The use and interpretation of ‘extreme’ and ‘worst-case’ climate scenarios in the UK

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Summary

This report reviews the current use and interpretation of ‘extreme’ and ‘worst-case’ climate scenarios in the UK, based on guidelines for risk and adaptation assessment, actual assessments that have been undertaken, Adaptation Reports produced as a requirement of the Climate Change Act, and approaches used in emergency planning.

The key findings are:

- There are no overall guidelines on the use and interpretation of climate scenarios in the UK, although there is an increasing trend towards concentrating on scenarios characterising 2^{o}C and 4^{o}C worlds.
- Guidance and best practice documents exist for most sectors – with the major exception of agriculture – but the details and requirements vary. This means that different organisations within a sector have sometimes interpreted scenarios differently.
- The RCP8.5 emissions scenario and corresponding UKCP18 projections have been interpreted differently between organisations, ranging from ‘business as usual’ through to ‘worst case’. RCP8.5 is often interpreted – mistakenly – as representing a 4^{o}C world.
- Similarly, ‘worst case’ has been interpreted differently: sometimes it is taken to be RCP8.5, and sometimes a more extreme change. Terminology varies considerably between different sets of guidelines and between organisations.
- Several sets of sector guidelines refer to the use of ‘credible maximum scenarios’, without specifically defining what these are.
- Organisations have used climate information differently, over different time scales, in their assessments and adaptation plans: some use scenarios to describe broad directions of change, whilst others require more quantitative projections for both strategy and design.

The three key implications are:

- It is necessary to develop clarity on the interpretation of RCP8.5, and on its implementation in UKCP18 with the ‘hot’ HadGEM models.
- It is necessary to develop procedures to construct pathways consistent with 2 and 4^{o}C worlds, partly to reflect increasing policy interest and partly to provide a reference for worst-case and extreme scenarios.

- It is necessary to develop some agreed consistent high-level nomenclature to describe climate scenarios for planning adaptation and resilience – for example distinguishing between ‘low’ and ‘high’ scenarios to represent uncertainty over emissions (and representing model uncertainty through ranges or extremes), and ‘worst case’ scenarios representing deep uncertainty in the response of the climate system to increasing emissions.

1. Introduction and purpose

This report presents a review of the current use and interpretation of ‘extreme’ and ‘worst-case’ climate scenarios in the UK, placed in the context of current guidance and practice in the use of climate scenarios in the UK in general.

Climate change assessments in the UK are now largely based on UKCP18 climate (Lowe et al., 2018) and sea-level (Palmer et al., 2018) projections (or are currently being updated to use UKCP18) – although as noted below there is one significant exception. The UKCP18 projections are based on four emissions pathways, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5 representing ‘low’, ‘medium’, ‘high’ and ‘very high’ emissions, although some strands (global, regional and local) are available only for RCP8.5. These projections are typically used for adaptation and resilience planning with most guidelines and assessments using a “lower” and an “upper” value, but – as is outlined in this report - are interpreted in different ways. RCP8.5 is currently the subject of much debate (e.g. Hausfather & Peters, 2020; Schwalm et al., 2020), as it is often claimed to be based on unrealistically high projections of future emissions. Working Group III of the IPCC concluded that ‘high-end emissions scenarios, such as RCP8.5…, are becoming less likely with climate policy and technology change…but high-end concentration and warming levels may still be reached with the inclusion of strong carbon or climate feedbacks’ (Riahi et al., 2022). It also concluded that RCP8.5 is useful as a high-end, high-risk scenario.

Low-likelihood high-impact climate scenarios in the UK are usually currently characterised through the H++ scenarios for change in sea level (Lowe et al., 2009) and for extreme weather events (Met Office et al., 2015). The H++ sea level rise scenario describes change in sea level over time, but the other H++ scenarios describe plausible extreme events not tied to a specific time period or level of warming. For emergency planning purposes, Reasonable Worst Case Scenarios (RWCS) represent extreme events in the current climate. Both the second and third Climate Change Risk Assessments describe potential low-likelihood high-impact changes to the earth system which could potentially affect the UK. There is an increasing emphasis in government on low-likelihood high-impact scenarios, highlighted in CCRA3 (HM Government, 2022a: Annex 2) and probably influenced by experience with COVID planning.

Interest in climate scenarios (extreme or otherwise) comes from two directions: resilience planning / risk assessment and climate change adaptation. Resilience planning and risk assessment by government and organisations (e.g. infrastructure operators) has conventionally had a focus on near-term response to, or consequences of, short term events, whilst adaptation planning takes a longer-term perspective. The two perspectives are converging, partly due to a recognition that climate change is altering the frequency or magnitude of challenging events and will continue to do so, and partly because one objective of adaptation is to increase resilience over the long term. However, in practice the two are not necessarily well coordinated. At the UK level, national policy is developing through the UK Government Resilience Framework (HM Government, 2022a) and the 3rd National Adaptation Programme (HM Government, 2023). Utility regulators (energy, water, transport and communications) ask for both resilience plans and longer-term climate change adaptation strategies.

This review looks at the use and interpretation of ‘extreme’ and ‘worst-case’ climate scenarios under four headings: in guidelines for risk and adaptation assessment, in actual climate change assessments, in Adaptation Reports submitted as a requirement under the Climate Change Act 2008, and in emergency planning and hazard assessment. Table 1 summarises some of the differing interpretations of RCP8.5, and Table 2 summarises differing interpretations of ‘extreme’ or ‘worst-case’ scenarios.

Table 1: Interpretation of RCP8.5-based scenarios

Source	Interpretation	Reference
Supplementary Green Book Guidance on Accounting for the Effects of Climate Change	A 4°C scenario	Defra (2024)
Coastal flood risk guidance: England	Higher-central (70th percentile) Upper end (95th percentile)	
Coastal flood risk guidance: Scotland	Un-named (95th percentile)	SEPA (2022)
Fluvial flood risk guidance: England	Central (50th percentile) Higher-central (70th percentile) Upper end (95th percentile)	
Fluvial flood risk guidance: Scotland	Un-named (67th percentile)	SEPA (2022)
Long-term development strategy (water)	Adverse (50th percentile)	Ofwat (2022)
Water Resources South East	'low probability-high impact' (regional strand)	Atkins (2020)
Network Rail	Higher	Network Rail (2021)
National Highways	Business-as-usual	Highways England et al. (2021)
Scottish National Adaptation Programme	High emissions	Scottish Government (2019)
Water resources	A 4°C world	Affinity Water (2021); Northumbrian Water (2021), Severn Trent (2021), Southern Water (2021)
Energy UK	Worst case	Energy UK (2021)
National Highways	A 4°C world	National Highways (2022)
Gatwick Airport	Highly precautionary	Gatwick Airport Limited (2021)
Luton Airport	Worst case	LLAOL (2021)
Peel Ports	Plausible worst case	Peel Ports Group (2021)
Environment Agency	A 4°C world	Environment Agency (2021d)
Natural England	A 4°C world	Natural England (2021)
Historic England	High emissions	Historic England (2022)
JBA	No-action warning scenario Baseline scenario	JBA (2022)

Table 2: Interpretation of ‘extreme’ or ‘worst-case’ scenarios

Source	**Interpretation**	**Reference**
Committee on Climate Change	Global warming greater than 4°C by 2100 or earth system instability	Watkiss & Betts (2021)
Supplementary Green Book Guidance on Accounting for the Effects of Climate Change	H++	Defra (2024)
Coastal flood risk guidance: England	Upper end (95th percentile from RCP8.5): credible maximum scenario	
Coastal flood risk guidance: Scotland	H++	SEPA (2022)
Fluvial flood risk guidance: England	Upper end (95th percentile from RCP8.5): credible maximum scenario	
Fluvial flood risk guidance: Scotland	90th percentile from RCP8.5	SEPA (2022)
Pluvial flood risk guidance: England	Upper (95th percentile RCP8.5)	
Pluvial flood risk guidance: Scotland	Upper (95th percentile RCP8.5)	
Long-term development strategy (water)	RCP8.5 50th percentile	Ofwat (2022)
National Policy Statement for Energy (2011, 2021)	Credible maximum scenario	DECC (2011); BEIS (2021)
National Policy Statement for Energy (2021)	High emissions	BEIS (2021)
Coastal risk to nuclear installations	Credible maximum scenario is H++	ONR/Environment Agency (2017)
Water Resources South East	UKCP18 regional strand RCP8.5	Atkins (2020)
Network Rail	90th percentile RCP8.5	Network Rail (2021)
National Highways	H++	Highways England et al. (2021)

The table summarises scenarios intended to represent the ‘most extreme’ case, and includes names where relevant.

2. Use and interpretation in guidelines for use of climate scenarios

2.1 Cross-sectoral guidance and recommendations

There are no overall formal national guidelines for the use of climate scenarios in risk, resilience and adaptation assessment, beyond an implicit expectation that scenarios should be based on the latest 'official' UK climate scenarios (currently UKCP18). The UK Environmental Improvement Plan 2023 (HM Government, 2023a) – which mostly covers policies relating to England only – has goals of adapting to climate change and reducing risk of harm from environmental hazards but does not specifically define planning scenarios. The UK government resilience framework (HM Government, 2023b) highlights the importance of resilience standards, but again does not specify planning scenarios. There are more specific guidelines for specific types of action or sectors (see subsequent sections): some of these guidelines come from government agencies, and others from industry groups. There are also sets of recommendations, focusing on resilience (produced by the National Infrastructure Commission and a House of Lords committee) and adaptation (produced by the Climate Change Committee).

The resilience of UK infrastructure to a range of shocks and stresses was reviewed by the National Infrastructure Commission (NIC, 2020). It highlighted inconsistencies and weaknesses in current planning for resilience and recommended three specific improvements: government should publish a full set of resilience standards every five years, infrastructure operators should carry out regular and proportionate stress tests, and operators should develop and maintain long-term resilience strategies. The review does not define specifically what these standards or stress tests should be but highlights the role of regulators in providing guidance. The House of Lords Select Committee on Risk Assessment and Risk Planning (House of Lords, 2021) reviewed risk assessment processes in general, and concluded that there was 'a bias against low likelihood-high impact risks'.

In its independent advice to government for the 3rd Climate Change Risk Assessment, the Climate Change Committee (CCC, 2021) introduced ten principles for good adaptation. One of these recommended 'adapt to 2°C and assess the risks for 4°C', and another recommended preparing for 'unpredictable extremes'. This recommendation is based on the potential for low-likelihood high impact changes outside the 'likely range' used in the CCRA3 assessment. The CCC specifically mentions global warming greater than 4°C by 2100 and earth system instabilities. It recommends both the use of storyline approaches or ‘what if’ scenarios for national risk planning and accounting for sudden extreme changes in headroom.

The Supplementary Green Book Guidance on accounting for climate change in public investments (Defra, 2024) specifies that, beyond 2035, it is necessary to use at least two climate scenarios – one consistent with a 2°C scenario and the other with a temperature rise of 4°C. The guidance specifically maps these onto RCP2.6 and RCP8.5 respectively – although RCP8.5 reaches an increase in temperature considerably above 4°C above pre-industrial levels (Figure 1). The guidance also states (p10):

> “Planning for more extreme change (e.g. aligned with H++ scenario) is likely to be appropriate in situations where there are high vulnerabilities, low risk tolerance and long planning or investment cycles”.

However, with the exception of coastal flooding, current H++ scenarios characterise events rather than progressive change, so do not provide information consistent with 2°C/RCP2.6 or 4°C/RCP8.5 scenarios.

The strategic plan for the Environment Agency in England follows the CCC guidance of preparing for 2°C warming and planning for ‘higher scenarios, such as a 4°C rise’ (Environment Agency, 2020a). The Environment Agency provides guidance to its staff on assessing climate impacts through its Climate Impacts Tool (Environment Agency, 2023). This is a high-level risk screening and communication tool designed to supplement sector guidance (see below). It follows the CCC advice, and specifically focuses on three scenarios – a mid-century increase of 2°C by 2050, a managed transition with 2°C by 2100, and runaway change of 4°C by 2100. The tool presents some indicators of climate change, many taken from the uk-cri.org website which specifically defines 2 and 4°C world pathways. The others are inferred from projections based on RCP2.6 and RCP8.5. The guidance refers to thresholds and tipping points, and notes that these would generally only be considered ‘for large-scale or long term and higher risk sensitive decisions’ (p19).

The National Adaptation Programme is in effect a sum of adaptation actions undertaken or planned by government departments and agencies (including in the devolved administrations), and these adaptation actions are based on sector- and agency-specific approaches. The English third National Adaptation Programme (HM Government, 2023) states that it follows the advice of the CCC and plans for 2°C of global warming by 2100 (p16), although this is more a high-level principle than a guide to action. It also – significantly – does not mention considering risks in a 4°C world.

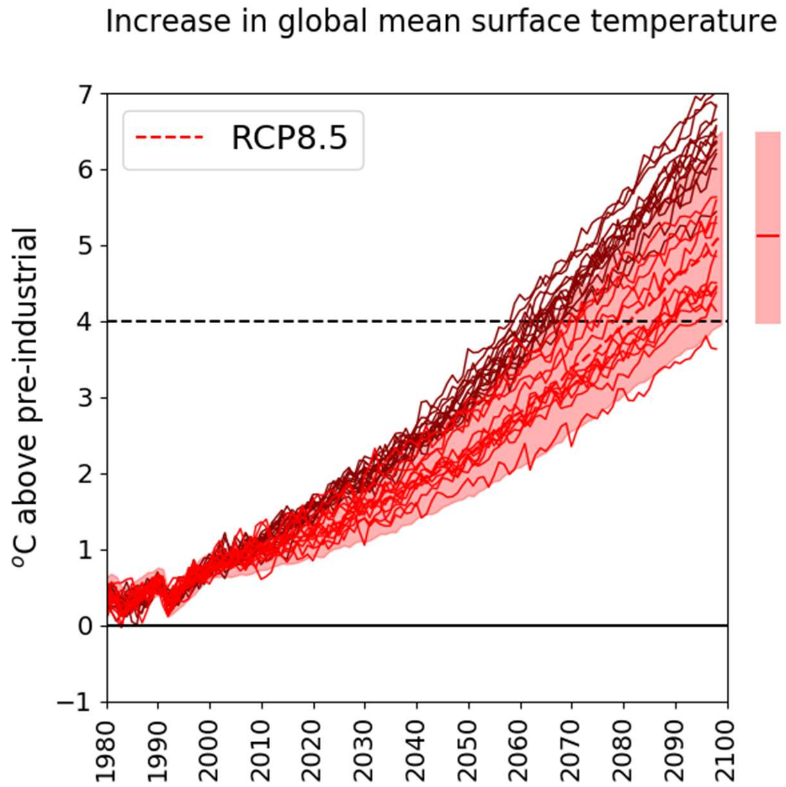

Figure 1: Increase in global mean surface air temperature in the UKCP18 RCP8.5 projections, relative to pre-industrial. The shaded area shows the 10th to 90th percentile range for the probabilistic strand, and the bar on the right shows change in 2100. The dark red lines show the HadGEM projections used in the global and regional UKCP18 strands, and the red lines show the CMIP5 projections in the global strand.

At the international scale, the Task Force on Climate-related Financial Disclosures provides guidance to companies on reporting climate risks (TCFD, 2017). As of June 2022, over 400 UK organisations are TCFD supporters (across a range of sectors – approximately a third are asset managers). The guidance explicitly recommends organisations use a 2°C or lower scenario to report their physical and transition risks, 'in addition to two or three other scenarios most relevant to their circumstances' – but does not specifically refer to extreme or high impact scenarios.

The ISO standards and guidelines on adaptation (ISO, 2019; 2021) set out some high-level principles but – beyond stating that approaches should be 'robust' and use 'appropriate methodologies and sources of information' – do not explicitly specify the types of scenarios to use in adaptation planning.

2.2 Flood risk

Explicit guidance for addressing the effect of climate change on coastal, fluvial and pluvial flooding is provided for England (HM Government, 2022b), Wales (Welsh Government, 2021; 2022), Scotland (SEPA, 2022), and Northern Ireland (Department for Infrastructure, 2019). In each case, the guidance is expressed in terms of a change factor to be applied to flood magnitudes estimated using conventional methods from observed data.

For coastal flood risk, the guidance in both England and Wales is to use the 70th percentile sea level rise from the UKCP18 RCP8.5 marine projection as a 'higher-central' estimate, and the 95th percentile from UKCP18 RCP8.5 as an 'upper-end'. The Scottish guidance is to use the 95th percentile from UKCP18 RCP8.5, and sensitivity testing using H++ for 'developments that are likely to be particularly vulnerable to climate change'. The Welsh guidance recommends H++ for contingency planning and developments that are very sensitive to flood risk or have lifetimes beyond the end of the century. The Northern Ireland guidance is based on UKCP09 projections, using the 50th percentile with medium emissions as a central case, and the 90th percentile as an upper case.

For fluvial flood risk, the guidance in England is to use the 50th, 70th and 95th percentiles from UKCP18 RCP8.5 respectively for 'central', 'higher central' or 'upper end'. The Scottish guidance is to use the 67th percentile and recommends using the 90th percentile for 'developments that are likely to be particularly vulnerable to climate change'. The percentiles are taken from analysis by Kay et al. (2021) applying UKCP18 probabilistic projections with response surfaces characterising change in flood magnitude with change in precipitation for different catchment types. The 'upper end' scenarios for the 2080s are similar to the lower end of the H++ flood peak scenarios. The Welsh guidance is still based on UKCP09 projections. It ambiguously states both that there is no current requirement to undertake sensitivity testing against the H++ scenario for fluvial risk management schemes and that only where the consequences of flooding or erosion would be extreme would the H++ scenario need to be considered. The Northern Ireland guidance is based on UKCP09 projections, using the 50th percentile with medium emissions as a central case, and the 90th percentile as an upper case.

For pluvial flooding, the English guidance is to use FutureDrainage (Chan et al., 2021) 'central' and 'upper' values, which are based on the 50th and 95th percentiles respectively derived from the UKCP18 RCP8.5 local strand scenarios (the FutureDrainage methodology combines estimated changes in rainfall from individual ensemble members plus uncertainty estimates for each model value to construct a probability distribution). The Scottish guidance only recommends using the central estimate "because the RCP8.5 emissions scenario is suitably precautionary" (SEPA, 2022; p16), but recommends using the upper value for developments particularly vulnerable to climate change. The 'upper' values for the 2080s are lower (40-50% increase) than the H++ scenarios (60-80% increase). The Welsh guidance for peak rainfall intensity is, like the fluvial flood guidance, based on UKCP09 projections. The Northern Ireland guidance is based on UKCP09 projections, using the 50th percentile with medium emissions as a central case, and the 90th percentile as an upper case.

The flood guidance for England specifically states that a 'credible maximum scenario' should be used for nationally significant infrastructure projects (NSIPs), new settlements or significant urban extensions. The credible maximum scenario is specified as H++ for sea level rise and the "upper end" allowance for peak river flow: there is no credible maximum scenario for pluvial flooding.

The flood scenarios are used to inform the design of flood defences and to determine risks to new developments and changes to flood outlines (Section 2.8). They do not map explicitly onto 2 and 4^{o}C worlds.

Under the European Union Floods Directive the devolved nations have been required to produce Flood Risk Management Plans (FRMPs), outlining actions to be taken to reduce flood risk by river basin. The second round of FRMPs (published in 2014) in England were influenced by the Environment Agency's (2014) long-term investment scenarios, which explored potential investments under different assumptions about climate change and future development in flood-prone areas. The climate change projections were based on the flood change factors contained in guidance at the time: these were based on UKCP09. The current round of FRMPs published in late 2022 use the coastal, fluvial and pluvial climate change allowances outlined above.

2.3 Energy sector

Guidance for dealing with climate change risks in the energy sector is included in the National Policy Statement for Energy (EN-1: DESNZ, 2023). Section 4.10 on climate change adaptation and resilience is not prescriptive about climate scenarios. It states that energy system operators should 'use government guidance and industry standard benchmarks' (4.10.9) in line with 'appropriate expert advice and guidance available at the time' (4.10.10), and demonstrate that proposal infrastructure can be adapted over their lifetimes to remain resilient to a 'credible maximum climate change scenario' (4.10.11) and where infrastructure has safety-critical elements, design should be based on a credible maximum climate change scenario (4.10.12). It also states that the Secretary of State needs to be satisfied that these conditions are met when assessing proposals. 'Credible maximum climate change scenarios' are not explicitly defined (although see Section 2.4), although the guidance refers to the IPCC and the Environment Agency.

The energy sector is divided into generators, transmission network operators, and distribution network operators (although some companies have several roles) and is regulated by Ofgem which undertakes periodic reviews to set prices. The current price control round – RIIO-2 – runs from 2021 to 2028, and Ofgem requires companies to produce business plans. The guidance for the RIIO-ED2 electricity distribution company plans (Ofgem, 2021) states that companies must include a dedicated climate resilience strategy (para 3.29), and specifically (para 3.30) must consider a range of ‘plausible’ climate projections and at minimum consider ‘the assumptions of temperature rises and/or relevant risks as outlined by the Paris Agreement, the National Infrastructure Commission, the UK Government and Committee on Climate Change, or other equivalent bodies’. In practice, companies have typically used UKCP18 RCP8.5, but have labelled it differently. Northern PowerGrid, for example, ‘plan for the worst’ which they define as a 4°C scenario but actually use RCP8.5 (Northern PowerGrid, 2021), SP Energy Networks (2021) state that ‘RCP8.5 is the most likely scenario at present’, and Northern Gas Networks (2021) state that ‘RCP8.5 is the worst-case high emissions scenario’. The assessments by the distribution companies are all based on a review commissioned by the Energy Networks Association (ENA, 2021), which also informs Adaptation Reports (Section 3).

2.4 Nuclear installations

The guidelines for assessing climate change risks for nuclear installations are more explicit than those for the energy sector as a whole. The summary guidance (ONR, Environment Agency, 2017) states

> For those nuclear sites and infrastructure on the coasts, the impacts from sea level rise, change to storm surges and wave climate (wave heights, period and direction) need to be considered over the life-time of the facilities. This includes operation, decommissioning and waste storage phases. The credible maximum scenario described in EN-1 is a peer-reviewed, high end, plausible, scenario. A current example of the credible maximum scenario for sea level rise and storm surge for the period to 2100 is provided by Government’s UKCP09, and is termed the H++ scenario

More detail on guidance for addressing coastal flood and erosion risks is provided by the Office for Nuclear Regulation (ONR, 2021a), with a supporting expert panel review (ONR, 2022a). Whilst not defining explicitly which scenarios to use, it does state that the design should be capable of accommodating an “adequately conservative” emissions scenario but not necessarily the “most conservative”. This phrasing is rather vague, as it is not clear whether ‘conservative’ means a small change (the conventional definition of conservative as ‘averse to change’) or a large change (conservative in the sense of being risk averse). The guidance states that the emissions scenario selected should be considered, and planned for, such that the risk arising from coastal flooding hazards is ‘as low as reasonably practicable’. It is not clear where RCP8.5 fits in with this guidance: is it adequately conservative, or the most conservative? The guidance also says that a maximum credible scenario, such as H++, should be used because “it is prudent to ensure that there are no features of the design which are completely undermined by more radical changes to the climate”. The supporting expert panel report (ONR, 2022a) reviews how climate change might affect coastal flood risk in the UK, but does not express a view on what is adequately conservative or most conservative, and how these compare with maximum credible scenarios.

A second set of ONR guidance (ONR, 2021b) covers other meteorological risks to nuclear installations (non-coastal flooding, wind, temperature, lightning, humidity). Beyond stating that ‘changes to meteorological hazards as a result of climate change could be significant’ it does not define specific climate scenarios to use. Instead, it states that ‘site-specific meteorological hazard analyses need to draw upon all available data sources, including palaeoclimate proxy data, historical, and instrumental data sources, where such data are likely to enhance nuclear safety significant arguments’. The supporting expert review panel report (ONR, 2022b) reviews potential mechanisms affecting changes in meteorological extremes (and describes H++), but does not provide specific guidance.

2.5 Water resources and the water environment

The management of water resources and the water environment is highly regulated, with variations across the UK.

All four devolved nations are required to produce River Basin Management Plans (RBMPs: originally required under the European Union Water Framework Directive), and the current round are due to be published by late 2022. The RBMPs cover a six-year planning period but must take a longer-term perspective. The guidance for the English RBMPs (Defra, 2021) specifically requires plans to be based on UKCP18 – although without specifying which scenario. In practice, the projected effects of climate change on river flows are used to identify general trends (such as towards lower low flows) which, together with information on other pressures, inform policies on regulations and measures to be implemented in individual catchments.

The private sector water supply companies in England and Wales are regulated by Ofwat, the Environment Agency and Natural Resources Wales. OFWAT undertakes regular Periodic Reviews in order primarily to set price limits (PR24 is in progress), and these are be based on water company plans to meet supply and environmental standards. Companies produce Water Resources Management Plans (WRMPs), and these are used along with other inputs to produce long-term delivery strategies. The WRMPs and the long-term delivery strategies follow guidance from the Environment Agency, Natural Resources Wales, and Ofwat.

The Environment Agency guidance for the latest round of Water Resources Management Plans (WRMP24: Environment Agency, 2021a; b) does not define specifically what climate scenarios should be used ('your choice of emissions scenario will be constrained by what products are available and the risk you face') but requires companies to justify their choices. Companies and water industry organisations have therefore worked together to produce some specific methodologies consistent with these guidelines. For the current Periodic Review, water companies in England have formed five regional groups to produce overarching regional plans (drafts published in 2022 and some final drafts published in late 2023): individual companies then formulate their own more localised plans within these regional contexts.

Regional groupings and companies have based their analyses on the same sets of data and projections (Atkins, 2020), but in practice have used them in different ways. The Atkins (2020) report constructed regional 'change factors' to adjust local rainfall and temperature as inputs to hydrological models, based on the UKCP18 RCP8.5 regional and global strands. In the original guidance, Atkins (2020) recommended using the CMIP5 global strand members as a central estimate, and the regional strand scenarios to characterise 'dry' scenarios. This was because HadGEM is 'hot and dry' which makes its projections 'very useful for risk assessment of low-probability high-impact outcomes and for stress testing plans but less useful for considering adaptive planning that requires consideration of a wider range of outcomes' (p70). In practice, only WRSE (2022) have used the RCP8.5 projections (treating the 28 global and regional strand projections as a single ensemble) whilst others (WReN, 2022; WRE, 2022; WRW, 2022) have scaled estimated changes in supply to correspond to RCP6.0 (using the temperature difference between the two scenarios to rescale). This is because RCP8.5 was perceived to be 'too high' – with warming above 4^{o}C. Some companies – including Thames Water and Southern Water – subsequently ran sensitivity assessments with subsets of the UKCP18 probabilistic strand to explore the effects of different emissions assumptions.

Environment Agency guidance also requires companies in England to demonstrate that their supply systems can cope with a 1 in 500-year drought. It recommends that such a drought is estimated using stochastic methods, and explicitly states (Environment Agency, 2021c) that the estimated 500-year drought is compared with the H++ drought.

The WRMP guidelines produced by Natural Resources Wales (2021) are more explicit and require that companies ensure a resilient supply of water in a 4°C scenario. This is interpreted in practice as RCP8.5. The Welsh guidance does not require companies to plan for a 500-year drought.

The Ofwat guidance for the development of long-term development strategies (Ofwat, 2022) is, confusingly, slightly different. Companies are required to test their preferred strategies against two reference scenarios for each of four drivers of change (climate change, demand, technology and restrictions on abstractions) representing a ‘benign’ and an ‘adverse’ scenario. For climate change, these are defined respectively as RCP2.6 and RCP8.5, representing “the lowest and highest plausible parameters for climate change”. Specifically, the guidance states that the 50th percentiles of the UKCP18 probabilistic projections should be used: it says that “Adding in a much lower or higher probability level to describe the impacts of each scenario would in effect combine two low-probability scenarios into an extreme scenario that is less useful for long-term investment planning”. The guidance notes that most of the consultation comments related to the selection of RCP2.6 and RCP8.5 as ‘benign’ and ‘adverse’ scenarios. In their final water resources management plans, some companies explicitly mapped their assessments onto the Ofwat scenarios.

Water resources planning procedures are different in Scotland and Northern Ireland, but in both nations regulators require the supply companies – Scottish Water and Northern Ireland Water respectively – to account for climate change in estimating future reliability of supplies. *(not clear how the Scottish approach works).* The most recent Northern Ireland Water Resources Management Plan (Northern Ireland Water, 2020) used the same approach as in WRMP19 in England and Wales.

Water resources management also includes treating and discharging sewage effluent and managing flooding from storm sewer overflows. Regulators set discharge consents for sewage treatment works, generally defining maximum volumes which can be discharged during low flow conditions as represented by the river flow exceeded 95% of the time (Q95).

Much of the UK’s sewerage network takes both raw sewage from buildings and rainwater from road and building drains and contains overflow values (Combined Sewer Overflows: CSOs) which discharge directly to watercourses when there is ‘excess’ rainfall. CSOs have become very controversial as they have significant adverse impacts on watercourses, but the causes of the large number of CSOs are complex. The Storm Overflow Discharge Reduction Plan (Defra, 2023) for England sets targets for the frequency of discharges from ‘unusually heavy rainfall events’ by 2050 and expects companies to ‘keep pace’ with increasing external pressures such as climate change. The target acceptable frequency is an average of 10 events per year, so extreme or worst case event scenarios will not be relevant: changes in the magnitude or frequency of relatively small events will be more important.

Alongside the Storm Overflow Discharge Reduction Plan, water companies in England have produced Drainage and Wastewater Management Plans (DWMPs). These lay out company plans to deal with storm sewer flooding, CSOs and failure to comply with discharge consents in the face of both population change and climate change. The plans use either the Future-Drainage factors outlined above or the UKWIR RED-UP tool (UKWIR, 2022) which uses the UKCP18-local strand RCP8.5 simulations to perturb observed storm rainfall profiles to correspond to changes by the 2030s, 2050s and 2070s. Some have explicitly described projections in terms of the 2 and 4°C pathways (using for example the 2030s RCP8.5 as a proxy for the 2050s 2°C pathway, although they have not used the same RCP scenarios to characterise the two pathways.

2.6 Transport

The Office of Rail and Road (ORR) regulates the rail network in the UK and monitors National Highways, the agency responsible for managing the UK's strategic road network.

ORR undertakes periodic reviews of funding for the rail network, which require Network Rail to develop business plans for specific Control Periods (CP6 covers 2019 to 2024). The ORR also requires Network Rail to produce Weather Resilience and Climate Change Action (WRCCA) Plans. Network Rail has developed a series of guidelines for the CP6 WRCCAs (Network Rail, 2021). These specify UKCP18 RCP6.0 90th percentile as a baseline scenario ("primary") for evaluation and decisions, and RCP8.5 90th percentile as a sensitivity test for assets with longer lifetimes ("higher"). For sea level rise, the primary scenario is defined by Network Rail to be the RCP4.5 95th percentile, because UKCP18 does not contain sea level projections for RCP6.0. Transport for London (2021) uses the same guidelines. A review for ORR (Ferranti et al., 2021) concluded that whilst the Network Rail WRCCAs broadly represented the state of the art, there were two specific recommendations: future plans should evaluate the effect of high-end low probability scenarios, and the sea-level rise scenarios (based on RCP4.5) were rather low compared with national guidance to use H++ scenarios for nationally-significant infrastructure.

HS2 is the new high speed rail line from London to the North West and is managed separately from the rest of the rail network. It has a bespoke 'climate change adaptation and resilience technical standard', which basically states that planning should follow national guidelines – particularly for flood risk and extreme rainfall (e.g. HS2, 2017).

ORR does not regulate the management of roads but does monitor the performance of National Highways which follows strategic requirements set by the Department for Transport. Internal guidelines for strategic national roads (motorways and A roads) (Highways England et al., 2021) specify that the UKCP high emissions scenario (50^{th} percentile) should be used to characterise climate trends (implicitly this is UKCP18 RCP8.5), and that H++ scenarios should be used to test the sensitivity of vulnerability safety critical features 'to ensure that such features will not be affected by more radical changes to the climate beyond that projected in the latest set of UK climate projections'. It is not clear how this would work in practice, given that – with the exception of sea level rise – the H++ scenarios are expressed in terms of events rather than in terms consistent with UKCP18 projections. The National Highways (2022) 3rd Adaptation Report uses a different set of scenarios.

2.7 Communications

The telecommunications sector is regulated by Ofcom, although adaptation to climate change is given a low priority primarily because technology in the communications sector changes very rapidly. Resilience guidance is provided by the Electronic Communications Resilience and Response Group (ER-RRG, 2018), but whilst this mentions physical risks from extreme weather events it does not define standards or mention climate change.

On a much more operational level, Ofgem specifies technical guidelines for the design of telecommunications infrastructure. This includes guidance on appropriate values of extreme rainfall (short-term rainfall intensities exceeded 0.01% of the time – about 10 5-minute periods per year) because it affects microwave attenuation. Ofgem acknowledges that these extremes are increasing (see Ofcom, 2013; Paulson, 2016) but does not specifically require operators to plan for future changes.

2.8 Land use planning

The National Planning Policy Framework (MHCLG, 2023) for England states that new development should be planned in ways that adapt to the effects of climate change (para 11) and that avoid increased vulnerability to the range of impacts arising from climate change (para 159a), but with the exception of flooding, without being more specific. It strongly discourages (with some exceptions) new development in flood-prone areas, effectively defined as areas with at least a 0.1% chance of experiencing flooding in a year. A 'high probability' Zone 3 has a greater than 1% chance of flooding in river floodplains, and a greater than 0.5% chance in coastal areas: the remaining area within the 0.1% floodplain is termed Zone 2. These zones are mapped by the Environment Agency, using a combination of modelling and observed experience. Local authorities must also produce a Level 1 Strategic Flood Risk Assessment (SFRA), which should include an assessment of the effect of climate change on identified flood zones and this SFRA should also inform planning decisions. Many SRFAs examine the effect of climate change on the extent of flood zones by applying the higher central and upper end allowances: this typically does not significantly change the extent of the high probability Zone 3 because this is often topographically-defined – the exceptions are areas with extensive low-lying land such as along the lower River Severn - but does alter the magnitude and frequency of floods within the Zone.

Developers of proposals potentially in flood zones need to produce a Flood Risk Assessment. Guidance states that this should use the central allowance, except for essential infrastructure which should use the higher central allowance. The guidance also states that the upper end allowance (credible maximum scenario) should be used for nationally-significant infrastructure projects, new settlements or urban extensions.

2.9 Built environment

New buildings in the UK have to follow Building Regulations, which vary in detail across the four nations. In terms of structural integrity, Building Regulations require construction follows Eurocode standards for snow (EN 1991-1-3), wind (EN-1991-4) and thermal (EN-1991-5) loading, and also national standards for rain. These currently do not explicitly define allowances for climate change.

Building Regulations also specify standards for the drainage of rainwater, with requirements depending on the characteristics of the development. Best practice guidance (BRE, 2018) is to use the 100-year 6 hours storm event, including an allowance for climate change (based on the peak rainfall factors). From 2022, revised Building Regulations in England, Scotland and Wales require builders to minimise the risk of overheating (for England HM Government, 2021). The simplified option for small developments just sets standards for glazing area, but the more detailed option requires the use of thermal modelling following pre-existing best practice guidance from CIBSE (CIBSE, 2017). This guidance specifies using a ‘design summer year’ (DSY), and at a minimum considering high emissions for the 2020s. The current DSYs are based on UKCP09 climate projections (CIBSE, 2014; Eames, 2016; Eames et al., 2011).

In England, the National Design Guide (MHCLG, 2021b) provide high-level guidance on design which includes an objective to ‘maximise resilience’ – but does not specify standards or criteria. The Future Homes Task Force (2021) delivery plan specifies that targets to define ‘healthy, safe and comfortable’ should be set for 2025, and these may be more explicit.

2.10 Geological disposal

Over the years, the UK has accumulated radioactive waste from a range of activities. Some of this waste has high radioactivity and will remain hazardous for hundreds or thousands of years. The safest way of dealing with this waste is through geological disposal – placing waste deep underground and containing it within barriers. Although no deep geological disposal facilities currently exist in the UK, it is highly likely that at least one will be needed. A National Policy Statement therefore exists to guide the development and approval of applications for a deep geological disposal facility (Department for Business, Energy and Industrial Strategy, 2019). This policy statement describes how to identify and adapt to climate change risks. Specifically, the policy statement states that applications should use scenarios that reflect ‘a medium and a high level of greenhouse gas concentrations at the 50%, 70% and 90% probability levels’ (para 4.6.9), and assess the potential impacts of a ‘credible maximum scenario’ (para 4.6.9). The policy statement emphasises that time horizons are very long for geological storage but that whilst applicants should demonstrate resilience whilst the site is operating they do not need to consider resilience beyond then.

3. Use and interpretation in climate change assessments

The Climate Change Act 2008 requires the UK government to undertake periodic climate change risk assessments (CCRA) and prepare a National Adaptation Programme (NAP). Although the CCRAs are based on the analysis of potential risks, the risks are actually assessed in terms of progress towards adaptation. There is no attempt to quantitatively evaluate the magnitudes of different risks using a consistent set of scenarios, and instead the second (2017) and third (2021) CCRAs were largely based on analysis of published studies which used and applied UK climate projections in different ways. Expert judgment is used to interpret the results of these studies in terms of guideline scenarios.

The studies used to inform CCRA2 (CCC, 2016) were largely (but not exclusively) based on UKCP09 climate projections and in the high-level synthesis were interpreted in terms of level of warming. The H++ scenarios (Met Office et al., 2015) - except for sea level rise - were originally constructed to inform CCRA2 (CCC, 2016). However, in practice H++ scenarios were only explicitly considered for coastal and fluvial flood risks (Sayer et al., 2015), and discussed only in the infrastructure chapter. The introductory chapter to the CCRA2 evidence report (Humphrey & Murphy, 2016) identified six potential low-likelihood high-impact abrupt changes relevant to UK climate and sea level (Table 3), although again the potential implications were not subsequently discussed in individual sector chapters.

Table 3: Low-likelihood high-impact earth system changes relevant to the UK as defined in Climate Change Risk Assessments

CCRA2 (Humphrey & Murphy, 2016)	CCRA3 (Slingo, 2021)
Weakening of the Atlantic Meridional Overturning Circulation (AMOC)	Weakening of the Atlantic Meridional Overturning Circulation (AMOC)
Ice sheet collapse	Accelerated loss of ice sheets
Permafrost carbon release	Permafrost thawing
Release of methane from ocean sediments	
Tropical forest dieback	Reduced uptake of carbon by the biosphere
Total loss of Arctic sea ice	
	Change in behaviour of the North Atlantic Jet Stream

CCRA3 interpreted published studies (which used a mixture of UKCP09 and UKCP18 projections) in terms of worlds which reached 2°C and 4°C by 2100 (CCC, 2021), although these do not correspond precisely to the emissions scenarios used in UKCP18 or indeed previous UK climate projections. As in CCRA2, the technical report (Slingo, 2021) describes a number of low-likelihood high-impact scenarios driven by earth system instabilities (Table 3), which are similar to – but not quite the same as – those described in CCRA2. These were explicitly intended not for the assessment of the magnitude of risks or for scoring the urgency of adaptation, but were presented as a wider context for those adaptation decisions sensitive to low-likelihood high-impact outcomes (Betts & Brown, 2021). The CCRA3 also states that RCP8.5 scenarios that exceed 4°C before the 2080s can be used as proxies for climate scenarios with high carbon cycle feedbacks or high climate sensitivities (Watkiss & Betts, 2021). In practice, low-likelihood high-impact scenarios were discussed only in a few places in the CCRA3 technical report. The natural environment chapter (Berry & Brown, 2021) highlights potential severe consequences for the natural environment of a serious and sustained drought, a succession of anomalous seasons, a series of extreme storms, and – for marine ecosystems – collapse of the Atlantic Meridional Overturning Circulation. The infrastructure chapter (Jaroszweski et al., 2021) simply refers to the risk of inundation of low-lying airports in high sea level rise scenarios, and the health chapter (Kovats & Brisley, 2021) focuses on low-likelihood high-impact outcomes (extreme floods etc) rather than drivers.

The CCRA3 includes national summaries for the four nations of the UK. These primarily summarise risks and adaptation priorities, but provide changes in temperature, rainfall and sea level as a context. They use UKCP18 probabilistic RCP2.6 (50^{th} percentile) and RCP6.0 (50^{th} percentile) to correspond to 2^oC and 4^oC worlds, but use RCP8.5 for sea level.

The CCRA informs the National Adaptation Programme. The 2^{nd} UK National Adaptation Programme (Defra, 2018), based on CCRA2, does not specifically present potential changes in UK climate, but the Scottish NAP (Scottish Government, 2019) does: it uses the UKCP18 RCP2.6 and RCP8.5 50^{th} percentiles to characterise 'low' and 'high' emissions respectively.

The National Flood Resilience Review (HM Government, 2016) sought to identify critical national infrastructure currently at risk of flooding: it did not consider future climate change. It basically summed infrastructure within the Extreme Flood Outline notionally representing a 0.1% annual chance (this is now defined as Zone 2 plus Zone 3), but undertook sensitivity tests in case study locations to see how plausible extreme floods compared with the Extreme Flood Outline. These plausible extreme floods were estimated in two ways. For fluvial flooding, the Met Office UNSEEN methodology (Thompson et al., 2017) was used to generate thousands of extreme monthly rainfall totals – including monthly totals more extreme than those recorded - and rainfall during historical extreme events was increased accordingly (by 20-30%) before being input to hydrological and hydraulic models to simulate flood extents. For coastal flooding, a recent extreme surge was superimposed onto the highest astronomical high tide.

The Prudential Regulation Authority (PRA) published in May 2022 (PRA, 2022) the results of the first 'stress test' of how companies in the finance sector in the UK would cope with climate change risks. This was based on a Climate Biennial Exploratory Scenario (CBES: PRA, 2021a), which consisted of three climate scenarios. Two are consistent with an increase in global temperature of around 1.8^oC but with different rates of transition ("Early Action" and "Late Action"), and one assumes no new climate policies ("No Additional Action") and reaches just over 4^oC by 2100. The scenarios define changes in risk for different regions across the globe, including the UK. The UK scenarios are defined at the national level, and primarily characterise by 2030 and 2050 change in temperature (annual average and average maximum), rainfall (winter, summer and annual), windspeed (mean and maximum) and sea level rise. They also define changes in soil moisture, area exposed to wildfire and extent of crop failure, but these are small for the UK.

4. Use and interpretation in Adaptation Reports

The Climate Change Act 2008 gives the Secretary of State for the Environment powers to require organisations providing public services or infrastructure to produce reports describing the impacts of climate change on the organisation and how they are adapting: these are known as Adaptation Reporting Powers. The powers apply to organisations providing services in England, and to organisations providing specific services in Scotland and Wales (because responsibilities for the provision of most services are devolved): there are now powers to require organisations in Northern Ireland to report. The primary purpose of Adaptation Reports is to enable Defra and the Committee on Climate Change to evaluate progress towards adaptation and support the development of the English National Adaptation Programme. The first round was in 2011, the second in 2016 and the most recent third round reports were submitted by early 2022. Although the Act allows Defra to force organisations to submit reports, for both the second and third rounds submission was voluntary so some organisations did not submit reports in some rounds. This was usually because they believed there was little change relative to the previous round. Guidelines for the Adaptation reports (e.g. Defra, 2018) require organisations to assess ‘current and future risks to that organisation presented by climate change’, but do not specify particular scenarios. The adaptation reports provide evidence on what organisations are actually doing to adapt to climate change.

There were 58 separate submissions to the second round in 2016 (including submissions covering several organisations). Most of these based their assessment of risks on UKCP09 projections, although varied in whether they focused on medium (A1B) or high (A1FI) emissions. One organisation (Peak District National Park, 2016) explicitly stated that their adaptation policy was based on preparing for 2 and 4^{o}C worlds, although did not describe how these were characterised. Two of the submissions (Heathrow Airport Limited, 2016; Peak District National Park, 2016) highlighted H++ scenarios, although did not describe explicitly how these affected adaptation plans. Trinity House (2016) explicitly noted that their sea level rise scenario was lower than the H++ scenario. The Environment Agency (2016) report described how its adaptation strategy used ‘high-end’ scenarios designed to ‘encourage long-term thinking and to facilitate discussions around climate extremes rather than averages’. These ‘high-end’ scenarios for high river flows, peak rainfall intensity, and sea level rise are less extreme than the H++ scenarios, whilst the low river flow scenario is more extreme. The temperature change scenarios are slightly lower than the H++ scenarios (accounting for differences in the way they are presented), and the wind speed scenarios are defined (as changes) for offshore rather than onshore.

Fifty-two submissions were made to the third reporting round by early 2022. This time, some sectors
(specifically water and energy) attempted to use consistent structures, although submissions differ in detail. In contrast with the second round, none of the submissions explicitly mentioned H++ or high-end scenarios although – as outlined below – RCP8.5 was often described as a ‘worst case’.

The submissions from the water sector generally used information from water resources management plans (either the previous WRMP19 or the WRMP24 plans under development) to characterise risks to water supplies. However, the information was presented and described differently. Some presented risks in terms of 2 and 4^{o}C scenarios (e.g. Affinity, Northumbrian, Severn Trent, South East and Southern), whilst some presented them in terms of low, medium and high emissions. ‘High emissions’ was typically based on RCP8.5, and in practice companies also used RCP8.5 to represent 4^{o}C worlds (although some use RCP4.5 and some RCP6.0 to represent the 2^{o}C world).

The submissions from electricity and gas distribution companies were all based on an industry-wide assessment produced by the Energy Networks Association (ENA, 2021). The submission from Energy UK, representing generators, is also based on RCP8.5 which it describes as an extreme ‘worst-case’ scenari, citing Hausfather & Peters (2020).

In the transport sector, Network Rail, TfL and National Highways all presented risks with RCP8.5, with National Highways describing this as a 4^{o}C world. Four of the strategic airport groups plus NATS (air traffic control) and all of the harbour authorities described risks under RCP8.5, with it variably described as ‘high emissions’, ‘highly precautionary’, ‘worst case’ and ‘plausible worst case’: one airport group used RCP6.0 as its upper end.

The Environment Agency and Natural England both used RCP8.5 as a proxy for a 4^{o}C world, but used RCP4.5 and RCP2.6 respectively as proxies for a 2^{o}C world. In its report, The Prudential Regulation Authority (PRA, 2021b) described the results of its CBES stress test (as outlined above).

The fourth round of adaptation reports should be submitted, on a compressed timetable, in late 2024 (HM Government, 2023). Defra consulted on whether reports should mandate specific climate scenarios, and whilst most respondents supported standardisation there was little consensus on what that should be, so the fourth round will adopt a flexible approach 'with guidance on the application of climate projections and scenarios according to the needs of different sectors and organisations' (p135).

5. Use and interpretation in emergency planning and hazard assessment

5.1 Introduction

Scenarios describing plausible extreme weather events are used in two areas: in emergency planning, and in the assessment of the potential consequences of an extreme event in terms of operational performance or financial risk.

5.2 Emergency planning

A wide range of organisations have responsibilities and duties to plan and prepare for extreme weather events now. Scenarios describing extreme weather events that could occur now are used in three areas: capability assessment for emergency planning, in planning to deal with 'major accidents', and in severe weather incident management plans.

Emergency planning in the UK is organised around preparing for the consequences of an event rather than focusing on specific drivers of emergencies (although there are additional specific plans for some specific emergencies, including flooding). This involves defining 'reasonable worst case scenarios' (primarily describing challenging events), estimating consequences, and determining what capabilities would be need to deal with the consequences. The 2020 National Risk Register (HM Government, 2020) says that reasonable worst case scenarios (RWCS) represent 'the worst plausible manifestation of that particular risk (once highly unlikely variations have been discounted) to enable relevant bodies to undertake proportionate planning' (it is worth noting that the most publicly accessible definition – it comes up first on Google – is incorrect: it says (Cabinet Office, 2020) the 'RWCS is the worst case once the high-impact low-likelihood manifestations of a risk have been discounted', whereas the RWCS is actually conceived in practice as a high-impact, low likelihood manifestation of risk). The RWCS are not defined in terms of likelihood or magnitude, although these two dimensions are used to classify risks. The likelihood of experiencing an event like a RWCS in a year (more precisely, occurring 'next year') ranges from less than 1 in 500 (0.2%) to more than 1 in 4 (25%), although most likelihoods are subjectively assessed. There are currently eight weather and climate-related RWCS. The 'reasonable worst case' events for coastal, river and surface water flooding have an assessed annual likelihood of between 1 and 5%, cold and hot events and windstorms have a likelihood of between 5 and 25%, and droughts and wildfire events have a likelihood of between 0.2 and 1% (HM Government, 2020). Specific definitions of these RWCS are not in the public domain. They are not all expressed in the same way as the H++ event scenarios (some are defined in terms of their manifestation, not the driving meteorological or hydrological variable), but the ones that can be compared are less extreme than the corresponding H++ scenarios. These national RWCS are used to define national capabilities for dealing with emergencies, and a similar approach – with different precise definitions – is used in Scotland. Local Resilience Forums are responsible for coordinating emergency response at the local scale, and in principle these should define their own planning scenarios: in practice, however, most use the national RWCS. The RWCS are defined to characterise current likelihoods and magnitudes, and explicitly do not take climate change into account: this is because risk assessment for emergency planning has a short time horizon.

The COMAH (Control of Major Accident Hazards) Regulations require operators of infrastructure and large facilities to submit safety reports to the Health and Safety Executive (HSE), the Office for Nuclear Regulation or the Environment Agency, Scottish Environmental Protection Agency or Natural Resources Wales. These safety reports must identify ‘Major Accident Scenarios’, which should include accidents with ‘natural causes’. There is specific guidance (COMAH Competent Authorities, 2018) for identifying flood risk, which essentially points to national flood guidance, but no specific guidance for other types of environmental hazard. Whilst high-level summaries of safety reports are publicly available, these do not provide details on the specific accident scenarios considered.

Many organisations also produce ‘severe weather emergency plans’ (with various labels), and regulated industries are typically required to do so. Plans vary in scope (and are rarely public), but typically involve definitions of events that trigger the implementation of the plan – sometimes events which create operating conditions such that normal management is unable to maintain standards and performance, and sometimes specific weather thresholds - and specifications of what to do during the event. These latter actions are often determined either from past experience during events, or by scenario analysis of what could happen if specific events were to occur. These scenario analyses are typically based on past extreme events. Whilst there is guidance for some specific types of emergency planning – such as water company drought management planning as outlined below – in practice there is currently little guidance to organisations – regulated or un-regulated – on how to construct emergency plans and what planning scenarios to use. Following widespread disruption during and after Storm Arwen in November 2021, a review by Ofgem (2022) concluded that winter planning by the affected companies was not adequate and recommended both regular revision of plans based on experience and stress-testing for specific components of the energy distribution network (actually call centres dealing with customer engagement). The Energy Emergencies Executive Committee review of Storms Arwen and Eunice (BEIS, 2022) specifically recommended a review of planning assumptions for severe weather risks and an update of the reasonable worst-case scenarios for testing response plans (although it does not provide any indication of how to interpret 'reasonable'). In some sectors, severe weather emergency plans are activated frequently (for example in the airport sector), whilst in others they are designed to be actioned rarely.

Water supply companies in England are required to submit Drought Plans to the Environment Agency. Drought Plan guidance (Environment Agency, 2020b) does not define explicitly the magnitude or likelihood of drought to plan for, although it does say plans 'should include short-term events with very low rainfall and longer-term droughts such as a second or third dry winter'. However, in practice, companies in their 2022 Drought Plans have typically planned to maintain public supplies – after various staged interventions – during the 'worst historical drought' or the 1 in 200-year drought (estimated via stochastic generation) where it is more extreme.

5.3 Hazard assessment using event sets

At the scale of an individual piece of infrastructure at a place – for example a structural flood defence – it is standard practice to design to a specific standard of protection using some form of extreme value analysis applied to local data (often bringing in relevant data from other areas). In other cases, however, it is necessary to design or plan around plausible extreme events which occur over time and space. Two specific examples are the insurance industry seeking to estimate maximum plausible losses in an event and plan accordingly, and the renewable energy industry designing a supply system to cope with 'extreme' seasons. Descriptions of plausible extreme events are known in the insurance industry as 'event sets', and the term is used increasingly widely. There is considerable overlap with severe weather emergency planning as outlined above, although the emphasis is on design to avoid the event rather than planning to cope with the event.

The insurance industry (direct insurers and reinsurers) needs to know the maximum size of losses that can be expected in an event and needs to demonstrate to regulators (specifically the Prudential Regulation Authority) that they can cope with extreme events. The EU Solvency II regulations (still in force in the UK) require insurance companies to have enough capital to withstand a 1 in 200-year loss. Insurance companies use (via third parties) catastrophe models to estimate losses in events, driven by sets of extreme weather events: in practice in the UK these are limited to flooding and windstorms. In its 2022 General Insurance Stress Test, the Prudential Regulation Authority (2022b) defines two specific windstorm and one specific inland flooding scenario, and points to specific events from event sets produced by a number of catastrophe modelling companies.

In principle, there are three broad ways of constructing event sets: historical events (perhaps with some plausible perturbations), stochastic generation based on statistics of past events, and dynamical simulation using weather or climate models. The flood event sets tend to be based on stochastic generation of rainfall (using a range of techniques) input to hydrological and hydraulic models, whilst the windstorm event sets tend to be based on numerical weather prediction models as used in reanalysis (see for example AIR (2018; 2019)). These event sets are usually designed to characterise current climate. The most recent flood event sets produced by JBA (2022) include sets representing 'intermediate emissions' (UKCP18 RCP4.5) and a 'no-action warning scenario' (RCP8.5), also described as a 'baseline' scenario.

The increasing reliance of renewable energy sources (specifically wind and solar) in the UK raises the potential for supply disruptions during adverse weather conditions. The Met Office therefore produced two sets of scenarios for the National Infrastructure Commission and the Climate Change Committee, and the energy industry. Both sets are based on a blend of reanalysis (ERA-5), the DePreSys seasonal forecast model (hindcasts) and UKCP18 local RCP8.5 projections. The first set (Dawkins et al., 2021a;b) represent adverse seasons, defining winter and summer 'wind droughts' coinciding with peak demands and summer surplus generation events, and define events with different return periods and for different levels of warming. Each event is expressed as gridded daily temperature, windspeed and surface solar radiation suitable for use by energy companies (it is important to note here that the primary effect of climate change is through changes in peak demand: there is little clear signal in change in windspeed or surface solar radiation, and in practice the scenarios are the same for warming up to 3^{o}C above pre-industrial levels). The second set (Rushby et al., 2022; Dawkins et al., 2021b) contains short-duration scenarios describing wind ramping events (short-duration changes in windspeed which result in rapid, instantaneous changes in generation). Again these are presented for different return periods: the climate change signal is small so it is assumed that these scenarios represent both current and future conditions.

6. Conclusions

This review has examined the interpretation of 'extreme' and 'worst case' climate scenarios in the UK and has necessarily therefore also explored more generally how climate scenarios have been specified and used. It is possible to draw a number of conclusions.

Over the years, a wide range of guidelines and plans have been produced covering most of the sectors in the UK exposed to the impacts of climate change. The major exception is agriculture, where there are no national guidelines for farmers: the 2nd National Adaptation Plan for England (Defra, 2018), for example, states that 'much of the planning will rightly fall to individual farm businesses'. The guidelines that have been produced by government, regulators and industry bodies vary in detail and levels of specificity. The general nature of some of the guidelines (for example for water resources planning) mean that different organisations have applied them differently (using different emissions scenarios for example), and there are differences between sectors. The most specific guidelines are for flood risk management. Overall, there is an increasing tendency for guidance and practice to concentrate on (to paraphrase) 'preparing for 2 and planning for 4'. This has important implications – outlined below – for the use of current climate projections.

Different organisations have used very different language to describe climate scenarios, and specifically have described RCP8.5 very differently (Table 1): it has been variably described as representing high emissions, very high emissions, a 4^{o}C world, a central, high-central or upper end scenario, an adverse scenario, business as usual, worst case or highly precautionary. However, RCP8.5 does not represent a 4^{o}C world (Figure 1). The 10th to 90th percentile range in 2100 across the probabilistic ensemble is 4 to 6.5^{o}C above pre-industrial, with a median of 5.1^{o}C, and the range over 2081-2100 across the HadGEM models in the UKCP18 regional strand is 4.1 to 5.0^{o}C (median of 4.5^{o}C).

Similarly, the review has highlighted the wide variety in how 'extreme' or 'worst case' scenarios are defined (Table 2). Some use H++ scenarios, whilst others use RCP8.5 (or percentiles from it): the method chapter in the technical report for CCRA3 (Watkiss & Betts, 2021) defines it as global warming greater than 4^{o}C or the result of earth system instability.

The review of the Adaptation Reports in particular highlighted that different organisations are concerned with different time horizons, and they use climate scenario information in different ways. Some sectors – including telecommunications but also some airport operators – do not consider time scales beyond the 2050s because they believe that the other factors that drive business planning are too uncertain, or assets are renewed frequently. In many sectors, climate scenarios are used qualitatively to indicate the directions of change in some relevant meteorological variable, such as the number of extreme high or low temperatures, or change in frequency in storms. This qualitative information is then used to inform policies for dealing with extreme events, even if specific numbers are not used in planning and design. In this case, the technical challenge is primarily to estimate changes in relevant indicators (such as exceedances of thresholds) from information provided in climate projections. In other sectors, climate scenarios are used quantitatively to determine not just specific designs but also adaptation strategies. The most obvious examples are in the water and flood risk sectors. Here, the technical challenge is to combine information from climate projections with impact models.

Several of the sets of guidance refer explicitly to ‘extreme’ scenarios, or H++. The Climate Change Committee’s (2021) principles include consideration of low-likelihood scenarios and recommend storyline and ‘what-if’ analyses. The Supplementary Green Book Guidance (Defra,2020) notes that planning for more extreme change is appropriate where there are ‘high vulnerabilities, low risk tolerance and long planning or investment cycles. Similarly, flood guidance recommends extreme scenarios when considering ‘vulnerable developments’ or ‘nationally-significant infrastructure’. Guidance in the energy sector generally states that critical features should be resilient to ‘credible maximum scenarios’, and this is stated more strongly in guidance to the nuclear sector. Guidance for roads recommends H++ for safety-critical features, but the rail guidance was criticised (Ferranti et al., 2021) for not considering low probability or H++ scenarios. The water resources planning guidance refers to extreme H++ scenarios only as a sense check on estimated extreme droughts. A few of the 2nd Round Adaptation Reports mention H++ scenarios, although it is not clear how they follow through into adaptation and resilience planning.

There are three broad implications of this review for the definition and construction of ‘extreme’ and ‘worst-case’ climate scenarios.

The first is to develop clarity on the interpretation of RCP8.5, and particularly its implementation in UKCP18 with the HadGEM models. This needs to address not only the plausibility of the emissions under RCP8.5, but also the HadGEM ‘hot model’ issue.

The second is to develop procedures to construct pathways consistent with 2 and 4°C worlds from UKCP18 products (this also involves defining precisely what is meant by 2 and 4°C worlds – do they include overshoot?). This is necessary given the increasing focus on these two worlds in adaptation planning, and to provide a context for ‘extreme’ and ‘worst-case’ scenarios. Some studies have defined 2 and 4°C scenarios by sampling from the probabilistic ensemble (Arnell et al., 2021a), and in the water sector attempts have been made to rescale estimated impacts. Other approaches could scale global and regional strand RCP8.5 projections, or use relationships between level of warming and impact (e.g. Arnell et al., 2021b) with projections of change in temperature under 2 and 4°C worlds.

The third is to develop some agreed consistent high-level nomenclature for climate scenarios as used for planning adaptation and resilience. In many areas of scenario planning, scenarios are often described as ‘central/most likely case’, ‘best case’ and ‘worst case’. However, this does not really work for climate change where increasingly a distinction is drawn between a ‘low’ case (e.g. 2^{o}C world) and a ‘high’ case (e.g. 4^{o}C world), with an extreme/worst case above the high case: adaptation and resilience planning rarely considers a central case – describing for example some intermediate state where some tighter climate policies are implemented but not are sufficient to limit the temperature increase to 2^{o}C. The ‘low’ and ‘high’ scenarios would primarily characterise uncertainty in future emissions, whilst the ‘worst case’ scenarios primarily characterise deep uncertainty in the response of the climate system to forcing (via climate sensitivity or earth system changes). Within each type, there would be scope for characterising the effect of model uncertainty, either through using ranges or, for example, using the 10th percentile with the low scenario and the 90th with the high scenario.

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