Office for Nuclear Regulation

Review of High-End Climate Scenarios

Main Report

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1. Introduction

1.1 Background

Future proofing for climate change is now a standard consideration in the planning and design of the built environment. Most often this involves adding marginal capacity to systems to allow for incremental, reasonably foreseeable changes. With respect to extreme environmental actions, this may be attempted by using the outputs of climate projection model ensembles as a natural extension of the probabilistic risk frameworks that underpin most engineering design standards.

However, where the time span under consideration is very long or the nature of the physical processes is not well characterised in the models, this process has potential to result in unreasonable design criteria or introduce unquantified risks (i.e. false precision). In these cases, scenario analysis can provide either a replacement or an adjunct for use of probabilistic projections, where the objective can be either to test the viability of adaptive strategies, where capacity is added as needed rather than at the outset, or to guard against risk of cliff edge[1] or black swan events[2].

Scenario analysis is a widely used concept, which can loosely be defined as the use of physically coherent "events" to stress test a particular system. This approach is used in many walks of life to identify vulnerabilities in complex systems under extreme but realistic conditions. For example, the bi-annual Bank Capital Stress Test carried out by the Bank of England to assess banking sector vulnerability to a large-scale financial crisis or earthquake scenarios used for seismic risk management. The Fukushima nuclear accident in 2011 prompted ONR for the need to reassess beyond design basis events, including stress testing against extreme events [1].

In the domain of climate science, "scenario" is most often used in relation to emissions pathways and the term "storyline" is preferred. Consistent use of terminology is a significant issue in the field. For the purposes of this report, preferred terms will be defined within the relevant sections and within a glossary located at the end of the document. However, as the term "high-end climate scenario" is central to the purpose of the report, it will be defined at the outset as one which is:

- A physically consistent unfolding of events, which can take place over short durations (e.g. a storm) or long ones (e.g. ice sheet destabilisation).
- Plausible/credible, associated with a low probability but not necessarily linked to a time frame or associated with a specific probability of occurrence.

A third criteria, which is implied but often not explicitly stated in the literature, is that the scenarios should be designed with a specific purpose in mind. There are a very large number of potential scenarios that could be screened for, so selection of a suitable subset requires consideration of the end goal. Definitions of generic climate scenarios or storylines may therefore stop short of something which is directly applicable by the end user, since it is impossible to simultaneously address all potential concerns across all industry sectors. Further work, including input from relevant stakeholders, is then needed to complete the process and produce a useable scenario definition.

1.2 Report purpose and structure

This document summarises work carried out to examine whether currently available guidance on high-end climate scenarios remains fit for purpose. This document will inform potential future updates to ONR guidance, including joint regulatory guidance on climate change.

Guidance on future climate extremes is available from many sources, including but not limited to:

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[1] ONR, "Cliff Edge: SAP 2014 – EHA.7: A small change in design basis fault or event assumptions should not lead to a disproportionate increase in radiological consequences.," 2014.

[2] Black Swan Event: a rare event with extreme impacts, whose probability was not well understood beforehand, and was therefore not predictable in advance, but may be rationalised after the fact.

- International bodies, such as the IPCC (Intergovernmental Panel on Climate Change).
- Regional or national bodies, such as the UK Climate Projections (currently UKCP18).
- Peer reviewed scientific research.

Of particular importance are the “H++ scenarios”, which are given as an example of a high-end climate scenario in current ONR guidance (discussed further in Section 2.1). With the exception of sea level rise, coastal flooding and peak river flows, the primary scientific basis for the H++ scenarios was developed by researchers at the UK Meteorological Office (UKMO) and University of Reading, in support of the second UK Climate Change Risk Assessment (CCRA2).

The conclusions of this work are laid out in a 2015 report [2], which is a focal point for the current review. The scenarios defined in this report are known as “the H++ scenarios” and remain part of the official UK national guidance for assessment of extreme climate change impacts. For the remainder of this document, the 2015 report will simply be referred to as “the H++ report”.

The current review is structured as follows:

- In Section 2, we provide a brief summary of ONR’s existing guidance on high-end climate scenarios and the associated scientific basis.
- In Section 3, we examine recent developments in methods used to develop high-end climate scenarios and the evidence base used to define them.
- In Section 4, we consider how the available evidence has changed since publication of the H++ scenarios and how this might have impacted their conclusions if it had been available at the time.
- In Section 5, we present an assessment of gaps between available high-end climate scenario guidance and ONR’s expectations.
- In Section 6, we present our overall conclusions and provide recommendations on how the identified gaps can be addressed.

2. Current ONR guidance and underlying scientific basis

2.1 ONR Guidance

ONR’s expectations for assessment of external hazards are primarily set out in ONR’s Safety Assessment Principles [3], the External Hazards Technical Assessment Guide (TAG 13 [4]) and the joint regulatory guidance on climate change (Use of UK Climate Projections 2018 Position Statement and the Principles for Flood and Coastal Erosion Risk Management [5]).

An appropriate design basis should be established for each hazard that is compatible with the intended use in analyses. For natural external hazards impacted by climate change, ONR expects dutyholders to consider the effects of climate change over the lifetime of the facility. Given the inherent large uncertainties in such assessments of future climatic extremes, dutyholders are expected to account for impacts due to “credible maximum scenarios”.

The guidance defines credible maximum scenarios as *“peer-reviewed, high-end, plausible scenarios of climate change”.* Within this report, the term is taken as interchangeable with “high-end climate scenario” and to include any events which are plausible in both current and future climates.

The purpose of the credible maximum scenarios is for “sensitivity testing” and is separate from analysis of design basis events, which already expects consideration of “reasonably foreseeable” climate change effects, and assessment of cliff edge effects.

Sensitivity testing in this context is intended to satisfy the following expectations:

1. Dutyholders[3] should demonstrate that it is *possible to maintain safety* for credible maximum scenarios, identifying trigger points where modifications would need to be implemented.
2. Dutyholders should identify *the potential effects* of the credible maximum scenarios, for example, to not foreclose modifications needed to enhance resilience in the future. They may take a *managed adaptive approach*, as it is recognised there is *large uncertainty* with future credible maximum scenarios.
3. Dutyholders are expected to use *the most up to date* credible maximum scenarios in any new analysis of climate change.

Within the joint position statement on the use of the UK Climate Projections 2018, the H++ scenarios are identified as an example of a credible maximum scenario in addition to Environment Agency guidance [6], which is cited for sea level rise, offshore winds, extreme waves, storm surge and peak river flows.

Climate projections currently typically only extend to 2100, though some nuclear licensed sites will have lifetimes that will extend well beyond 2100. UKCP18 has produced some extended projections for sea level rise that extend to 2300 for RCP (Representative Concentration Pathways) scenarios. The Position Statement draws on Environment Agency guidance that climate assessments beyond 2125 use RCP 8.5 from the exploratory post-2100 sea level rise dataset, however for sensitivity testing the credible maximum scenario is not expected to be extrapolated beyond 2100 (or 2125 for peak river flow). For *credible maximum scenarios beyond 2100*, the approach should be discussed with the relevant regulator(s).

2.2 Guidance from the UK environmental regulators

Since the publication of H++ scenarios, which were based on the previous iteration of UK climate projections (UKCP09), the Environment Agency, NRW and SEPA have updated their climate change guidance to incorporate estimates for RCP8.5[4] from UKCP18 (including 95th percentile as an upper end). The H++ sea level rise scenarios have not been updated and are still based on UKCP09. At the time of issue in 2018 the Met Office [7] considered this "still a reasonable plausible high-end scenario based on… current interpretation of the evidence" [8]. H++ estimates for storm surge, offshore wind speed and wave height are based on the UKCP18 Marine Report.

For climate change impacts on storm rainfall and river floods the Environment Agency and SEPA's guidance is based on UKCP18 (see sections 4.5.3 and 4.6.3). These are based on the worst-case climate emissions scenario, RCP8.5, and upper end allowances are provided based on the 95th confidence intervals. The Environment Agency and SEPA position is that the upper end allowances are suitable to assess a credible maximum climate change scenario.

2.3 The H++ scenarios

While ONR's guidance does not prescribe the scenarios to be used by dutyholder's to meet their expectations, the H++ scenarios are widely recognised as an example of a credible maximum scenario. The H++ scenarios are therefore an important focus for dutyholders in interpretation of the guidance.

The existence of the H++ scenarios have encouraged policy makers to think in more detail about flexible adaptation strategies and limits to adaptation. In the words of the authors:

"H++ scenarios can be useful scenarios for identifying a wide range of adaptation options or adaptation pathways and discovery of the 'limits to adaptation'. They may help to identify specific types of adaptation, for example flexible plans that can be adjusted if rates of warming are greater or less than anticipated or used to highlight the importance of monitoring to understand trends or rates of change. They could be useful for screening risks or to set the boundaries for more detailed sensitivity analysis, impacts assessment or risk assessment studies."

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[3] The term 'dutyholder' refers to nuclear site licensees, potential licensees, current and potential environmental permit holders for radioactive waste disposal, applicants for planning consents and Requesting Parties undergoing the Generic Design Assessment process.

[4] RCP8.5 refers to the highest emission scenario (highest level of warming) used in UKCP18 and CMIP5 projections.

The scenarios were produced using an informal expert elicitation process, in which a structured approach was used to synthesise different types of evidence, with the outcome being determined based on a mixture of quantitative arguments and expert judgment. Evidence types considered included (but were not restricted to):

- Historical observations;
- Global and regional climate projections;
- Limiting physical arguments;
- Palaeoclimatological evidence of past extremes.

Evidence was gathered and assessed on a hazard-by-hazard basis, with each scenario being expressed in different forms, depending on the constraints of the evidence upon which it is based.

The most recent national projections at the time the work was carried out were those from UKCP09, which were based on global climate projections from Phase 3 of the Coupled Model Intercomparison Project (CMIP3). The authors were also able to draw on the then recently published IPCC AR5 scientific findings and accompanying CMIP5 global models, as well as the first Met Office climate change simulations at a very high resolution of 1.5km (the CONVEX project [9]).

The main hazards covered by the 2015 H++ report are:

- Heatwaves;
- Low rainfall;
- Low (river) flows;
- High rainfall;
- High (river) flows;
- Wind storms;
- Cold Snaps;
- Sea Level Rise.

Taken together, these hazards encompass a range of systemic effects related to potential changes in large scale climatic drivers, including tipping point mechanisms which may lead to regional cooling (e.g. collapse of the Atlantic Meridional Overturning Circulation). Detailed discussion for each hazard is provided in Section 4.

3. Recent and future developments

3.1 UK Climate Change Risk Assessments 3 & 4

UK Climate Change Risk Assessments are mandated every five years by the Climate Change Act (2008) and are used to inform national adaptation policies [10]. Since the 2017 publication of the second such assessment, which was informed by the H++ scenarios, one further assessment (CCRA3) has been published and a further (CCRA4) is in preparation ahead of scheduled publication in 2027. At the time of writing, the draft CCRA4 technical report has been made available for public comment.

CCRA3 did not provide an update of the H++ scenarios, but recommended the storylines approach should be further investigated to inform CCRA4. The authors note [11]:

"[Storylines] are particularly applicable to extreme or unprecedented events whose probability cannot be quantified, but whose impacts could be profound….When co-developed by climate scientists and stakeholders, event-based storylines can provide a useful way of communicating and assessing climate-related risk in a specific decision-making context. Event-based storylines allow for conditional explanations,

without full attribution of every causal factor, which is crucial when some aspects of the latter are complex and highly uncertain."

Along with an updated assessment of projected future extremes and potential impact of climate tipping points, the draft CCRA4 technical report [12] lists development of the storylines approach as a key advance since CCRA3 and makes explicit use in its discussion on compound, multi-hazard risks, which were not considered in developing the H++ scenarios but are of potential high importance for nuclear facilities. The following "wet-windy winter" example is provided for a plausible sequence of high impact events taking place over a 1-2 week period (citations removed):

1. A severe windstorm akin to the infamous 15th October 1987 storm, exacerbated by an increased likelihood of sting jets, with a southern UK storm track.
2. Extreme, widespread flooding exceeding Desmond or Babet levels given a wetter future climate.
3. A major storm surge like that of Xaver (2013) but with a 0.6 m higher sea level, leading to coastal flooding exceeding the impact of the 1953 event in the National Risk Register.

Overall, the CCRA4 climate framing is designed to cover a greater range of uncertainty in high-end scenarios, offering guidance on high climate hazard sensitivities to be examined at 2°C for the 2030s and 2.5°C for the 2050s [12]. These are noted as plausible scenarios at the high-end of climate uncertainty, extending to 3.5°C for the 2080s and 4°C by 2100.

3.2 Climate models

3.2.1 Overview

Climate projections are modelled simulations of the Earth's climate in the future. Coordination of international efforts in continuous improvement of global climate projections is carried out under the Coupled Model Intercomparison Project (CMIP). To date, outputs from CMIP have been delivered in five distinct phases, with CMIP6 being the latest released in March 2023 and a further phase (CMIP7) underway. The main purpose of each phase has been to support the periodic IPCC Assessment Reports, though the project is gradually evolving to deliver a more continuous output.

The H++ scenarios were based on a mixture of evidence drawn from CMIP3, which was the basis for the UKCP09 high resolution national projections at the time, and CMIP5, which offered significant improvements over the CMIP3 models at global scale but had yet to be translated into detailed national level projections for the UK. National projections such as UKCP products from the Met Office are produced from downscaling global models at a low spatial resolution, to a finer spatial resolution for regional areas. Downscaling is the general name for taking data at large scales to infer the behaviour at a local scale, and this can be done spatially and/or temporally.

The major developments in the intervening 10 years have been the publication of the UKCP18 national level projections for the UK in 2018, and CMIP6 model results released with the IPCC Sixth Assessment Report (AR6) in 2023. These are discussed in the following sub-sections.

3.2.2 UKCP18

UKCP18 is the most up-to-date set of projections for the UK climate and is used in current ONR guidance [5]. It has largely been produced through downscaling of CMIP5 data, along with data from HadGEM3-GC3.05, a coupled model closely related to the model the Met Office contributed to CMIP6.

There are similarities with UKCP09, such as the use of probabilistic projections at 25km resolution. However, UKCP18 does not include a statistical weather generator, providing direct access instead to daily, and sub-daily numerical model data. Other notable changes include the use of RCP (Representative Concentration Pathways, in line with CMIP5 and IPCC AR5) instead of SRES (Special Report on Emission Scenarios) to define future changes in emissions. RCP scenarios represent more comprehensive pathways for determining future climate effects, such as accounting for policy changes and mitigation [13].

The modelling of potential extreme scenarios has improved with UKCP18 due to the higher spatial resolution (12km, 2.2km) and sub-daily (hourly and 3-hourly) projections. The 2.2km local projections are convection-permitting, meaning smaller scale, thermally driven weather features are simulated directly. This allows capturing of climate effects over the UK which were not as well addressed in UKCP09 or other climate datasets, such as the influence of mountains, urban heat islands and coastal cooling.

UKCP18 offers exploratory sea level rise data up to 2300, rather than the more typical 2100 for UKCP09 and other climate variables. This allows exploration of high-end scenarios further into the future, aligning to expected asset lifetimes in the nuclear industry.

Further improvements in extremes and insights into high-end scenarios include the newer product of Probabilistic Projections of Climate Extremes. This consists of long return-period events (1 in 20 years, 1 in 50 years, 1 in 100 years) for daily maximum temperature, daily precipitation and 5-day accumulated precipitation. These use extreme value theory to understand long term extreme events in return periods and are available across the UK [14]. There is also more information on large scale drivers of UK climate through weather pattern data relating to changing sea level pressures.

UKCP18 remains the latest dataset as part of the UK Climate Projections (UKCP). The Met Office have been further developing UKCP18 for users, such as inclusion of projections at Global Warming Levels (GWL) and updates to the user interface. Future iterations of UK Climate Projections have not been announced, such as a new dataset using CMIP6 models. Any major updates would likely take several years to deliver [15].

3.2.3 CMIP6

The latest global projections are CMIP6, used in the AR6 report. The emission scenarios used in CMIP6 represent SSP (Shared Socioeconomic Pathways). Unlike previous iterations of emission scenarios of RCP and SRES, these scenarios relate to increased radiative forcing as well as socioeconomic factors such as urbanisation and technological advances [16].

Comparisons between CMIP3 and CMIP6 show the latest models better simulate historical temperatures and precipitation patterns, and thus show smaller global mean biases, as well as presenting more spread in climate sensitivity. The improvements in model performance relate to a variety of factors including increased spatial resolution and better representation of complex Earth system processes, which are now possible due to increased computational power available for running climate models [17].

Limitations to the CMIP6 projections remain. Some CMIP6 models are known as “hot models”, with much higher rates of warming than any previous models and large temperature biases. There are differences in opinion in the inclusion of these models when considering future climate studies, however the Met Office technical notes state “models should not be screened out simply on the basis that they run ‘hot’”. Limitations in realistically representing global precipitation patterns across the globe also still exist in the latest global models, however CMIP6 has shown skilful representation over much of Europe, with limitations largely centred around regions where precipitation is projected to decrease, such as part of Africa [18].

The increased resolution offered by the CMIP6 family of models has delivered a significant improvement in representation of large scale weather patterns. However, realistic simulation of the North Atlantic Jet Stream remains a significant challenge and an ongoing driver of uncertainty in UK climate projections [11]. Free running simulation of the current North Atlantic climatology is challenging, even for advanced models, due to the prominent role of highly non-linear and eddy driven flow mechanics [19]. Spatial structure, including storm track positioning is improved in CMIP6 but significant biases remain in under-representation of frequency and persistence of high-pressure blocking patterns. These phenomena have entered the public consciousness in recent years under the label “heat domes”, which are associated with a range of hazards, including droughts, heatwaves and low river flows.

3.2.4 IPCC AR7 and CMIP7

AR7 features an on-going focus on improvements in modelling of climate extremes and an increased focus on the simulation of climate tipping points. It is expected to be released in late 2029 and will include a chapter on high-end scenarios: “Chapter 8: Abrupt changes, low-likelihood high impact events and critical thresholds, including tipping points, in the Earth system” [20]. Release of CMIP7 models is expected before the AR7 synthesis report date in 2029.

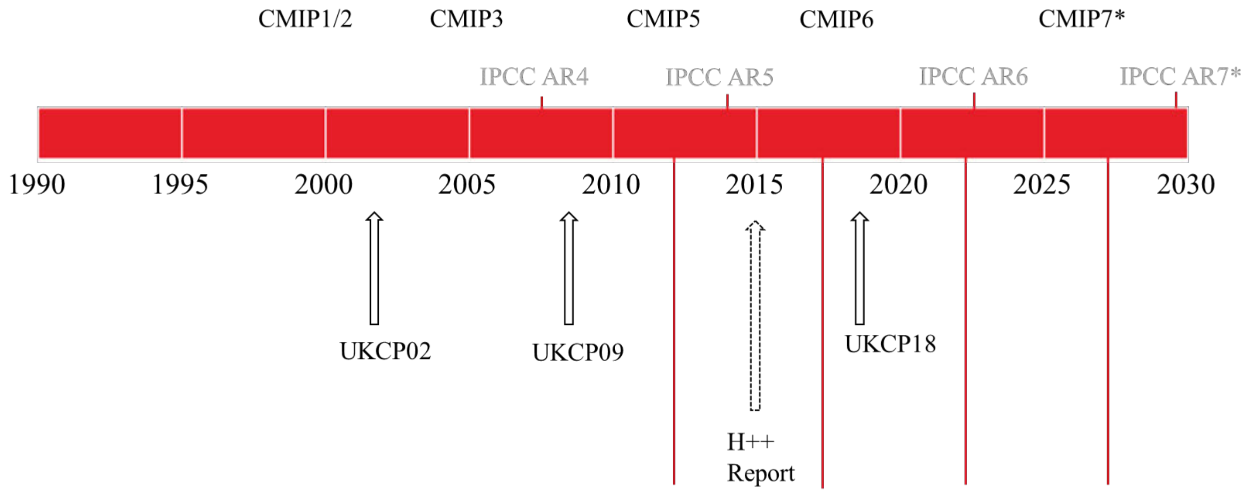
The World Climate Research Programme (WCRP) will contribute to this chapter, from a working group "Understanding High-Risk Events". Their research to improve high-end scenarios includes improved understanding of the physical processes, improved Earth Systems Models, and strategies to incorporate high-end scenarios into risk analysis [21].

Whilst CMIP7 may be released at higher spatial resolutions than CMIP6, there is a general view from world leading climate scientists that 1km resolutions rather than 100km resolutions are required for fully representing extreme events. However, this is not expected for CMIP7 and would require a step change in international collaboration and computing power available for running such models [22]. The use of artificial intelligence (AI) is an emerging trend to improve climate projection modelling. The Met Office currently have a range of research programmes using AI to downscale climate models to finer resolutions [23].

However, the use of data driven models to make "out of sample" predictions about extremes in future climates is a significantly harder challenge than the operational weather forecasting applications for which they currently show good promise.

3.2.5 Summary timeline

A combined timeline for major UK and international developments is shown in Figure 3-1.



*Expected release

Figure 3-1: Timeline for updates in key sources of scientific evidence and/or guidance.

3.3 Climate storylines

3.3.1 Overview

Climate storylines are a concept which is rapidly gaining prominence as an alternative to the traditional use of climate change projections for evidence-based decision-making. The concept has been introduced in Section 1 within the general context of scenario analysis, this section offers a more detailed definition and provides a summary of recent developments in its use to assess the impact of high-end climate scenarios.

The core ideas are set out in seminal papers by Hazeleger et al. [24] and Shepherd et al. [25] which explain the limitations of the traditional approach as well as presenting the storylines approach as a solution. Hazeleger et al. describe the traditional approach as follows (paraphrased from original):

"One traditional methodology for constructing [reliable probabilities for future weather phenomena].....is to use a current generation of climate models to simulate events on global and regional scales, downscale these simulations to generate local geophysical information and then translate the results into quantities of interest."

They then go on to state the following regarding the limitations of the approach:

"While desirable, obtaining the probabilities of future events may be considered impossible when multi-model ensembles do not provide a good proxy for the true probability of future events."

Both Hazeleger et al. and Shepherd et al. frame this as a fundamental limitation in the approach, resulting from:

- Structural errors and biases in global climate models, which cannot be corrected for and are carried through to localised, high-resolution representations of the "real" weather processes, which are of relevance to the end user.
- Lack of representation of nonlinear feedbacks between the localised (downscaled) representation of the climate to the global representation and resulting potential for internal inconsistencies.

While these limitations are fundamental from a theoretical perspective, their practical importance is linked to the ability of global climate models to represent the physical phenomena of interest. The gap between what can be achieved using the traditional and storylines approach might therefore be expected to diminish as further, higher resolution global model ensembles continue to be developed which can represent physical processes in a more accurate and precise way.

However, the storylines approach offers other qualitative benefits over the traditional approach (quoting directly from Shepherd et al. [25]):

- *Improving risk awareness by framing risk in an event-oriented rather than a probabilistic manner, which corresponds more directly to how people perceive and respond to risk;*
- *Strengthening decision-making by allowing one to work backward from a particular vulnerability or decision point, combining climate change information with other relevant factors to address compound risk and develop appropriate stress tests;*
- *Providing a physical basis for partitioning uncertainty, thereby allowing the use of more credible regional models in a conditioned manner;*
- *Exploring the boundaries of plausibility, thereby guarding against false precision and surprise.*

Additional benefits include enhanced possibilities to link physical and human aspects of climate change [25] and design scenarios to assess risk due to compound events [24].

3.3.2 Storm Desmond UK Case Study

The above definitions are philosophical in nature and can seem intangible to readers seeking an understanding of how they can be used in practice. The authors of both papers include case studies to address this, including a UK specific example in a later paper by Sillman et al. [26], in which both Hazeleger and Shepherd appear as co-authors.

In the wake of high impact flooding resulting from Storm Desmond in 2015, the UK Met Office and Environment Agency produced a worst-case scenario for the current climate to stress test national policy guidance on extreme flooding. The resulting scenario was developed from the ground up, based on existing global climate model data, which was used to establish a plausible uplift on historic extremes. This uplift was then applied to regional simulations of Storm Desmond, with the outputs being carried through to a standard flood impact assessment. An outline of this process is shown in Figure 3-2.

A key observation by the authors is the need for a chain of models to translate global scale climate information, potentially covering long time scales, into local information that meets the specific needs of the end user. When developing scenarios for general use, an important question must therefore be answered as to how far along this chain the scenario should be taken.

The further to the right (i.e. towards the specific needs of the end user), the more prescriptive the resulting guidance can be – at the cost of limiting the utility by pre-judging what those needs are. Further to the left, more flexibility is retained as to how the information is used, at the cost of additional work required to reach a final outcome.

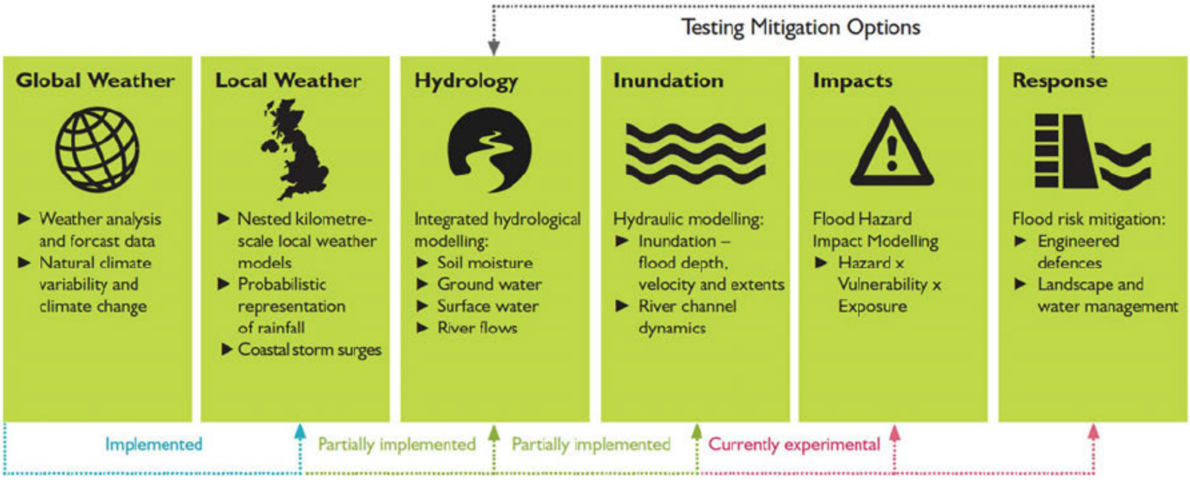


Figure 3-2: Example of a seamless modelling pathway for assessing flood risk that allows storylines and exploration of the options for reducing risk (reproduced from Sillman et al [26] and based on NFRR, 2016).

3.3.3 High-Impact Low-Likelihood (HILL) scenarios for the UK

The "High-impact low-likelihood (HILL) climate scenarios" are a recently published set of UK-focussed climate storylines [27]. The research was commissioned by the Met Office as part of the UK Climate Resilience Programme, and engaged with stakeholders, principally from the Environment Agency, EDF and the Met Office. It has been shared with the UK Climate Change Committee, but it is not anticipated to be included in the 2026 fourth UK Climate Change Risk Assessment (CCRA4) due to publication timelines.

The HILL framework defines two sets of scenarios for the UK. Which, in the words of the authors *"are designed to supplement and contextualise the UKCP18 climate projections, and to meet requirements of users for plausible high-end or worst-case climate scenarios."*

The first set are the **transient scenarios** (shown in Table 1) which consider long-term climate change to 2100. The scenarios are designed to explore how the UK climate may be affected by climate system forcings and/or climate system responses which lie outside of conventional ranges represented within the current generation of climate models. They include the UK relevant tipping points identified in the Met Office seminal report [28] and in the ONR Technical Report for ONR-RRR-115 [29], for example a step change in North Atlantic Ocean circulation (such as Atlantic Meridional Overturning Circulation (AMOC)) and rapid ice sheet destabilisation.

Whilst they do not explicitly include all the currently identified global climate tipping points [30, 31], those with less complex impacts on the UK, such as Amazon forest dieback, boreal forest dieback, and permafrost melt, may be regarded as implicitly represented through some scenarios (e.g. HILL-1) as for the UK they result in faster than expected global warming.

Name	Scenario	Storyline
HILL-1	Enhanced global warming	The rate and magnitude of climate change is greater than assumed, resulting in global warming in excess of 4°C above pre-industrial levels by 2100.
HILL-2	Rapid aerosol reductions	Air quality concerns result in large, rapid reduction to anthropogenic aerosol emissions, which accelerate greenhouse gas driven warming for a few decades.
HILL-3	Volcanic eruption	A major volcanic eruption ejects large quantities of aerosol into the stratosphere, cooling the earth for several years.
HILL-4	Stronger Arctic Amplification	More extreme Arctic Amplification and/or a more extreme response to it, leading to changes in the position of the jet stream and therefore UK weather and climate.
HILL-5	Ocean circulation change	A step change in ocean circulation in the North Atlantic leads to cooling across western Europe. Includes two scenarios, one which is full shut-down and one is partial.

HILL-6	Enhanced sea level rise	Accelerated ice loss from Antarctica and Greenland will substantially enhance sea-level rise.

Table 1: Storylines for each HILL Transient Scenario in Arnell et al. (2025) [27]

The scenarios are intended to be applied within the context of existing UK guidance (primarily UKCP18), such that climatic datasets can be generated which reflect the impact of the large-scale drivers on local scale weather patterns.

To consider climate change being greater than assumed, HILL-1 uses the upper UKCP18 data for RCP8.5, either the 95th percentile for the UKCP18 Probabilistic strand, or the highest value from the model ensemble for the UKCP18 Global, Regional and Local strands. Note, this is a higher percentile than used in the H++ report, which considered the 90th percentile as a lower bound for H++ when using UKCP09. Other HILL transient scenarios use an offset to UKCP18, so an AMOC collapse scenario can be constructed by taking an existing UKCP18 projection and applying adjustments to specified variables, with a change ramping up from 2030 and peaking at 2050 (see Figure 3-3). The extraction of extreme weather events from within the adjusted dataset then requires further work by the end user.

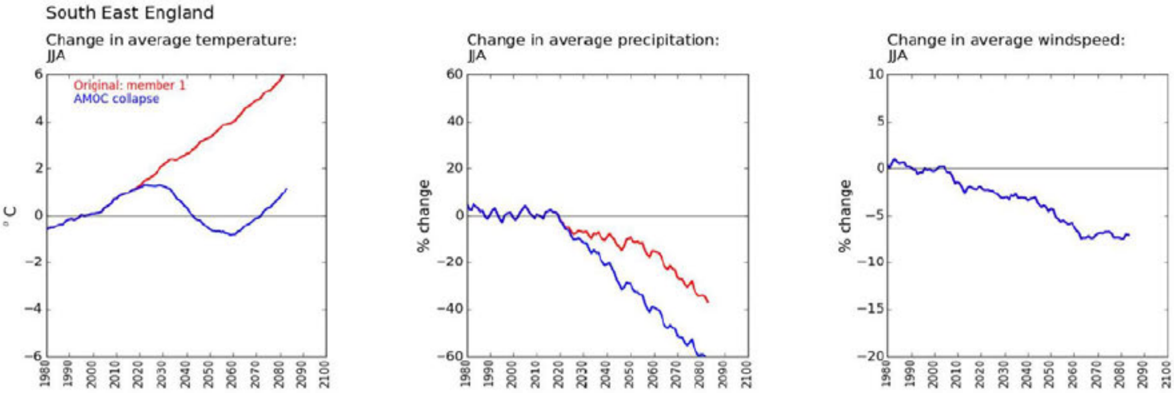


Figure 3-3: Example application of HILL-5a AMOC collapse scenario to a UKCP18 projection timeseries in South East England for summer (JJA June, July, August) (reproduced from [32]). Red lines show trajectories in mean summer temperature, precipitation and wind speeds for a UKCP18 projection where no AMOC interruption occurs, blue lines show the adjusted trajectory with the impact of AMOC collapse included.

The second set of scenarios are the **extreme anomaly scenarios**, which consider how synoptic weather patterns can create sustained periods of extreme weather on a timescale of months or seasons. Anomalies considered include: heat, cold, wet, dry, windy, persistently cyclonic (low pressure) conditions, persistently anti-cyclonic (high pressure) conditions and alternating cyclonic/anti-cyclonic conditions across seasons. A set of months representing historic extremes is also provided.

These scenarios are intended to be applied as an adjustment to a long-term mean, defined over a period of multiple decades. They are intended for use in planning for maximum monthly excursions from a climatic mean and not for definition of short-term extreme events, associated with specific synoptic weather events occurring over hours or days – e.g. a heatwave or high winds during a storm.

3.3.4 Storylines for long range UK Sea Level Rise

Credible maximum scenarios for sea level rise have been an area of active research since the publication of the H++ scenarios. Guidance from the Environment Agency and Met Office finds the previous H++ scenario of 1.9m by 2100 is still considered a reasonable plausible high-end scenario [8]. More recent literature from IPCC AR6 [33] and van de Wal et. al. [34] use storylines for high-end sea level rise, with consideration of deep uncertainty regarding ice sheet dynamics and melt rate. These storylines, alongside more moderate ones, are localised to the UK by Palmer et al. [35] and referenced in the draft CCRA4 report [12].

Recent work by Weeks et al offers a framework approach using a storylines approach, which has been co-produced with the Environment Agency in the role of a “super user” [36]. Further details are provided in Section 4.9.

3.3.5 International use of storylines

A range of international resources focussing on high-end scenarios were identified as part of the current review but, while they informative, were felt to be unlikely to be of high value for defining high-end scenarios in the UK context. This comment excludes upcoming, scenario based assessments by the IPCC, as discussed in Section 3.2.4.

In the identified examples, high-end scenarios are most commonly explored in a storyline context and do not have direct quantitative metrics for a range of climate variables as seen in the H++ report and more recent UK work. Prominent examples include:

- Various on-going international projects employ storylines to understand possible future climate and are described in the CICERO workshop (2019) [37] and AMS meeting summary (2022) [38]. These projects are not directly comparable with H++ and cover purposes from understanding a high-end event to stakeholder engagement in impacts.
- Storylines are used by the Dutch (KNMI) to capture the spread of future projected precipitation change with a dry trending storyline and wet trending storyline [39].
- The US Department of Energy are using storylines to engage stakeholders in research for number of high impact climate events through the HyperFACETS framework [40]. The events considered include worst-case hurricane tracks, wildfires in western US, and winter windstorms.
- At a broader scale, the RECEIPT project in Europe uses storylines to explore the impacts of climate change elsewhere in the world on Europe, for example the impacts on supply chains [41].

3.3.6 Ensemble boosting

Ensemble boosting, is a method used to generate large samples of data from climate models, to supplement the available observed time series with synthetic ones. This approach can be used to identify plausible extremes by allowing long running simulations to develop naturally from a consistent, historically observed initial condition, or by applying minor adjustments in boundary conditions and/or initial conditions to provoke a more rapid departure from the historical record. In either case, the result is an ensemble of unobserved/synthetic time series, which reflect paths the actual events may have taken but didn’t.

The UK Met Office has used such an approach, referred to as the UNSEEN (Unprecedented Simulated Extremes using Ensembles) to explore plausible bounds for a range of meteorological phenomena. The method was first explored for precipitation in the UK in 2017 [42], with further research on temperatures in 2025 [43]. The method has primarily been based on hindcasts[5] produced from the Met Office Decadal Prediction System, which is in turn based on the 60km HadGEM3-GC2 global coupled model. However, the method is not linked to a specific climate model and higher resolution models, such as the 2.2km UKCP-Local, convection permitting model has been used, with coarser models used to provide boundary conditions (forcing).

When used in a historical context, these methods differ from reanalysis models such as ERA5[6], which is intended to provide an accurate representation of actual historical weather events, rather than a range of virtual historic scenarios. In an industry context, hindcasting is also often assumed to be aimed at simulation of actual events, for example wave climate time series used in the design of offshore structures, which are produced from models which are forced by “actual” surface wind data derived from atmospheric models.

Ensemble boosting with model simulations are becoming a widely used method that have been used to explore:

- Plausible upper limits to heatwaves in the Pacific Northwest region, following the 2021 heat dome event, which produced temperatures 5°C above the previous observed maximum in some areas and would have been judged as statistically improbable prior to its occurrence [44].

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[5] Retrospective forecasts, initialised from a known historical weather condition but allowed to develop along alternative trajectories to those that actually occurred.

[6] https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

- Potential financial losses associated with the 1967 European tornado outbreak, were it to have occurred in 2017 over France, Belgium and the Netherlands [45].
- Plausible upper limits to precipitation intensity for the 2012 UK floods, based on perturbation of the potential vorticity anomaly that combined with an incoming extratropical cyclone to enhance the severity of the event [46].
- Simulating extreme hot and wet winters in the UK in the ExSamples project to simulate extreme hot and wet winters across the UK to show more extreme outcomes than the UKCP18 projections were feasible [47].

The above examples illustrate how a storyline based on the physical drivers of an extreme climate event, can be used in a climate model simulation and translated into outcomes such as extreme rainfall or temperature time series which are of direct use in impact assessments. However, the types of extreme events which can be explored is still limited by the spatial resolution of the climate models used to produce the ensembles. Higher resolution models, particularly those with a grid resolution of 1km or below, have greater potential to shed light on a broader range of phenomena, though these models are typically only run on a regional level and most draw their boundary conditions from coarser global models, which may pass their model errors and biases through to the regional model.

4. Re-examining the evidence base for H++ scenarios

4.1 Overview

With the exception of sea level rise, the basis for the current H++ scenarios is set out in a 2015 report by the CCC Adaptation Sub-Committee [2]. A brief background discussion is provided here, followed by a hazard-by-hazard examination of how the conclusions may have been impacted by evidence which has emerged in the intervening period. The goal is not to comment on the process itself or the conclusions reached at the time, but rather to form a judgement on whether the authors would have likely reached different conclusions given the information we have today.

The 2015 report follows two earlier studies to develop scenarios for:

- Sea level rise, carried out for the Thames Estuary 2100 plan [48].
- Peak river flows, carried out by the Environment Agency to inform their flood risk management policy guidance [49].

Experience gained on these two projects emphasised the important role of expert judgement in synthesising evidence which may take qualitatively different forms and may at times be conflicting.

The full set of scenarios are defined both in terms of quantitative statements and narrative arguments on why the supporting evidence was chosen and how it has been interpreted. This leads to a variety of outcomes, some of which provide information which can be used with limited further interpretation and some which requires substantial interpretation to develop into something that could inform an impact assessment.

4.1.1 Drivers of UK Climate

The UK climate is strongly influenced by large scale circulations within the North Atlantic Ocean and atmospheric circulation patterns above it. Specifically:

- The North Atlantic Current and broader Atlantic Meridional Overturning Current (AMOC) system.
- The North Atlantic Jet Stream.

AMOC collapse is a well publicised tipping point mechanism, that would lead to very substantial cooling of the UK climate. It was not represented in any H++ scenario as, at the time, it was considered “highly unlikely” this century. Current views of AMOC collapse differ, with some studies stating a stable AMOC [50], and others projecting a collapse in the middle of the century [51]. The latest IPCC report (AR6) has shown a weaker AMOC to be likely by 2050 and very likely by 2100 [52]. The broad spread of projections highlights the current deep uncertainty around this issue and reinforces the need to plan for high-end scenarios, such as AMOC collapse, affecting the UK climate.

The North Atlantic Jet Stream plays an important role in almost all hazards covered by the H++ scenarios, being a key driver in the formation of strong extratropical cyclones, that can generate extreme wind speeds and precipitation intensities, and persistent anticyclonic or blocking systems, that can produce extreme droughts and heatwaves.

Accurate representation of Jet Stream dynamics has been an ongoing challenge in global and regional climate models and is a significant driver of uncertainty in UK climate change projections. This is particularly the case for anticyclonic conditions, where the frequency and persistence of these systems is governed by complex nonlinear behaviour and is generally underestimated by climate models [19]. The ability of current state-of-the-art climate models to simulate North Atlantic circulation patterns in the current climate remains under question [12], making projections of future behaviour a continuing acute challenge for characterisation of high-end scenarios.

4.2 Heatwaves

4.2.1 Hazard background

In recent decades, the UK has seen an increase in annual warming due to climate change [53, 28]. High temperatures in the UK pose threats to human health and well-being, as well as risks to infrastructure, supply chains and power and water supply. This can be due to very hot days, where temperatures are intensely high for a short period of time, or heatwaves where the temperatures are high for prolonged periods of time, commonly caused by persistent high-pressure systems in summer [54].

The State of the UK Climate in 2024 report (released July 2025) show from observations the warming of the UK climate from greenhouse gas emissions has the biggest impact on the frequency and intensity of extreme temperatures [55]. Other hazards related to periods of intense heat include drought, wildfires, and thunderstorms which cause severe flooding [56].

4.2.2 Basis for current H++ scenario

The H++ report states that peak temperatures and heatwaves will likely be hotter and last longer than previous recorded events [2]. The report concluded that by the 2080’s, annual averages of summer maximum temperatures over much of the UK would exceed 30ºC, with central and southern England seeing annual averages over 34ºC. Summer maximum daily temperatures over individual years were expected to exceed 40ºC across the UK and 48ºC in London.

The H++ heatwave scenarios used daily maximum temperatures in an observed baseline climate, along with record breaking events such as the hottest recorded days, heatwave events and summers. UKCP09 projections for average summer maximum temperatures were used alongside these historical temperatures to derive the H++ scenarios for heat. These data sources were combined to give the H++ conclusion for average summer maximum temperatures and the temperatures of the hottest days for the UK.

4.2.3 Recent and emerging evidence

Advances in climate modelling and increased spatial resolution of simulations have tended to lead to progressive improvements in representation of historical temperatures, including peaks. On a global scale, the CMIP6 models have been shown to be more skilful in simulating historical temperatures than the CMIP3 models used to inform the UKCP09 projections, upon which the H++ heatwave scenario is based. For example, the global mean bias of surface temperatures in CMIP6 models are 0.08ºC, compared to -0.45ºC for CMIP3 [17]. CMIP6 models also present more spread in climate sensitivity. The effective climate sensitivity (ECS) is the response of the climate models to the forcing (essentially increase in greenhouse gas emissions). For CMIP3 the ECS range was 2.1-4.4ºC, whereas for CMIP6 this increased at both the lower and upper end to 1.8- 5.6ºC [17].

On a regional scale, the finer spatial resolution available with UKCP18 offers improved potential to resolve temperature peaks at the local scale, which can be sensitive to spatial variations in topography and land cover. UKCP18 provides data at 12km and 2.2km, in comparison with the 30km offered by UKCP09, with the 2.2km local projections also containing a better representation of the effect of soil moisture and urban heat island effects to capture these higher temperatures at sub-daily resolutions.

The HILL scenarios (see Section 3.3.3) include pathways such as enhanced global warming above 4ºC, where maximum temperatures could increase by 6.7ºC to the 2050s and 9.1ºC in the 2070s. Another storyline affecting extreme heat is that of rapid aerosol reduction, where average temperatures in the UK for the 2040s could be 0.75ºC in the 2040s higher than any conventional UKCP18 projections. The project also explores more prolonged heat periods, such as extreme anomalies of months or seasons. These can be used in addition to the transient storylines or other climate projections. Periods of hot, wet, dry, windy, persistently anticyclonic and persistently cyclonic weather are explored, showing additional uplifts of 3ºC across UK seasonal temperatures.

Since the record-breaking temperatures of over 40ºC in the UK in 2022, the Met Office has released a study based on extreme temperatures and the likelihood of this event reoccurring. The study also explores high temperatures, up to 45ºC and heatwaves [43]. The UNSEEN method (Unprecedented Simulated Extremes using Ensembles) is used to simulate thousands of synthetic but possible historical weather scenarios, expanding the data available from observational records. This study also used a storyline approach to investigate hot days over prolonged heat periods. The simulations showed variations including maximums of:

- Five days above 40ºC within the same month
- Twenty days over 35ºC
- Heatwaves (above 28ºC) lasting over a month.

The study demonstrated how high-end scenarios greater than that in our observed weather is plausible in the UK, where the model simulated a possible extreme of 46.6ºC.

Finally, the H++ scenarios alluded to the “dynamical and thermodynamic” limits on how high temperatures in the UK could physically reach [2], however it was not confirmed what these limits were at the time of the report in 2015. Whilst research in this area is still limited, studies have shown that 50ºC should not be ruled out as a plausible extreme for urban areas in Western Europe [57].

4.2.4 Discussion

H++ scenarios for high temperatures and heatwaves were developed using a range of data including historical records for extreme heatwaves and high temperatures. The UKCP09 projections were also considered, specifically changes in summer temperature. Since the report was published in 2015, there have been updates to the UK climate projections with UKCP18, but also record-breaking temperatures experienced across the UK.

Table 2 shows updates in record breaking temperatures since the publication of the H++ report in 2015.

UK Region	Pre 2015 H++ [2]		Post 2015 H++ [54]		Temperature Difference (ºC)
	Hottest Daily Maximum (ºC)	Date	Hottest Daily Minimum (ºC)	Date	
Scotland	32.9	8/9/2003	34.8	7/19/2022	1.9
England	38.5	8/10/2003	40.3	7/19/2022	1.8
Northern Ireland	30.8	7/12/1983	31.3	7/2/2022	0.5
Wales	35.2	8/2/1990	37.1	7/18/2022	1.9

Table 2: Record breaking temperatures before and after H++ publication

Europe is warming at a faster rate than the global average, with studies showing that climate projections could be underestimating warming in Europe due to a range of model limitations, such as underestimation of aerosol reduction [58]. For most of the UK, current record temperatures are close to 2ºC higher than the then record values used in the derivation of the H++ scenarios. As the H++ scenarios based their findings on historical maximum temperature records, specifically August 2003, it follows that the 2022 record breaking temperatures in the UK would have impacted the previous conclusions.

On top of new records in observed temperatures, the climate projections used to define the uplifts applied to the observed data have also seen significant changes. UKCP09 projections used to inform the H++ scenario used future average summer maximum regional temperatures for the UK from the 2080s high emission scenario at the 90th probability level (model probability). This was a 6.0-8.1°C increase compared to a 1961-1990 baseline. An equivalent projection using UKCP18 (similar spatial scale from the 25km probabilistic projections, RCP8.5, 1961-1990 baseline, 2080s (2070-2099)) gives a wider range but higher maximum of 4.5-8.8°C.

The UKCP18 probabilistic projections of climate extremes also give direct estimates of peak hourly mean temperatures, with return periods up to 100 years. This dataset shows higher temperature than using mean anomalies for most locations. In London, the projections show for RCP8.5, the 95th percentile models of the summer 1 in 100 return period of around 51°C[7] at the end of the century, which exceeds the H++ scenario of 48°C.

With the increase in the upper range of summer temperature anomalies in UKCP18, there is a potential for high-end climate scenarios to reach a more extreme condition than concluded in H++ from UKCP09 projections. UKCP18 probabilistic projections of future return periods show some models exceeding the previous H++ for the 1 in 100 year maximum temperature projection. However, studies using the UNSEEN methodology suggest that temperatures in the mid-forties may already be possible in the current climate.

4.3 Low rainfall

4.3.1 Hazard background

Low rainfall refers to periods of reduced precipitation, otherwise known as meteorological droughts. Rainfall accumulation deficits for periods ranging from 6 months to 60 months are the technical indicator for a meteorological drought. Six months is indicative of a short meteorological drought, which most water resource systems should be resilient to, whereas longer, multi-season, multi-annual low rainfall anomalies pose more of a challenge to systems, as well as to methods of assessing changes in frequency in these due to relatively short time periods covered by observational data records and climate simulations. A significant drought period is expected every 5-10years. UK droughts are typically associated with increased frequency and persistence of large scale blocking high pressure systems.

4.3.2 Basis for current H++ scenario

The H++ scenarios are:

- increase in 6-month duration summer drought occurrence with rainfall deficits up to 60%
- rainfall deficits of up to 20% lasting 3 to 5 years, similar to the most severe long droughts on record

The scenarios were developed using a seven-model subset of the CMIP5 models, which were selected based on a statistical comparison against observed patterns of rainfall deficit in the HadUK-P dataset for the 1900-1999 period. The credibility of the seven selected models in their representation of rainfall patterns in the England and Wales region is described by the authors as marginal. Outside of the England and Wales region no credible models were found. Having identified models that provide a reasonable representation of the historical data, percentage changes in the probability of encountering precipitation deficits of a given magnitude and over a range of accounting periods were estimated relative to a future period spanning 2070-2099.

The H++ scenarios are based on the largest changes in probability of occurrence estimated from the seven model subset under the RCP8.5 emissions pathway. For the probability of 6-month summer drought occurrence, this indicated an increase from 50% to 60% in summer, with no change from the historical 50% probability in winter. No change was indicated for the probability of multi-year deficits and the scenario is therefore based directly on the historical probabilities.

Palaeoclimatological analysis of tree ring data is noted to suggest that long term variability has exceeded that seen in the HadUK-P data over substantial periods. Specifically, deficits of between 15-50% were seen over

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[7] Extracted from the UKCP18 user interface

a period of up to 50 years around 500 AD. The upper bound rainfall deficit for such a scenario is similar in magnitude to the chosen 6- month deficit H++ scenario but clearly far exceeds it in duration.

4.3.3 New and emerging evidence

At the time of writing (August 2025) England is experiencing a "nationally significant incident" in regards to drought. Rainfall in July was 89% of long-term average for the month across England [59] and 59% for Wales [60]. Dorset, England recorded just 44% of the long-term average, disrupting rail travel due to soil moisture deficits. While drought conditions vary from region to region, this is the sixth consecutive month of below average rainfall, and the driest start to a year since the 1976 drought which is often used for benchmarking in water resource plans. There have also been several other regional drought events in the last decade, which would likely have been considered in developing the H++ scenario.

4.3.4 Discussion

Based on the observational record and the warmer, drier climate predictions in UKCP18 compared to UKCP09, in addition to new research on drought understanding and prediction (see further discussion in Section 4.4), it is likely that a review of potential credible maximum scenarios may result in a change in values from those presented in the H++ scenarios.

As noted in CCRA3 and draft CCRA4 outputs, the ability of climate models to accurately represent behaviour of persistent high pressure systems in the North Atlantic region remains a major challenge in understanding how risk of heatwaves and droughts will change in future. However, use of CMIP6 data is now an option and can be considered as an alternative to the CMIP5 based H++ scenarios.

4.4 Low flows

4.4.1 Hazard background

Low flows refers to periods in which rivers or other water channels see reduced throughput and may dry out. The indicator for low flows is the percentage change in Q95, which is the flow exceeded 95% of the time. Occurrence of low flows are closely linked to rainfall deficits, however, catchment characteristics, e.g size, soil type, geology and snow fall and melt patterns are significant controls regulating the hydrological response, and therefore occurrence of hydrological drought, to meteorological drought.

In addition, UK rivers are regulated and influenced by abstractions (and discharges, e.g. industrial and reservoir) which are managed during drought conditions- these impacts are not considered in the climate change scenarios. Hydrological drought can continue to persist even after rainfall deficits return to normal or above normal as groundwater and soil moisture recharge takes place.

4.4.2 Basis for current H++ scenario

There are three low flows scenarios covering different durations as impact and management options are likely to differ as drought prolongs.

- summer low flows (Q95) are reduced by between 40 and 70 percent in England and Wales and 30 and 60 percent for Scotland and Northern Ireland.
- for multi-season (2-3 seasons) droughts across consecutive summers there is a 20 to 60 percent reduction in flows in England and Wales and 20 to 50 percent reduction in Scotland and Northern Ireland.
- for longer droughts (2 years or more) the H++ scenario is for up to 50 percent and 45 percent reductions in flow for England and Wales and Scotland and Northern Ireland respectively

The assessment of changes in low flows builds on the analysis of rainfall deficits using the subset of CMIP5 models used to assess change in low rainfall. Response surfaces representing the sensitivity of a river flow to meteorological drought (rainfall deficit and duration) were generated as part of a separate project [61]. The results are based on the analysis of 6 catchments across England and Wales of the 9 modelled in the Environment Agency research project SC120048, selected based on their location and model performance.

There are significant caveats to the analysis mainly related to the spatial coverage/representativeness of the six catchments analysed. It is stressed that more extreme responses could occur at the local scale.

4.4.3 New and emerging evidence

At the time the H++ scenarios were produced there had historically been much more focus in the research community on understanding flood risk (i.e. high rainfall/flows). However, over the last 10 years there have been several research projects focussing on understanding drought dynamics and improving drought prediction, e.g. IMPETUS, MaRIUS and ENDOWS all part of the UK Droughts & Water Scarcity research programme[8].

The recent research significantly increases the spatial scale of analyses of drought trends compared to earlier studies. The eFLaG dataset is a national dataset of hydrological projections, based on UKCP18 regional projections using 4 different hydrological models. The CEH hydroprojections portal [62] can be used to view and download the results. Drought durations, intensities and severities are all projected to increase in most catchments [63]; drought intensity is predicted to increase by >50% for more than half the catchments modelled. The presented results for the Q90 suggest that changes of >60% are predicted by some models towards the end of the century; however, the results vary regionally and between models.

4.4.4 Discussion

Hydrological droughts take time to build up and can last from weeks to years. This gives time for dutyholders to act and manage the risk, which makes predicting future change in drought challenging as assumptions have to be made regarding management (i.e. feedback loops in human behaviour must be considered).

Because low flows are so strongly impacted by regulation (e.g. by preventing abstraction) and local, physical characteristics which require local scale modelling, making use of regional to local scale rainfall projections is likely to be most informative rather than national approaches.

It is noted that many studies of future hydrological drought use change factors applied to observed records, therefore do not include potential change in probability of drought duration or intensity. Because of the longer response times of hydrological processes to changes in rainfall, approaches using statistical downscaling of climate model data may need to be explored to capture potential change in interseasonal, annual and decadal variations driven by larger scale met-ocean dynamics. In addition, the impact of changing temperatures on evapotranspiration and therefore soil moisture should be considered- increased rates of evaporation will prolong drought conditions.

4.5 High rainfall

4.5.1 Hazard background

Higher than average seasonal rainfall affects fluvial and groundwater flood risk due to increases in baseflow and antecedent conditions affecting runoff rate response and/or resulting peak water levels to event rainfall. Heavy sub daily or daily event rainfall directly affects pluvial flood risk and very closely relates to fluvial flood risk.

In H++ scenarios (and the environmental regulators' scenarios) rainfall is presented as a percentage change from a baseline period.

4.5.2 Basis for current H++ scenario

The scenario is presented as an increase of 70-100% on average winter rainfall (from 1961-1990 baseline) by 2080s. For heavy daily and sub-daily rainfall over the same period, a 60% to 80% increase in rainfall depth for summer or winter events is suggested.

The H++ scenario is significantly higher than the UKCP09 high emissions scenario. These projections were used alongside historical data, high resolution climate modelling and use of empirical scaling based on the Clausius-Clapeyron equation.

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[8] https://aboutdrought.info/about-us/projects/

4.5.3 New and emerging evidence

The EA, NRW and SEPA have updated their climate change guidance to incorporate estimates for RCP8.5 from UKCP18 local projections. These are high spatio-temporal resolution, convective permitting climate models, anticipated to improve projections of sub-daily and daily rainfall changes with climate change. However, it is a very limited ensemble (due to computational requirements).

The FUTURE-DRAINAGE project provided outputs from these ensembles for industry users [64] estimating changes to 1, 3, 6, 12 and 24-hour duration rainfall events for various return periods. Projected change factors varied spatially and with duration and return period. The outputs are available as an equal area gridded dataset, however, the Environment Agency and SEPA presents uplifts regionally (by management catchment), albeit as a higher spatial resolution than for previous guidance. The highest predicted change factor in the Environment Agency Upper End scenarios is 50%; this is lower than the current H++ scenario.

4.5.4 Discussion

Both the Environment Agency and SEPA guidance is based on the FUTURE-DRAINAGE 3-hr uplifts for all durations as it tended to have the highest uplift [64]. There is some concern regarding localised spurious errors in the 2.2km scale data [65, 66], which are deemed physically unrealistic. However, the Met Office have suggested that it is acceptable to use the 5km data and associated FUTURE DRAINAGE projections which the Environment Agency and SEPA's uplifts are based on. This is because the spatial averaging and rounding used in the derivation of the 5km data is believed to limit the potential impact of the localised errors. Confidence in these data is now lower than when first published, however, still considered best available uplifts.

Despite the improved confidence that may be attached to more recent high-resolution modelling studies, the H++ scenarios may still provide a more suitable basis for credible maximum high rainfall. The use of expert judgement and theoretical considerations is noted as having played an important role in determining the outcome and these arguments remain relevant.

4.6 High flows

4.6.1 Hazard background

A flood is defined as 'any case where land not normally covered by water becomes covered by water' [66] [61]. There are different sources of flooding, e.g. surface water (pluvial), fluvial, groundwater, coastal, sewers etc. These sometimes overlap, or compound, meaning that sometimes floods result from a combination of sources, and can be exacerbated due to issues such as channel restrictions, e.g. bridges and culverts, and blockages.

Climate change impacts on coastal flooding are overwhelmingly governed by projected changes in sea level rise, which are discussed in Section 4.9. Other contributing factors, namely storm surge and wave climate, are most strongly associated with wind storms (discussed in Section 4.7).

Fluvial flooding is typically caused by high flows (units of volume per unit time, e.g. m^3/s) in a river channel in response to antecedent rainfall, resulting in the capacity of the channel being exceeded and overland flow occurring. The risk from flooding is typically described by the Annual Exceedance Probability (AEP) – which expresses the likelihood of a particular magnitude flow occurring in a given year. The parameters of typical interest for engineering design and planning are high flows with an AEP of 3.3%, 1% or 0.1%. For nuclear facilities, the relevant AEP is an order of magnitude lower at 0.01%.

High flows of 'present day' (baseline) are estimated through hydrological analyses, e.g. using rainfall-runoff modelling and/or statistical analyses of peak flows, using observations of precipitation, flow and catchment characteristics. Traditionally these analyses tend to focus on use of continuous gauge records which are relatively short, e.g. 40-60 years, compared to the design event rarity of interest.

In the UK climate change is expected to increase the risk of fluvial flooding. This is due to projected increases in event (sub- daily to daily) rainfall magnitudes, with increases in more rare events to be greater. However, the magnitude of change varies geographically and over time [67].

Climate change impact on design floods is typically assessed through estimated uplifts on either baseline design storm rainfall estimates, e.g. if flows are being estimated using a hydrological model, or on baseline flows. Changes in peak flows are not directly proportional to changes in rainfall due to catchment dynamics influences on runoff rates.

4.6.2 Basis for current H++ scenario

The current H++ guidance presents regional estimates of percentage changes in peak flows (defined as 2% AEP) due to climate change, from a baseline period of approximately 1961-2001. These uplifts are to be applied to peak flows in the current climate. Results are presented regionally for a lower end estimate of H++ (see Table 1) for different future epochs (time slices), with an upper end increase of 290% presented as a single maximum value applying across all regions.

River-basin region	2020s (2010-2039)	2050s (2040-2069)	2080s (2070-2099)
Northumbria	20	35	65
Humber	20	35	65
Anglian	25	40	80
Thames	25	40	80
South East England	30	60	120
South West England	25	50	105
Severn	25	45	90
Dee	20	30	60
North West England	25	45	95
West Wales	25	50	100
Orkney and Shetland	30	55	110
North Highland	25	40	80
North East Scotland	15	25	55
Tay	20	35	75
Forth	25	45	90
Tweed	20	35	75
Solway	20	35	75
Clyde	25	50	100
Argyll	30	65	125
West Highland	30	65	125
North East Ireland	20	40	80
Neagh Bann	15	30	70
North West Ireland	20	35	75

Figure 4-1: Lower bound adjustments for H++ high flow scenarios, expressed as percentage changes in fluvial flood peaks (50-year return period) compared to 1961-1990 (re-created from H++ report [2]).

The scenario is based on the UKCP09 Sampled Data for UK river basin regions, combined with a national scale hydrological model[9]. The lower end of the H++ range has been taken as the 90th percentile from the 'Enhanced-High' impact curves for 50-year return period (2% AEP) flood peaks, using high (A1F1) emissions for the 2080s but medium (A1B) emissions for the 2020s and 2050s. The upper end of the H++ range is taken as the maximum, over all of the river-basin regions, of the 100th percentile from the 'Enhanced-High' impact curves for 50-year return period flood peaks, using high (A1F1) emissions for the 2080s.

4.6.3 New and emerging evidence

SEPA and the Environment Agency have updated their climate change peak flow allowances to incorporate data from UKCP18. These are based on the study by Kay et al. [67] using the UKCP18 probabilistic projections, RCP8.5 and the 50-year return period (highest return period available from the Kay et al analysis).

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[9] Note that hydrological model structure is a form of uncertainty in the estimation method. Estimates of change may vary if different hydrological models are used.

In 2021 the Environment Agency (England) updated their fluvial peak flow climate change allowances. These included 3 scenarios based on RCP8.5: a central (50th percentile) a higher central (70th percentile) and Upper End scenario (95th percentile); the current Environment Agency guidance for a credible maximum scenario is to use the upper end allowance for peak flows. The uplifts are provided for 92 river management catchments[10]; the median for the Upper End scenario by 2080 is 68% (which is lower than the median of the 23 lower end regional estimates of H++) and the 95th percentile is 103% with a maximum of 127% (Test and Itchen catchment, SE England).

In Scotland the peak river flow uplifts are based on the 67th percentile for the 50-year return period and provided for 10 geographical regions from UKCP18 for RCP8.5. They range from 34% in North-East Scotland to 59% in Argyll and the Tweed. These values are lower than the current H++ values.

In Wales suggested uplifts for flow are still based on UKCP09. The upper end estimates (90th percentile) for 2080 range from 45% for the Dee catchment to 70 and 75% for the Severn and West Wales regions respectively. These values are lower than the current H++ values.

The issue of uncertainty and non-stationarity in hydrological practice has long been a consideration but not necessarily accounted for in traditional methods which assume stationarity (i.e. the statistical properties of the data remain constant over time). However, the response of a catchment to a rainfall event is sensitive to changes in the catchment such as: land use (e.g. increasing urbanisation), changes in the river channel and floodplain connectivity (e.g. introduction of flood defences), operation of control structures (e.g. dams, fish passes, weirs and sluices) and multi-decadal climate variability, which introduce non-stationarity into the observed records of flow.

It is important that these factors are considered in the assessment of present day high, low likelihood flow events using observed records (eg datasets are tested for non-stationarity and catchment history reviewed). Hydrological studies rely significantly on observed records of precipitation and flow which are rarely in excess of the low likelihood events being estimated in terms of record length. Recent methodological developments have attempted to incorporate historical evidence into the statistical analysis of peak flows using continuous data [68].

There are also recent examples of attempts to estimate past extreme flood magnitudes from paleo records. Sediment records from ungauged upland rivers, lowland floodplains and lakes have all been used to extend the flood data series beyond the instrumental record, allowing impacts from longer term climate variability mechanisms to be considered. Depending on the site, risk, and data availability, consideration of the historical records and potential modelling of historical events may generate plausible high impact, low likelihood events for testing outside the range of the predicted climate change signal; however, care needs to be taken to consider the impact of possible catchment changes on the flood response.

4.6.4 Discussion

The coarse spatio-temporal resolution of climate models means that they do not necessarily capture a number of key processes at the catchment scale required for flood estimation. The release of the UKCP18 local data offered a unique opportunity to look at how shorter duration, high intensity events may change under climate change; however, the ensemble is very limited in number and therefore only samples a small part of the uncertainty space. For instance, simulations were driven only by versions of the Met Office Hadley Centre HadGEM3 GCM (Global Climate Model), which is known to be ‘warm’ compared to the CMIP5 ensemble benchmark. The Environment Agency guidance on climate change uplifts to rainfall incorporates results from the high resolution models, however, the flow estimates do not.

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[10] The values presented for each scenario and epoch is the areal mean of the change across the management catchment. The results are based on a 1km gridded hydrological model (Grid-to-Grid, G2G) of Great Britain; however, results are only available for cells with upstream contributing catchment areas >100km^2 due to concerns regarding representatives of the results for more fast responding catchments [67]. Although the spatial results can be viewed via the CEH portal, the decision was made by the Environment Agency to represent the climate factors at the larger catchment management area scale due to lack of coverage in some locations and the requirement for more complex guidance and review process and risk in misapplication of the results at higher spatial resolution [97]. The management catchments are a higher resolution than was previously used, and represent logical hydrometric boundaries made up of whole waterbodies. It is considered that in most locations the 1km grid projections of change will be within 10% of the management catchment allowance. The Environment Agency guidance also allows for different approaches where local data indicates deviation from national guidance.

Predicting changes in high flows (and low flows) related to climate change is complicated by a cascade of uncertainty in the modelling chain including limitations of observed data and the spatial scale and heterogeneity of factors affecting the hydrological response to rainfall, e.g. soil type and land use, and of flood-producing rainfall patterns themselves, e.g. due to topographic effects. Therefore, although changes in rainfall events associated with flooding may not be well represented in climate models the uncertainty in the hydrological modelling approach, and the potential changes which may happen within a catchment over time, e.g. increasing urbanisation and river management practice, will have a significant influence on the prediction of the change in flow to a projected change in rainfall, and this uncertainty could be equal to or greater than the climate change signal, and should be considered as part of the risk equation.

It is worth noting that uncertainty in the present day estimates of peak flows could be of similar proportion to the climate change signal.

4.7 Wind storms

4.7.1 Hazard background

Extreme winds in the UK are primarily related to the actions of extra-tropical cyclones, which track from West to East and are strongly influenced by the position and dynamic behaviour of the North Atlantic Jet Stream. Engineering design standards for the UK (e.g. BS EN 1991-1-4) are calibrated against wind speeds generated by these storms, with limited consideration given to other storm mechanisms. Extreme ocean waves are generated by these storms and are therefore closely linked with respect to future trends.

The distribution of cyclone intensities and the rate (i.e. cyclones per annum) at which they cross a particular location are both key determinants of the probability of a significant wind effect threshold being exceeded. This makes realistic historic baseline simulation of both dynamic behaviour and North/South positioning of the North Atlantic Jet Stream (and therefore the resulting storm track) a necessary condition to form reliable judgements of future changes.

An important associated climate driver is the North Atlantic Oscillation (NAO), which is loosely defined based on relative positions of the semi-permanent pressure systems known as the Azores High and the Icelandic Low. Multi-decadal swings in the typical position of these systems leads to natural variability in the European wind climate, which has potential to mask long term trends due to climate change.

Significant wind effects can result from convective storms, such as tornados and thunderstorm downbursts, which are currently of secondary importance in terms of risk to people and assets but may not remain so under future climate scenarios. This is also true for tropical cyclones, which may plausibly track as far as the UK under extreme departures from current northern hemisphere circulation patterns.

4.7.2 Basis for current H++ scenario

The H++ scenario for wind storms (i.e. extra-tropical cyclones) is a 50-80% percentage increase in the number of wind storms (extra-tropical cyclones) over the UK by 2070-2100 in comparison to a 1975-2005 baseline. No guidance is offered on how this scenario is to be used by practitioners.

The scenario is based on analysis of a subset of 13 CMIP5 models, which have been selected based on their “reasonable representation” of the North Atlantic storm track over the historical reference period [69]. A spatially averaged time series of daily mean wind speed at an 850 hPa pressure level has been used to identify a mean annual frequency of “strong wind days”, which are defined as those days which exceed the 99th percentile of the distribution of daily mean speeds for the historic period (see Figure 4-2). The 50-80% increase is based on the outliers within this 13-model subset.

The 99th percentile is an arbitrary threshold, which is set sufficiently high to ensure that a strong wind storm was present over the UK on that day but does not otherwise carry any special significance. The scenario is therefore principally an adjustment to the rate at which wind storms may occur but says nothing about any potential changes to the distribution of wind storm intensity.

Evidence for changes to storm intensity is discussed based on assessments of both CMIP3 and CMIP5 model ensembles. In each case, the model mean prediction is for negligible change in rate of strong cyclones crossing the UK[11] but an increase in their intensity. It may seem more likely than not that the CMIP5 models which form the basis for the 50-80% increase in strong wind days are also associated with increases in intensity but this is not confirmed.

Other key conclusions reached include:

a. A lack of clear long term trends which can be separated from natural, multi-decadal variability.

b. An absence of physical arguments that can be applied to establish theoretical upper bounds.

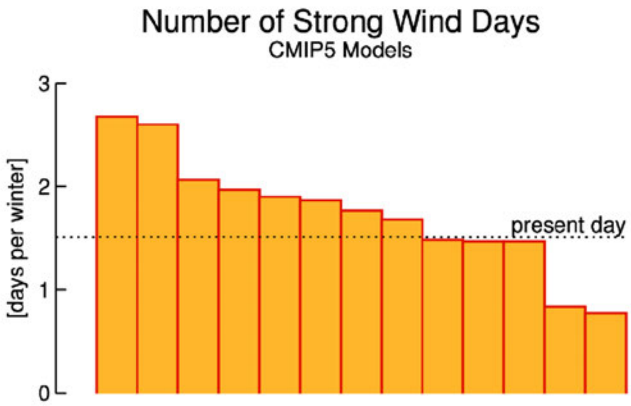

Figure 4-2: Annual number of strong wind days for a subset of 13 CMIP5 models (each bar representing one model), selected based on representativeness of the wind climate over the historical reference period. Strong wind days are defined as those with daily mean wind speeds – spatially averaged over the UK at an 850 hPa pressure level – exceeding the 99th percentile (reproduced from the 2015 H++ report).

4.7.3 New and emerging evidence

The most significant developments over the intervening period have been the improvements in winter storm track position present within the CMIP6 model ensemble and the availability of hourly mean wind speed time series via UKCP18. Access to surface level, hourly mean wind speeds is an important step forward in that it enables assessment of extreme wind speeds at time scales located within so called "spectral gap", which separates large scale atmospheric turbulence (with typical time scales of around 4 days) and atmospheric boundary layer turbulence. This allows derivation of peak wind speeds which align with those used in engineering standards such as BS EN 1991-1-4.

As for other hazards, confident estimates of future trends in storminess are challenged by difficulties in representation of Jet Stream behaviour by climate models and multi-decadal variability related to climate drivers such as the NAO. The current and future behaviour of the Jet Stream was highlighted as a fundamental knowledge gap in CCRA3 [11] and concluded that it was not yet possible to separate a climate change signal from natural long term variability in the available observational data. However, absence of evidence is not evidence of absence and a tendency towards increased storminess was suggested based on analysis of climate model data.

The draft CCRA4 outputs indicated that an increase in surface wind speeds is expected, but state that this cannot be confidently attributed to climate change and may be the result of natural variability. The draft report concludes that models of the large-scale, North Atlantic circulation are still not robust and higher resolution models are needed to improve predictions of Jet Stream dynamics and storm generation.

4.7.4 Discussion

A key limitation of the H++ wind storm scenario is that it is not expressed in terms that are likely to be directly applicable by the end user. With the publication of the UKCP18 hourly data, it is now possible to frame a scenario in terms of extreme hourly mean speeds, which are directly useable for assessment of wind

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[11] Note that the 50-80% uplift in strong wind days is only in relation to a selected subset of models and is not reflective of the model mean.

loading on structures. Issues with realistic representation of Jet Stream dynamics remain but, as UKCP18 and the existing H++ scenario largely rely on CMIP5 data, the underlying basis would remain the same. The authors are not aware of any systematic comparison between Eurocode wind speeds and equivalent values derived from the UKCP18 baseline climate data, which would be an important step towards gaining confidence in projected changes.

The HILL extreme anomaly scenarios offer an alternative means to explore plausible upper bounds to extreme wind storm intensities. Targeting specific historic events or subsets of the historical period associated with specific weather patterns can provide an appropriate starting point, which can be explored through ensembles of high-resolution weather models as described in Section 3.2.3.

Current and future generations of climate models, offering greater spatial resolution of large-scale North Atlantic circulations would be expected to offer improvements over the CMIP5 models used to inform the H++ scenario. Care is still needed to select model subsets which offer a reasonable representation of the baseline climate. Characterisation of baseline climate using observational data also requires care to ensure that extreme value estimates are not biased by natural variability.

The above discussion also informs consideration of future trends in extreme ocean waves and storm surge, which are an important contributor to coastal flood risk. Limiting physical arguments can be straightforwardly applied to specify credible maximum wave heights, since beyond a certain limit the wave will break. Ensemble boosting has been used to simulate credible maximum present-day storm surge around the UK, although maximum wave heights were largely confined to deeper water rather than at the coast [70]. The UKCP Marine Report high-end projection has an additional contribution from climate change to storm-surge of 2-3mm/year due to potential changes in atmospheric storminess [71] .

Other characteristics of an extreme wave condition may be more onerous though, depending on the system under study. For example, Storm Babet (2023) exposed the east coast of Scotland to waves to which were not just large but which also persisted for an unusually long period, resulting in extensive erosion damage in some areas due to progressive loading. Understanding how the risk of such events may change in future is subject to all the limitations presented above regarding wind speeds.

4.8 Cold snaps

4.8.1 Hazard background

Cold conditions in winter in the UK are usually caused by high pressure systems in the atmosphere. Extreme cold conditions can cause increased loads and damage to mechanical and electrical equipment. Icy conditions can cause pipes to freeze, human safety concerns and issues accessing sites [54].

Due to the effects of climate change, the UK climate has steadily warmed, with air and ground frost declining since the 1980s [55]. Many climate projection scenarios show increased seasonal temperatures in the future UK climate.

4.8.2 Basis for current H++ scenario

The H++ report referred to cold snaps as L—scenarios. The basis for the scenario refers to UKCP09 data, which showed no evidence for decreasing temperatures or more extreme cold weather in the future [2]. Therefore, the L-- scenario instead considers what would need to happen within the climate systems to lead to colder winters in the UK. This is conceptually in line with storyline approaches used to determine impacts of future climate change, based on a conditional “big picture” scenario having first occurred.

The L-- scenario also considered historical data such as the cold winter of 1962/63, the coldest recorded temperatures (1987) and the lower end of the UKCP09 projections, meaning the low emission scenario at 10th percentile model (of model uncertainty). The main basis for the future cold temperatures centres around the slowdown or collapse of the Atlantic Meridional Ocean Circulation (AMOC). This was modelled through simulations to give a mean UK temperature change of -4.7°C. Reduction in solar outputs is also considered as a potential climate phenomenon to cause a colder UK climate in the future, however with lower impacts, on average -0.68°C.

The L--scenario concludes UK average winter temperatures of 0.3°C in the 2020s and -4°C by the 2080s. The mean temperatures on extreme cold days would be -7°C in the 2020s and -11°C in the 2080s.

4.8.3 Recent and emerging evidence

There has been a shift in the views of the climate science community regarding the likelihood of AMOC collapse, which would lead to substantially reduced temperatures in the UK. The H++ report states that there is low confidence in the AMOC slowing or collapsing as it is unlikely to happen this century [2]. Since the latest IPCC report (AR6), the climate science has shown a weaker AMOC to be likely by 2050 and very likely by 2100 [72, 52].

The latest UKCP18 data has several improvements over the UKCP09 data used to inform the previous H++ scenarios. The finer spatial resolution available with UKCP18 better captures a wider range of climate phenomena. The 2.2km UKCP18 local projections also contain better representation of the effect of coastal weather processes on temperatures.

The HILL scenarios did not consider the reduction of solar outputs as explored in H++. However, studies show any reduction in temperatures from reduced solar output would not offset warming from greenhouse gas emissions [73]. The HILL scenarios and H++ both explore the potential impacts of AMOC collapse. The HILL scenario is based around changes in ocean circulation, which includes lower sea surface temperatures and AMOC collapse reducing temperatures by 5ºC [27]. H++ specifies it did not consider volcanic eruptions, which is one of the storylines in the HILL report with high confidence that this would cause a decrease in temperatures.

Other HILL storylines related to increased cold weather in the UK relate to a stronger arctic amplification. The extreme anomalies causing persistent cold weather could decrease mean winter temperatures by 7ºC, with persistent cyclonic/anticyclonic conditions which reduce seasonal weather by 3ºC. Historical anomalies which explore combined events include cold and dry and cold and wet conditions in UK regions.

4.8.4 Discussion

The occurrence of very cold winters has been declining through the decades. However, even with a warmer climate, natural variability means cold winters are still possible. Since the H++ report, the severe winter in February 2021 bought deep snow to the UK, with a minimum temperature in Scotland of -23.0°C, a record lowest temperature since December 1995 [74]. February to March 2018 also saw periods of extreme cold temperatures and high snowfall, where the Met Office issued multiple red weather warnings.

The UK record coldest temperatures remain unbroken since publication of the H++ report. Since then, there have been updates in global (CMIP6) and local projections (UKCP18). UKCP09 projections used to inform the H++ report used future average mean winter regional temperatures for the UK from the 2080s low emission scenario at the 10th probability level (model probability). This was a 0.2-0.5ºC increase in the 2020s and 1.0-1.4ºC increase compared to a 1961-1990 baseline.

An equivalent projection using UKCP18 (similar spatial scale 25km probabilistic projections, RCP2.6, 1961-1990 baseline) gives a UK average increase of 0.2ºC in the 2020s and 0.3ºC in the 2080s, therefore lower values than previously.

There have been no new record temperatures since the H++ report. Recent UKCP18 models show lower temperature anomalies than UKCP09 in the long term, however still an increase in winter temperatures. Using these pieces of data and a similar method to derive H++ scenarios, is unlikely the cold extreme L-- previously concluded would be more extreme.

4.9 Sea Level Rise

4.9.1 Hazard background

Extreme sea levels cause coastal flooding, erosion and saltwater intrusion, which are likely to increase with sea level rise. Global mean sea level has risen faster in the 20th century than in any prior century over the last three millennia, increasing by 20cm between 1901 and 2018 [33]. The average rate of sea level rise has more than doubled since the start of satellite records, from 2.1mm per year (1993-2002) to 4.7mm per year (2015 to 2024) [75]. Sea level rise around the UK is around 19.5cm since 1901, is accelerating, and may now be rising faster than the global average [55]. The IPCC state it is certain that sea level will rise until at least 2100, and by 2100 the Arctic will become practically ice-free in September. In contrast, Heuzé et al. (2024) suggest the first ice free day in the Arctic Ocean could occur before 2030 [76].

There are many mechanisms which contribute to sea level rise, as demonstrated in Figure 4-3. At a global scale, warming causes thermal expansion of the oceans and ice loss on land. Global sea levels are affected by changes in land-water storage, through processes such as groundwater extraction and reservoir storage. From 1971–2018, studies show sea level rise was 50% due to thermal expansion, 22% from ice loss from glaciers, 20% from ice sheets and 8% from changes in land-water storage [77].

At a regional level, sea level rise is impacted by changes in ocean circulation and isostatic readjustment. The latter is where the Earth's crust responds to melting glaciers and other processes where there is a change in weight distribution, causing the North of the UK to rise.

At a local level maximum sea levels vary around the coastline with wave levels and storm surges. Note, future climate change impacts on atmospheric conditions may result in changes in future storminess, see Section 4.7.4. Additional geophysical processes can affect the local sea level change, for example vertical land motion from subsidence or sediment movement. There are secondary inshore effects from sea level rise due to a change in the position of the surf zone, which may increase the wave energy and risk of over-topping and coastal erosion.

Climate projections often give sea level changes at a regional level. Site-specific assessments of future sea level change should incorporate additional data on local sea level extremes, local vertical land motion from GPS stations or satellite, and potential secondary inshore effects.

The regional and local adjustments generally show sea level rise in the south of the UK similar to the global mean, and in the north of the UK substantially lower than the global mean with minimum values in South West Scotland [71]. The UKCP Marine Report and other UK studies present sea level rise at UK capital cities as indicative of these regional differences [35, 36, 71].

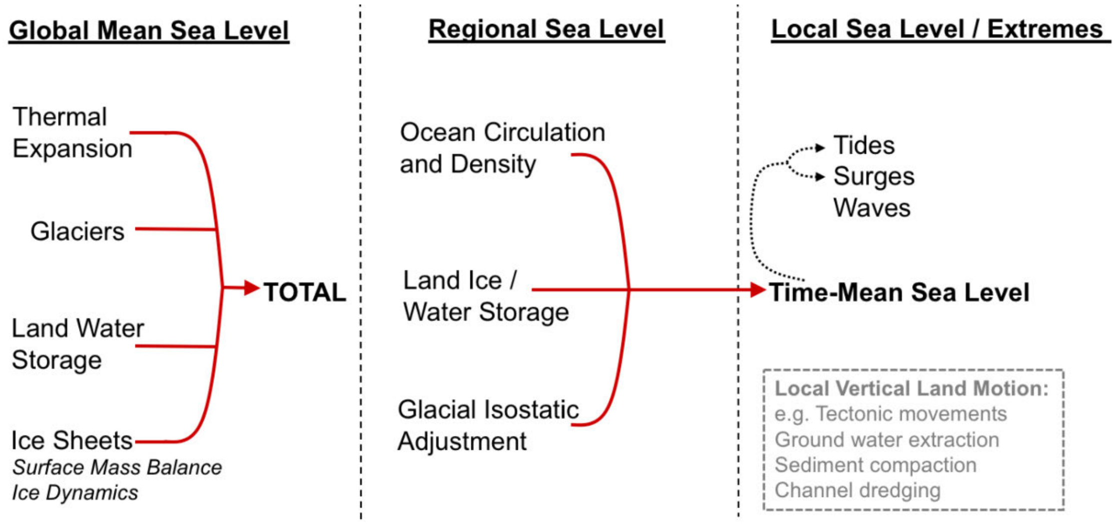

Figure 4-3: The different components of sea level rise both at the global, regional and local scales. This is from the UKCP Marine guidance note [71] to show the components represented in the UKCP18 sea level projections, the same components are widely used in other literature for sea level rise.

The largest component in high-end future sea level rise for the UK comes from rapid Antarctic ice loss, particularly the rate of melting of the West Antarctic Ice Sheet. Changes in regional ocean circulation such as AMOC collapse would also impact regional UK sea levels.

Sea level rise projections often use a "process-based" method which sums the modelled components of sea-level change. There are also 'semi-empirical' projections which rely on a statistical relationship of sea-level observations with global mean temperature or radiative forcing. The "process-based" method has been used by UKCP and IPCC AR6. As modelling of ice-sheet processes has improved, the process-based method has improved.

Unlike other climate variables which are typically modelled up to 2100, there are some sea level rise projections and scenarios that extend beyond 2100, typically to 2300. IPCC AR6 has some high-end projections to 2300. The UKCP published sea level rise data to 2300 for various scenarios, including RCP 8.5 scenario at the 95th percentile [78, 71]. This is a high-end scenario, but does not include the rapid ice sheet melting which could give rise to additional metres of sea level rise (see Figure 4-4). The UKCP sea level rise to 2300 is higher than H++ of 1.9m by 2100, and may already prompt stakeholders to think beyond 2100.

4.9.2 Basis for current H++ scenario

The upper end of H++ was derived from expert judgement, using historic rates of sea level rise from the last interglacial period (~125,000 years ago) , when the global mean surface temperature and ice-sheet configuration were similar to present day [79]. This gave a varying amount of sea level rise, from 0.93-m-1.9m around the UK coast for 2100 compared to 1990 [79]. Environment Agency guidance uses the upper value of 1.9m as H++ [6]. Current ONR guidance is that the Environment Agency expects the current H++ allowances not to be extrapolated beyond 2100 [5]. The guidance notes that there are projections for UK sea level rise to 2300 for RCP 8.5, although this does not include potential large contribution from ice sheet melt.

When UKCP18 was released, the H++ sea level rise value, which was based on UKCP09 data, was re-considered. This value of 1.9m sea level rise by 2100 (compared to 1990 baseline) was concluded to still be a reasonable plausible high-end scenario [8], with the caveat that it will be updated based on work that is yet to be published.

4.9.3 Recent and emerging evidence

The future contribution of Antarctic ice sheet melt is a key area of uncertainty for UK sea levels. When the H++ scenario was derived, limited evidence based on modelling studies of ice sheet dynamics was available. This is highlighted by the Met Office as being a rapidly moving area of research, which is informed by emerging data as ice-sheet melt occurs and there is more evidence of possible melt rates and processes [61].

Modelling of ice-sheet processes has improved in CMIP6, with higher confidence in models simulating climate processes, and good comparisons between modelled values and observations. Advances in high-end modelling have included numerical modelling of dynamic ice-sheet processes such as MICI (Marine Ice Cliff Instability) and MISI (Marine Ice Sheet Instability), self-sustaining ice-loss mechanisms triggered by rapid collapse of ice shelves.

As a result of deep uncertainty in the ice-sheet processes, including the possibility of rapid melting due to positive feedback, there has been a shift in the literature to a storyline approach. AR6 was the first IPCC study to present a low-likelihood, high-impact storylines for future global mean sea level rise with rapid and runaway Antarctic ice sheet melt. This could contribute an additional 1m of sea level rise by 2100. These AR6 storylines are also referred to as "low confidence projections".

The IPCC AR6 SSP5-8.5 high-end scenario projects global sea level rise of 1.6m by 2100, 4.8m by 2150, and up to 16.2m by 2300 for the 83rd percentile (relative to a baseline of 1995–2014), or 2.3m by 2100 for the 95th percentile. (This is significantly higher than projections without ice sheet melt from IPCC AR6 for SSP5-8.5 which are 1m by 2100 and 1.9m by 2150 (83rd percentile).) The IPCC high-end storylines are also available for lower global emissions, for example an SSP1-2.6 low confidence scenario, as the impacts of global warming are more long-lasting in the ocean and rapid ice-sheet melt may still occur even with lower global emission. Since IPCC AR6, another high-end sea level rise scenario has been published by van de Wal et al [34], using an approach based on expert judgement, intended to complement rather than replace the IPCC AR6 high-end scenarios. Van de Wal's projections are lower than the high-end scenario in IPCC AR6, for SSP5-8.5 the sea level rise could be 1.6m by 2100 and 10.4m by 2300 (relative to 1995-2014).

AR6 and recent international literature project global mean sea level to 2150 or 2300 for high-end scenarios. Extending beyond 2100 is important as models show sea level rise could rapidly increase following 2100. UKCP18 includes projection to 2300 for different RCP scenarios, but does not include high-end climate scenarios.

High-end sea level rise scenarios for the UK have been developed combining recent AR6 scenarios and van de Wal with UKCP modelling to extend to projections to 2300 in the papers listed below:

- The evolution of UK sea-level projections - 2023 (J. H. Weeks, F. Fung, B. J. Harrison and M. D. Palmer) [79].
- A framework for physically consistent storylines of UK future mean sea level rise – 2024 (M. D. Palmer, B. J. Harrison, J. M. Gregory, H. T. Hewitt, J. A. Lowe & J. H. Weeks) [35].

- A new framework to explore high-end sea level rise for the UK: updating H++ (to be published) (J. H. Weeks, L. C. Allison, A. Beverton, J. A. Lowe, H. G. Orr, H. Roberts and M. D. Palmer) [36]

Analysis by Weeks et al. (2023) [79] compared high-end sea level rise estimates presented in AR6 and UKCP09 H++. Their choice of storyline based on the high-end AR6 scenario is lower in 2100 than the UKCP09 H++ value of 1.9m but rapidly increases post-2100 and by 2150 is more than double H++, see Figure 4-4.

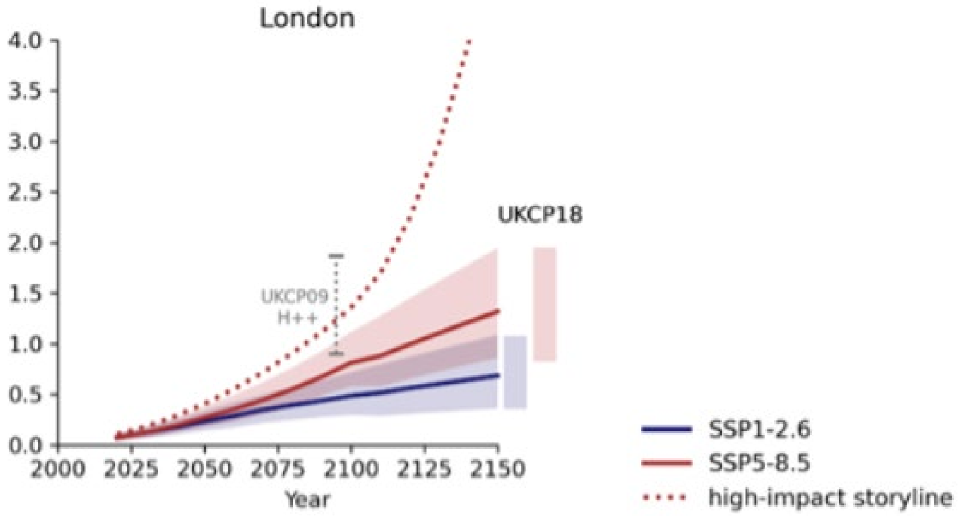

Figure 4-4: High-impact storyline based on AR6 for mean sea level rise in London to 2150 compared to UKCP09 H++, and to mean sea level rise scenarios without ice-sheet melt. For sea level rise without ice-sheet melt, the trajectories show the likely range from AR6 for SSP1-2.6 and SSP5-8.5 (adjusted for London location) and bars show the 5th-95th range for UKCP18 at 2150 for RCP2.6 and RCP8.5 scenarios. This is from Weeks et al [79].

The Palmer et al [35] storylines contain timeseries outputs for UK covering the five underlying processes of sea level rise: (i) the Antarctic ice sheet; (ii) the Greenland ice sheet; (iii) glaciers; (iv) thermosteric sea level; (v) land water storage. There are two high-end storylines, H1 based on van de Wal et al. (2022) and H2 based on the IPCC AR6 (83rd percentile). To obtain timeseries for the storyline, a large set of Monte Carlo simulations are run, with one selected that meets the target global mean sea-level for that storyline and best fits the level for each of the processes driving the storyline. Each storyline is combined with processes used in UKCP18 to extend to 2300 and project local mean sea level rise. The storylines give substantially different future sea level rise by 2300 for UK coastal capital cities, sea level rise for H1 has between 8.2m (Belfast) and 9.2m (London), and between 16.3m to 17m for H2.

Most recently, this line of research has been developed into a framework by Weeks et al. [36], co-produced with the Environment Agency as a "super-user", and building on the storylines methodology in Palmer et al [35]. The design intent behind the framework is informed by the following requirements set out by the Environment Agency:

- A well-illustrated scenario space that spans a wide range of possible outcomes setting H++ in context with other scenarios;
- Easy to explore with "what if" questions;
- Underpinned by clear, easy-to-use and scientifically robust data;
- Can provide updated sea level rise information responding to Conference of the Parties (COP) and future global warming level commitments;
- Allows exploration of the impacts associated with rates of sea level rise;
- Includes time-horizons that extend to at least 2200 for long-term infrastructure and land use planning and;

- Ability to update following emerging evidence, including tracking whether thresholds have been met or early warnings triggered.

It therefore provides downstream users with the ability to explore a broad range of scenarios, which collectively inform a decision making process which is specific to the needs of that user.

A separate recent set of high-end storylines for the UK for sea level rise to 2100 are given in the HILL storylines [27]. The storylines presented with sea level rise are HILL-1 enhanced global warming, HILL-5 ocean circulation change and HILL-6 enhanced sea level rise including ice-sheet processes. The HILL-6 scenario is based on the AR6 report high-end storyline (95th percentile) with regional sea level rise by 2100 of 2.11m in the South and East, and 1.91m in the North and West. Under HILL-6 it is noted that between 2100 and 2150 there could be a further 3.4m sea level rise, so regional sea level rise by 2150 would be 5.5m-5.8m. These projections for local sea level rise for the UK coastline are based on the NASA regional modelling of sea level rise in the NASA Sea Level Projection Tool [80]. The IPCC AR6 scenario is used rather than van de Wal as a more conservative, higher estimate of future sea level rise.

These global sea level rise scenarios form the basis of international literature. The French, Swedish and Danish [81] use the AR6 high-end scenario, and the Dutch use van de Wal [39] and structured expert judgement used in AR6. New York extreme sea level rise is based on the NASA Sea Level Projection Tool.

International literature and guidance on high-end sea level rise are more evident than other variables. The Fifth National Climate Assessment (NCA5) by the US Government defines a high scenario of global mean sea level rise of 2m from 2020-2150, based on CMIP6 models [82]. The previous assessment NCA4 reported a higher extreme scenario for global mean sea level rise of 2.5m by 2100 [83]. However, NOAA considers that this amount of sea level rise is less likely based on the latest science, due to improved understanding of the timing of possible large future contributions from ice-sheet loss [84, 85].

4.9.4 Discussion

Sea level rise has been reviewed and updated since H++, with considerations of different storylines and incorporation of UKCP18 model projections. The recent publication by Weeks et al is an update to previous H++ scenarios, and commissioned with the Environment Agency for this purpose.

Recent estimates for high-end UK sea level rise to 2100 give similar values to H++, despite being produced in different ways, which validates the value of 1.9m. However, research since 2015 has generally shown higher potential for sea level rise beyond 2100 than the 1.9m reported in H++ and used in current Environment Agency and ONR guidance.

The overall conclusion from the latest global CMIP6 models used by the IPCC in AR6 shows global mean sea level rise approaching 2m by 2100 and 5m by 2150 (relative to 1995-2014). The report states these high levels cannot be ruled out due to deep uncertainty in ice-sheet processes [77]. Whilst this is a similar sea level rise value at 2100 than H++, there is a substantial increase post-2100, as seen by other recent literature by Weeks and Palmer, and the HILL storylines.

Recent projections for high-end sea level rise are based on the scenario in IPCC AR6 which includes the ice-sheet dynamics and MICI and referred to as the ‘SSP5-8.5 Low Confidence’ scenario. The choice of percentile from this scenario varies, however the percentile should not be interpreted as model likelihood, more a subjective characterisation of how extreme the storyline is. The ethos of storylines is the numerical value is not treated as an exact quantification, but as a starting point to explore the impacts. When using the AR6 ‘SSP5-8.5 Low Confidence’ scenario, the NASA Sea Level Projection Tool displays the 50th percentile [80], and the UK literature on storylines for high-end sea level rise is based on the 83rd percentile [35], or the 95th percentile [27].

The recent work by Weeks provides an update to H++ as a framework method, using a storylines approach and extending to 2300, to capture increases in the high-end scenarios between 2100 and 2300 not explored with UKCP09 previously [36]. Currently the H2 scenario in Palmer et al together with the HILL-6 scenario [35, 27] could be used as the highest projections of future high-end UK sea level rise.

How the storylines are applied in practice to sensitivity test against the different storylines of sea level rise is an area needing further exploration with consideration of the asset. Further modelling is needed to understand the impact of the sea level rise on coastal inundation and flooding. There is an upcoming publication by Matt Palmer with University of Bristol to use a UK-wide flood model to demonstrate the high-end sea level rise coastal inundation challenge and overlay this with information about population and infrastructure etc. The Environment Agency will publish their Long-term Investment Scenarios (LIS) and include a high-end scenario. The LIS (long term investment scenarios) is an economic cost-benefit assessment of future flood and coastal erosion risk management over the next 50 years in England. The current Long-term Investment Scenarios were published in 2019 and used the H++ scenario with 0.7m sea level rise by 2060 (compared to 2014), it is not stated what high-end scenario will be used in the upcoming publication [86].

Ice sheet melt is an area of deep uncertainty, so a conservative approach that considers the highest sea level rise is recommended. It is also an area of rapidly improving science, modelling and data, so the latest research should be considered when constructing storylines of high-end sea level rise.

4.10 Other hazards, wildfires and combined events

4.10.1 Wildfires

Unlike the other hazards in the H++ report, wildfires were reported qualitatively and further research for quantitative analysis was suggested. Therefore, it is presented differently than previous hazards in this report.

The qualitative conclusion of H++ states there is a high risk to conditions causing fire over the UK, particularly in the South-East. The evidence between climate change and frequency of fires is explored primarily through exploring historical events, temporal and spatial analogues and model simulations.

Historical events were used to demonstrate current risk included the 2011 Swinley fires, and wildfires corresponding to hot and dry years of 1995 and 2003. Since the H++ report, the UK has seen record breaking wildfires. In 2025, 33,000 hectares were burned over 99 wildfires in the first 6 months alone, a record since the Global Wildfire Information monitoring began in 2012 [87].

Simulations using record breaking temperatures in 2022 show conditions which could cause “very high” fire risk are six times more likely, with hotter and drier conditions exacerbating the risk [88, 77] . The H++ report used regional simulations to approximate high-end scenarios through climate models showing greatest chance of fire and calculating future fire danger [2]. More recently, UKCP18 data has been used as a proxy to quantify wildfire risk in the UK, using variables such as temperature, rainfall, vapour pressure relative humidity and windspeed [89].

The H++ report noted wildfire risk is not solely based on climate, with human activity usually causing wildfires and with the presence of the right fuels, wildfires could happen in the near term as much as the end of the century. High-end wildfire scenarios are therefore difficult to quantify and should be considered with impact rather than the risk of the hazard alone [2].

Studies around high-end wildfire scenarios in the UK are limited, with qualitative findings or limited simulations requiring further research and quantification.

4.10.2 Lightning

Lightning strikes are unpredictable transient events in the UK and can cause damage to electrical equipment, electrical fires and even structural damage [54].

Lightning was not included in the H++ report, nor in the latest HILL scenarios. Previous UKCP09 projections only considered lightning qualitatively, whereas UKCP18 offers quantitative projections on total lightning flashes at the local UKCP18 spatial scale [90].

Information on high-end scenarios for lightning is limited. The latest UKCP18 projections at the upper end of the RCP8.5 climate projections allow quantitative analysis of lightning through a flash rate variable. However, in the UK context, studies have determined a 1 in 10,000 year lightning strike intensity of 300kA [91].

4.10.3 Humidity

High humidity and elevated WBGT (Wet Bulb Globe Temperatures) in the UK can contribute to heat stress, fog, condensation and reduced performance of mechanical equipment.

Humidity or references to WBGT were not included in the H++ report. A maximum relative of humidity of 100% can be tested with high-end scenario DBT (Dry Bulb Temperature), such as those discussed in Section 4.2. UKCP18 projections provide humidity projections for RCP8.5 and a 4°C GWL. The latter show annual [92] decreases in relative humidity, up to 6% lower than present day in the Southeast of England.

The HILL report focuses on scenarios for temperature, rainfall and windspeeds, however states changes in other variables such as humidity can be derived from the storylines to infer changes in the high-end scenarios [27]. An example is given for HILL-1 in extracting projections relating to the enhanced global warming scenario. In this case humidity can be taken from UKCP18 RCP8.5 projections as the maximum model from the local or regional data, or 95th percentile from the probabilistic projections.

4.10.4 Snow

Cold snaps, discussed in Section 4.8, can be associated with heavy snowfall. This is mentioned in the H++ report, along with snow avalanches in Scotland, but snow is not explicitly analysed as a climate hazard.

As with cold snaps, UKCP18 projections show decreases in both falling and lying snow [93]. However, climate scenarios such as the Met Office tipping point reports suggest increases in snowfall magnitude and duration are possible with AMOC collapse [28]. High-end scenarios for snow are not quantified in the HILL report with the storyline related to AMOC collapse. In the absence of high-end scenarios for the UK, snow loads from Eurocodes of other countries with colder climates could be considered, for example Norway which experiences colder, more snowy winters.

4.10.5 Sea Surface Temperatures

Changes in sea surface temperatures (SST) were not discussed in the H++ report. They are explored in the HILL storylines, primarily in relation to its impacts on other hazards such as temperature. The HILL scenario related to changes in ocean circulation and links to AMOC could lower SST, which itself causes lower temperatures [27]. Another scenario references high pressure over Scandinavia causing higher SST around the UK. The extreme anomalies scenarios of persistent cyclonic and persistent anticyclonic conditions also affect SST and exacerbate these extreme conditions further. Whilst these are discussed in HILL storylines, they are not quantified.

Recent marine heatwaves (July 2025) in the south of the UK have shown SST uplifts of up to 3°C compared to a 1982-2012 average. As explored in the HILL storylines, SST increases can be due to a range of reasons, including anticyclonic conditions, weaker winds and increased [94] sunshine. Increased SST can cause a range of climate phenomena including increased land temperatures, reduced sea breezes and extreme rainfall events.

Global projections from CMIP6 for the SSP5-8.5 scenario at the 95th percentile show SST increases of 5.8°C around Northern Europe at the end of the century, compared to a 1981-2010 baseline.

4.10.6 Combined Events

Combined or compound events occur when multiple events occur simultaneously or concurrently. These events can produce system failures which would not result from exposure to each component on an individual basis, i.e. the failure may be produced from combinations of below design basis events. The system response can be sensitive to the sequence and timing of the events as well as their magnitude, making these scenarios hard to define without reference to a specific system vulnerability that the scenario is designed to test.

The Bank of England system-wide exploratory scenario (SWES) is a prominent example of how these type of events can be used to assess resilience in complex systems. The current SWES scenario is designed to address concerns resulting from specific historical events – the “dash for cash” at the onset of the Covid-19 pandemic and the 2022 UK pensions crisis. It is therefore informed by these events but is designed to assess the impact of a market shock, which is faster, wider ranging and more persistent.

The H++ report provided some discussion of combined events, such as storms associated with heavy rain and wind, but this was qualitative. The storylines approach in HILL can be used to combine transient scenarios (for instance enhanced global warming and ocean circulation change) and gives detail on how these may simultaneously affect climate hazards. As with the general concept of storylines, the joint probabilities of high-end events occurring are not available through this approach.

More recently, the draft CCRA4 report outlines two high impact, compound event scenarios – “wet and windy” and “hot and dry”, where a series of extreme meteorological events occur within a period of weeks.

However, compound events do not need to be limited to meteorological factors, but can include factors such as human activity or other natural hazards such as earthquakes. Storylines are an effective method to combine multiple hazards and are widely used in global disaster risk management with multi-risk scenarios, which could inform dutyholders’ consideration of high-end, combined events [95].

A study in the UK shows how a storylines approach could be used to fully consider the full extent of climate extremes. When considering fluvial flooding along with changes in the UK spatial structure, flood risk was shown to be 1.5 times greater than if the spatial structure was ignored [96]. To determine the response of the network and any adaptation measures to high-end cascading/escalating events, an events-based approach could be used, as this cannot be tested with traditional return period-based analysis.

4.11 Summary

4.11.1 General comments

This report section has provided a summary of existing scientific understanding of high-end/credible maximum scenarios for a range of meteorological hazards. In almost all cases, our ability to confidently define appropriate scenarios for the UK is severely impacted by uncertainty over current and future behaviour of the North Atlantic Jet Stream. This issue presents a significant challenge and has been highlighted as such in both the CCRA3 and draft CCRA4 technical reports [11] [12].

The current review has focussed on the H++ scenarios, which is justified by their status as a specific example of credible maximum scenarios in ONR’s guidance. These scenarios are based on a mixture of CMIP3 and CMIP5 model data, which has since been supplemented by the release of CMIP6. While analysis has suggested that CMIP6 offers significant improvements in its representation of the Jet Stream, a substantial degree of uncertainty remains, particularly with respect to predicting the behaviour of persistent regions of high pressure known as “blocking patterns”.

Given the continued level of uncertainty over a critical driver of the UK climate, scientific information produced since the publication of the H++ scenarios should be viewed as adding to the available evidence base rather than superseding evidence that was available to the H++ authors at the time. With this point in mind, the below table summarises the conclusions of the review.

Hazard	H++ scenario	Comments
High Temperatures	Annual average summer maximum temperatures over 34°C. Hottest days such over 40°C across the UK and 48°C in London.	The record UK temperatures seen in the 2022 heatwave, combined with the higher projected shift in summer maximum temperatures in UKCP18, already suggest that the H++ scenario is set too low. Studies based on the UNSEEN methodology have indicated that peak temperatures of up to 46.6°C are plausible in the current climate and, while this method is still affected by limitation in the underlying climate models, a similar approach has shown the approach to be capable of identifying plausible extremes which are not represented in historical data [44]. Use of the UNSEEN method or other ensemble boosting methods could be considered for use in future time periods but requires substantial effort and expertise. Adjusting the methodology used for the H++ scenario to reflect more current temperature records and updated climate projections may offer a more practical alternative. The HILL scenarios provide a means to extend this to account for accelerated timelines towards a warmer world.

Low Temperatures	UK average winter temperatures of 0.3°C in the 2020s and -4°C by the 2080s. The mean temperatures on extreme cold days would be -7°C in the 2020s and -11°C in the 2080s.	The L - - scenarios were derived from a storyline approach, based on the slowdown or collapse of the Atlantic Meridional Ocean Circulation (AMOC). While uncertainty remains high, expectations for earlier than previously anticipated AMOC slowdown have grown in recent years and this should bring more extreme timelines and resulting impacts into consideration. The HILL scenarios provide the means to explore a range of possible storylines related to change in ocean circulation, leading increased risk of colder temperatures in the UK.
Wind	Wind storms (i.e. extra-tropical cyclones) show a 50-80% percentage increase in the number of wind storms by 2070-2100 in comparison to a 1975-2005 baseline.	The draft CCRA4 technical report concludes with medium confidence that surface wind speeds are likely to increase, though it is not known if this is attributable to climate change or natural climate variability. An important focus for consideration of upper bound plausible wind speeds in the current UK climate should be selection of appropriate reference periods for extreme value analysis – avoiding biases due to multi-decadal natural variability – as well as uncertainties and biases in the observational data records. For consistency with end user expectations, assessment of future trends in wind speed should be communicated in terms of impact on hourly or sub-hourly wind speeds. The current framing of the H++ scenario makes it challenging to make direct use of in an impact assessment. In the long term, the assumption that extreme winds speeds are governed by extra-tropical cyclones may need to be challenged. Convective storms may become the dominant storm mechanism at high return periods in future climates.
Low Rainfall	Increase in 6-month duration summer drought occurrence with deficits up to 60%. Rainfall deficits of up to 20% lasting 3- 5 years, similar to the most severe long droughts on record.	Recent years have had very low rainfall totals. Based on the observational record and the warmer, drier climate predictions in UKCP18 compared to UKCP09, use of updated projections would likely lead to an increase in credible maxima. Given the direct link with frequency and persistence of high-pressure blocking patterns, risk of extreme rainfall deficits and/or deficits with extreme durations is not well understood for current or future climates. Updating guidance to account for CMIP6 model data would help to fill out some of the uncertainty space but further investigation of past long-term variability is also an important activity.
Low Flows	Summer low flows are reduced by 30-70% across the UK. For multi-season droughts with consecutive summers there is a 20-60% reduction in flows. For longer droughts (2 years or more) the H++ scenario is for up to 50% reductions in flow.	Since publication of the H++ scenarios, there has been significant research developments related to drought, e.g. IMPETUS, MaRIUS and ENDOWS (all part of the UK Droughts & Water Scarcity research programme). The recent research significantly increases the spatial scale of analyses of drought trends compared to earlier studies. The eFLaG dataset is a national dataset of hydrological projections based on UKCP18 regional projections using 4 different hydrological models. As for low rainfall, current and future trends are not well understood and a precautionary approach, giving weight to all available forms of evidence (e.g. paleoclimatological), is needed to ensure long term climate variability has been adequately captured. The influence of current and future catchment characteristics should also be considered in defining extreme scenarios.

High Rainfall	Increase of 70-100% on average winter rainfall (from 1961-1990 baseline) by 2080s. For the same period heavy daily and sub-daily rainfall a 60% to 80% increase in rainfall depth for summer or winter events is suggested.	The EA, NRW and SEPA have updated their climate change guidance to incorporate estimates for RCP8.5 from UKCP18 local projections. The FUTURE-DRAINAGE project provided outputs from these ensembles for industry users. The highest predicted change factor in the Environment Agency Upper End scenarios is 50%; this is lower than the current H++ scenario. Given the uncertainties in the underlying models and the important role played by expert judgement and theoretical arguments in the H++ scenario definition, a cautious approach should be taken when comparing against more recent guidance.
High Flows	An upper end uplift of 290% by the 2080s, accompanied by lower bound regional uplifts for the 2020s, 2050s and 2080s.	SEPA and the Environment Agency have updated their climate change peak flow allowances to incorporate data from UKCP18. These are based on the study by Kay et al. [67] using the UKCP18 probabilistic projections, RCP8.5 and the 50-year return period (highest return periods available from the Kay et al analysis). The Upper End scenario is suggested as a credible maximum scenario. Studies of historical (pre gauge record) and paleo records have suggested evidence of past floods greater than the predicted climate change signal. The historical reference period used to assess future trends may therefore be subject to bias in itself. As for high rainfall, current and future trends are not well understood and a precautionary approach, giving weight to all available forms of evidence (e.g. paleoclimatological), is needed to ensure long term climate variability has been adequately captured. The influence of current and future catchment characteristics should also be considered in defining extreme scenarios.
Sea level Rise (SLR)	1.9m by 2100	Updated UK research using UKCP18 projections give values to 2100 which are similar to H++. However recent research shows a potential doubling in high-end SLR variables post 2100. The highest storyline shows 2300 SLR of up to 17m. The HILL storylines were derived to complement H++, with the HILL-6 (enhanced SLR) scenario giving regional SLR values by 2100 of up to 2.11m and 5.5m-5.8m by 2150. Recent work by Weeks uses UKCP18 to explore high-end scenarios to 2300, based on the storylines methods used by Palmer et al . It provides a framework to explore different future scenarios of future SLR, which is an update to having a single value for a location such as in H++. Scenarios will extend to 2300, to capture increases in the high-end scenarios between 2100 and 2300, not explored with UKCP09 previously.

Table 3: Hazard summary for main quantified hazards in H++ report.

The hazards identified in Table 4 were not quantified in the H++ report. The literature review has shown high-end scenarios for these variables are limited, however identified information which could be used to develop high-end scenarios. Whilst pre-defined credible maximum scenarios are not available for dutyholders to use, data for large return period events or extremes at the highest emission scenarios are available.

Hazard	Details of other known high-end scenarios in the UK context
Wildfires	H++ provided qualitative commentary, however pointed to need for further work in this area. It also stressed the socioeconomic factors such as consideration of human activity on wildfires are important. Studies around high-end wildfire scenarios in the UK are limited, with qualitative findings or limited simulations requiring further research and quantification. In 2025, 33,000 hectares were burned over 99 wildfires in the first 6 months alone, a record since the Global Wildfire Information monitoring began in 2012. UKCP18 data has been used as proxy to quantify future wildfire risk in the UK [89]. Storylines are an effective method for considering wildfires due to the combination of climate and socio-economic inputs.
Lightning	Lightning was not included in the H++ report, nor in the latest HILL scenarios. Previous UKCP09 projections only considered lightning qualitatively, whereas UKCP18 offers quantitative projections on total lightning flashes at the local UKCP18 spatial scale . Information on high-end scenarios for lightning is limited. The latest UKCP18 projections at the upper end of the RCP8.5 climate projections allow quantitative analysis of lightning through a flash rate variable. In the UK context, studies have determined a 1 in 10,000 year lightning strike intensity of 300kA [91].
Humidity	Humidity or references to WBGT were not included in the H++ report. A maximum relative of humidity of 100% can be tested with high-end scenario DBT. UKCP18 projections provide humidity projections for RCP8.5 and a 4ºC GWL. High-end humidity changes can be derived from the storylines to infer changes. In HILL-1 projections relating to the enhanced global warming scenario for humidity can be taken from UKCP18 RCP8.5 projections as the maximum model from the local or regional data, or 95th percentile from the probabilistic projections.
Snow	UKCP18 projections show decreases in both falling and lying snow [93]. However, climate scenarios such as the Met Office tipping point reports increased in snowfall magnitude and duration with AMOC collapse [28]. High-end scenarios for snow are not quantified in the HILL report with the storyline related to AMOC collapse. Snow loads from Eurocodes from countries with colder, more snowy climates than the UK could be used for reference as a high-end scenario for the UK.
Sea Surface Temperatures	Changes in sea surface temperatures (SST) were not considered in the H++ report but are explored in the HILL climate scenarios. In HILL, SST is considered mainly in terms of its influence on other climate hazards, such as air temperature. However, these SST changes are discussed qualitatively and are not quantified. Recent events, such as the July 2025 marine heatwaves in southern UK waters, have shown SST increases of up to 3°C compared to the 1982–2012 average global climate projections from CMIP6 under the SSP5-8.5 scenario suggest that SSTs around Northern Europe could rise by up to 5.8°C by the end of the century.
Combined Events	H++ did provide some discussion on combined events, such as storms associated with heavy rain and wind, but this was qualitative. The storylines approach in HILL can be used to combine transient scenarios. The draft CCRA4 report provides two scenarios for "wet and windy" and "hot and dry" sequences of extreme events. Storylines in an effective method to combine multiple physical hazards, as well as socioeconomic factors such as consideration of human activity on wildfires, or impact of events to the population. This is widely used in international disaster risk management with multi-risk storylines.

Table 4: Hazard summary for other key UK hazards

5. Existing ONR Guidance

Current guidance on consideration of high-end (or credible maximum) climate change scenarios places expectations on dutyholders, principally:

1. Dutyholders should demonstrate that it is *possible to maintain safety* for credible maximum scenarios.
2. Dutyholders should identify *the potential effects* of the credible maximum scenarios, for example, to not foreclose modifications needed to enhance resilience in the future. They may take a *managed adaptive approach*, as it is recognised there is *large uncertainty* with future credible maximum scenarios.
3. Dutyholders are expected to use *the most up to date* credible maximum scenarios in any new analysis of climate change.

It is important to note that these expectations are in addition to those concerning definition of design basis events, which already expect consideration of the reasonably foreseeable impacts of climate change in some respects. Design basis events are intended, so far as possible, to be precisely calibrated to maintain risk system failures to an acceptable level.

Credible maximum scenarios are intended to prompt exploration of impacts from events that may fall far beyond the design basis and would not be economically practical to design for. There is no expectation as to what level of probability they target and no standard governing how they should be defined. However, the H++ scenarios, as defined in the 2015 H++ report [2], are specifically referenced in ONR's guidance [5] as an example of credible maximum scenarios and have therefore acted as a key reference for dutyholders.

Setting aside for a moment the continued scientific validity of the scenarios, it is relevant to also ask if the framing is appropriate to meet the goals of stress testing aspects of a system that may be subject to otherwise hard to identify vulnerabilities. Examples of extreme scenario analysis being used effectively elsewhere (see discussion of the Bank of England stress tests in Section 4.10.6), show the important role of past events in identifying potentially vulnerabilities and guiding the development of scenarios describing "enhanced" versions of these events.

This conceptual approach, where the potential vulnerability is identified first and the extreme scenario designed in response, is also seen in the climate storylines literature. Hazeleger et al. [24] state the following:

"The development of storylines is founded in understanding the physical processes, as this is the basis for confidence in plausible future physical climates. Just as importantly, insights from [storylines] must be expressed in a manner meaningful to policy- and decision-makers. This translation creates the need for transdisciplinary collaboration in targeting plausible future weather events and investigating their societal consequences. Stakeholders are not end recipients of authoritative information from scientists but become co-producers of the scenarios. A truly interactive process of co-development of scenarios includes both scientific and stakeholder perspectives transparently, and deals with each in a balanced manner."

Involvement of dutyholders in co-producing an appropriate set of scenarios has the potential to identify previously unanticipated vulnerabilities, by requiring holistic discussions across dutyholder organisations and providing climate scientists with greater insight into the intended purpose of the scenarios.

This way of working facilitates a "system aware" approach and provides a transparent way of documenting how the scenarios were devised to stress test the system response under consideration. It also offers a practical route towards identifying where compound events should form part of the scenario and where specific thresholds need to be targeted. For example, coastal flood risk is impacted by simultaneous occurrence of storm surge and extreme waves and takes place in the context of ongoing sea level rise. There can be an "on off" mechanism, where either coastal defences are overtopped or they are not, making it important that scenarios are designed in a way they do cross the threshold. The risk may also be impacted by prior events, such as another storm, which has resulted in coastal erosion, making the sequencing of events an important part of the scenario design.

This methodology provides a framework for continuous assessment and updating of high-end scenarios, which can be developed as new information is available. The benefit of this is that guidance is less likely to become outdated or can be transparently updated when new climate models are available, the UK surpasses previous historical records or we approach certain tipping points.

It is understood that such an approach may be too onerous for smaller scale nuclear licensed sites. In these cases, a generic set of scenarios may be beneficial. However, for large scale sites, providing a framework for dutyholders to set objectives for high-end scenarios based on their own expert knowledge, then co-produce the scenarios with input from technical specialists in climate and meteorology, can offer a structured and transparent route to demonstrating compliance with ONR’s expectations.

The existing scientific guidance on high-end scenarios may be sufficient to define scenarios in some cases – for example, uplifts in rainfall intensity and/or peak flow can be applied readily in standard industry studies of flood risk. However, this is not the cases for all hazards – for example, the increase in windiness that defines the “wind storm” H++ scenario cannot be used directly in an engineering assessment of wind loading on a structure.

With or without the storyline approach, further work is often required by the end user to translate a scenario into something that can be used directly in an impact assessment. Further guidance would therefore be of benefit on appropriate processes to achieve this goal.

6. Conclusions

Conclusion 1: The H++ scenarios in their current form no longer reflect current understanding of credible maxima for some hazards.

The H++ scenarios were informed by projections based on a mixture of the CMIP3 and CMIP5 generation of global climate models. They were largely retained for UKCP18 and remain a key reference for dutyholders with respect to definition of credible maximum scenarios – not just for the scenarios they produced but for the methods used in developing them.

Since their publication, data from a new generation of global climate models (CMIP6) has been published and data from a further generation (CMIP7) will emerge in the near future (see Section 3.2). Events such as the July 2022 UK heatwave have also heightened awareness that important features of the large-scale climate processes that govern the UK's weather may be changing in ways that are not well captured by climate models. Use of ensemble boosting methods – such as the UNSEEN method – have potential to reduce our exposure to "black swan" type events but remain subject to the limitations of the underlying climate models.

It is likely that the authors of the H++ scenarios would have reached different conclusions in at least some respects should they have had access to the information we now hold. An argument can therefore be made that they should be updated. However, the pace at which new scientific evidence emerges will if anything increase, particularly as the CMIP project moves towards more continuous releases of new data, making it hard for such updates to stay aligned with the scientific state-of-the-art.

Notwithstanding this point, a systematic update to the H++ scenarios, timed to allow access to early results from CMIP7, would be beneficial to assist dutyholders in meeting ONR's expectations.

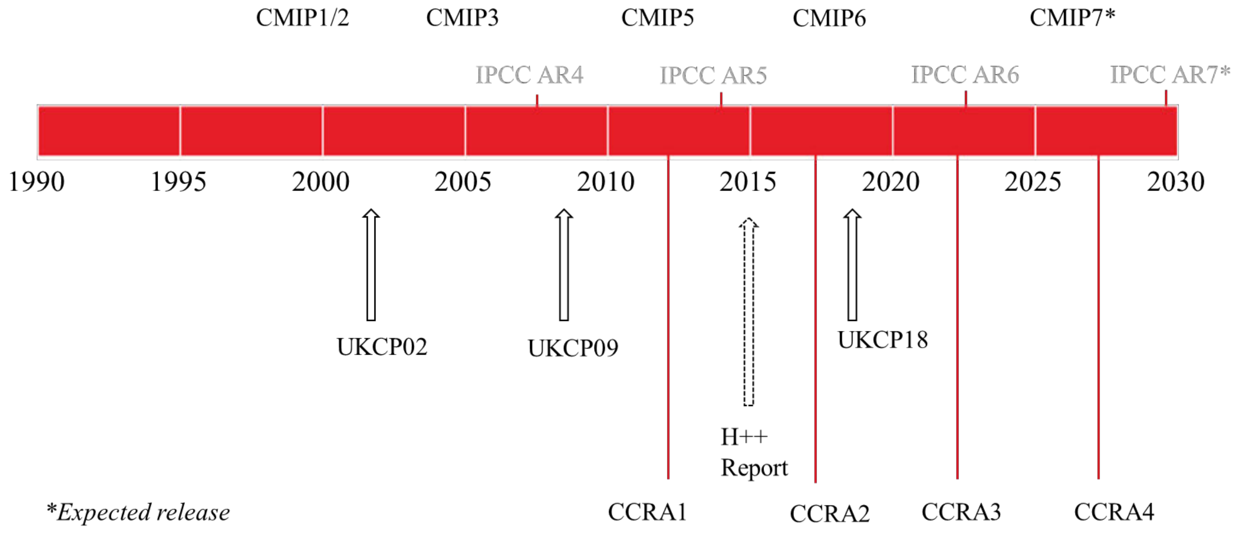

Figure 6-1: Timeline for updates in key sources of scientific evidence and/or guidance.

Conclusion 2: More recent guidance is available to dutyholders, but may not be sufficient to meet ONR's expectations.

Newly published research, such as the HILL scenarios [27] or work by Weeks at al. [36] on extreme sea level rise scenarios, provide updated frameworks for dutyholders to explore the potential range of future climatic pathways. However, they do not always translate through to information which is directly useable in impact assessments. They also leave important questions open as to where and how to draw the line on credible upper bounds for specific types of extreme events and their knock on impacts.

As such, while dutyholders have greater access to "toolkits" that can be used to explore the impact of a range of high-end, plausible scenarios, these do not offer an off the shelf solution to demonstrate they have met ONR's expectations.

Conclusion 3: Climate storylines have potential to provide a structured process for dutyholders to demonstrate they have met ONR's expectations.

The storylines concept would allow dutyholders to co-produce scenarios that are designed with their needs in mind, with active involvement from dutyholders alongside expertise from climate scientists, meteorologists and engineers. This is attractive for a number of reasons:

- It ensures deep understanding of the system being tested is built into the design of the scenarios at the outset.
- It encourages cross disciplinary conversations that may help to identify vulnerabilities that would not be properly tested by a generic set of scenarios.
- It provides a mechanism to transparently document subjective decision making that would otherwise be obscured.
- It ensures the scenarios are framed in a way that they can be straightforwardly used as an input to standard engineering workflows to assess impacts.

The storylines concept is becoming widely used across a range of other fields, which suggests the skills to facilitate the process are likely to be accessible to dutyholders and there is benefit for ONR to consider this further. Use of storylines was identified in CCRA3 as a key focus area for CCRA4. While the full outputs from CCRA4 are yet to be published, the draft technical report contains many references to storylines, makes use of the concept in defining two compound hazard scenarios for the UK and lists use of storylines as a key advance since CCRA3.

While there are many useful actions that could be taken to clarify the current state of scientific understanding of high-end climate scenarios, this is a time-consuming activity and would likely soon be superseded by ongoing developments. Perhaps of greater value to dutyholders, would be an industry led effort to develop methods which can be used alongside relevant specialists to co-produce a curated set of scenarios; thus allowing dutyholders to tailor the scenarios with their specific needs in mind and keep up with the rapid pace of scientific developments.

Conclusion 4: Long term climate variability requires an ongoing focus alongside anthropogenic climate change.

Our understanding of long-term fluctuations in the large scale mechanisms that govern the UK climate is still evolving and should form an important part of dutyholders' considerations regarding credible maxima. In some cases, the influence of natural cycles that take place over multiple decades may leader to greater uncertainties than those associated with climate change.

7. Abbreviations

AEP	Annual Exceedance Probability
AI	Artificial Intelligence
AMOC	Atlantic Meridional Overturning Circulation
AMS	American Meteorological Society
CCC	Climate Change Committee
CCRA	UK Climate Change Risk Assessment
CEH	Centre for Ecology and Hydrology
CICERO	Centre for International Climate and Environmental Research
CMIP2	Coupled Model Intercomparison Project 2
CMIP3	Coupled Model Intercomparison Project 3
CMIP5	Coupled Model Intercomparison Project 5
CMIP6	Coupled Model Intercomparison Project 6
CMIP7	Coupled Model Intercomparison Project 7
CONVEX	CONVective Extremes
DBT	Dry-bulb temperature
ECS	Effective Climate Sensitivity
ENDOWS	Engaging Diverse Organisations in Water Scarcity
GCM	Global Climate Models
GWL	Global Warming Level
HILL	High Impact Low Likelihood
IMPETUS	Improving Predictions of Drought for User Decision-Making
IPCC	Intergovernmental Panel on Climate Change
LIS	Long-term Investment Scenarios
KNMI	Koninklijk Nederlands Meteorologisch Instituut/Royal Netherlands Meteorological Institute
MICI	Marine Ice Cliff Instability
NAO	North-Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCA4	Fourth National Climate Assessment (US)
NCA5	Fifth National Climate Assessment (US)
NFRR	National Flood Risk Review
NOAA	National Oceanic and Atmospheric Administration
NRW	Natural Resources Wales
ONR	Office for Nuclear Regulation
RCP	Representative Concentration Pathways
RRR	Regulatory Research Report
RECEIPT	REmote Climate Effects and their Impact on European sustainability, Policy and Trade
SAP	Safety Assessment Principles
SEPA	Scottish Environment Protection Agency
SLR	Sea Level Rise
SRES	Special Report on Emission Scenarios
SSP	Shared Socioeconomic Pathways
SST	Sea-Surface Temperature
SWES	System-Wide Exploratory Scenario
TAG	Technical Assessment Guides
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
UKMO	UK Meteorological Office
UNSEEN	Unprecedented Simulated Extremes using Ensembles
WBGT	Wet Bulb Globe Temperature
WRCP	World Climate Research Programme

8. Glossary

Term/ Acronym	Definition
Atlantic Meridional Overturning Circulation (AMOC)	A major ocean current influencing UK climate that transports warm water northwards from the tropics northwards.
Coupled Model Intercomparison Project (CMIP)	A framework for comparing climate models (e.g., CMIP3, CMIP5, CMIP6).
Climate Storyline	A physically plausible sequence of climate events used to explore impacts without assigning probabilities.
Credible Maximum Scenario	High-end scenario used for sensitivity testing in safety assessments and stress testing vulnerabilities.
Downscaling	Translating global climate model outputs to regional/local scales.
Extreme Value Theory	Statistical method for estimating rare events, for example a 1-in-1000-year floods.
Fluvial Flooding	Flooding from rivers exceeding their capacity.
Global Warming Level (GWL)	Indicating the level of global temperature increase from greenhouse gas emissions.
Heat Dome	High-pressure system trapping warm air, causing extreme heat.
High-End Climate Scenario	A physically consistent, low-probability but plausible climate event used for stress testing. An example is the 2015 H++ scenarios for the UK.
Hydrological Drought	Periods of reduced river flow due to prolonged dry conditions.
HyperFACETS	A Framework for Improving Analysis and Modelling of Earth System and Intersectoral Dynamics at Regional Scales. HyperFACETS is a research project funded by the U.S Department of Energy
Intergovernmental Panel on Climate Change (IPCC)	A global body assessing climate science.
Jet Stream	Fast-flowing air current influencing storm tracks and weather patterns.
Marine Ice Cliff / Sheet Instability (MICI/MISI)	Processes contributing to rapid ice sheet collapse and sea level rise.
Managed Adaptive Approach	Strategy allowing for incremental adaptation based on evolving risks.
North Atlantic Oscillation (NAO)	A climate pattern affecting weather variability in Europe. The NAO is defined by the difference in atmospheric pressure between the Azores High and the Icelandic Low.
Pluvial Flooding	Flooding caused by heavy rainfall overwhelming drainage systems.
RECEIPT	REmote Climate Effects and their Impact on European sustainability, Policy and Trade. RECIEPT was a EU-funded research project that ran from 2019 to 2023.
Representative Concentration Pathways (RCP)	Emission scenarios used in climate modelling which represents a radiative forcing value.
SAPs	Safety Assessment Principles used by ONR.

Shared Socioeconomic Pathways (SSP)	Scenarios combining socioeconomic trends with climate projections such as increased greenhouse gas emissions.
Scenario Analysis	Method for exploring system vulnerabilities under extreme but plausible conditions.
Sea Level Rise (SLR)	Increase in ocean levels due to climate change.
Storm Surge	Rise in sea level due to atmospheric pressure and wind during storms.
Synoptic	Refers to weather systems spanning roughly 1,000 to 2,500 kilometres horizontally, lasting a few days to a few weeks
TAG 13	ONR's Technical Assessment Guide for external hazards.
Tipping Point	Tipping points are sudden, dramatic, and potentially irreversible changes to the climate system. They represent thresholds beyond which a small change in conditions can lead to a disproportionately large impact, often with cascading effects across environmental and human systems.
UK Climate Projections (UKCP)	Climate projections produced by the UK Met Office e.g. UKCP09 and UKCP18.
Unprecedented Simulated Extremes using Ensembles (UNSEEN)	A method developed by the UK Met Office to simulate plausible but unobserved extreme events to generate synthetic data.

9. References

[1] Office for Nuclear Regulation, “European Council “Stress Tests”, National Final Report,” 2011. [Online]. Available: https://www.onr.org.uk/media/s1pgw2yl/stress-tests-301211.pdf >.

[2] Met Office, UK Centre for Ecology and Hydrology, University of Reading, “Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps, Adaptation Sub-Committee, Second Climate Change Risk Assessment,” 2015. [Online]. Available: https://www.theccc.org.uk/wp-content/uploads/2015/10/Met-Office-for-the-ASCDeveloping-H-climate-change-scenarios-for-heatwaves-droughts-floods-windstormsand-cold-snaps3.pdf.

[3] Office for Nuclear Regulation, “Safety Assessment Principles (SAPs) – 2014 Edition,” 2014. [Online]. Available: https://www.onr.org.uk/publications/regulatory-guidance/regulatory-assessment-and-permissioning/safety-assessment-principles-saps/2014/11/saps-2014. [Accessed June 2025].

[4] Office for Nuclear Regulation, “NS-TAST-GD-013 - External hazards Technical Assessment Guide and Annexes,” 2023. [Online]. Available: https://www.onr.org.uk/publications/regulatory-guidance/regulatory-assessment-and-permissioning/technical-assessment-guides-tags/nuclear-safety-tags/ns-tas.

[5] Office for Nuclear Regulation, Environment Agency, Natural Resources Wales and Scottish Environment Protection Agency,, “Use of UK Climate Projections 2018 (UKCP18), Position Statement,” 2022.

[6] Environment Agency, “Flood risk assessments: climate change allowances,” 2019.

[7] Met Office, “UK Climate Projections Factsheet: Sea level rise and storm surge,” 2019. [Online]. Available: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-fact-sheet-sea-level-rise-and-storm-surge.pdf .

[8] Lowe, J. et al, “UKCP18 Science Overview Report, March 2019, Version 2.0,” 2019.

[9] Newcastle University, “CONVEX: Using Observational Evidence and Process Understanding to Improve Predictions of Extreme Rainfall Change,” [Online]. Available: https://research.ncl.ac.uk/convex/.

[10] UK Climate Risk, University of Exeter, Met Office, “UK Climate Risk Independant Assesment (CCRA3) Technical Report,” [Online]. Available: https://www.ukclimaterisk.org/wp-content/uploads/2021/06/Technical-Report-The-Third-Climate-Change-Risk-Assessment.pdf.

[11] Slingo, J., “Latest scientific evidence for observed and projected climate change. In: The third UK Climate Change Risk Assessment Technical Report [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)] Prepared for the Climate Change Committee,” London, 2021.

[12] G. C. Leckebusch and M. McCarthy, “UK Climate Risk Independent Assessment (CCRA4): Technical Report, Chapter 1: State of the Climate,” Climate Change Committee, 2025.

[13] Met Office, “UKCP18 Guidance: Representative Concentration Pathways,” [Online]. Available: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---representative-concentration-pathways.pdf.

[14] Murphy JM, Brown S and Fung F et al, “UKCP Factsheet: Probabilistic Projections of Climate Extremes.,” Met Office, 2020.

[15] Met Office, “UKCP FAQs,” [Online]. Available: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/about/guides-faqs#topic8.

[16] Gidden, J et al, “Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century,” *European Geosciences Union,* vol. 12, no. 4, p. 1443–1475, 2019.

[17] Bock, L., et al, “Quantifying progress across different CMIP phases with the ESMValTool,” *Journal of Geophysical Research: Atmospheres,* vol. 125, no. 21, 2020.

[18] Donat, M et al, “How Credibly Do CMIP6 Simulations Capture Historical Mean and Extreme Precipitation Changes?,” *Geophysical Research Letters,* vol. 50, no. 14, 2023.

[19] Dorrington et al, “How well does CMIP6 capture the dynamics of Euro-Atlantic weather regimes, and why?,” *Weather and Climate Dynamics,* 2022.

[20] World Climate Research Programme, “High-impact climate events, tipping points, and irreversible regional impacts assessment,” [Online]. Available: https://www.wcrp-climate.org/slc-activities/tpa. [Accessed 3 August 2025].

[21] World Climate Research Programme, “Safe Landing Climates: Understanding High-Risk Events,” 2025. [Online]. Available: https://www.wcrp-climate.org/working-groups/slc-high-risk . [Accessed 4 August 2025].

[22] Slingo et al, “Nature Climate Change,” *Ambitious partnership needed for reliable,* vol. 12, no. 6, pp. 499-503, 2022.

[23] Met Office, “AI4 Climate: Harnessing artificial intelligence to transform climate science,” [Online]. Available: https://www.metoffice.gov.uk/research/approach/collaboration/ai4climate.

[24] Hazeleger, W. et al, “Tales of Future Weather, Nature Climate Change,” *Nature Climate Change,* vol. 5, p. 107–113, 2015.

[25] Shepherd. T.G., “Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Climatic Change,” vol. 151, p. 555–571, 2018.

[26] Sillman, J. et al, “Event-based storylines to address climate risk,” *Earth’s Future,* vol. 9, no. 2, 2020.

[27] Arnell, N.W et al, “High-impact low-likelihood climate scenarios for the UK: background report. Project CR20-4,” Department of Meteorology, University of Reading, 2025.

[28] Hanlon, H. et al, Met Office, “Effect of potential climate tipping points on UK impact,” 2021. [Online]. Available: https://www.ukclimaterisk.org/wp-content/uploads/2021/06/Effect-of-Potential-Climate-Tipping-Points-on-UK-Impacts.pdf.

[29] Office for Nucelar Regulation Expert Panel on Natural Hazard, “Technical Report for ONR-RRR-115: Tipping Points in the Climate System,” 2024.

[30] Armstrong Mckay D. et al, “Exceeding 1.5°C global warming could trigger multiple climate tipping points,” *Science,* vol. 377, 2022.

[31] IPCC, “Chapter 4: Future Global Climate: Scenario-based Projections and Near-term Information; Section 4.7.2,” [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-4/#4.7.2.

[32] Sutton, R. T, “ESD Ideas: a simple proposal to improve the contribution of IPCC WGI to the assessment and communication of climate change risks,” *Earth Syst. Dynam.,* vol. 9, no. 4, p. 1155–1158, 2018.

[33] Fox-Kemper B et al, “Ocean, cryosphere and sea level change,” IPCC, 2021.

[34] van de Wal R. S. W. et al, “A High-End Estimate of Sea Level Rise for Practitioners,” *Earth's Future,* vol. 10, no. 11, 2022.

[35] Palmer, M.D., Harrison, B.J., Gregory, J.M. et al, “A framework for physically consistent storylines of UK future mean sea level rise. Climatic Change 177, 106,” *Climatic Change,* vol. 177, no. 106, 2024.

[36] Weeks, J. H. et al, “A new framework to explore high-end sea-level rise for the UK: updating H++,” in *Copernicus GmbH*, 2025.

[37] Silman, J et al, “Physical modeling supporting a storyline approach,” Oslo, 2019.

[38] Bukovsky M. et al, “Climate Storylines,” *American Meteorological Society,* vol. 104, no. 1, p. E96–E98, 2023.

[39] van Dorland, R. et al, “KNMI National Climate Scenarios 2023 for the Netherlands. KNMI de Bilt, Scientific Report WR-23-02,” KNMI, 2024 .

[40] HyperFACET, “HyperFACETSv3 Storylines,” [Online]. Available: https://hyperfacets.ucdavis.edu/storylines/.

[41] Climate Storylines, “Climate Risk Storylines Connecting Europe to the World,” [Online]. Available: https://climatestorylines.eu/.

[42] Thompson, V., Dunstone, N.J., Scaife, A.A. et al, “High risk of unprecedented UK rainfall in the current climate,” *Nat Commun,* vol. 8, no. 107, 2017.

[43] Kay, G. et al, “Rapidly increasing chance of record UK summer temperatures.,” *Weather,* vol. 80, pp. 268-276, 2025.

[44] Fischer, E. M. et al, “Storylines for unprecedented heatwaves based on ensemble boosting.,” *Nat. Commun.15,* vol. 24, p. 4643, 2024.

[45] Antonescu, B. et al, “What is the Worst That Could Happen? Re-examining the 24–25 June 1967 Tornado Outbreak over Western Europe,” *Weather Climate and Society,* 2018.

[46] Hardy, S. et al, “The 23–26 September 2012 U.K. Floods: Using PV Surgery to Quantify Sensitivity to Upper-Level Forcing,” *Monthly Weather Review,* vol. 145, no. 10, p. 4055–4079, 2017.

[47] Leach, N.J. et al. (2022), “Generating samples of extreme winters to support climate adaptation,” *Weather and Climate Extremes ,* vol. 36, 2022.

[48] Environment Agency and Department for Environment, Food & Rural Affairs , “Thames Estuary 2100 (TE2100) Plan,” 2023. [Online]. Available: https://www.gov.uk/government/collections/thames-estuary-2100-te2100. [Accessed 22 Aug 2025].

[49] Environment Agency, “Adapting to climate change: guidance for risk management authorities. [Withdrawn 22 July 2020],” GOV.UK, 2011. [Online]. Available: https://www.gov.uk/government/publications/adapting-to-climate-change-for-risk-management-authoritie. [Accessed 8 July 2025].

[50] Baker JA, et al, “Continued Atlantic overturning circulation even under climate extremes,” *Nature,* vol. 638, no. 8052, pp. 987-994, 2025.

[51] Ditlevsen P, Ditlevsen S, “Warning of a forthcoming collapse of the Atlantic meridional overturning circulation,” *Nature Communications,* vol. 14, no. 4254, 2023.

[52] Weijer, W. et al, “CMIP6 models predict significant 21st century decline of the Atlantic Meridional Overturning Circulation,” *Geophysical Research Letters,* vol. 47, 2020.

[53] Met Office Hadley Centre, "UKCP18 Factsheet: Temperature," [Online].

[54] Office for Nuclear Regulation, "NS-TAST-GD-013 Annex 2 Reference Paper: Analysis of Meteorological Hazards for Nuclear Sites. Expert Panel Paper No: GEN-MCFH-EP-2021-2.," 2021. [Online]. Available: https://www.onr.org.uk/media/izknjgu0/ns-tast-gd-013-annex-2.pdf. [Accessed 1 August 2025].

[55] Kendon, M., A. Doherty, D. Hollis, et al, "State of the UK Climate in 2024," *International Journal of Climatology,* vol. 45, 2025.

[56] Cabinet Office, "National Risk Register 2025," 2025. [Online]. Available: https://assets.publishing.service.gov.uk/media/67b5f85732b2aab18314bbe4/National_Risk_Register_2025.pdf. [Accessed 18 August 2025].

[57] Noyelle, R. et al, "Maximal reachable temperatures for Western Europe in current climate," *Environmental Research Letters,* vol. 18, no. 9, p. 094061, 2023.

[58] Schumacher, D.L., Singh, J., Hauser, M. et al., "Schumacher, D.L., Singh, J., Hauser, M. et al.," *Communications Earth & Envrionment,* vol. 5, no. 182, 24.

[59] Environment Agency , "National Drought Group meets to address "nationally significant" water shortfall,'," GOV.UK, 2025. [Online]. Available: https://www.gov.uk/government/news/national-drought-group-meets-to-address-nationally-significant-water-shortfall.. [Accessed 12 August 2025].

[60] Met Office, "UK Climate Summaries," [Online]. Available: https://www.metoffice.gov.uk/research/climate/maps-and-data/summaries/index. [Accessed 14 July 2025].

[61] Environment Agency, "Understanding the performance of water supply systems during mild to extreme droughts: Summary. SC120048/S.," 2015. [Online]. Available: https://assets.publishing.service.gov.uk/media/5a8016cced915d74e622c663/Performance_of_water_supply_systems_during_mild_to_extreme_droughts_summary.pdf. [Accessed 2 August 2025].

[62] UK Centre for Ecology & Hydrology, "Hydroprojections Portal: Enhanced Future Flows and Groundwater (eFLaG)," 2025. [Online]. Available: https://hydroprojections.ceh.ac.uk/. [Accessed 4 August 2025].

[63] Parry, S et al, "Divergent future drought projections in UK river flows and groundwater levels," *Hydrol. Earth Syst. Sci,* vol. 28, p. 417–440, 2024.

[64] Chan, S.C. et al, "New extreme rainfall projections for improved climate resilience of urban drainage systems," *Climate Services,* vol. 30, p. 100375, 2023.

[65] Met Office, "UKCP18 guidance: Extreme rainfall features in UKCP Local," [Online]. Available: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_guidance_extreme_rainfall.pdf.

[66] UK Government, "Flood and Water Management Act 2010, c.29.," 210. [Online]. Available: https://www.legislation.gov.uk/ukpga/2010/29/contents. [Accessed 22 July 2025].

[67] Kay, A.L. et al, "Climate change impacts on peak river flows: Combining national-scale hydrological modelling and probabilistic projections," *Climate Risk Management,* vol. 31, p. 100263, 2020.

[68] Dixon, H., Faulkner, D., Fry, M., Kral, F., Lamb, R., Macklin, M., Prosdocimi, I., Reed, D., Rogers, P., Sefton, C., Stewart, L., Vesuviano, G, "Making better use of local data in flood frequency estimation.," Environment Agency, Bristol, 2017.

[69] Zappa, G. and Shaffrey, L.C., “The Ability of CMIP5 Models to Simulate North Atlantic Extratropical Cyclones,” *Journal of Climate,* vol. 26, no. 15, p. 5379–5396, 2013.

[70] K. Horsburgh, I. Haigh, J. Williams, M. De Dominicis, J. Wolf, A. Inayatillah and D. Byre, ““Grey swan” storm surges pose a greater coastal flood hazard than climate change,” *Ocean Dynamics,* vol. 71, pp. 715-730, 2021.

[71] Palmer M, et al, “UKCP18 Marine report,” Met Office, 2018.

[72] IAEA, “SSG-18 Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations,” 2011.

[73] Ineson, S et al, “Regional climate impacts of a possible future grand solar minimum,” *Nature Communications,* vol. 6, p. 7535, 2015.

[74] Kendon, M, “Severe winter weather and storm Darcy,” February 2021. [Online]. Available: https://weather.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2021/2021_02_low_temperatures.pdf..

[75] World Meteorological Organization, “State Of The Global Climate,” World Meteorological Organization, 2024.

[76] C. J. A. Heuzé, “The first ice-free day in the Arctic Ocean could occur before 2030.,” *Nature Communications,* vol. 15, 2024.

[77] IPPC, “Summary for Policymakers,” *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* p. 3−32, 2021.

[78] Environment Agency, “Flood and Coastal Erosion Risk Management Research Programme,” 2019.

[79] Weeks, J.H. et al, “The evolution of UK sea-level projections,” *Environmental Research Communications,* vol. 5, no. 3, 2023.

[80] NASA, “IPCC AR6 Sea Level Projection Tool,” NASA Sea Level Change Portal, 2021. [Online]. Available: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool.

[81] DMI, “Methods used in Klimaatlas, the Danish Climate Atlas (v2024b). DMI Report 24- 12,” 2024.

[82] USGCRP, “Fifth National Climate Assessment,” *U.S. Global Change Research Program,* 2023.

[83] USGCRP, “Climate Science Special Report: Fourth National Climate Assessment,” *U.S. Global Change Research Program,* vol. 1, p. 470, 2017.

[84] Newcastle University, “CONVEX,” [Online]. Available: https://research.ncl.ac.uk/convex/.

[85] Lindsey, Rebecca, “Climate Change: Global Sea Level,” 22 08 2023. [Online]. Available: https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level#. [Accessed 20 08 2025].

[86] Environment Agency, “Long-term investment scenarios (LTIS),” GOV.UK, 2019. [Online].

[87] Fire Brigades Union, “UK breaks wildfire records as hot, dry weather hits unusually early in the year,” Firefighter Magazine, 2025. [Online]. Available: https://www.fbu.org.uk/magazine/junejuly-2025/uk-breaks-wildfire-records-hot-dry-weather-hits-unusually-early-year. [Accessed 18 June 2025].

[88] Burton, C. et al, “Very high fire danger in UK in 2022 at least 6 times more likely due to human-caused climate change,” *Environmental Research Letters,* vol. 20, no. 4, 2025.

[89] Arnell, N, Freeman, A. and Gazzard, R., “The effect of climate change on indicators of fire danger in the UK,” *Environmental Research Letters,,* vol. 16, no. 4, p. 044027, 2021.

[90] Met Office, “UK Climate Projections Factsheet: Storms,” 2023. [Online]. Available: https://www.metoffice.gov.uk/research/approach/ collaboration/ukcp/data/factsheets.

[91] Office for Nuclear Regulation, “ Step 4 Assessment of external hazards for the UK Advanced Boiling Water Reactor. In Assessment Report,” 2017. [Online]. Available: https://www.onr.org.uk/media/xcmmvbct/onr-nr-ar-17-027.pdf.

[92] Met Office, “UKCP18 Derived Projections of Future Climate over the UK,” 2018.

[93] Met Office, “ UK Climate Projections Factsheet: Snow,” [Online]. Available: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-factsheet-snow.pdf .

[94] Met Office, “Waters surrounding UK experiencing significant marine heatwave,” 2025. [Online]. Available: https://www.metoffice.gov.uk/blog/2025/waters-surrounding-uk-experiencing-marine-heatwave.

[95] Marciano, C. et al, “A participatory foresight approach in disaster risk management: the multi-risk storylines,” *Int. J. Disaster Risk Reduc,* vol. 114, p. 104972, 2024.

[96] Sayers, P., Griffin, A., Lowe, J. et al, “Beyond the local climate change uplift – The importance of changes in spatial structure on future fluvial flood risk in Great Britain,” *Nat Hazards,* vol. 120, p. 3773–3798, 2024.

[97] Environment Agency, “Climate change and fluvial flood peaks supplementary report,” 2023. [Online]. Available: https://assets.publishing.service.gov.uk/media/64021bb7d3bf7f25f5948f92/SC150009_Climate_change_and_fluvial_flood_peaks_supplementary_report.pdf.