fog occurs when the atmospheric humidity reaches 100% and is the name given to cloud at ground level. Freezing fog occurs when the air temperature is around 0°C and can lead to ice accumulation onto cold surfaces. Fog dispersal techniques have been tried, but are very expensive and of limited effectiveness. This hazard is one of the hardest to predict, but of importance because of its potential widespread temporary effects on e.g. transport infrastructure (Oliver, 2008).

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[7] https://www.newscientist.com/article/dn4259-european-heatwave-caused-35000-deaths/.

[8] https://www.metoffice.gov.uk/learning/learn-about-the-weather/weather-phenomena/case-studies/heatwave.

127. *Lightning:* Lightning often is associated with extreme precipitation events. Lightning observations over the UK are becoming standard observations provided by meteorological services and represent increasing concern on the impact of electromagnetic pulses on digital/electronic systems. The UK Met Office (Anderson et al., 2014) lightning network now provides real time data on lightning strikes in the UK. There are currently estimated to be about 300,000 strikes annually, of which approximately 25%, are of the critical cloud to ground strikes. Lightning strikes have not been well studied and the current knowledge is very much a statement of awareness; to produce a hazard curve at this time would be challenging. Lightning is generated from the electric fields generated by the interaction of ice and small hail (graupel[9]) particles and dependent on liquid water content of individual clouds. Strong convection often enhances electric field generation and lightning strikes.

128. Guidelines for ensuring safety and integrity of buildings and electronic systems in the UK are covered in BS EN/IEC 62305 (2011). The data used is comprehensive, but other countries have different guidelines, with the requirements of the USNRC for power reactors presented in 2005 as Regulatory Guide (RG) 1.204 (USNRC, 2005a), based on contractor report CR-6866 (USNRC, 2005b).

129. Future lightning occurrence is generally believed to be increasing with increasingly strong convection. In the US, projected lightning strikes are estimated to increase by 12% per degree C, and by at least 50% by the end of the century (Romps et al., 2014), and other research supported by NASA shows an increase in forest fires caused by an increase in lightning (Veraverbeke et al., 2017). Some climate model simulations suggest that over parts of Africa, lightning will decrease (Finney et al., 2018) in a warming climate. However, these low resolution models do not include convection processes and therefore may not capture important physical processes driving lightning. In 1984, York Minster was hit by lightning for the first time in 600 years and such events are likely to become more frequent and should encourage more research on the development on hazard analysis methods.

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[9] Graupel: Small particles of snow with a fragile crust of ice, soft hail.

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10 FIGURES & TABLES

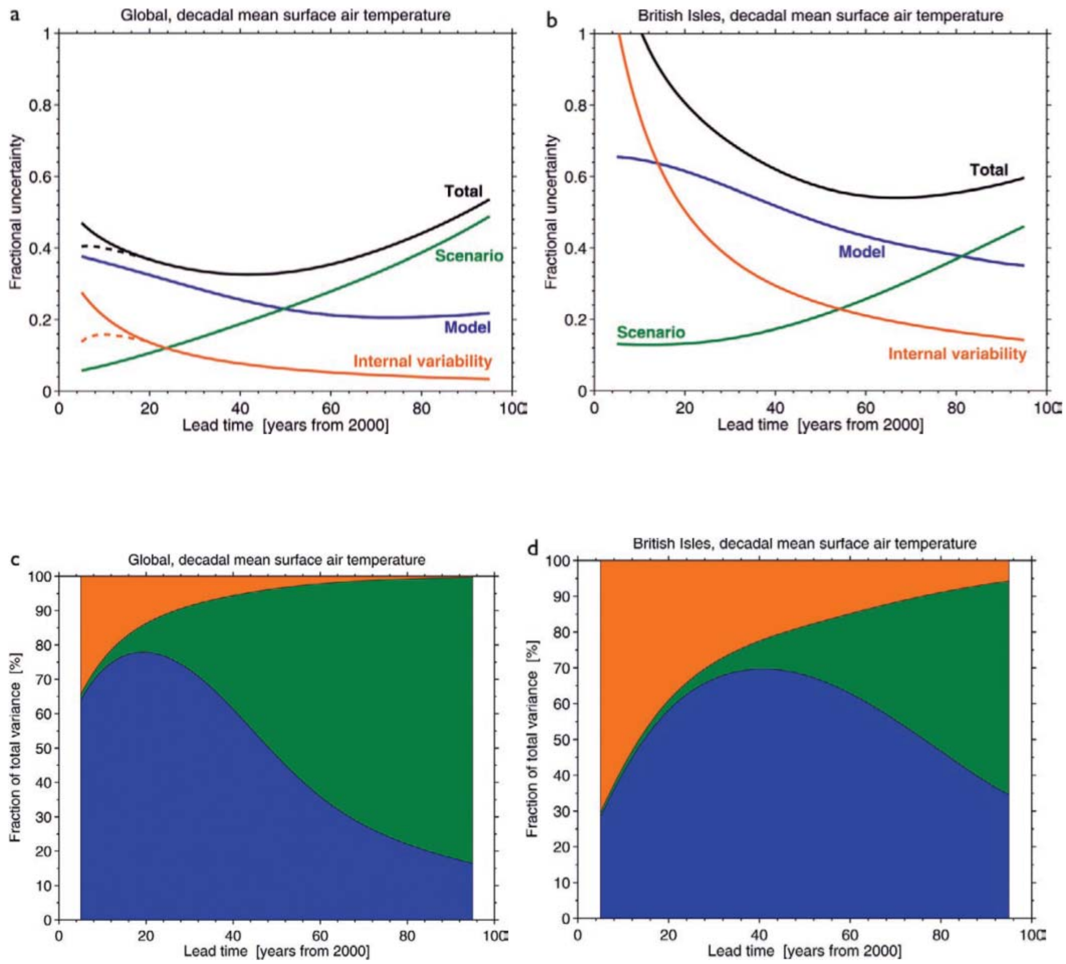

Figure 1

The relative importance of various sources of model uncertainty in decadal mean surface temperature projections is shown by the fractional uncertainty (the 90% confidence level divided by the mean prediction) for (a) the global mean, relative to the warming from the 1971–2000 mean, and (b) the British Isles mean, relative to the warming from the 1971–2000 mean.

The importance of model uncertainty is clearly visible for all policy-relevant timescales. Internal variability grows in importance for the smaller region. Scenario uncertainty only becomes important at multidecadal lead times. The dashed lines in (a) indicate reductions in internal variability, and hence total uncertainty, that may be possible through proper initialisation of the predictions through assimilation of ocean observations. The fraction of total variance in decadal mean surface air temperature predictions explained by the three components of total uncertainty is shown for (c) a global mean and (d) a British Isles mean. Green regions represent scenario uncertainty, blue regions represent model uncertainty, and orange regions represent the internal variability component. As the size of the region is reduced, the relative importance of internal variability increases (from Hawkins and Sutton, 2009).

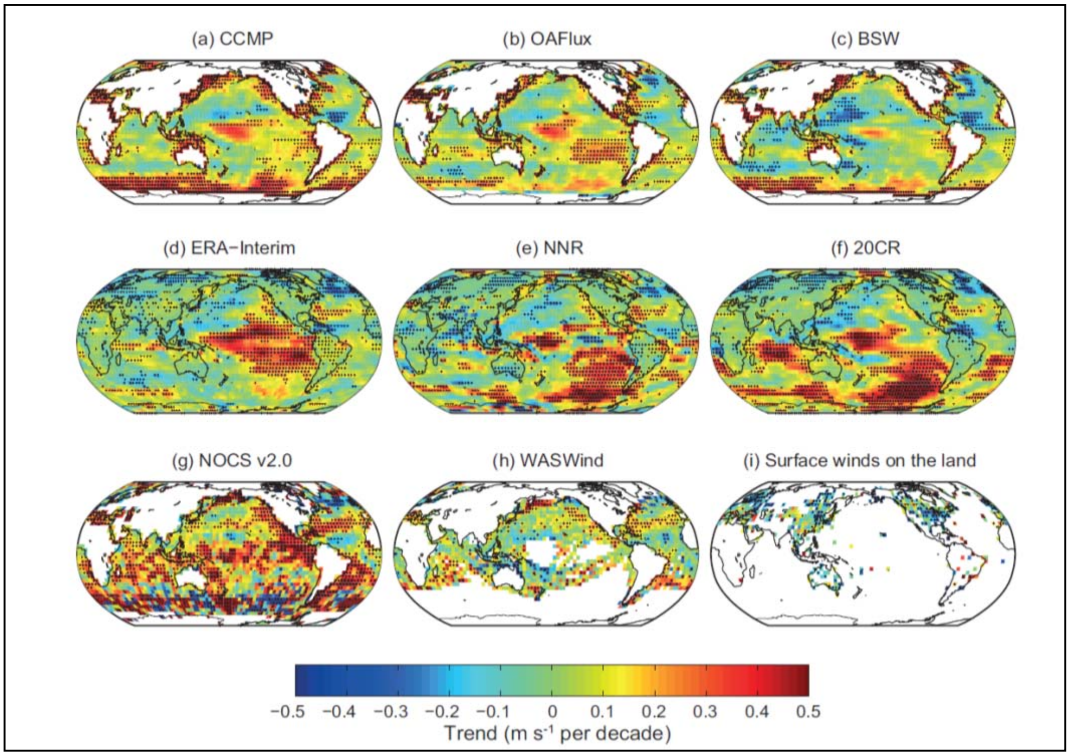

Figure 2

(From IPCC AR5 WG1). Global trends in wind speeds. Top row: datasets based on the satellite wind observations: (a) Cross-Calibrated Multi-Platform wind product (CCMP; Atlas et al., 2011); (b) wind speed from the Objectively Analysed Air-Sea Heat Fluxes dataset, release 3 (WHOI OAFlux Project 2018); (c) Blended Sea Winds (BSW; Zhang et al., 2006). Middle row: datasets based on surface observations: (d) ERA-Interim; (e) NCEP-NCAR, v.1 (NNR); (f) 20th century Reanalysis (20CR, Compo et al., 2011). Bottom row: surface wind speeds from atmospheric reanalyses: (g) wind speed from the Surface Flux dataset, v.2, from NOC, Southampton, UK (see Berry and Kent, 2009); (h) Wave- and Anemometer-based Sea Surface Wind (WASWind; Tokinaga and Xie, 2011)); and (i) Surface Winds on the Land (Vautard et al., 2010).

Wind speeds correspond to 10 m heights in all products. Land station winds (panel f) are also for 10 m. Black plus signs (+) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval).

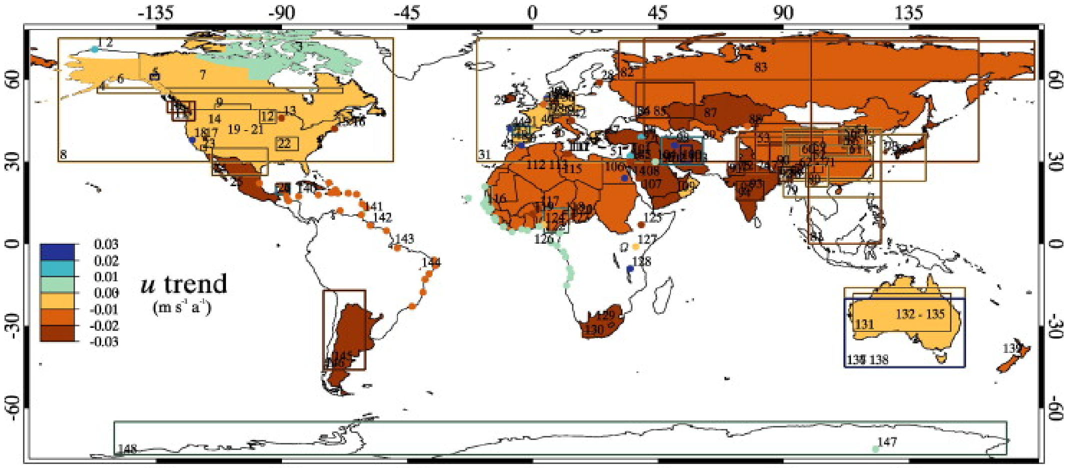

Figure 3

Global distribution of observed *u* (wind speed) trends (from McVicar et al., 2012). The values refer to the study numbers provided in original paper. Either points, geographic domains or countries are identified depending on the level of geographic detail provided in the study. If there are multiple studies for a country (eg, China) then the average *u* trend for that country is used.

Scenario storyline (SRES) TAR and AR4 (2001 and 2007)	**Description**
A1	A future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
A1 split into three groups (including A1FI)	These characterise alternative developments of energy technologies and include: A1FI (fossil intensive), A1B (balanced across energy sources).
A2	A very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines
B1	A convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
B2	A world in which the emphasis is on local solutions to economic, social and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.
Scenario from AR5 (2013). Representative Concentration Pathways (RCPs)	**Description**
RCP8.5, RCP6, RCP4.5 and RCP2.6 - the last is also referred to as RCP3-PD. (The numbers refer to forcings for each RCP; PD stands for *Peak* and *Decline*).	Their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas concentrations. The numbers refer to radiative forcing. Each describe an emission trajectory and concentration by the year 2100, and consequent forcing.

Table 1

Climate scenarios and descriptions used in recent IPCC assessment reports. SRES (Special Report on Emissions Scenarios); TAR (Third Assessment Report, 2001); AR4 (Fourth Assessment Report, 2007); AR5 (Fifth Assessment Report, 2013).

Model	Description
ECHAM	Run at European Centre Hamburg and developed by the Max Planck Institute for Meteorology from the 1987 version of the global numerical weather prediction model. The model produces a state of the art representation of physical processes, and allows for coupling to an advanced representation of the terrestrial biosphere through the JSBACH submodel, as well as an advanced description of atmospheric aerosol processes.
HadRM3	Hadley Centre Regional Climate Model Version 3 is the Met Office Hadley Centre's regional climate model used to produce regional (~25 km resolution) projections of the future climate. Used in UKCP09 to produce 11 runs of regional climate projections at the medium emissions scenario (A1B) on a daily time scale.
HIRHAM	HIRHAM is a regional atmospheric climate model (RCM) based on a subset of the HIR LAM and ECHAM models and combining their dynamics and physical parameterisation schemes.
HIRLAM	High Resolution Limited Area Model. In Europe these are being developed by consortia of collaborating National Meteorological Services (NMS’s). HIRLAM was the first of these consortia and established in 1985 in Nordic countries.

Table 2

Climate models discussed in text and their description.

Climate Change Reports	**Description**
IPCC First Assessment Report	FAR (1990)
IPCC Second Assessment Report	SAR (1995-1996)
IPCC SRES	Special Report on Emissions Scenarios (2000)
IPCC Third Assessment Report	TAR (2001)
UKCIP02	The UKCIP02 scenarios are based on four different IPCC SRES emissions scenarios and three future time-slices. The projections are not probabilistic and run at a spatial resolution of 50 km.
IPCC Fourth Assessment Report	AR4 (2007)
UKCP09	The UKCP09 probabilistic projections provide projections of climate change, and absolute future climate for climate averages at different timescales; at 25 km spatial scales; seven 30 year time periods and using three IPCC SRES emissions scenarios (B1, A1B and A1FI). Projections of climate change are based on change relative to a 1961-1990 baseline.
IPCC SREX	2012. Special Report on managing the risks of extreme events and disasters to advance climate change adaptation.
IPCC Fifth Assessment Report	AR5 (2013-2014)
UKCP18	New UK climate projections released in 2018 and supersede the UKCP09 products. New climate runs at 12 km resolution developed and at 2.2 km resolution for assessing convection storm climatologies.

Table 3

Climate reports mentioned in the text.

Name	**Radiative Forcing**	**CO_2 equiv. (ppm)**	**Temp anomaly (°C)**	**Pathway**	**SRES temp anomaly equiv.**
RCP 8.5	$8.5Wm^2$ in 2100	1370	4.9	Rising	**A1FI**
RCP 6.0	$6Wm^2$ post 2100	850	3.0	Stabilisation without overshoot	**B2**
RCP 4.5	$4.5Wm^2$ post 2100	650	2.4	Stabilisation without overshoot	**B1**
RCP 2.6	$3Wm^2$ before 2100 declining to $2.6Wm^2$ by 2100	490	1.5	Peak and decline	**None**

Table 4

Probabilistic estimates of temperature increase above pre-industrial levels using representative ECS distribution for the six SRES marker scenarios and the four RCPs. (From Rogelj et al., 2012).