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Analysis of Meteorological Hazards for Nuclear Sites

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Sub-Panel on Meteorological & Coastal Flood Hazards

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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, 2020a), generally referred to as TAG 13.

2. Annex 2 of TAG 13 (ONR, 2020b) 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 1-4.

2. OVERVIEW OF UK CLIMATE & WEATHER

3. The British Isles experiences one of the most variable weather 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. These are largely controlled by the contrast in air-mass temperature that, in turn, drives the storm track of mid-latitude lows steered by the jet stream, one or sometimes two fast moving currents of air in the extratropical middle to upper troposphere (see Hall et al., 2015). The main air masses are tropical maritime (south-westerly airflow) and polar maritime (north-westerly) that originate over the Atlantic Ocean; and continental easterly airstreams and, less often, southerly or south-easterly continental tropical airstreams originating from Spain or North Africa. The dynamics of the system are dominated by proximity to the Atlantic Ocean, to the Eurasian continent and to Arctic influences. In addition, cold air outbreaks in winter over North America strengthen the pressure gradient and the trans-Atlantic storm track. The interplay between these airstreams largely explains the weather and climate variability of the region. See also the discussion in Section 5.8.

4. The dominant wind direction over the British Isles is south-westerly to westerly, associated with alternating relatively fast moving cyclonic and anticyclonic systems embedded in the storm track across the Atlantic Ocean. These systems bring to the region generally mild, often wet weather and strong winds. If the cyclones become frequent and slow moving, then heavy and persistent rainfall and flooding may occur, especially in western areas where the rainfall is enhanced by hills and mountains (orographic or relief rainfall). 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, generate a still, often cloud-free atmosphere that 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 the procession of low-pressure systems in the storm track and these are called 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. 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 3,000 mm per year in some western mountains. Rising air over mountain slopes expands and cools (Roe, 2005). High saturation vapour pressure is associated with warm air and, as a result, the amount of water vapour that an air mass can contain is 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 usually greater than over surrounding lowlands. Rain-shadow 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 variability 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 (NH). The NAO is commonly defined as the difference between the standardised 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 circa 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. This is called 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]). 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 has high sea-level pressure.

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 stronger than normal. This is associated with an enhanced westerly air flow from the Atlantic over the British Isles. The NAO index (NAOI) measures the anomalous strength of the pressure gradient that is responsible for driving the westerly wind. The positive phase is associated with anomalous warm 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 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 in extreme cases 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 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.

10. The NAO drives variations in the pressure gradient of the North Atlantic and these strongly affect the strength of the North Atlantic westerlies and the storm track. The NAO winter index has varied considerably over the 20th century, having persistent negative values from the 1940s to the late 1960s, persistent positive values 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 NAO has increased since the 1950s, which recent research suggests largely represents a forced climate signal rather than mainly chaotic atmospheric variability. On inter-annual time scales 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. Because of the larger longitudinal extent of the AO, it accounts for a larger amount of NH surface air temperature variance than the NAO, which is largely confined to the North Atlantic/European sector. The northern centre of the AO teleconnection (described in Section 2.1.) pattern covers the whole Arctic while the southern centre covers the mid-latitudes of the whole NH.

12. Precipitation drivers 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 25 mm 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 ten 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 extra-tropical 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 deep convection thunderstorms. The precise location and timing of such thunderstorms is difficult to predict more than a few hours in advance given limitations in weather modelling.

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 waves in the westerlies over 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 models from the Coupled Model Intercomparison Project (CMIP) phase 5 (CMIP5) to analyse the projected increase in the frequency and magnitude of ARs in the North Atlantic. A doubling of AR frequency by 2074-2099 is projected under the RCP (Representative Concentration Pathway) emissions scenario RCP8.5. 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 are better 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 have 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.

2.1. Teleconnections

18. Teleconnections[1] 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 extra-tropical climate and weather systems are also linked to a variety of phenomena elsewhere on the globe, for example the El Niño Southern Oscillation (ENSO) atmospheric and oceanic coupled system in the Pacific, variations in tropical rainfall elsewhere (Scaife et al., 2017) 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 on-going global climate warming increases. So, a global approach is needed to understanding regional weather and climate variations, such as those over the British Isles.

[1] 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 geological (where appropriate), historical and instrumental data sources. Where some of these data are not readily available (as might be the case for sediment cores, which 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 may 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 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; Gallego-Sala et al., 2015), 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 are 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).
- Lake sediments: Analysis of lake sediments using dated sediment cores to reconstruct past flood frequency and, potentially, flood magnitude (e.g. Chiverrell et al., 2019).

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. Further, it may be difficult to distinguish between event types (e.g. 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 associated hazardous waste repositories (Baker 1987; O'Connor et al., 2014). In some cases, sedimentary deposits give the most complete geological 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 meteorological 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. For example, particular interest has focused on 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, because 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 geological 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 behind this rapidly developing field of water-resource risk assessment and planning, in part because the larger river catchments in Europe and the USA have driven the need for this integrated approach, compared with the UK.

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. The UK Met Office 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 UK Met Office extends back to 1853 for a small number of sites. The UK Met Office also produces long-term climate monitoring series such as the UK 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 (EVA) 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 UK Met Office Integrated Data Archive System (MIDAS) (UK Met Office, 2012). Digital records exist for a small number of sites back to 1949. However, these data are 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 rain gauges 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 (CEH) Flood Estimation Handbook (2016) represents the most comprehensive collection of data from the Environment Agency, the UK Met Office and distributed Water Boards. There is now the Flood Estimation Handbook Web Service that provides data on catchment descriptors and rainfall estimation procedures for more than four million sites across the UK.

34. Automated measurements for snow depth are sparser, 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 snowpack 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. Analysts should utilise data from multiple sites to reduce the uncertainty in assessments (e.g. Subedi and Fullen, 2009).

3.4. Synthetic Data

36. Stochastic weather generators are a form of statistical models that 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 the UK Climate Projections 2018 (UKCP18) (Lowe et al., 2019), which employs higher resolution models compared with UKCP09 (see section 5.6.), provide an important data resource. These are considered to be relevant good practice, even if model uncertainties should be recognised by users.

38. Synthetic datasets are required to assess the behaviour of climate and weather variables in situations where observational data are 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. Approaches used to develop these data include the use of probabilistic models for wind characteristics that 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, ERA-40, ERA-5, 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. Reanalysis data provide a physically consistent and globally complete dataset at high space and time resolution that can be used both to understand climate dynamics and to evaluate climate-model performance. Reanalysis can also generate the initial states of data (initial conditions) to enable NWP models to begin integrations. Similarly, reanalysis data are used to provide boundary conditions to force regional climate models (RCMs) (see downscaling section 5.2.).

3.5. Bias Corrections

40. All NWP models contain biases due to their coarse resolution and limitations in the representation of physical processes. As these biases can adversely affect the dynamical downscaling results, it is important to first bias-correct such data before use. There are several approaches that can be used, but for example, the approach of Bruyère et al. (2014; 2015) is typical. This method uses global and surface reanalysis data to correct the mean bias in the global fields. The bias correction method only corrects the mean state, whilst the synoptic and climate-scale variability is maintained. For future and current weather models (e.g. Gadian et al. 2018) this can be achieved, for example, by combining a 20-year mean annual cycle from the reanalysis data with the 6-hourly perturbation terms from the model being run. The bias correction data are then used as initial and boundary conditions in model runs. When applying models to look at specific site variables such as temperature, the mean off-set of the model compared with observations often needs to be considered before applying predictions for future values. Bias corrections have significant relevance when considering downscaling in climate models as discussed in section 5.2.

3.6. Numerical Model Developments

41. With the development of “exascale” computational platforms that are capable of ~ 10^{18} calculations per second, there is a challenge to develop new weather forecast and climate models that use such hardware. A new UK Met Office model is being developed (Adams et al., 2019) at high resolution that will enable convective, storm permitting weather prediction models to be used for projections. Parallel developments are occurring, for example in the US the Model for Prediction across Scales (MPAS) and in Germany the Icosahedral Nonhydrostatic (ICON) models. These approaches remove the problem of clustering of grid points near the poles, but present numerical integration issues such as diffusion, off-centering, conservation of core variables and tuning of parameterisation schemes needed in climate models (Lawrence et al., 2018). The new computers will have millions of cores, and data movements and storage

present new problems, not to mention significant power consumption. Parallel in time computations are being applied as a further alternative (Schreiber et al., 2017). These next generation models have the potential to radically improve short range and climate forecasts and represent a new generation of weather forecast models. The ability to model convective structures and smaller-scale processes will greatly enable the models' ability to represent and replicate past and future extreme-weather events. These developments will have a direct impact on climate models, as discussed in Section 5.

42. While numerical climate models are used to assess future climate change, other types of numerical models have been developed to model flood risk (see 0).

4. USE OF STATISTICAL METHODS IN ANALYSIS OF METEOROLOGICAL HAZARDS ANALYSIS

43. 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 are 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.

44. For example, assessment of future wind characteristics has used EVA 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 EVA 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.

45. 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) that 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 likelihood, based on the annual exceedance probability associated with each event.

46. Similar techniques with similar limitations are used in the analysis of extreme sea levels (ONR Expert Panel on Natural Hazards, 2020).

47. The annual exceedance probability is the probability that a flood will exceed a given level in any year[2], and is the inverse of the return period, or frequency

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

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 events. In the UK, 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 10,000 year events (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 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.

48. A major assumption with statistical models of extreme events 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

49. The only viable approach available for generating data on future climate change is by use of mathematical (or numerical) 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's surface, oceans and atmosphere into three-dimensional (3D) grids. The processes within each grid square are computed and discretised, and equations integrated through time (although see Section 3.6.).

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

51. From the late 1950s, attempts to model the global climate originally used general circulation models to examine the nature of atmospheric 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.

52. The size of grid squares defines the model resolution, and for the current generation of global models this is about 100 km for the atmosphere and around 30 km for the 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 decreased their grid box size from about 250 to 200 km from IPCC fourth assessment report (AR4) (2007). RCMs in the Coordinated Regional Climate Downscaling Experiment (CORDEX) programme have grid spacings of around 50 km with special cases operating at 10 km or better resolution (see Tables 3 and 4 and Kendon et al., 2012).

53. In order for these models to run, information needs to be provided to them on concentrations of greenhouse gases in the atmosphere. A scenario approach has been used to estimate future greenhouse concentrations as these cannot be measured. These include six IPCC 1992 (IS92) scenarios used in the IPCC second assessment report (SAR), six Special Report on Emission Scenarios (SRES) used in the IPCC third assessment report (TAR) and AR4, and four RCP scenarios used in the IPCC fifth assessment report (AR5). Nine forcing scenarios have been developed for the upcoming IPCC sixth assessment report (AR6) based on the Shared Socioeconomic Pathways (SSPs). The SRES scenarios in TAR and AR4 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.

54. For AR5 a different approach was used that was not accompanied by a narrative on how society would evolve. This approach used RCPs, with emissions increasing successively through RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The

number represents the radiative forcing[3] in Wm^{-2} at the top of the troposphere at the end of the 21st century. The A2 SRES is broadly 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.

55. Recorded emissions to date have tended to follow approximately those of scenario A2 and of RCP8.5.

56. The independent Climate Change Risk Assessment 3 (CCRA3, 2021) is the latest climate assessment, producing a set of 61 defined risks and requiring urgent action and implemented in the National Adaptation Plans envisaged for 2023. The UK Met Office, EDF Energy, Mott Macdonald has addressed some of these compound hazards (Institute of Mechanical Engineers, 2021).

5.1. Types of Climate Models

57. There are three main types of climate models:

- **Atmosphere-Ocean Global Climate Models (AOGCMs):** These models are 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). They do not include representation of biogeochemical cycles, and other important processes such as those determining ice sheet behaviour.

- **Earth System Models (ESMs):** For IPCC AR5 (2013) these formed the most complex models in terms of processes as they include 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. Most ESM models run at coarser resolution than AOGCMs owing to the computational demand of the complexity they seek to resolve. There is sometimes a loss of fidelity in the fluid circulation that accompanies the reduction in resolution.

- **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, an ESM created by coupling of five GCMs; Loch-Vecode-Ecbilt-Clioaglsm-Mode (LOVECLIM) 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).

58. The latest generation of ESMs is being brought together under the CMIP phase 6 (CMIP6) banner, which includes a new ensemble of CMIP-endorsed Model Intercomparison Projects (MIPs) that will be specific to a particular phase of CMIP. These have been developed to coincide with the new IPCC AR6 (Eyring et al., 2016).

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

5.2. Downscaling from Climate Models

59. AOGCMs and ESMs simulate global climate which is necessary because processes are able to communicate across the earth system thereby connecting distant elements of climate. However, adaptation planners, risk managers, infrastructure developers and other end users (such as nuclear site licensees) of climate services require climate projections at small spatial (and sometimes temporal) scales. Various techniques have been used to downscale information from GCMs to regional scales. One route is through the use of RCMs. As a result, RCMs have been developed to represent climate processes at scales finer than that possible with the typical resolution of global models and thereby to provide data on regional-scale climate change (e.g. Marioti et al., 2011; Jacob et al., 2014). RCMs are normally the atmospheric component of a numerical model, which can be run over a limited regional (not global) domain. Since the regional model requires data on the evolution of the atmosphere beyond the domain over which the regional model is defined to run, data on the atmospheric conditions around the edge of the regional model domain are passed every few hours from global models to the regional model. The regional model computes the evolution of the atmosphere inside the domain but is constrained by the trajectory taken by the global model which forces it.

60. Commonly used RCMs in climate change downscaling studies include the UK Met Office Hadley Centre Regional Climate Model Version 3 (HadRM3) and the German HIRHAM model, which is 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; Giorgi et al. (2009) provides a global coordination of regional climate downscaling for improved regional climate-change adaptation and impact assessment.

61. 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 that force the RCMs, which the RCM climate is dependent on, 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.

62. Statistical downscaling seeks to find transfer functions between coarse grid climate-model outputs and fine-scale observational data. The transfer functions can then be used to downscale the coarse grid data (von Storch, 1999). Regional climate information is obtained by developing a statistical model that 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).

63. Statistical downscaling assumes that any statistical relationships that exist 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 are lacking.

5.3. Climate Model Uncertainty

64. 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 are one of the success stories of modern science, giving unrivalled insight into the workings of the climate system. Despite this, large uncertainties in the outputs from GCMs remain (Stainforth et al., 2005; 2007a; 2007b; Hawkins and Sutton, 2009). Model (or epistemic) uncertainty may be classified as: forcing uncertainty; microscopic initial condition (IC) uncertainty; macroscopic IC 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.

65. 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 in the climate system 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 shorter timescales, internal variability may dominate and even produce a direction of change that runs counter to the long-term forced trends.

66. Finally, different models will produce different projections of the nature and patterns of climate change, even with the same ultimate level of global 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.

67. While models are mathematical representations of the climate system, not all models simulate all processes in the climate system or in the same way. In addition, certain physical processes operate at smaller scales than that of the model grid cells. These processes must be parameterised from variables that are resolved by understanding of the physical processes and estimated values of these parameterised processes calculated. Projections produced by any model will change in response to small changes in the state variables (e.g. temperature, pressure, humidity) of the model since the value of those parameters depends, in part, on uncertain parameterised processes.

68. As a result of these differences in model design, parameterisation schemes, and changes to the initial conditions in different runs of the same model, these

produce diverse projections. In addition, relatively small changes to the structure of a model may have a large impact on the projections produced.

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

- The identification of a preferred model based, for example on expert judgement. However, there is no clear evidence to demonstrate that this selection can be achieved objectively.
- The identification of a small number of preferred models from the complete ensemble. Recently, the approach taken in process-based evaluation involves model selection, dependent on the models which simulate realistic processes that control key characteristics of climate. Numerous National Communications to the UNFCCC have taken the approach of using a model ensemble subset.
- Average all members of an ensemble. The IPCC reports often show the projected climate from the mean of a CMIP ensemble. In this instance, each model is given the same weighting in the averaging process. Some models that are very similar may appear multiple times in the ensemble and thus may skew the averaging towards the climate of those models.
- Creating 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 (perturbed physics ensembles). This is the approach partly used in UKCP09, and partly by UKCP18 (although both also used some probabilistic projections from other modelling groups). However, this approach assumes that the model uncertainty derives mostly from the parameters that are set to be different from one model to the next in the ensemble. As such it does not deal well with the model uncertainty and inadequacy attached to any single GCM.

70. IPCC AR4 included 25 models from 18 modelling centres; AR5 included 56 models from 23 modelling centres. Similar numbers of models have been developed to inform future AR6 projections, and AR6 included more than 60 models from 40 modelling centres (e.g. Meehl et al., 2020). With the numerous projections derived from each of the models, various interpretive approaches have been used both by the IPCC and elsewhere.

71. The simplest approach is to take average values across all members, in other words individual projections within an ensemble. This is a common 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.

- Second, 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.

72. Regardless of which route is taken to derive specific projections, it is useful to assess the range of possible climates 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. 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 is calculated to capture 95% or 99% of parameter uncertainty.

73. 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 potential disadvantage of this approach is that the vast amount of information produced can readily overwhelm the user.

74. It should be noted that the natural variability seen in observed historical datasets is currently greater than predicted by many climate simulations. This is the case for modelling extreme Atlantic storminess for instance. Here projections from CMIP phase 3 (CMIP3) and 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 versus SSPs

75. 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).

76. Given these requirements, the first IPCC report in 1990 published the first set of scenarios (IS92); these were replaced in 2000 by SRES that were used until the 4th Assessment Report in 2007 (Table 3). SRES scenarios were in turn replaced by the RCPs, which were used in IPCC AR5. IPCC described the RCPs 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".

77. However, it must be recognised that there are two ways in which the RCPs have been used. Although they are primarily defined in terms of concentrations and the associated radiative forcing at 2100 there are also standard emissions scenarios associated with each RCP. Confusingly, these are given the same name, even though there is not a one-to-one mapping between emissions and concentrations due to uncertainties in climate-carbon cycle feedbacks. As a result, a given emissions scenario can give rise to a range of concentration pathways (e.g. Booth et al., 2017). Conversely, any given concentration pathway is compatible with a range of emissions scenarios (e.g. Jones et al., 2013). This is an issue when comparing modelling studies that used different experimental designs. For example, UKCP09 and UKCP18 use emissions-driven models while CMIP5 uses concentration-driven models, although the same RCP names are used. As a result, RCPs are very often referred to as "emissions scenarios" even when they are actually being used as concentration pathways. The difference is non-trivial as the standard reference concentrations for the RCPs are NOT in the centre of the distribution, they are at the low end. This means an emissions-driven projection like UKCP18 tends to give more warming.

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

79. For the forthcoming IPCC AR6, a new set of emissions scenarios have been issued. These are called Shared Socioeconomic Pathways (SSPs) and were developed in parallel with the RCPs, which did not include any socioeconomic narratives, but the SSPs took much longer to develop. They are used to model how socioeconomic factors may change over the next century by including variables such as population, economic growth, education, urbanisation and the rate of technological development. The SSPs assess global evolution in the absence of climate policy and how different levels of climate-change mitigation could be achieved when the mitigation targets of RCPs are combined with the SSPs. As a result, RCPs and SSPs are complementary. RCPs set pathways for greenhouse gas concentrations and investigate likely future warming, while SSPs provide a characterisation of different socioeconomic futures that could accompany particular emissions scenarios. As a result, they are meant to be illustrative, not predictions or assessments of feasibility. The baseline SSP

scenarios should be considered as reference cases for mitigation, climate impacts and adaptation analyses (Riahi et al., 2017), and are being used in CMIP6 and for the IPCC AR6.

5.5. Climate Sensitivity

80. 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 adjusted change in the 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."

81. Recent estimates from CMIP6 place the sensitivity range between 1.8°C and 5.6°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 (see Sherwood et al., 2020).

5.6. Climate Change Projections for the UK

82. Over the last 15 years three sets of climate-model projections have been produced for the UK by the UK Met Office and partners. These are UK Climate Impacts Programme 2002 (UKCIP02) (a development from UK Climate Impacts Programme 1998), UKCP09 and UKCP18. 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 SRES used in AR4 (Table 3). UKCIP02 uses four different scenarios (A1FI, A2, B2 and B1) while UKCP09 uses three scenarios (A1FI, A1B and B1; see Table 1). The model projections come from the CMIP3 set of model experiments. In 2018, these were replaced by new UKCP18 projections, which were a development from the UKCP09 projections in several ways:

- UKCP18 used the wider CMIP5 models to allow a wider range of regional-climate responses to be captured and increased the resolution of the regional models to allow for representation of convection.
- UKCP18 has a better modelling capability over the land and provides new assessments of projection uncertainties. Both the UKCP09 and UKCP18 land projections use an emissions-driven approach, unlike CMIP5 which uses a concentrations-driven approach. This means that UKCP18 projections are capturing the uncertainties in carbon cycle feedbacks as part of the climate-system response to emissions, whereas CMIP5 does not do this. Instead, the CMIP experimental design allows for the calculation of a range of emissions compatible with the specified concentration pathway. Projection data are provided at a resolution of around 60 km although there have been downscaled numerical experiments run at a resolution of around 5 km to better simulate convection

storms for adaptation planning (Gadian et al., 2018). 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 (Kendon et al., 2014; Gadian et al., 2018).

83. There are also new assessments of future sea-level rise (ONR Expert Panel on Natural Hazards, 2020). Note also that the UKCP18 package includes the marine report that uses a different approach to the land projections. The marine report uses CMIP5 projections, so the warming pathways for specific RCPs are different to those in the land projections. On the whole, for a given RCP, the rate of global warming in the UKCP18 marine projections is lower than in the land projections, because it uses different models and also a different experimental design (concentration-driven rather than emissions-driven – see paragraph 77). Model projections outlined as part of AR5 (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.

84. 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.

5.6.1 Sea Level Changes and High Water Extremes

85. This sub-section provides a summary of sea-level changes and high-water extremes – see ONR Expert Panel on Natural Hazards (2020) for further details.

86. Satellite observations of the Global Mean Sea Level (GMSL) commenced in 1993 and sea-level rise by 2018 was 81 mm over this 25 year time period (Blunden and Arndt, 2019). This is considered to be mainly due to ice melt, rather than thermal expansion, although the report also shows the deeper ocean continues to warm. In 2018 the GMSL trend reached 3.7 mm/yr., the highest since 1993, the seventh consecutive year of an increase and the 23rd in the last 25 years of data. Regionally, such as in the Eastern Atlantic, the rise in sea level has been a little smaller, due to fresh water mixing and salinity changes, but overall the accelerating trend is observed globally. There is also an on-going trend of year-to-year increase in the magnitude and frequency of positive sea-level extremes that cause flooding and erosion (Sweet et al., 2014; Blunden and Arndt, 2019). Nuisance level flooding, defined as more than 0.5m above the mean higher high water level (where the water levels exceed a threshold by the top 1% of daily maxima), shows an increase in both frequency and the height, a result which especially applies to the western coastline of Europe.

87. These recent studies (Sweet et al., 2014; Blunden and Arndt, 2019) have suggested that the GMSL increase will be greater than previously suggested in the IPCC AR5 report and UKCP18 (Lowe et al., 2019). In the high-emission

scenario, RCP8.5, sea-level rise is projected to be 340 mm by 2050 and 1,110 mm (1.11 m) by 2100 above the GMSL observed in 2000. There is a possibility that the rise will be beyond 2 metres by 2100 in the high-emission scenario. This projection lies within the 90% uncertainty for the high-emission bounds. This is more than twice the upper value put forward in IPCC AR5 and UKCP18 (Lowe et al., 2019). This suggests a sea-level rise trend of ~ 9 mm/yr. for the next 30 years and over 111 mm/yr. by 2100. This worst case scenario, which fits within the 95th percentile, predicts an average of well over 20 mm/yr. average over the next 80 years. There are no current estimates at the 84th percentile. The "Imbie" experiment assessment of the accelerating melting of the Greenland ice sheet argues that the Arctic has warmed 0.75°C in the last decade compared with the 1951-1980 average suggesting the shortfall in sea-level rise for the Greenland is likely to be underestimated by ~ 70 mm, (alongside the Antarctic underestimate of ~ 100 mm) and needs to be modified for AR6 (Shepherd et al., 2019). These results (Sweet et al., 2014; Blunden and Arndt, 2019; Shepherd et al., 2019) suggest increases over UKCP18 projections for the end of the century. It should also be made clear that relative sea-level rise around coasts is variable, and depends on a number of factors including the amount of glacio-isostatic rebound.

5.7. Analysis of Combination Events in Climate Change

88. 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. There are relatively few studies that assess the risk and consequences of compound climate or weather events, even though there are clear physical reasons why such events might be combined. For instance, low-pressure cyclonic atmospheric systems are likely to produce high rainfall and consequently high-river discharge, at the same time as producing storm surges that can slow or block river discharge into the sea and cause inland flooding. A recent analysis of combination events, in this case called Compound Flooding (CF), used the Historical Analysis of Natural Hazards in Europe (HANZE) database (Paprotny et al., 2018) to identify 24 CFs around European coasts (Bevacqua et al., 2019). These projections show that CF will increase, particularly along the western British coast, northern France and the east and south coasts of the North Sea. As Bevacqua et al., (2019) report:

"*In a warmer future climate, the probability of CF is projected to robustly increase particularly along the west coast of Great Britain, northern France, the east and south coast of the North Sea, and the eastern half of the Black Sea…. The fraction of coastlines experiencing return periods lower than 6 years is projected to increase from presently 3 to 11% by the end of the 21st century. Hot spot regions where return periods will fall below this value are the Bristol Channel and the Devon and Cornwall coast in the United Kingdom.*"

89. 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).

90. The climate systems that may exhibit tipping point behaviour in the future include the Greenland and West Antarctic Ice Sheets; Amazon Rainforest; Atlantic Meridional Overturning Circulation (AMOC); and the Southern Annular Mode (SAM). 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 suggested that melting of Arctic sea ice has affected high latitude atmospheric circulation patterns and temperature (e.g. Overland et al., 2015), although more recent analysis has questioned these results (Blackport and Screen, 2020). What is clearer is that changes in Arctic Amplification (AA) (section 0) partly associated with sea ice loss is leading to increased negative mass balance of the Greenland Ice Sheet and consequent ice loss. 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.

91. The analysis of such combination effects can produce events that potentially lie within the probability set out by H++ scenarios (Wade et al., 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. A report prepared for the second UK Climate Change Risk Assessment (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

92. High Impact Weather (HIWeather) is now a major programme of the World Weather Research Programme (WWRP) in the World Meteorological Organisation[4] (WMO). The research programme is carrying out an ensemble of simulations at ~12 km resolution (Kotlanski et al., 2014). The UK Met Office, 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., 2018). Both the Kendon et al. (2014) and Gadian et al. (2018) 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.

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

This mirrors similar weather simulation experiments being carried out over a US domain (Bruyere et al., 2014).

93. Preliminary results from both Gadian et al. (2018) 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, although UKCP18 has now rectified this (Kendon et al., 2019). They also suggest that over the UK, models predict longer dry spells and shorter, heavier periods of convective precipitation. Gadian et al. (2018) further suggests that this under-representation is by as much as a factor of ten in terms of frequency. Furthermore, by the period 2031-2036, the amount of precipitation in these events 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 examines precipitation in the next century.

94. Summer wind speeds are projected to reduce, corresponding to prolonged periods of high pressure. Work by Gadian et al. (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. Kendon et al. (2019) report on the convection permitting models (CPMs) and show that UKCP18 uses an ensemble of 12 projections, run at 2.2km resolution that are able to represent hourly rainfall characteristics, including extremes, much more realistically than conventional climate models run at coarser spatial scales. However, uncertainties in these are not known and require further research.

5.8.1 Storm Tracks

95. Changes in storm tracks are of concern to coastal infrastructure, especially on the eastern seaboards of the NH Atlantic and Pacific Oceans (e.g. Tamarin and Kaspi, 2017). Using an idealised model, Tamarin and Kaspi (2017) suggest that there is a latitudinal shift of ~ 0.21° for every degree Celsius of planetary global warming. This is consistent with other research, and the UKCP18 results that suggest possible changes in storm surges and tracks. Examples include the great storms of 1703 and 1607, (Wheeler, 2003) and are discussed in section 3.2. The poleward migration of tropical cyclone maximum intensity has been estimated to be about 50km per decade (Kossin et al., 2014). This suggests that great storms, with surges of over 2m, are increasingly likely to happen with more extreme wind storms likely to hit Western Europe. However, there are also suggestions that reduction in the temperature and pressure differences between the poles and mid-latitudes might reduce wind speeds. Currently there are no quantifiable estimates to the 84^{th} percentile (Section 7.4. and Annex 3).

5.8.2 Atlantic Meridional Overturning Circulation (AMOC)

96. Global oceans contain the memory of the climate system on seasonal to millennial scales, by absorbing CO_2 and heat from the atmosphere and through dynamical processes on all timescales. The overall global Sea Surface Temperatures (SST) warming trends since the 1950s have continued, giving a value of ~ 0.1°C +/- 0.01°C per decade from 1950 - 2018 (Blunden and Arndt, 2019). The SST anomalies reflect variability in response to departures in sea

temperatures such as ENSO (e.g. maximum in 0.44°C +/- 0.05°C in 2016). However, these do not affect the long-term temperature trends, and the report shows that the deeper ocean continues to warm annually.

97. The global ocean Meridional Overturning Circulation (MOC) and - of particular relevance to the UK - the AMOC, are responsible for the northward transport of heat and many climatic consequences (e.g. colder European winters). The AMOC plays an important role in climate variability on seasonal to longer timescales, particularly for northern Europe and the UK. Climate models (IPCC, 2013) have predicted that under the influence of global warming the AMOC will decline and decreases have been observed both directly and indirectly. Using a sustained North Atlantic observing array, Smeed et al. (2014) reported decreases between 2007-2011 in the AMOC larger than those predicted by climate models but noted that these relatively short period observations most likely represented decadal variability rather than a long-term trend due to climate change. Smeed et al. (2018) confirmed that observations between 2012-2017 showed that there had been no further decrease in the state of the AMOC but that it remained in a weaker circulation state than previously. Using patterns of SST, Ceasar et al. (2018) inferred a 15% weakening of the AMOC since the mid-twentieth century due to reduced northwards heat transport and an associated shift in ocean currents

98. A significant reduction in the strength of the AMOC (~ 5%) could lead to cooling in Western Europe by up to 5˚C in the worst case scenario (Jackson et al., 2015), with the possibility of less precipitation and a significant increase in the strengthening of the North Atlantic storm track. In this case, winter precipitation would increase along with stronger winds. The UK summer, in such a regime, would have increased possibility of stronger summer heatwaves (Jackson et al., 2015) (section 8.1.) as a result of weaker westerlies decreasing the maritime cooling effect. However, considerable uncertainty remains in understanding the long-term stability of the AMOC and its potential for rapid change (Weijer et al., 2019). Sustained monitoring of the AMOC through the so-called RAPID array will play a vital role in understanding the nature of current and future changes (Frajka-Williams et al., 2019).

5.8.3 Arctic Amplification (AA)

99. AA is the increased rate of temperature rise experienced in northern, high latitudes compared with the rest of the world. It is caused by several positive feedback mechanisms. These include: reduced albedo as Arctic sea and land ice is melted; increased stratification of the ocean; and, increases in atmospheric water vapour and methane from melting permafrost (Coumou, 2018). The effects of meandering jet streams and changes in the mid-latitudinal storm tracks (as discussed in section 0) provide the necessary structures linking the Arctic (Vallis et al., 2015) and mid-latitude weather patterns (Cohen et al., 2014). The Southern Hemisphere (SH) circumpolar jet stream is primarily zonal, but in the NH, large meanders result in more significant advection of warm wet subtropical air into Arctic regions, enhancing ice melt (Vallis et al., 2015) (section 0). With possible changes to the AMOC the mid-latitudes could experience hotter dryer extremes, weaker storm tracks and amplified quasi-stationary heat waves (section 8.1.).

6. ANALYSIS OF PLUVIAL & FLUVIAL FLOODING

6.1. Pluvial Flooding

6.1.1 Extreme Rainfall

100. Intense rainfall is associated with events such as ARs (that occur largely in winter) and convective thunderstorms that 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.

101. 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). December 2015 was the wettest month in the instrumental record and the winter (December-February) was the second wettest in the series since 1910. The winter was exceptional because of the spatial scale of the flooding and its duration, and also because it followed closely on from the severe 2013/14 winter. The largest event in 2015 was Storm Desmond from 4-6 December. Exceptional rain totals fell in the Lake District, giving the highest rainfall measured for any 24 hour period when Honister Pass experienced rainfall of 341.4 mm in the 24-hours to 18:00 GMT on 5th December 2015 as did other regions in the northwest. A 48 h rainfall record of 405 mm was achieved at Thirlmere (Parry et al., 2016). This period has been called "*one of the most extraordinary hydrological episodes witnessed in the UK in recent decades*" (Barker et al., 2016). It is assessed that these had a return period of around 1300 years and a 0.08% probability (Barker et al., 2016; Burt et al., 2016; Parry et al., 2016; Chiverrell et al., 2019).

102. 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.

6.1.2 Snowfall

103. *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 2°C), snow will reach the ground without melting into rainfall and, if temperatures remain cold, accumulate into a snowpack.

104. 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 580 mm at Balmoral in Aberdeenshire and 550 mm 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 (Prior and Kendon, 2011). In February 2018, the "*Beast from the East*", a cold Arctic polar vortex transported cold air from Siberia, combined with storm Emma produced heavy snowfall of up to 500 mm over UK and Ireland. These events are continuing examples of extreme snowfall events.

6.1.3 Rain on Snow

105. Where a snowpack 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.

6.1.4 Climate Change Effects

106. 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 can hold more water and more energy is available for the generation of convective thunderstorms, leading to an increase in the likelihood of extreme rainfall (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 that 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).

107. 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 that 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 NH (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 (Section 5.3.), but do not include possible changes in AMOC (section 0).

108. Freezing rain occurs when supercooled rain at a temperature below 0°C impacts on the surface. Rain falling through a layer of sub-zero temperatures causes freezing rain and is often found as a warm front arrives and passes over cold air. It can be very dangerous, as surfaces become extremely slippery. These dangerous conditions can cause significant ice and weight build up on telephone and power lines causing severe disruption as they break under the weight. Cheng et al. (2011) argue that in NE Canada, freezing rain will increase in the colder months, in a warming climate, but would decrease to a lesser extent over the warmer months and possibly the planet in general. Freezing rain has not been common in the UK but this may change in a warming climate. Occurrences of supercooled rain over warm frontal air can happen anywhere in the UK and should be considered as a hazard.

6.2. Fluvial Flooding

109. Analysing river flood hazard involves:

- Collection of data (including statistical data on flood events and magnitude; meteorological data on weather events and trends; and, topographic data for inundation modelling).
- Flood frequency analysis – in other words 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.

6.2.1 Potential Climate Change Effects in Recent Flood Events and Short Datasets

110. 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. 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 £1.3 billion 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 and the amount of water vapour in the atmosphere, increasing the likelihood of extreme precipitation (Huntingford et al., 2014; Schaller et al., 2016).

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

112. The use of short-term datasets, use of local data in flood frequency estimation and potential climate change effects from recent floods in England and Wales are discussed in the Environment Agency (2021) report.

6.2.2 Fluvial Flooding and Flood Frequency Analysis

113. 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 duration 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.

114. 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.

115. 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 to predict the magnitude of an extreme event with a 0.01% annual probability of exceedance.

116. 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). A clear pattern exists in the palaeoflood record of times showing that floods are concentrated in periods of wet stormy conditions (e.g. Macklin and Lewin, 2003) associated with positive NAO conditions; and also times when floods are associated with negative NAO conditions and with convective storms. Recent convection storms include the floods at Boscastle in 2004 (Roca and Davison, 2010) and 2017 at Coverack (Archer and Fowler, 2018; Flack et al., 2019) in southwest England. This association of floods with both negative and positive NAO conditions, means that flood risk assessments cannot be based upon modelled NAO behaviour, and it also complicates flood attribution.

117. Analysis of recent flooding events provided by the CEH for the 2019-2020 winter provide further guidance on recent extreme events in the UK (Sefton et al., 2021).

118. There are local data sources in flood frequency estimation being developed on government websites on flood and coastal erosion risk management (FECRM, 2021) including non-stationarity in flood forecasting. In addition, the work undertaken by the Flooding From Intense Rainfall (FFIR) project in the UK is providing more flood data and analysis (JBA-trust, 2021).

119. Statistical methods are used in hazard analysis and for non-stationarity and compound hazards and in the development of the interim national guidance on non-stationary fluvial flood frequency estimation in the UK (FCERM, 2021). This examines methods to estimate Probable Maximum Precipitation (PMP) and Probable Maximum Flooding (PMF). Phase 2 of this programme will implement these new methods to high-risk infrastructure. Further, the Flood Hydrology Road Map project is setting-out a 25 year vision and producing a strategic plan for investing in the data, methods, models, scientific understanding and ways of working required to make operational flood hydrology and hydrometry fit to meet the changing requirements of inland flood risk management in the UK.

6.2.3 Flood Modelling

120. There are two primary types of flood model: *hydrological* and *hydraulic*. Hydrological 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.

121. 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 hydrological 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.

122. 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 that 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).

123. 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 (Bates et al., 2006; Néelz et al., 2006) or satellite imagery (Brivio et al., 2002; Archer et al., 2018; Hawker et al., 2019) 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 are 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 that 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.

124. 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 (0.1% annual probability of exceedance), areas that 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.

6.2.4 Approaches for Hydraulic Flood Modelling

125. 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.

126. 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 that 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 accurately simulate topographically complex floodplain environments where flow is inherently at least two-dimensional. Hybrid approaches have also been developed that 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 (e.g. Bellos and Tsakiris, 2015).

127. Within 2D approaches, the modelling grid represents the topographical land surface. Small topographical variations, on the floodplain will affect the flow of water during a flood event, particularly during floodplain wetting and drying. Airborne remote sensing using Light Detection and Ranging (LiDAR) now permits the routine collection of detailed topographical data that include these important features at spatial resolutions of around 1-2 m, with a vertical accuracy of around 150 mm (Habib, 2008), or even smaller. The level of detail in the representation of topographical 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 that solve the full shallow water equations are all suitable to support flood-risk management in most scenarios, except where the model's application area is large (>1,000 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 that are capable of capturing hydraulic shock waves were found to have superior performance.

7. ANALYSIS OF WIND

128. 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

129. 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 Objectively Analysed air-sea Fluxes (OAFlux) for global oceans (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 ten 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% per 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., (2018) 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.

130. 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 wind speed (*u*) 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 systematically underestimate the wind speed over land, as well as in coastal regions (Kent et al., 2012). However Zeng et al. (2019) has completed a new statistical analysis using more data and found that the trend of -0.08 m/s per decade for 1978-2010 has now reversed and 2010-2017 indicates an increase of 0.24 m/s per decade, using a set of NH surface stations. The signal is found for all of North America, Asia and Europe. The suggested reasons for this reversal are related to the NAO and other equivalent indices for Asia and North America regions, and possibly related to SST. However, an eight year sample is small for long-term predictions and there is no indication whether this reversal is a temporary phenomenon.

131. In summary, there is evidence that wind speeds globally are reducing (global atmospheric stilling) 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. Recent evidence suggests that global wind speeds have increased from 2010-2017, reversing this trend.

7.2. SREX Report

132. 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 extra-tropical 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 extra-tropical storm tracks that is associated with a large proportion of high wind speed events.
- Second, they noted that there is currently low confidence in observed trends on tornadoes and hailstorms and this is due to inhomogeneities and uncertainties in observational data.
- Third, projections of small-scale extreme events such as tornadoes are made uncertain because there are several ways in which future atmospheric trends might evolve. The small-scale nature of such events means that the physical processes driving them must be parameterised in climate models with the uncertainties that follow from this.
- Fourth, 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 future cyclone extreme winds will likely increase in magnitude, but this is not a clear projection for all ocean basins. The frequency of such events will likely either decrease or remain unchanged.
- 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.

133. 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

134. 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).

135. 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 of 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.

136. Projections from CMIP3 and CMIP5 models and downscaled RCMs from these show 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

137. The winter storms affecting the British Isles in 2013-14 and 2015-16 were unusually severe and associated with extreme rainfall and coastal flooding (UK Met Office 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 AA, the expansion of sub-tropical cells and the influence of teleconnections between NH wind regimes and multi-annual oscillations such as ENSO.

138. 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 SH, with greater storm activity at higher latitudes*'' (Meehl et al., 2007).

139. 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) (see also section 0).

140. 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 inter-annual 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 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).

141. 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. Tornadoes

142. While there is no clear consensus whether tornadoes 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 that partly drives convective storms (Riemann-Campe et al., 2009). Additionally, in a study covering the US, Gallus et al. (2008) classified the types of parent storms that were most likely to produce tornadoes and since all are generally associated with supercell structures. Supercells are strong convective cumulonimbus storms, sometimes quasi-stationary, but often have a slowly rotating cores, intense precipitation, large anvils and exist for long periods (hours) and their occurrence is likely to increase in the British Isles, as discussed in Section 7.2.

143. Tornadoes 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 are of short duration. Perhaps the most famous destructive UK tornado was in 1091, when London Bridge was destroyed (leading to the nursery rhyme, “*London Bridge is falling down*”) and caused by a 200+ mph tornado (Rowe et al., 1976). Similarly, the Scottish Tay Railway Bridge disaster in 1879 was possibly the result of a twin tornado with wind speeds greater than 90+ mph (Doe, 2015). Using data from 1980-2012, Mulder and Schultz (2015) showed that most UK tornadoes (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 tornadoes where wind speed could be measured or estimated were on the F0 or F1 scale, with the remainder reaching F2. No F3 tornadoes (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

144. 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 current active research.

8.1. Heat Waves

145. Heat waves are associated with prolonged periods of relatively extreme high temperature, sometimes with high humidity and provide significant heating, ventilation and air conditioning challenges for power-generation systems. In mid-latitudes they are commonly associated with quasi-stationary, high-pressure systems in the summer. There are numerous examples of note, including:

- The European heat wave of 2003 that was approximately 8 days in duration, and estimated to have killed more than 35,000 people[5,6]https://www.newscientist.com/article/dn4259-european-heatwave-caused-35000-deaths/). In France, 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).
- In 2018, nuclear plants in five European countries were shutdown or had to significantly reduce output due to the European summer heat wave[7,8], where temperatures were up to 6°C warmer than the climatological norm.
- In summer 2019, western Europe experienced a severe heat wave. Towards the end of July, temperatures of more than 40°C were recorded for the first time in several countries and over 4 days. The heat wave over 3 days had a return period assessed as 50-150 years, and in France and the Netherlands this was about 100 times higher than expected in a stationary climate. Comparing the 2003 and 2019 heat waves is difficult as the relationships between mortality and temperature may not have been the same in the two events, given advances in medical science and heat mitigation schemes (Mitchell et al., 2019).

146. Adapting to heat-waves has become increasingly important for governments to address, both in terms of infrastructure and human health and these are the subject of recent research (e.g. Mitchell et al., 2019).

147. In mid-latitudes, these low frequency heat wave type weather systems are often called 'blocking' patterns. Some opinion argues that such systems are associated with SST anomalies around the globe and particularly in the western Atlantic (Holton and Hakim, 2012). Others argue that a reduction in AMOC strength (section 0) and general reduction in the meridional temperature gradient (Woollings et al., 2018) will increase blocking events. At the surface, quasi-stationary, high-pressure weather systems are observed to be several thousand kilometres in diameter, and evidence suggests that in the NH mid-latitude regions, their longevity is enhanced when simultaneously associated with numerous smaller-scale cyclonic systems (Holton and Hakim, 2012).

5 https://www.newscientist.com/article/dn4259-european-heatwave-caused-35000-deaths
6 https://www.metoffice.gov.uk/learning/learn-about-the-weather/weather-phenomena/case-studies/heatwave.
7 https://www.neimagazine.com/news/newseuropes-heatwave-affects-npps-6271432
8 https://www.theguardian.com/news/2018/sep/07/weatherwatch-nuclear-power-plants-feel-the-heat

148. 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.

149. High resolution weather models, run for future climate scenarios, suggest that these events might become more common. UKCP18 (Lowe et al., 2019) indicates an increase of maximum temperatures of above 30°C for two or more days from a current 0.25 to 4.3 occurrences per year by 2070. Other work (e.g. Gadian et al., 2018) suggests this could occur by the 2030s. Much of current scientific opinion is that hot summers leading to conditions that could support heat waves, could become more frequent by 2050. These higher temperatures, with prolongation of dry spells, are also discussed in Section 5.

8.2. Fog – High humidity

150. Fog (and low visibility generally) is one of the costliest weather events in terms of financial and human losses, in some situations comparable to the losses from tornadoes or even 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 this can lead to ice accumulation onto cold surfaces. Fog dispersal techniques have been tried, but are very expensive and of limited effectiveness. A summary of fog hazards (Croft, 2013) includes discussion of the effects on basic infrastructure and human health. No comprehensive change in frequency of fog events is discussed in the recent scientific literature, but any increase in low wind speed regimes (e.g. Gadian et al., 2018) is likely to change this frequency. Fog hazard is one of the hardest to predict, but of importance because of its potential widespread, if temporary, effects on infrastructure including transport (Oliver, 2008). Air travel and road transport will be affected in such events, and this could present challenges in any emergency scenarios. While fog will not occur during large-scale storms, but could provide difficulties if occurring at the same time as seismic events, and could also obstruct remote sensing observations from aircraft and satellites. A new study by Bergot and Koracin (2021) provides a comprehensive review of fog, and provides estimations of future frequency and patterns in a warmer climate based on observations and simulations. The study concludes that fog remains a difficult phenomenon to predict.

8.3. Lightning

151. Lightning is largely generated from the electric fields generated by the interaction of ice and small hail (graupel[9]) particles and is also critically dependent on the liquid water content of individual clouds (Miller et al., 2001). Strong convection often enhances electric field generation and lightning strikes (Blyth et al., 2001). Lightning occurs when there is an electrostatic discharge between two charged regions that can create a significant electric field potential. Lightning can be induced by weak electric fields, such as when a spacecraft launch occurs, where there are moderate electric fields of sufficient thickness at the freezing level. Electric field mills are utilised to measure the electric field potential at launch

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

sites, to avoid lightning during launches. However, lightning is much more often associated with extreme precipitation events and thunderstorms (Latham et al., 2004; Baker et al., 1999). Critically, therefore, with an increase in severe convection (as suggested by Kendon et al. 2014 and Gadian et al. 2018), the incidence of lightning is projected to increase. Satellite Lightning Imaging Sensor; (LIS) observations also suggest that global lightning and global temperature are well correlated on the annual time scale (Williams et al., 2016).

152. 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. Most lightning strikes are intra-cloud, or cloud-to-cloud discharges between differently charged regions. Discharges, though most commonly in clouds, sometimes occur, for example, in active volcanic plumes and other areas where charged regions are generated. Cloud-to-ground strikes can produce of the order of a billion joules of energy, and can cause significant damage to infrastructure, if not protected. Lightning strike research is now receiving more attention, but current knowledge is very much a statement of awareness; to produce a hazard curve at this time would be challenging. As atmospheric models gain greater resolution, meteorological organisations are now actively producing lightning forecasts

153. 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). More recent information on enabling a resilient UK Energy Infrastructure has been produced in conjunction with the UK Met Office (ETI Handbook, 2018).

154. Future lightning occurrence changes in a warming climate is subject to further study. The UKCP18 convection-permitting model projections: science report (Kendon et al., 2019) includes high resolution 2.2km simulations and these will be used to assess changes in lightning frequency in future decades. There is a common view that lightning frequency will increase with strong convection caused by a warming environment. In the US, projected lightning strikes are estimated to increase by 12% per °C of warming and by at least 50% by the end of the century (Romps et al., 2014). 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, a criticism of low-resolution models is that they do not include convection processes and therefore may not capture important physical processes driving lightning. Declan et al. (2018) argue that there could be a 15% decrease worldwide in lightning strikes by the end of the century. The method of calculation of future lightning frequency is different between the publications. However, in 1984, York Minster was hit by lightning for the first time in 600 years and it is extremely plausible from purely physical arguments, that with stronger atmospheric convection, such lightning events could become more frequent. More research is required on the topic of lightning hazards. The distribution of

lightning frequency was observed by the Optical Transient Detector satellite (Christian et al., 2003). However, lightning is a significant hazard and it would be wisest to assume the worst case scenario, that there could be up to a 50% increase in lightning activity by the end of the century (Romps et al., 2014).

8.4. Space Weather

155. Space weather has sometimes been associated with meteorological hazards. Space weather events present challenges to electrical infrastructure (Cabinet Office, 2015). The solar storm of 1859 ("*the Carrington Event*") immobilised telegraph systems. The damage to electrical grid infrastructure today would be much greater and could have significant impact, disabling electrical systems in a parallel manner to direct lightning strikes. An example of a solar storm in 2012 (Gopalswamy et al., 2016*)* missed the earth by nine days and such events represent a hazard to infrastructure. Space weather is discussed in more detail in Appendix 2 of TAG 13 (Electromagnetic Interference and Space Weather).

9. REFERENCES

Acreman, M. (1989). Extreme Rainfall in Calderdale, 19 May 1989. *Weather*, 44, pp.438–446. DOI:10.1002/j.1477-8696.1989.tb04980.x.

Adams, S.V. R.W. Ford, M. Hambley, J.M. Hobson, I. Kavčič, C.M. Maynard, T. Melvin, E.H. Müller, S. Mullerworth, A.R. Porter, M. Rezny, B.J. Shipway, R. Wong. 2019. LFRic: Meeting the challenges of scalability and performance portability in Weather and Climate models.
Journal of Parallel & Distributed Computing, . https://doi.org/10.1016/j.jpdc.2019.02.007.

Adaptation Sub Committee (2015). Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps. Committee on Climate Change. https://www.theccc.org.uk/wp-content/uploads/2015/10/Met-Office-for-the-ASC-Developing-H-climate-change-scenarios-for-heatwaves-droughts-floods-windstorms-and-cold-snaps3.pdf

Aksoy, H., Toprak, Z.F., Aytek, A. and Unal, N.E. (2004). Stochastic generation of hourly mean wind speed data. *Renewable Energy*, 29, pp.2111–2131.

Alexander, L.V. and Jones, P.D. (2001). Updated precipitation series for the U.K. and discussion of recent extremes. *Atmospheric Science Letters*, 1, pp.1-9. DOI:10.1006/asle.2001.0025.

Anderson, E., Harrison, S., Passmore, D.G., Mighall, T. and Wathan, S. (2004). Late Quaternary river terrace development in the Macgillycuddy's Reeks, southwest Ireland. *Quaternary Science Reviews,* 23, pp.1785-1801.

Anderson, G. and Klugmann, D. (2014). A European lightning density analysis using 5 years of ATDnet data. *Natural Hazards and Earth Systems Sciences,* 14, pp. 815-829. https://doi.org/10.5194/nhess-14-815-2014.

Archer, D.R. and Fowler, H.J., 2018. Characterising flash flood response to intense rainfall and impacts using historical information and gauged data in Britain. *Journal of Flood Risk Management*, *11*, pp.S121-S133.

Archer, L., Neal, J. C., Bates, P. D., and House, J. I. 2018. Comparing TanDEM-Xdata with frequently used DEMs for flood inundation modeling. *Water Resources Research*,54. https://doi.org/10.1029/2018WR023688

Armstrong, R.A. (2006). Seasonal growth of the crustose lichen Rhizocarpon geographicum (L.) DC. in South Gwynedd, Wales. *Symbiosis,* 41, pp. 97–102.

Atlas, R., Hoffman, R., Ardizzone, J., Leidner, S., Jusem, J., Smith, D. and Gombos, D. (2011). A cross-calibrated multiplatform ocean wind velocity product for meteorological and oceanographic applications. *Bulletin of the American Meteorological Society,* 92, pp.157-174.

Baker, M., Blyth, A.,. Christian, H. , Latham, J., Miller, A and Gadian., A (1999) Relationships between lightning activity and various thundercloud parameters: satellite and modelling studies. *Atmospheric Research,* 51, Issues 3-4, pp 221-236

Baker, V.R., 1987. Paleoflood hydrology and extraordinary flood events. *Journal of Hydrology*, *96*(1-4), pp.79-99.

Baker, V.R., Webb, R.H. and House, P.K. (2002). The scientific and societal value of paleoflood hydrology. In: *Ancient floods, modern hazards—Principles and applications of paleoflood hydrology. [*House, P.K., Webb, R.H., Baker, V.R. and Levish, D.R. (Eds)]. Washington, D.C., American Geophysical Union, Water Science and Application Series, 5, pp.127–146.

Bakker, A.M.R., van den Hurk, B.J.J.M. and Coelingh, J.P. (2013). Decomposition of the windiness index in the Netherlands for the assessment of future long-term wind supply, *Wind Energy,* 16, pp.927–936.

Bamber JL, Oppenheimer M, Kopp RE, Aspinall WP, Cooke RM. Ice sheet contributions to future sea-level rise from structured expert judgment. (2019) *Proceedings of the National Academy of Sciencesi U S A*. ;116(23):11195–11200. doi:10.1073/pnas.1817205116

Barber, K.E., Maddy, D., Rose, N., Stevenson, A.C., Stoneman, R.E. and Thompson, R. (2000). Replicated proxy-climate signals over the last 2,000 years from two distant UK peat bogs: new evidence for regional paleoclimate teleconnections. *Quaternary Science Reviews,* 18, pp.471–479.

Barber, K., Brown, A., Langdon, P. and Hughes, P. (2013). Comparing and cross-validating lake and bog paleoclimatic records: a review and a new 5,000 year chironomid-inferred temperature record from northern England. *Journal of Paleolimnology*, 49, pp.497-512.

Barker, L., Hannaford, J., Muchan, K., Turner, S. and Parry, S., 2016. The winter 2015/2016 floods in the UK: a hydrological appraisal. *Weather*, *71*(12), pp.324-333.

Bates, P. and De Roo, A. (2000). A simple raster-based model for flood inundation simulation. *Journal of Hydrology*, 236(1-2), pp.54–77.

Bates, P.D., Wilson, M.D., Horritt, M.S., Mason, D.C., Holden, N. and Currie, A. (2006). Reach scale floodplain inundation dynamics observed using airborne synthetic aperture radar imagery: Data analysis and modelling. *Journal of Hydrology*, 328(1-2), pp.306–318.

Bellos, V. and Tsakiris, G., 2015. Comparing various methods of building representation for 2D flood modelling in built-up areas. *Water Resources Management*, *29*(2), pp.379-397.

Benito, G. and O'Connor, J.E. (2013). Quantitative paleoflood hydrology, Wohl, E.E. [Ed], In Shroder, J. [Ed. in chief], *Treatise on geomorphology*, Volume 9—Fluvial geomorphology: San Diego, Academic Press, pp. 459–474.

Bergot, T. and Koracin, D., (2021). Observation, simulation and predictability of fog: review and perspectives. *Atmosphere*, 12(235). https://doi.org/10.3390/atmos12020235

Berry, D.I. and Kent, E.C. (2009). A new air–sea interaction gridded dataset from ICOADS with uncertainty estimates. *Bulletin of the American Meteorological Society*, *90*(5), pp.645-656.

Bevacqua, E., Maraun, D., Vousdoukas, M.I., Voukouvalas, E., Vrac, M., Mentaschi, L. and Widmann, M., 2019. Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. *Science Advances*, *5*(9), p.eaaw5531.

Black, E., Blackburn, M., Harrison, G., Hoskins, B. and Methven, J. (2003). Factors Contributing to the Summer 2003 European Heatwave. Dept of Meteorology, University of Reading, UK
https://web.archive.org/web/20051013071340/http://www.met.reading.ac.uk/~swrmethn/summer2003/heatwave2003_reading_incfigs.pdf.

Blackport, R. and Screen, J.A., 2020. Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves. *Science Advances*, *6*(8), p.eaay2880

Blundell, A. and Barber, K. (2005). A 2800-year paleoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. *Quaternary Science Reviews,* 24, pp.1261-1277.

Blunden, J and D.S. Arndt, Eds. (2019) State of the climate in 2018 . *Bulletin of the American Meteorological Society.* **100** , S1—S305, (2019) doi: 10101775/2019BAMSStateof the Climate.1

Blyth AM, Christian HJ, Driscoll K, Gadian AM, Latham J. 2001. Determination of ice precipitation rates and thunderstorm anvil ice contents from satellite observations of lightning. *Atmospheric Research .* **59**, pp. 217-229

Booth, B.B., Harris, G.R., Murphy, J.M., House, J.I., Jones, C.D., Sexton, D. and Sitch, S., 2017. Narrowing the range of future climate projections using historical observations of atmospheric CO2. *Journal of Climate*, *30*(8), pp.3039-3053.

Bourassa, M.A., Gille, S.T., Jackson, D.L., Roberts, J.B. and Wick, G.A. (2010). Ocean winds and turbulent air-sea fluxes inferred from remote sensing. *Oceanography,* 23, pp. 36-51.

Bradbrook, K.F., Lane, S.N., Waller, S.G. and Bates, P.D. (2004). Two dimensional diffusion wave modelling of flood inundation using a simplified channel representation. *International Journal of River Basin Management*, *2*(3), pp.211-223.

Bradwell, T. (2010). Studies on the growth of Rhizocarpon geographicum in NW Scotland, and some implications for lichenometry. *Geografiska Annaler*, 92, pp.41–52.

Brivio P.A., Colombo, R., Maggi, M. and Tomasoni, R. (2002). Integration of remote sensing data and GIS for accurate mapping of flooded areas. *International Journal of Remote Sensing*, 23(3), pp.429–441.

Browning, K.A. (1990). Rain, rainclouds and climate. *Quarterly Journal of the Royal Meteorological Society*, 116, pp.1025–1051. DOI:10.1002/qj.49711649502.

BS EN/IEC 62305-1:2011 (2011). Protection against Lightning. General Principles.

Bruyere, C. L., Done, J.M., Holland, G.J. and Fredrick, S.M. (2014). Bias corrections of global models for regional climate simulations of high-impact weather. *Climate Dynamics*, 43, pp. 1847-1856, doi:10.1007/s00382-013-2011-6.

Bruyère CL, Monaghan AJ, Steinhoff DF, Yates D. (2015). Bias-corrected CMIP5 CESM data in WRF/MPAS intermediate file format. NCAR Technical Note TN-515+STR, National Center for Atmospheric Research: Boulder, CO, 27 pp., doi: 10.5065/D6445JJ7. https://opensky.ucar.edu/islandora/object/technotes%3A527 (accessed November 2019)

Bryant, E.A. and Haslett, S.K. (2007). Catastrophic Wave Erosion, Bristol Channel, United Kingdom: Impact of Tsunami? *The Journal of Geology*, 115, pp.253-269.

Burt S. 2016. New extreme monthly rain fall totals for the United Kingdom and Ireland: December 2015. *Weather* 71: 333–338

Cabinet Office (2015) Space Weather preparedness strategy, BIS/15/457 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/449593/BIS-15-457-space-weather-preparedness-strategy.pdf

Caesar, L., Rahmstorf, S., Robinson, A. *et al.* (2018) Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* **556,** 191–196 doi:10.1038/s41586-018-0006-5

Catto, J., Shaffrey, L. and Hodges, K. (2011). Northern Hemisphere extratropical cyclones in a warming climate in the HiGEM high-resolution climate model. *Journal of Climate*, 24, pp.5336–5352.

CCRA3, (2021). Climate Change Risk Assessment (3) https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/

Centre for Ecology and Hydrology (2016). Flood estimation handbook, https://www.ceh.ac.uk/services/flood-estimation-handbook-web-service.

Chan, S.C., Kendon, E.J., Fowler, H.J., Blenkinsop, S. and Roberts, N.M. (2014). Projected increases in summer and winter UK sub-daily precipitation extremes from high resolution regional climate models. *Environmental Research Letters*. 9, pp.1-8.

Cheng, C, Li G. & Auld H. (2011) Possible Impacts of Climate Change on Freezing Rain Using Downscaled Future Climate Scenarios: Updated for Eastern Canada, *Atmosphere-Ocean*, 49:1, 8-21, DOI: 10.1080/07055900.2011.555728

Christian, H. J., et al. (2003), Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, *Journal of Geophysical Research.*, *108*(D1), 4005, DOI https://doi.org/10.1029/2002JD002347

Christensen, J .H. and Christensen, O.B. (2003). Climate modelling: severe summertime flooding in Europe. *Nature*, 421(6925), pp.805-806.

Cohen, J. et al. Recent Arctic amplification and extreme mid-latitude weather. *Nature. Geoscience.* **7**, 627–637 (2014).

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet ,T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J. and Wehner, M. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. Chapter 12 in: *Climate Change 2013: The Physical Science Basis*. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T.F., Qin, D., Plattner, G-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. [Eds]). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter12_FINAL.pdf There is a new hyperlink for this document: WG1AR5_Chapter12_FINAL.pdf (ipcc.ch)

Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R.J., Yin, X., Gleason, B.E., Vose, R.S., Rutledge, G., Bessemoulin, P.and Brönnimann, S. (2011). The twentieth century reanalysis project. *Quarterly Journal of the Royal Meteorological Society*, 137(654), pp.1-28.

Coumou, D., Di Capua, G., Vavrus, S. *et al. (2018)* The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications* **9,** 2959 doi:10.1038/s41467-018-05256-8

Croft P.J. (2013). Fog Hazards, In: Bobrowsky P.T. (Ed) Encyclopedi of Natural Hazards, Encyclopedia of Earth Sciences Series, Springer, Dordrecht, Doi:10.1007/978-1-4020-4399-4_143

Dacre, H.F., Clark, P.A., Martinez-Alvarado, O. and Stringer, M.A. (2015). How Do Atmospheric Rivers Form? *Bulletin of the American Meteorological Society*, Diabatic Influence on Mesoscale Structures in Extratropical Storms (DIAMET) Special Collection, pp.1243-1254.

Declan L. Finney, Ruth M. Doherty, Oliver Wild, David S. Stevenson, Ian A. MacKenzie, Alan M. Blyth. (2018) A projected decrease in lightning under climate change. *Nature Climate Change* ; DOI 10.1038/s41558-018-0072-6

Davini, P. and Cagnazzo, C. (2014). On the misinterpretation of the North Atlantic Oscillation in CMIP5 models, *Climate Dynamics,* 43, pp.1497-1511.

Dawson, A.G., Elliott, L., Noone, S., Hickey, K., Holt, T., Wadhams, P. and Foster, I. (2004). Historical storminess and climate 'see-saws' in the North Atlantic region. *Marine Geology,* 210, pp.247– 259.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P. and Bechtold, P. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), pp.553-597.

Doe, R. (Editor) (2015). Extreme Weather: Forty years of Tornado and Storm Research Organisation (TORRO) Wiley ISBN: 978-1-118-94995-5

Donat, M.G., Renggli, D., Wild, S., Alexander, L.V., Leckebusch, G.C. and Ulbrich, U. (2011). Reanalysis suggests long-term upward trends in European storminess since 1871. *Geophysical Research Letters*, 38, L14703.

ECHAM (2018). http://www.mpimet.mpg.de/en/science/models/mpi-esm/echam/.

Environment Agency (2011). Advice for Flood and Coastal Erosion Risk Management Authorities.
Flood and coastal risk projects, schemes and strategies: climate change allowances - GOV.UK (www.gov.uk) and Flood risk assessments: climate change allowances - GOV.UK (www.gov.uk)
https://www.gov.uk/government/publications/adapting-to-climate-change-for-risk-management-authorities.

Environment Agency (2021) Evidence on the costs of floods in England and Wales, https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/evidence-on-the-costs-of-floods-in-england-and-wales?web=1&wdLOR=cDFCE4ADC-EFE1-3F45-8EE3-2112C5CDF384
and use of local data, https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/making-better-use-of-local-data-in-flood-frequency-estimation?web=1&wdLOR=c13CD04F9-2A4D-5C45-8557-9717F09C6DCB

ETI Handbook (2018) Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies , Volume 9, https://www.imeche.org/docs/default-source/1-oscar/themes/eti-documents/vol9_lightning.pdf?sfvrsn=2 Accessed November 2019

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geoscientific Model Development*, 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

FCERM, (2021). Development of Interim national guidance on non-stationary fluvial flood frequency estimation**,** https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/development-of-interim-national-guidance-on-non-stationary-fluvial-flood-frequency-estimation?web=1&wdLOR=c6A7A4657-8F29-5045-88FC-A18936B41F28
and compounded hazards**,** https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/planning-for-the-risk-of-widespread-flooding; https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/spatial-coherence-risk-of-widespread-flooding

FECRM, (2021). Flood frequency estimation and coastal risk Management.
https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/making-better-use-of-local-data-in-flood-frequency-estimation
and non-stationarity in flood forecasting, https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/development-of-interim-national-guidance-on-non-stationary-fluvial-flood-frequency-estimation

Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.D., Plattner, G.-K., Allen, S.K., Tignor, M. and Midgley, P.M. [Eds.] (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Finney, D.L., Doherty, R.M., Wild, O., Stevenson, D.S., MacKenzie, I.A. and Blyth, A.M.(2018). A projected decrease in lightning under climate change. *Nature Climate Change*. 8, pp.210-213, DOI:10.1038/s41558-018-0072-6.

Flack, D.L., Skinner, C.J., Hawkness-Smith, L., O'Donnell, G., Thompson, R.J., Waller, J.A., Chen, A.S., Moloney, J., Largeron, C., Xia, X. and Blenkinsop, S., 2019. Recommendations for improving integration in national end-to-end flood forecasting systems: An overview of the FFIR (Flooding From Intense Rainfall) programme. *Water*, *11*(4), p.725.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S. and Hurrell, J.W. (2009). The summer North Atlantic Oscillation: past, present and future. *Journal of Climate,* 22, pp. 1082–1103. DOI: 10.1175/2008JCLI2459.1.

Foulds. S. and Macklin, M. (2016). A hydrogeomorphic assessment of twenty-first century floods in the UK. *Earth Surface Processes and Landforms,* 41(2), pp. 256-270.

Frajka-Williams E., et al. (2019). Atlantic Meridional Overturning Circulation: Observed Transport and Variability, *Frontiers in Marine Science* ,6, pp 260 https://www.frontiersin.org/article/10.3389/fmars.2019.00260 doi: 10.3389/fmars.2019.00260

Frances, F., Salas, J.D. and Boes, D.C. (1994). Flood frequency analysis with systematic and historical or paleoflood data based on the two-parameter general extreme value models. *Water resources research*, 30(6), pp.1653-1664.

Gadian, A.M., Blyth, A.M., Bruyere, C.L., Burton, R.R., Done, J.M., Groves, J., Holland, G., Mobbs, S.D., Pozo, J.T.D., Tye, M.R. and Warner, J.L. (2018). A case study of possible future summer convective precipitation over the UK and Europe from a regional climate projection. *International Journal of Climatology,* 38, pp.2314-2324. doi: 10.1002/joc.5336

Gallego-Sala, A.V., Charman, D.J., Harrison, S.P., Li, G. and Prentice, I.C., 2015. Climate-driven expansion of blanket bogs in Britain during the Holocene. *Climate of the Past Discussions*, *11*(5), pp.4811-4832.

Gallus, W. A., Jr., N. A. Snook, and E. V. Johnson, 2008: Spring and summer severe weather reports over the Midwest as a function of convective mode: A preliminary study. *Weather Forecasting*,23, 101–113, doi: https://doi.org/10.1175/2007WAF2006120.1

Garcia, A., Torres, J.L., Prieto, E. and De Francisco, A. (1998). Fitting wind speed distributions: a case study. *Solar Energy*, 62(2), pp.139–144.

Giorgi, F., Jones, C. and Asrar, G.R. (2009). Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organization (WMO) Bulletin*, 58(3), pp.175-183.

Glaser, R., Riemann, D., Schönbein, J., Barriendos, M., Brázdil, R., Bertolin, C., Camuffo, D., Deutsch, M., Dobrovolný, P., van Engelen, A. and Enzi, S. (2010). The variability of European floods since AD 1500. *Climatic Change*, 101, pp.235–256. DOI 10.1007/s10584-010-9816-7.

Gopalswamy, N.; S. Yashiro; N. Thakur; P. Mäkelä; H. Xie; S. Akiyama (2016). "The 2012 July 23 Backside Eruption: An Extreme Energetic Particle Event?". Astrophysical Journal. 833(2): 216. *arXiv*:*1610.05790*. *Bibcode*:*2016ApJ...833..216G*. *doi*:*10.3847/1538-4357/833/2/216.*

Goosse, H., Brovkin, V., Fichefet, T., Haarsma, R., Huybrechts, P., Jongma, J., Mouchet, A., Selten, F., Barriat, P-Y., Campin, J-M., Deleersnijder, E., Driesschaert, E., Goelzer, H., Janssens, I., Loutre, M-F., Morales Maqueda, M. A., Opsteegh, T., Mathieu, P-P., Munhoven, G., Pettersson, E.J., Renssen, H., Roche, D.M., Schaeffer, M., Tartinville, B., Timmermann, A. and Weber, S. L. (2010). Description of the Earth system model of intermediate complexity LOVECLIM version 1.2. *Geoscience Model Development*, 3, pp. 603-633. DOIi:10.5194/gmd-3-603-2010.

Gultepe, I., Tardif, R., Michaelides, S.C., Cermak, J., Bott, A., Bendix, J., Müller, M., Pagowsk, M., Hansen, B., Ellrod, G., Jacobs, W., Toth, G.,and Cober, S.G. (2007). Fog research: A review of past achievements and future perspectives. *Pure and Applied Geophysics,* 164(6-7), pp.1121-1159.

Haarsma, R.J., Hazeleger, W., Severijns, C., de Vries, H., Sterl, A., Bintanja, R., van Oldenborgh, G.J. and van den Brink, H.W. (2013). More hurricanes to hit Western Europe due to global warming. *Geophysical Research Letters*, 40(9), pp.1783-1788. DOI:10.1002/grl.50360.

Habib, A. (2008). Accuracy, Quality Assurance, and Quality Control of LiDAR Data: Principles and Processing in Topographic Laser Ranging and Scanning, pp.269-294.

HadRM3. Hadley Centre for Climate Prediction and Research (2008). UKCP09: Met Office Hadley Centre Regional Climate Model (HadRM3-PPE) Data. NCAS British Atmospheric Data Centre.

Hall, R., Erdélyi, R., Hanna, E., Jones, J.M. and Scaife, A.A., 2015. Drivers of North Atlantic Polar Front jet stream variability. *International Journal of Climatology*, *35*, pp.1697-1720.

Hand, W.H., Fox, N.I. and Collier, C.G. (2004). A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. *Meteorological Applications*, 11, pp.15–31. DOI:10.1017/S1350482703001117.

Hartmann, D.L., Klein Tank, A.M.K., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M. and Zhai, P.M. (2013). Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (Stocker, T.F., Qin, D., Plattner, G-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley,, P.M. [Eds.]), IPCC, 2013. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Hawker, L., Neal, J. and Bates, P., 2019. Accuracy assessment of the TanDEM-X 90 Digital Elevation Model for selected floodplain sites. *Remote Sensing of Environment*, *232*, p.111319.

Hawkins, E. and Sutton, R. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin American Meteorological Society*, 90, pp.1095-1107.

HC826 (2018)Heat Waves Adapting to climate change, House of Commons Environmental Audit Committee, HC826 , 9th report https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/826/826.pdf

Held, I.M. and Soden, B.J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climatology*,19, pp.5686–5699, DOI:10.1175/JCLI3990.1.

Herget, J., Kapala, A., Krell, M., Rustemeier, E., Simmer, C. and Wyss, A., (2015). The millennium flood of July 1342 revisited. *Catena*, *130*, pp.82-94.

Holton, J. and Hakim, G. (2012). An Introduction to Dynamical Meteorology, Academic Press ISBN 978-0-12-384866-6.

Hunter, N.M., Horritt, M.S., Bates, P.D., Wilson, M.D. and Werner, M.G. (2005). An adaptive time step solution for raster-based storage cell modelling of floodplain inundation. *Advances in Water Resources*, 28(9), pp.975–991.

Hunter, N.M., Bates, P.D., Horritt, M.S. and Wilson M,D. (2007). Simple spatially-distributed models for predicting flood inundation: A review. *Geomorphology*, 90(3-4), pp.208–225.

Huntingford, C., Marsh, T., Scaife, A.A., Kendon, E., Hannaford, J., Kay, A., Lockwood, M., Prudhomme, C., Reynard, N., Parry, S., Lowe, J., Screen, J., Ward, H., Roberts, M., Stott, P., Bell, V., Bailey, M., Jenkins, A., Legg, T., Otto, F.E.L., Massey, N., Schaller, N., Slingo, J. and Allen, M.R. (2014). Potential influences on the United Kingdom's floods of winter 2013/14. *Nature Climate Change*, 4, pp.769-777.

Hurrell, J.W. and van Loon, H. (1997). Decadal variations in climate associated with the North Atlantic Oscillation*. Climate Change,* 36, pp.301–326.

Institute of Mechanical Engineers (2021). Enabling resilient UK Energy Infrastructure: Natural Hazard Characterisation.
https://www.imeche.org/policy-and-press/from-our-perspective/energy-theme/enabling-resilient-uk-energy-infrastructure

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Ceorgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hemplemann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Maritn, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Presuchmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M. Samuelsson, P., Somot, S., Soussana, J-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. and Yiou, P. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change,* 14, pp. 563-578. DOI:10.1007/s10113-013-0499-2.

Jackson, L.C., Kahana, R., Graham, T. et al. *Clim Dyn* (2015) 45: 3299.
https://doi.org/10.1007/s00382-015-2540-2

JBA-trust (2021) Flood From Intense Rainfall Project additional flood data
https://www.jbatrust.org/how-we-help/publications-resources/rivers-and-coasts/uk-chronology-of-flash-floods-1/

Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., Bopp, L., Brovkin, V., Hajima, T., Kato, E., Kawamiya, M. and Liddicoat, S., 2013. Twenty-first-century compatible CO2 emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *Journal of Climate*, *26*(13), pp.4398-4413.

Justus, C.G., Hargraves, W.R., Mikhail, A. and Graber, D. (1978). Methods for estimating wind speed frequency distributions. *Journal of Applied Meteorology*, *17*(3), pp. 350-353.

Kay, A.L. (2016). Snow in Britain: the historical picture and future projections. Snow LWEC Working paper, CEH, Wallingford. 24pp.

Keeley, S.P.E, Sutton, R.T. and Shaffrey, L.C. (2012). The impact of North Atlantic sea surface temperature errors on the simulation of North Atlantic European region climate. *Quarterly Journal of the Royal Meteorological Society,* 138, pp.1774–1783.

Kjeldsen, T.R., Macdonald, N., Lang, M., Mediero, L., Albuquerque, T., Bogdanowicz, E., Brázdil, R., Castellarin, A., David, V., Fleig, A. and Gül, G.O. (2014). Documentary evidence of past floods in Europe and their utility in flood frequency estimation. *Journal of Hydrology*, 517, pp.963-973.

Kendon, E.J., Roberts, N.M., Senior, C.A. and Roberts, M.J. (2012). Realism of rainfall in a very high-resolution Regional Climate Model. *Journal of Climate,* 25, pp.5791-5806.

Kendon, E., Roberts, N., Fowler, H.M., Roberts, S., Chan, C. and Senior, K. (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change,* 4, pp.570–576. https://doi.org/10.1038/nclimate2258.

Kendon EJ, Fosser G, Murphy J, Chan S, Clark R, Harris G, Lock A, Lowe J, Martin G, Pirret J, Roberts N, Sanderson M and Tucker S (2019). UKCP18 Convection-permitting model projections: Science report, Met Office. Available at: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/UKCP- Convection-permitting-model-projections-report.pdf.

Kent, E.C., Fangohr, S. and Berry, D.I. (2012). A comparative assessment of monthly mean wind speed products over the global ocean. *International Journal of Climatology,* 33, pp.2530-2541.

Kochel, R.C. and Baker, C.R. (1982). Paleoflood Hydrology. *Science*, 215(4531), pp.353-361. DOI: 10.1126/science.215.4531.353.

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Georgen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulun, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V. (2014). Regional Climate Modelling on European Scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geoscientific Model Development,* 7, pp.1297–1333. https://doi.org/10.5194/gmd-7-1297-2014.

Kossin, J. P., K. A. Emanuel, and G. A. Vecchi, (2014): The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**, 349-352.

Krueger, O., Schenk, F., Feser, F. and Weisse, R. (2013). Inconsistencies between long-term trends in storminess derived from the 20CR reanalysis and observations. *Journal of Climate*, 26, pp.868–874.

Kumar, D., Mishra, V. and Ganguly, A.R. (2014). Evaluating wind extremes in CMIP5 climate models. *Climate Dynamics,* 45, pp.441-453. DOI 10.1007/s00382-014-2306-2.

Kunkel, K.E., Karl, T.R., Brooks, H., Kossin, J., Lawrimore, J.H., Arndt, D., Bosart, L., Changnon, D., Cutter, S.L., Doesken, N., Emanuel, K., Groisman, P.Y., Katz, R.W., Knutson, T., O'Brien, J., Paciorek, C.J., Peterson, T.C., Redmond, K., Robinson, D., Trapp, J., Vose, R., Weaver, S., Wehner, M., Wolter, K. and Wuebbles, D. (2013). Monitoring and Understanding Trends in Extreme Storms: State of Knowledge. *Bulletin of the American Meteorological Society,* 4(94), pp.499-514.

Lamb, H.H. (1991). Historic Storms in the North Sea, British Isles and Northwest Europe, Cambridge University Press, 204pp.

Latham J, Blyth AM, Christian HJ, Deierling W, Gadian AM. 2004. Determination of precipitation rates and yields from lightning measurements. *JOURNAL OF HYDROLOGY.* **288**(1-2), pp. 13-19

Lavers, D.A., Allan, R.P., Wood, E.F., Villarini, G., Brayshaw, D.J. and Wade, A.J. (2011). Winter floods in Britain are connected to atmospheric rivers, *Geophysical Research Letters*, 38(23), L23803. DOI:10.1029/2011GL049783.

Lavers, D.A., Villarini, G., Allan, R.P., Wood, E.F. and Wade, A.J. (2012). The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation. *Journal of Geophysical Research,* 117, D20106.

Lavers, D.A., Allan, R.P., Villarini, G., Lloyd-Hughes, B., Brayshaw, D.J. and Wade, A.J. (2013). Future changes in atmospheric rivers and their implications for winter flooding in Britain. *Environmental Research Letters.* 8(3), pp.1-8.

Lawrence B.N., Rezny M., Budich R., Bauer P., Behrens J., Carter M., Deconinck W., F ord R., Maynard C., Mullerworth S., Osuna C., Porter A., Serradell K., Valcke S., Wedi N., Wilson S. (2018) Crossing the chasm: How to develop weather and climate models for next generation computers? *Geoscientific Model Development, 11*, pp. 1799-1821. DOI: 10.5194/gmd-11-1799-2018

Lechner, A., Simiu, E., Heckert, N.A. (1993). Assessment of 'peaks over threshold' methods for estimating extreme value distribution tails. *Structural Safety,* 12, pp.305–314.

Lenton, T.M., Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J. (2008). Tipping elements in the Earth's climate system, *Proceedings of the National Academy of Science,* 105, pp.1786–1793.

Lewin, J. and Macklin, M.G. (2010). Floodplain catastrophes in the UK Holocene: messages for managing climate change. *Hydrological Processes*, 24, pp.2900-2911.

Liu, K. and Fearn, M. (2000). Reconstruction of Prehistoric Landfall Frequencies of Catastrophic Hurricanes in Northwestern Florida from Lake Sediment Records. *Quaternary Research*, 54, pp. 238–245.

Liu, J., Chen, Z., Francis, J.A., Mote, T. and Hu, Y. (2016). Has Arctic sea ice loss contributed to increased surface melting of the Greenland ice sheet? *Journal of Climate*, 29, pp.3373-3386. DOI:10.1175/JCLI-D-15-0391.1.

Lowe J. A. et al. (2019) UKCP18 Overview Report- Met Office https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf

Macklin, M.G., Johnstone, E. and Lewin, J. (2005). Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. *The Holocene*, 15(7), pp.937-943.

Macklin, M.G., Jones, A.F. and Lewin, J. (2010). River response to rapid Holocene environmental change: evidence and explanation in British catchments, *Quaternary Science Reviews*, 29, pp.1555-1576.

Macklin, M.G., Lewin, J. and Woodward, J.C. (2012). The fluvial record of climate change. *Philosophical Transactions of the Royal Society* A, 370, pp.2143-2172.

Macklin, M.G., Lewin, J. and Jones, A.F. (2013). River entrenchment and terrace formation in the UK Holocene. *Quaternary Science Reviews*, 76, pp.194-206.

Mann, M. E., Woodruff, J. D., Donnelly, J.P. and Zhang, Z. (2009). Atlantic hurricanes and climate over the past 1,500 Years. *Nature*, 460, pp.880-883.

Mariotti, L., Coppola, E., Sylla, M.B., Giorgi, F. and Piani, C. (2011). Regional climate model simulation of projected 21st century climate change over an all-Africa domain: Comparison analysis of nested and driving model results. *Journal of Geophysical Research*, 116, D15111, DOI:10.1029/2010JD015068.

Marsh, T., Lewis, M., Parry, S., Clemas, S. (2012). Hydrological summary for the United Kingdom: November 2012. Wallingford, UK, NERC/Centre for Ecology & Hydrology, 12pp. (CEH Project Number: C04215).

McInnes, K.L., Macadam, I., Hubbert, G.D. and O'Grady, J.G. (2009). A modelling approach for estimating the frequency of sea level extremes and the impact of climate change in southeast Australia. *Natural Hazards*, 51(1), pp.115-137.

McVicar, T.R., Roderick, M.L., Donohue, R.J., Li, L.T., Van Niel, T.G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N.M., Mescherskaya, A.V., Kruger, A.C., Rehman, S. and Dinpashoh, Y. (2012). Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *International Journal of Hydrology,* 416-417, pp. 182-205.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A. and Raper, S.C.I (2007). Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. [Eds]). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Meehl, G.A., Senior, C.A., Eyring, V., Flato, G., Lamarque, J.F., Stouffer, R.J., Taylor, K.E. and Schlund, M., 2020. Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, *6*(26), p.eaba1981.

Miller K, Gadian A, Saunders C, Latham J, Christian H. 2001. Modelling and observations of thundercloud electrification and lightning. *Atmospheric Research.* **58**(2), pp. 89-115

Mitchell, D., Kornhuber, K., Huntingford, C. and Uhe, P., 2019. The day the 2003 European heatwave record was broken. *The Lancet Planetary Health*, *3*(7), .290-292.

Mulder, K.J. and Schultz, D.M. (2015). Climatology, Storm Morphologies, and Environments of Tornadoes in the British Isles: 1980–2012. *Monthly Weather Review,* 143, pp.2224-2240.

Murphy, S.J. and Washington, R. (2001). United Kingdom and Ireland precipitation variability and the North Atlantic sea level pressure field. *International Journal of Climatology,* 21, pp.939-959.

National Research Council (2012). *A National Strategy for Advancing Climate Modeling*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13430.

Neal, J.C., Bates, P.D., Fewtrell, T.J., Hunter, N.M., Wilson, M.D. and Horritt, M.S. (2009). Distributed whole city water level measurements from the Carlisle 2005 urban flood event and comparison with hydraulic model simulations. *Journal of Hydrology*, 368(1-4), pp.42–55.

Néelz, S., Pender, G., Villanueva, I., Wilson, M., Wright, N.G., Bates, P., Mason, D. and Whitlow, C. (2006). Using remotely sensed data to support flood modelling. *Proceedings of the ICE - Water Management*, 159(1), pp.35–43.

Néelz, S. and Pender, G. (2010). Benchmarking of 2D Hydraulic Modelling Packages, Environment Agency, Bristol, United Kingdom. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/290884/scho0510bsno-e-e.pdf

Nikulin, G., Kjelström, E., Hansson, U., Strandberg, G. and Ullerstig, A. (2011). Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. *Tellus A,* 63, pp.41–55.

NOAA (2007). *Fujita Tornado Damage Scale.* http://www.spc.noaa.gov/faq/tornado/f-scale.html

O'Connor, J.E., Atwater, B.F., Cohn, T.A., Cronin, T.M., Keith, M.K., Smith, C.G., and Mason, R.R. (2014). Assessing inundation hazards to nuclear powerplant sites using geologically extended histories of riverine floods, tsunamis, and storm surges. United States Geological Survey, Reston, VA*. Scientific Investigations Report,* 2014–5207, 65pp.

Oliver, J. (2008). Encyclopedia of World Climatology, 2008. Springer ISBN 978-1-40203-264-6.

ONR (2020a). NS-TAST-GD-013 Rev. 8, Nuclear Safety Assessment Technical Guide: External Hazards.

ONR (2020b). NS-TAST-GD-013 Annex 2, Rev.2: Meteorological Hazards.

ONR Expert Panel on Natural Hazards (2020). Analysis of Coastal Flood Hazards for Nuclear Sites, Expert Panel Paper No: GEN-MCFH-EP-2021-2.

Orme, L.C., Davies, S.J. and Duller, G.A.T. (2015). Reconstructed centennial variability of Late Holocene storminess from Cors Fochno, Wales, UK. *Journal of Quaternary Science*, 30(5) pp.478–488.

Ortega, P., Lehner, F., Swingedou, D., Masson-Delmotte, V., Raible, C.C., Casado, M. and Yio, P. (2015). A model-tested North Atlantic Oscillation reconstruction for the past millennium. *Nature,* 523, pp.71-74.

Overland, J.E., Francis, J.A., Hall, R., Hanna, E., Kim, S-J. and Vihma, T. (2015). The melting Arctic and mid-latitude weather patterns: Are they connected? *Journal of Climate*, 28, pp.7917-7932.

Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D. and Allen, M.R. (2011) Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, 470, pp.382-385.

Paprotny, D., Morales-Nápoles, O., and Jonkman, S. N.(2018). HANZE: a pan-European database of exposure to natural hazards and damaging historical floods since 1870, Earth Syst. Sci. Data, 10, 565–581, https://doi.org/10.5194/essd-10-565-2018.

Parry, S., Barker, L., Prosdocimi, I., Lewis, M., Hannaford, J. and Clemas, S. (2016). *Hydrological summary for the United Kingdom: December 2015.* Wallingford, UK, NERC/Centre for Ecology & Hydrology, 12pp. (CEH Project no. C04954).

Pinto, J.G., Spangehl, T., Fink, A., Leckebusch, G.C. and Ulbrich, U. (2009). Factors contributing to the development of extreme North Atlantic cyclones and their relationship with the NAO.*Climate Dynamics*, 32, pp.711–737.

Pirazzoli, P.A. and Tomasin, A. (2003). Recent near-surface wind changes in the central Mediterranean and Adriatic areas. *International Journal of Climatology,* 23(8), pp.963-973.

Prior, J. and Kendon, M. (2011). The UK winter of 2009/2010 compared with severe winters of the last 100 years. *Weather*, 66, pp.4-10.

Pryor, S.C., Barthelmie, R.J., Clausen, N.E., Drews, M., MacKellar, N. and Kjellström, E. (2012). Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. *Climate Dynamics,* 38, pp.189-208.

Reynolds, D.J. (1999). A revised U.K. tornado climatology, 1960–1989.*Journal of Meteorology,* 24, pp.290–321.

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O. and Lutz, W., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change*, *42*, pp.153-168.

Riemann-Campe, K., Fraedrich, K. and Lunkeit, F. (2009). Global climatology of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) in ERA-40 reanalysis. *Atmospheric Research,* 93, pp.534–545.

Roca, M. and Davison, M., 2010. Two dimensional model analysis of flash-flood processes: application to the Boscastle event. *Journal of flood risk Management*, *3*(1), pp.63-71.
Rodda, H.J.E, Little, M.A., Wood, R.G., MacDougall, N. and McSharry, P.E. (2009). A digital archive of extreme rainfalls in the British Isles from 1866 to 1968 based on British Rainfall. *Weather*, 64, pp.71-75.

Roe, G.H. (2005). Orographic Precipitation*. Annual Review of Earth and Planetary Sciences*, 33, pp.645-671.

Rogelj, J., Meinshausen, M. and Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change*, 2, pp.248–253.

Rogers, J.C. (1984). The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Monthly Weather Review,* 112(10), pp.1999-2015.

Romps, D., Seeley, J.T., Vollaro, D., Molinari, J. (2014). Projected increase in lightning strikes in the United States due to global warming. *Science*, 346(6211), pp.851-854. DOI: 10.1126/science.1259100.

Rowe, M. W. (1976). Tornadoes in medieval Britain. *Journal of Meteorology*. **1** (7): 219–222. ISSN 1748-2992 http://www.ijmet.org/wp-content/uploads/2014/09/7.pdf#page=7 , accessed March 2020

Rumsby, B.T. and Macklin, M.G. (1994). Channel and floodplain response to recent abrupt climate change, The Tyne basin, northern England. *Earth Surface Processes and Landforms* 19, pp.499-515.

Rydval, M., Gunnarson, B.E., Loader, N.J., Cook, E.R., Druckenbrod, D.L. and Wilson, R. (2016). Spatial reconstruction of Scottish summer temperatures from tree rings, *International Journal of Climatology*, 37(3), pp.1540-1566. DOI: 10.1002/joc.4796.

Sahin, A.D. and Sen, Z. (2001). First-order Markov chain approach to wind speed modelling. *Journal of Wind Engineering and Industrial Aerodynamics,* 89, pp.263–269.

Scaife, A.A., Knight, J.R., Vallis, G.K. and Folland, C.K. (2005). A stratospheric influence on the winter NAO and North Atlantic surface climate. *Geophysical Research Letters,* 32 (18), L18715. https://doi.org/10.1029/2005GL023226

Scaife, A.A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R.T., Dunstone, N., Eade, R., Fereday, D., Folland, C.K., Gordon, M., Hermanson, L., Knight, J.R., Lea, D.J., MacLachlan, C., Maidens, A., Martin, M., Peterson, A.K., Smith, D., Vellinga, M., Wallace, E., Waters, J. and Williams, A. (2014). Skilful Long Range Prediction of European and North American Winters. *Geophysical Research Letters,* 41(7), pp.1540-1556. DOI: 10.1002/2014GL059637.

Scaife, A.A, Comer, R.E., Dunstone, N.J., Knight, J.R., Smith, D.M., MacLachlan, C., Martin, N., Peterson, K.A., Rowlands, D., Carroll, E.B., Belcher, S. and Slingo, J. (2017). Tropical rainfall, Rossby Waves and regional winter climate projections. *Quarterly Journal of the Royal Meteorological Society*, 143(702), pp.1-11.

Schaller, N., Kay, A., Lamb, R., Massey, N.R., Van Oldenborgh, G.J., Otto, F.E.L., Sparrow, S., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S.M., Haustein, K., Huntingford, C., Ingram, W.J., Jones, R.G., Legg, T., Miller, J., Skeggs, J., Wallom, D., Weisheimer, A., Wilson, S., Stott, P.A. and Allen, M.R. (2016). Human influence on climate in the 2014 southern England winter floods and their impacts. *Nature Climate Change* 6(6), pp.627–634.

Schreiber, M., Peixoto, P., Haut, T., Wingate, B., (2017) Beyond spatial scalability limitations with a massively parallel method for linear oscillatory problems. *International Journal of High Performance Computing Applications*, 32, pp. 1-21

Sefton, C., Muchan, K., Parry, S., Matthews, B., Barker, L., Turner, S. and Hannaford, J. (2021), The 2019/2020 floods in the UK: a hydrological appraisal. *Weather*. https://doi.org/10.1002/wea.3993

Sexton, D.M. and Harris, G.R. (2015). The importance of including variability in climate change projections used for adaptation. *Nature Climate Change*, *5*(10), pp.931-936.

Shamshad, A., Bawadi, M.A., Wan Hussin, W.M.A., Majid, T.A. and Sanusi, S.A.M. (2005). First and second order Markov chain models for synthetic generation of wind speed time series. *Energy,* 30, pp.693–708.

Shepherd, A., Ivins, E., Rignot, E. *et al.* (2019). Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature,* doi:10.1038/s41586-019-1855-2

Sherwood, S.C., Webb, M.J., Annan, J.D., Armour, K.C., Forster, P.M., Hargreaves, J.C., Hegerl, G., Klein, S.A., Marvel, K.D., Rohling, E.J. and Watanabe, M., 2020. An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, *58*(4), eRG000678.

Shimura, T. Mori, N. and Mase, H. (2013). 2013 Ocean Waves and Teleconnection Patterns in the Northern Hemisphere. *Journal of Climate,* 26(21), pp.8654-8670. DOI: http://dx.doi.org/10.1175/JCLI-D-12-00397.1.

Skamarock, W., Klemp, J., Dudhia, J., Gill, D., Barker, D., Wang, W. and Powers, J. (2008). A description of the advanced research WRF version 3. NCAR Technical Note NCAR/TN–475+STR, National Center for Atmospheric Research: Boulder, CO, 113 pp. http://www2.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf

Smeed, D. A., McCarthy, G. D., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., et al. (2014). Observed decline of the Atlantic meridional overturning circulation 2004-2012. *Ocean Science*, **10**(1), 29–38. https://doi.org/10.5194/os-10-29-2014

Smeed, D.A., et al. (2018) The North Atlantic is in a state of reduced overturning, *Geophys. Res. Let,* **45,** 1527-1533 . DOI: https://doi.org/10.1002/2017GL076350

Smits. A., Klein Tank. A.M.G.and Können, G.P. (2005). Trends in storminess over the Netherlands, 1962–2002. *International Journal of Climatology*, 25, pp. 1331–1344. DOI:10.1002/joc.1195.

Stainforth, D.A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D.J., Kettleborough, J.A., Knight, S., Martin, A., Murphy, J.M., Piani, C., Sexton, D., Smith, L.A., Spicer, R.A., Thorpe, A.J. and Allen, M.R. (2005). Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature,* 433(7024), pp.403–406.

Stainforth, D.A., Allen, M.R., Tredger, E.R. and Smith, L.A. (2007a). Confidence, Uncertainty and Decision-Support Relevance in Climate Predictions. *Philosophical Transactions of the Royal Society,* 365, pp. 2145-2161.

Stainforth, D.A., Downing, T.E., Washington, R., Lopez, A. and New, M. (2007b). Issues in the interpretation of climate model ensembles to inform decisions. *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences,* 365, pp. 2163-2177.

Stephenson, D., Pavan, V., and participating CMIP1 modelling groups. (2003). The North Atlantic Oscillation in coupled climate models: a CMIP1 evaluation, *Climate Dynamics,* 20, pp.381-399.

Sterl, A., Bakker, A.M.R., den Brink, H., Haarsma, R., Stepek, A., Wijnant, I.L. and de Winter, R. (2015). Large-scale winds in the southern North Sea region: the wind part of the KNMI14 climate change scenarios. *Environmental Research Letters,* 10, 035004.

Subedi, M. and Fullen, M.A., (2009). Spatial variability in precipitation within the Hilton Experimental Site, Shropshire, UK (1982–2006). *Hydrological Processes: An International Journal*, *23*(2), pp.236-244.

Sutton, R.T. and Dong, B. (2012). Atlantic Ocean influence on a shift in European climate in the 1990s, *Nature Geoscience*, 5, pp.788–792. DOI:10.1038/ngeo1595.

Sweet, W.V et al., (2017) Global and Regional Sea Level Rise Scenarios for the United States, NOAA Technical Report (Silver Spring, MD, USA: NOAA/NOS Center for Operational Oceanographic Products and Services), https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

Tamarin T. and Kaspi, Y (2017) *The poleward shift of storm tracks under global warming Lagrangian perspective*, Geo. Res. Letters, 44, 20 https://doi.org/10.1002/2017GL073633

Thielen, J. and Gadian, A. (1997). Influence of topography and urban heat island effects on the outbreak of convective storms under unstable meteorological conditions: a numerical study. *Meteorological Applications*, 4, pp.139–149. DOI:10.1017/S1350482797000303

Thomas, B., Kent, E., Swail, V. and Berry, D. (2008). Trends in ship wind speeds adjusted for observation method and height. *International Journal of Climatology*, 28, pp.747-763.

Tokinaga, H. and Xie, S.P. (2011). Wave-and anemometer-based sea surface wind (WASWind) for climate change analysis. *Journal of Climate*, *24*(1), pp.267-285.

Toonen, W.H.J. (2015). Flood frequency analysis and discussion of non-stationarity of the Lower Rhine flooding regime (AD 1350–2011): Using discharge data, water level measurements, and historical records. *Journal of Hydrology,* 528, pp.490–502.

U.K. Meteorological Office and Natural Environment Research Council (NERC) Centre for Ecology and Hydrology (CEH) Joint report (2014). The Recent Storms and Floods in the U.K. Available from http://www.metoffice.gov.uk/media/pdf/1/2/Recent_Storms_Briefing_Final_SLR_20140211.pdf

U.K. Meteorological Office (2012). Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current). NCAS British Atmospheric Data Centre.

Ulbrich, U., Leckebusch, G.C. and Pinto, J.G. (2009). Extra-tropical cyclones in the present and future climate: A review. *Theoretical and Applied Climatology,* 96(1–2), pp.117–131. DOI:10.1007/s00704-008-0083-8.

U.S. Interagency Advisory Committee on Water Data (1982). Guidelines for determining flood flow frequency, Bulletin 17-B of the Hydrology Subcommittee: Reston, Virginia, U.S. Geological Survey, Office of Water Data Coordination, 183pp.

USNRC (2005a). Regulatory Guide 1.204, Guidelines for Lightning Protection of Nuclear Power Plants. https://www.nrc.gov/docs/ML0522/ML052290422.pdf

USNRCb (2005b). Technical Basis for Regulatory Guidance on Lightning Protection in Nuclear Power Plants, NUREG/CR-6866, ORNL/TM-2001/140. https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6866/.

Vallis, G. K., Zurita-Gotor, P., Cairns, C. & Kidston, J. (2015) Response of the large-scale structure of the atmosphere to global warming. *Quaterly Journal of the Royal Meteorological Society,* **141**, 1479–1501.

Vautard, R., Cattiaux, J., Yiou, P., Thépaut, J.N. and Ciais, P. (2010). Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geoscience,* 3, pp.756-761.

Veraverbeke S, Rogers BM, Goulden ML, Jandt RR, Miller CE, Wiggins EB and Randerson JT (2017). Lightning as a major driver of recent large fire years in North American boreal forests *Nature Climate Change,* 7(7),529-+. DOI: 10.1038/NCLIMATE3329.

Von Storch, H. (1999). Misuses of statistical analysis in climate research. In *Analysis of Climate Variability*, pp. 11-26. Springer, Berlin, Heidelberg.

Wade, S.D., Townend, I., Udale-Clarke, H., Rance, J., Betts, R., Hames, D. and Nash, E., (2012). The UK Climate Change Risk Assessment Evidence Report. Prepared for Defra.

Wade, S., Sanderson, M., Golding, N., Lowe, J., Betts, R., Reynard, N., Kay, A., Stewart, L., Prudhomme, C., Shaffrey, L., Lloyd-Hughes, B. and Harvey, B. (2015). Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps. Report for CCRA.

Washington, R., Hodson, A., Isaksson, E. and MacDonald, O. (2000). Northern Hemisphere teleconnection indices and the mass balance of Svalbard glaciers. *International Journal of Climatology,* 20, pp.473-487.

Weijer, W., Cheng, W., Drijfhout, S. S., Federov, A.V., Hu, A., Jackson, L. C., et al. (2019). Stability of the Atlantic Meridional Overturning Circulation: A review and synthesis. Journal of Geophysical Research: Oceans, 124, 5336– 5375. https://doi.org/10.1029/2019JC015083

Wheeler, D. (2003). The Great Storm of 1703. *Weather*, 58(11), pp.419-427.

WHOI OAFlux Project (2018). http://oaflux.whoi.edu/.

Wick, G.A., Neiman, P.J., Ralph, F.M. and Hamill, T. (2013). Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Weather and Forecasting,* 28, pp.1337–1352.

Wilby, R.C., O'Hare, G., Barnsley, N. (1997). The North Atlantic Oscillation and British Isles climate variability, 1865–1996. *Weather,* 52, pp.266-276.

Williams, E., Guha, A., Boldi, R., Christian, H. and Buechler, R. (2016) Global Lightning Activity and the Hiatus in Global Warming. *World Meeting on Lightning, Cartegena de Indias, Columbia.* http://www.acofi.edu.co/womel/wp-content/uploads/2016/04/Earle-R.-Williams.pdf (accessed March 2020)

Wilks, D. and Wilby, R. (1999). The weather generation game: a review of stochastic weather models. *Progress in Physical Geography*, 23(3), pp.329-357.

Woollings, T., Barriopedro, D., Methven, J. et al. Curr Clim Change Rep (2018) 4: 287. https://doi.org/10.1007/s40641-018-0108-z

Yu, L. and Weller, R. (2007). Objectively analyzed air-sea heat fluxes for the global ice-free oceans (1981-2005). *Bulletin of the American Meteorological Society,* 88, pp.527-539.

Zhang, H., Bates, J. and Reynolds, R. (2006). Assessment of composite global sampling: sea surface wind speed. *Geophysical Research Letters,* 33(17), L17714.

Zappa, G., Shaffrey, L.C., Hodges, K.I., Sansom, P.G. and Stephenson, D.B. (2013). A Multimodel Assessment of Future Projections of North Atlantic and European Extratropical Cyclones in the CMIP5 Climate Models. *Journal of Climate,* 26, pp.5846-5862.

Zeng, Z., Ziegler, A.D., Searchinger, T. *et al.* A reversal in global terrestrial stilling and its implications for wind energy production. *Nature Climate Change* **9,** 979–985 (2019). https://doi.org/10.1038/s41558-019-0622-6

10. FIGURES & TABLES

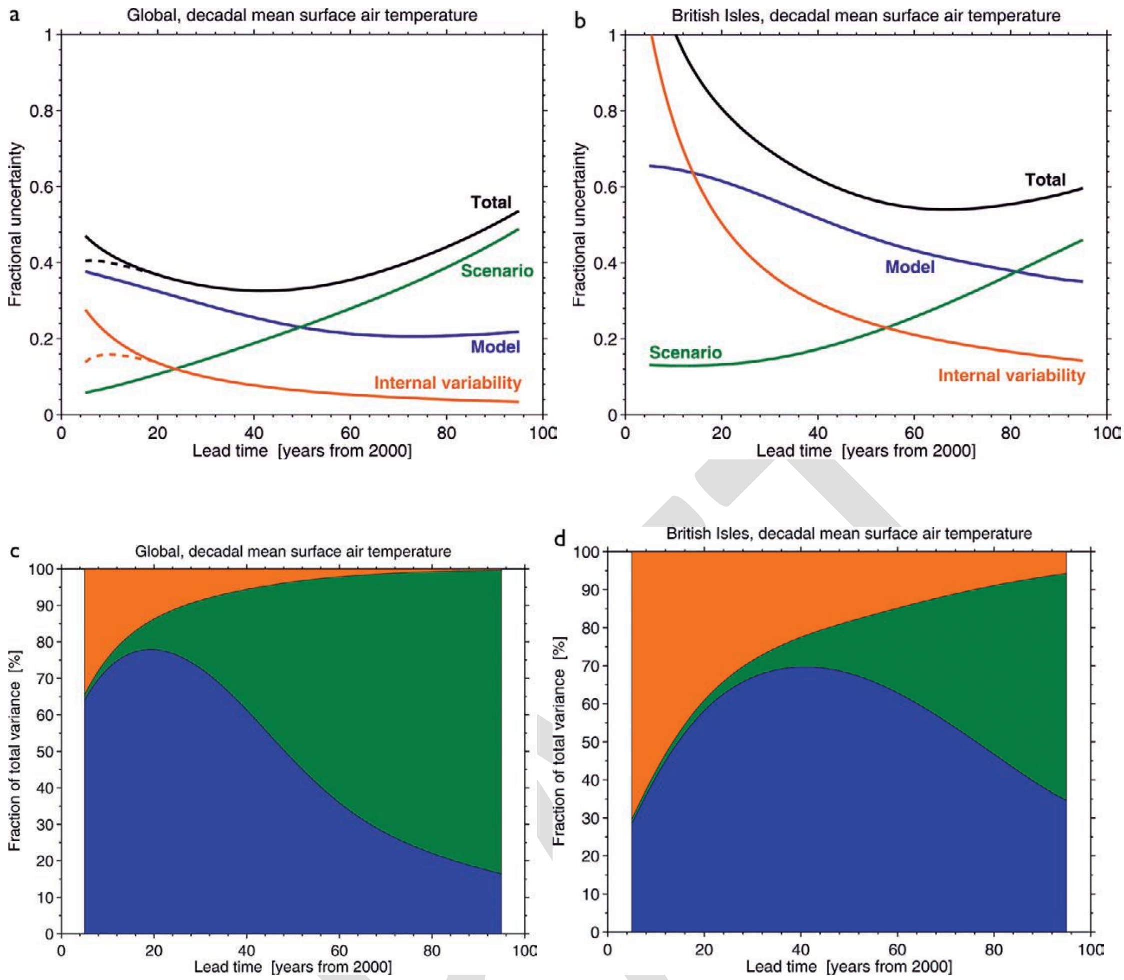

Figure 1

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).

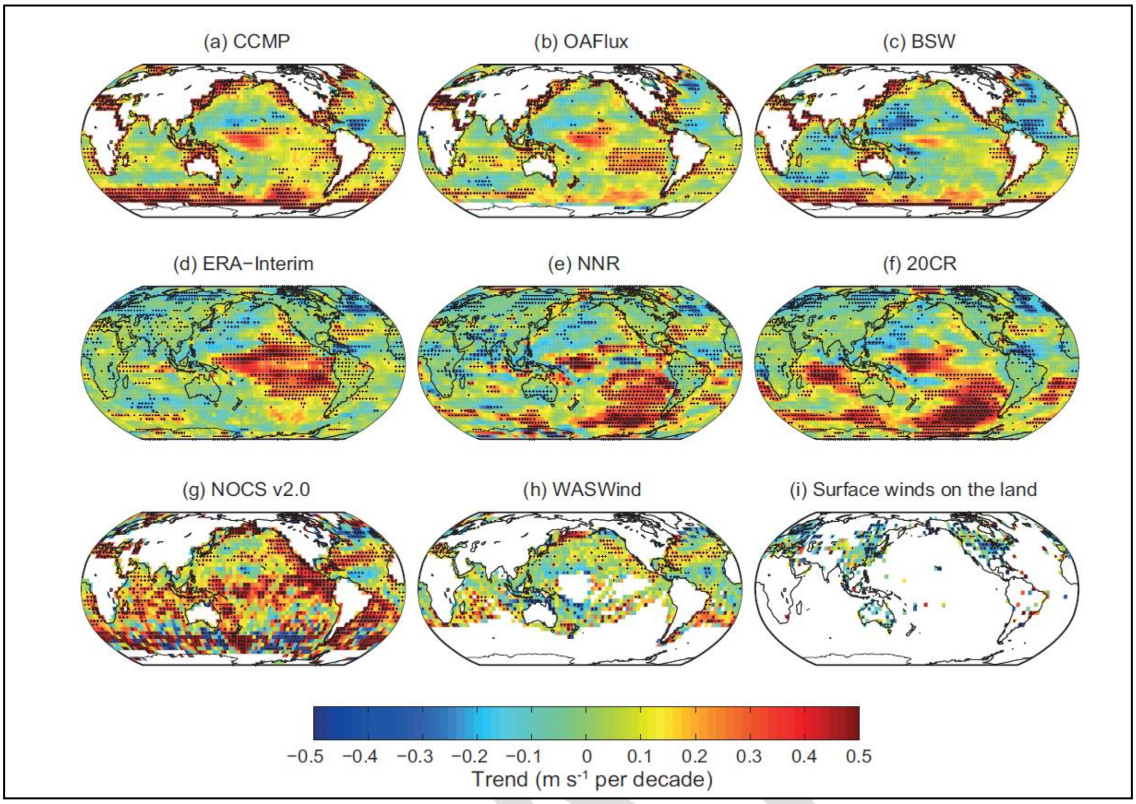

Figure 2

(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).

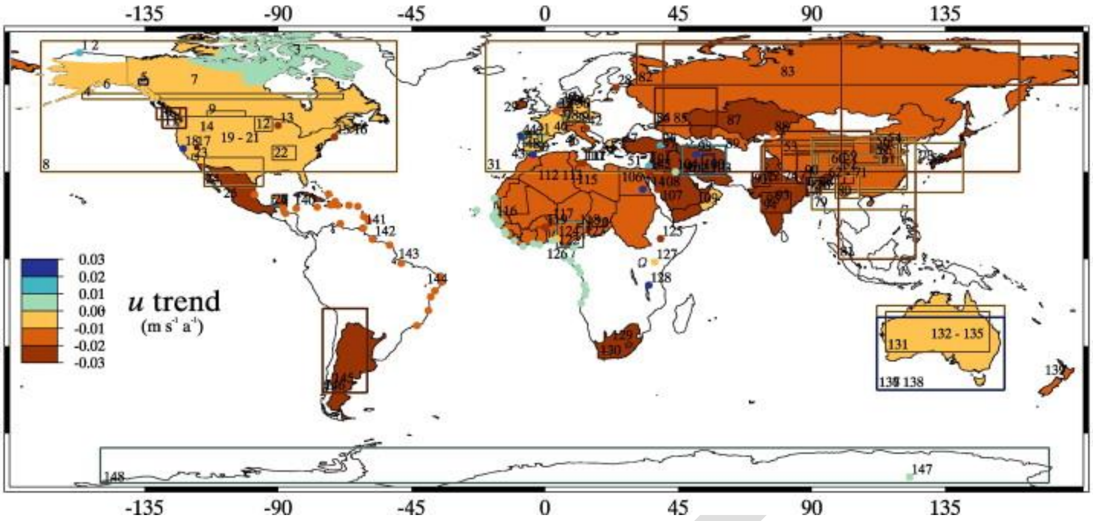

Figure 3

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.
Shared Socioeconomic Pathways (SSPs)	**Description** (from Riahi et al., 2017)
SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)	The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.

SSP2 Middle of the Road (Medium challenges to mitigation and adaptation**)**	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.
SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)	A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues.
SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)	Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries.
SSP5 Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)	This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development.

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) and SSPs (Shared Socioeconomic Pathways (due to be used in Sixth Assessment Report 2021-22). It should also be noted that the RCPs come with a standard pairing of emissions scenarios and concentration pathways which are used in most (but not all) applications. There is no one-to-one mapping between emissions scenarios and concentration pathways due to uncertainties in climate-carbon cycle feedbacks which means that a given RCP emissions scenario can give rise to a range of concentration pathways and conversely, any given RCP concentration pathway is compatible with a range of emissions scenarios. This is an important point when comparing UKCP18 with CMIP5, because UKCP uses emissions-driven models while CMIP5 uses concentration-driven models, although the same RCP names are used. The difference is non-trivial as the standard reference concentrations for the RCPs are NOT in the centre of the distribution, they are at the low end, which means an emissions-driven projection like UKCP tends to give more warming.

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)
IPCC Sixth Assessment Report	AR6 (due 2021-2022)
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.
CMIP6	Latest generation of climate models and their projection to be used in IPCC AR6

Table 3

Climate reports mentioned in the text.

Name	Radiative Forcing	CO_2 equiv. (ppm) by 2100	Temp anomaly (°C) 66% range	Pathway	SRES temp anomaly equiv.
RCP 8.5	8.5Wm^2 in 2100	1370	4.0 to 6.1	Rising	**A1FI**
RCP 6.0	6Wm^2 post 2100	850	2.6 to 3.7	Stabilisation without overshoot	**B2**
RCP 4.5	4.5Wm^2 post 2100	650	2.0 to 3.0	Stabilisation without overshoot	**B1**
RCP 2.6	3Wm^2 before 2100 declining to 2.6Wm^2 by 2100	490	1.3 to 1.9	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).

LIST OF ABBREVIATIONS

AA	Arctic Amplification
AOGCM	Atmosphere Ocean General Circulation Model
AMO (C)	Atlantic Meridional Overturning (Circulation)
AO	Arctic Oscillation
AR	Atmospheric River
AR4	Fourth IPCC Assessment Report
AR5	Fifth IPCC Assessment Report
AR6	Sixth IPCC Assessment Report
BSW	Blended Sea Winds
CCMP	Cross-Calibrated Multi-Platform
CEDA	Centre for Environmental Data Archival
CEH	Centre for Ecology and Hydrology
CF	Compound Flooding
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
EVA	Extreme Value Analysis
FFA	Flood Frequency Analysis
FFIR	Flooding From Intense Rainfall
GCM	Global Climate Model
GMSL	Global Mean Sea Level
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 (UK Met Office)
HadUKP	Hadley Centre UK Precipitation (UK Met Office)
HIRLAM	High Resolution Limited Area Model
HIWeather	High Impact Weather
IC	Initial Condition
ICON	Icosahedral Nonhydrostatic Model

IPCC	Intergovernmental Panel on Climate Change
IS92	IPCC Emissions Scenario 1992
Knot	Speed. One nautical mile per hour
LIDAR	Light Detection and Ranging
LIS	Lightning Imaging Sensor
LOVECLIM	Earth System Model created by coupling of five GCMs (Loch-Vecode-Ecbilt-CLIoaglsm-Mode)
MIDAS	UK Met Office Integrated Data Archive System
mph	Speed. Miles per hour
MPAS	Model for Prediction across Scales
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
TAR	Third IPCC Assessment Report
u	Wind speed
UKCIP	United Kingdom Climate Impacts Programme
UKCP	United Kingdom Climate Projections
UNFCCC	United Nations Framework Convention on Climate Change
USNRC	US Nuclear Regulatory Commission
WG1	Working Group 1 of the IPCC
WMO	World Meteorological Organisation

WWRP World Weather Research Programme

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