High-impact low-likelihood climate scenarios for risk assessment in the UK

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High-Impact Low-Likelihood Climate Scenarios for Risk Assessment in the UK

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Key Points:

- We present two sets of high-impact low-likelihood climate scenarios for the UK, designed for risk assessment and complementing conventional climate scenarios
- One set describes "worst-case" changes in climate and sea level to 2100, and the other describes plausible extreme months and seasons
- Each set consists of a narrative storyline and an indicative quantification

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract There is an increasing interest amongst policymakers in understanding the implications of high-impact low-likelihood (HILL) risks for climate mitigation, adaptation and resilience. Whilst extreme sea level rise scenarios have been used and there is awareness of some HILL risks, in practice there are currently few scenarios which can be applied in risk assessments. Here we present two sets of HILL climate scenarios for the UK, complementing existing UK climate projections. Both are based around storylines describing physically-plausible changes, were developed using observations, models and theory, and describe HILL drivers of change as inputs to impact models or stress tests. The storylines provide a narrative framework for understanding risk, and indicative quantifications provide the basis for quantitative risk assessments. One set describes six storylines for transient climate change to 2100 and beyond, reflecting plausible forcings and system responses outside the range conventionally assumed. These describe enhanced global warming, rapid reductions in aerosol emissions, volcanic eruptions, enhanced Arctic Amplification, changes to ocean circulation, and accelerated sea level rise. The other set describes extreme monthly and seasonal anomalies, representing hot, cold, wet, dry and windy extreme years. This set includes storylines describing persistently anomalous weather.

Plain Language Summary Policymakers are increasingly interested in "high-impact low-likelihood (HILL)" or "worst-case" climate scenarios to help in planning for the risks of climate change. Whilst such scenarios have been developed and used previously for extreme sea level rise, so far no scenarios for other worst cases have been produced which can be used in practice. Here we present two sets of HILL climate scenarios for application in the UK. One set describes six plausible drivers which may lead to greater change in climate than is conventionally assumed: enhanced warming, rapid reductions in aerosol emissions, volcanic eruptions, enhanced Arctic Amplification, changes to ocean circulation, and accelerated sea level rise. The other describes plausible extreme months and seasons. Both sets of scenarios consist of a narrative storyline and illustrative quantifications, and are designed to complement the climate projections currently used for risk assessment in the UK.

1. Introduction

There is increasing scientific and policy interest in the risk that climate change may lead to very high impacts, outside the range conventionally estimated using current scenarios and climate models. This is often linked to concern over "tipping points" (Armstrong McKay et al., 2022; Kemp et al., 2022) and their implications for future reductions in emissions (Mercure et al., 2021; Möller et al., 2024), but there is an increasing interest in the implications of HILL outcomes for adaptation and resilience and a concern that they are not taken sufficiently seriously (Sharp, 2019; Sutton, 2019; Wood et al., 2023). The impacts of climate change could plausibly be much worse than conventionally assessed (see Ritchie et al., 2020, for example). Within the UK the House of Lords Select Committee on Risk Assessment and Planning (House of Lords, 2021) concluded that there was a bias against low-likelihood high-impact risks. Laybourn et al. (2024) claimed that ignoring the impacts of climate tipping points represented a "security blind spot" and threatened national security. The UK—like other countries —is therefore unprepared for climate risks outside the range implied by conventional climate scenarios.

There is a recognition in principle in the UK of the threat posed by extreme climate change. Guidance from several government agencies in the UK recommends considering "credible maximum scenarios" for some types of investment and development (Arnell, 2024; Defra, 2024; DESNZ, 2023; HM Government, 2022a; MHCLG, 2021; ONR, Environment Agency, 2017). The third UK Climate Change Risk Assessment (CCRA4)

(HM Government, 2022b) highlights an increasing emphasis by government in the future on HILL scenarios. However—with the notable exception of extreme sea level rise (Palmer et al., 2024; van de Wal et al., 2022)—there are few practical examples of the development and application of HILL climate scenarios appropriate for adaptation and resilience planning. This presents a barrier to adaptation.

Wood et al. (2023) proposed a "climate-science toolkit" for the development of HILL scenarios, defining categories of scenarios and proposing a research framework. We present here a summary of the development of HILL climate scenarios for the UK based on existing research, evidence and tools, which may serve as a template for the development of similar scenarios elsewhere. The scenarios describe drivers of impact, and can be used for stress testing and as input to impact models.

2. Principles

The HILL climate scenarios are designed to supplement existing UK climate (Lowe et al., 2018) and sea level (Palmer et al., 2018) projections, and to be easy to apply in practice. They focus on changes in the UK, and do not consider changes in other parts of the world which could have indirect impacts on the UK. The scenarios are based around the concept of storylines (Shepherd, 2019; Shepherd et al., 2018), which are defined here as narrative descriptions of physically-plausible future worlds. Storylines must be evidence-based, describe causal relationships and characterize complex and compound linkages between components of the climate system. The storylines presented here are based on a combination of observed and historical experience, model simulations and theory. They were informed by an analysis of how "extreme" climate change scenarios have been interpreted so far in the UK (Arnell, 2024), and by discussions with user stakeholders.

We distinguish between two types of HILL climate scenario. One set describes *transient* changes to 2100 that are outside or at the edge of the range of "conventional" climate scenarios. The other describes shorter-term *extreme monthly and seasonal climate anomalies*, which can occur at any time. Both sets describe HILL climate *drivers* of impact, rather than HILL *outcomes* or impacts. Each scenario is presented both as a narrative description and an illustrative quantification. The narrative descriptions provide the basis for qualitative assessments of future risks. The quantifications support quantitative risk assessment and can be revised as more evidence becomes available. More storylines can also be added to define new scenarios of plausible HILL climate changes. The scenarios themselves are described in more detail in Arnell et al. (2025a, 2025b).

The scenarios are explicitly not assigned likelihoods due to deep uncertainty in their drivers and likelihood: they are simply described as being physically plausible.

One key set of climate scenarios for the UK are currently defined by the UKCP18 projections (Lowe et al., 2018; Palmer et al., 2018). The land projections consist of three strands based on ensembles of climate models (the global, regional and local strands) with very high RCP8.5 emissions, and one set of probabilistic projections with RCP2.6, RCP4.5, RCP6.0 and RCP8.5 emissions. Different UKCP18 strands are used by different users, so the HILL scenarios are presented in ways that can be applied to each strand. There are inconsistencies in guidance and practice in the UK in the definition of a "conventional" climate scenario for risk assessment and adaptation planning (Arnell, 2024). There is an emerging trend toward assuming that a world reaching 4°C by 2100 represents climate change with no further initiatives to reduce emissions, but this is a smaller increase than with the RCP8.5 emissions scenario in the widely-used global, regional and local UKCP18 strands. The fourth UK CCRA4, to be completed in 2026, defines two core climate scenarios representing increases in global average temperature by 2100 of around 2.8 and 3.5°C (CCC, 2024). Impacts in these core scenarios are estimated by extracting time slices from UKCP18 projections consistent with defined warming at specific time periods.

3. Transient Scenarios

The six transient scenarios (Table 1; Figures 1 and 2; Figure S1 in Supporting Information S1) describe the evolution of changes in climate to 2100, under six plausible HILL storylines. These storylines describe changes in climate outside the extreme range that is conventionally assumed (specifically here in the UKCP18 projections), either because the *forcings* of change are outside the conventional range or because the large-scale climate system *response* is outside the range projected by most current climate models. These transient scenarios provide a high-level picture of how future UK climate could be different to that implied by the conventional UKCP18

Table 1
High-Impact Low-Likelihood Transient Scenarios for the UK

Scenario		Storyline
HILL-1	Enhanced global warming	Global temperature increases well above 4°C due to very high emissions, stronger carbon cycle feedbacks or high climate sensitivity
HILL-2	Rapidly reduced aerosol forcing	Lower aerosol emissions increase warming across the UK by up to 0.75°C
HILL-3	Volcanic eruption	Cooling follows a major volcanic eruption, by up to 2.5°C
HILL-4	Stronger Arctic Amplification	A strong increase in Arctic warming leads to circulation changes which increase the frequency of winter cold and dry periods. The jet stream in winter is weakened and shifrts to the south.
HILL-5	Ocean circulation change	Changes in circulation in the North Atlantic Ocean lead to cooling across the UK. Two variants (HILL-5a collapse of the Atlantic Meridional Overturning Circulation, and HILL-5b collapse of the sub-Polar Gyre) describe different levels of cooling—of up to 6 and 2.5°C respectively.
HILL-6	Enhanced sea level rise	Rapid deglaciation in Greenland and Antarctica leads to an increase in sea level around the UK of up to 2.2 m above current levels by 2100

projections. In principle, any of the scenarios can be combined with any other as they are physically independent, although the likelihood of some of the scenarios materializing may depend on other scenarios.

Specific details of the scenarios and how they can be applied are presented in Arnell et al. (2025a). As an illustration, Figure 1 compares the HILL scenarios with the changes in temperature, rainfall and windspeed in a

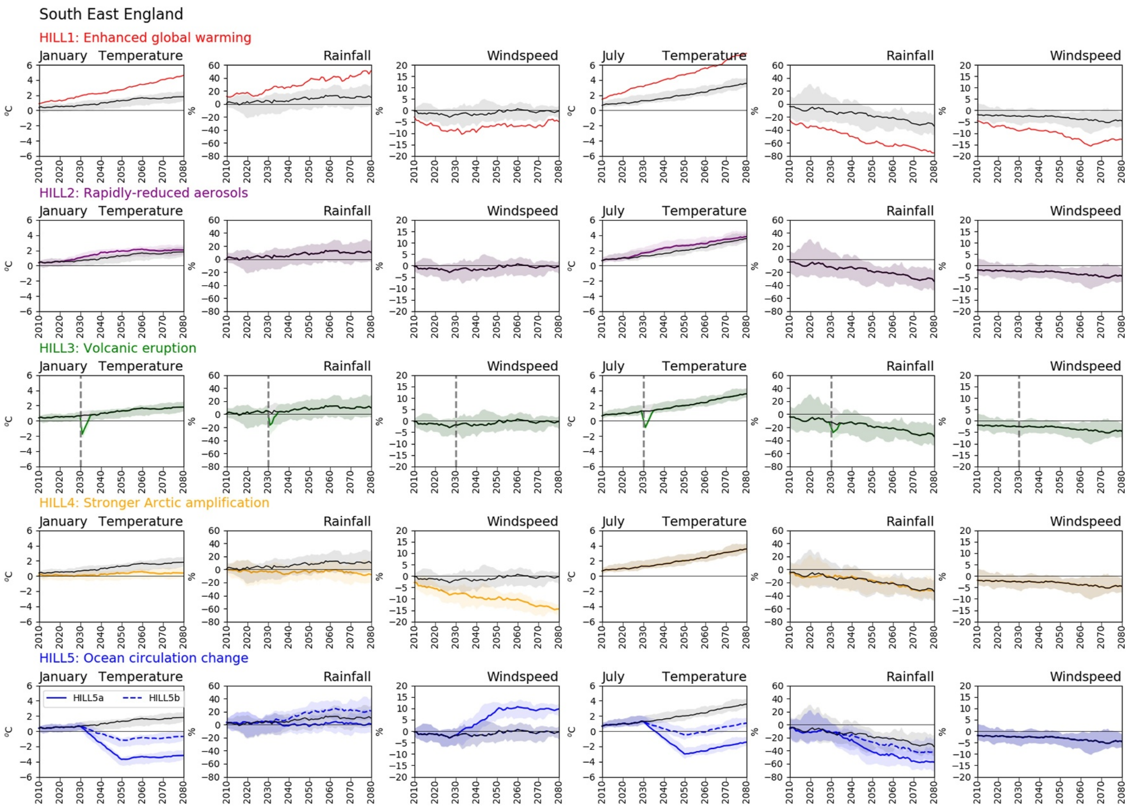

Figure 1. The effect of transient scenarios HILL-1 to HILL-5 on temperature, rainfall and windspeed projections for January and July for an example location in southern England, along with changes (in gray) in a world which reaches 4°C above pre-industrial levels by 2100. The changes are relative to the 1981–2010 average. Not all scenarios describe changes in all variables. HILL-2 to HILL-5 are applied here as perturbations to the UKCP18 HadGEM PPE-15 RCP8.5 ensemble (Met Office Hadley Centre, 2018b), rescaled to represent a world with an increase of 4°C by 2100. HILL-1 is defined as the most extreme UKCP18 HadGEM PPE-15 RCP8.5 member. The volcanic eruption in HILL-3 is assumed to occur in March 2030.

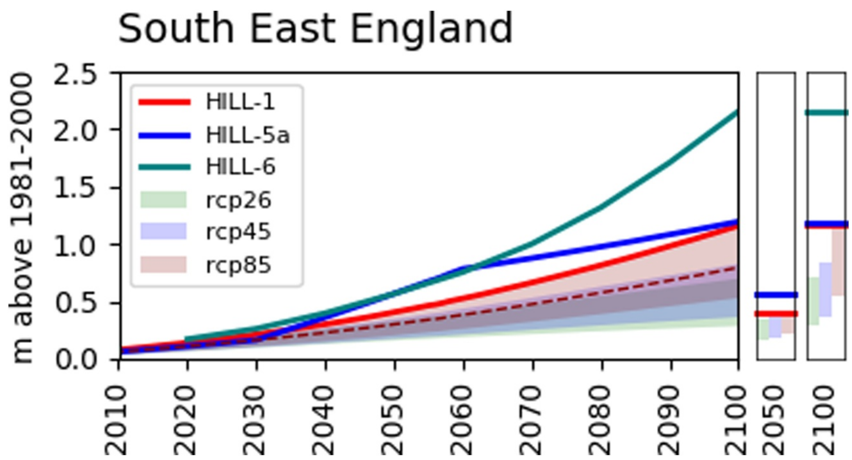

Figure 2. The effect of the transient scenarios HILL-1, HILL-5a and HILL-6 on mean sea level rise, for an example location in south east England. The plot also shows rise in sea level (5th to 95th percentile range) with the three UKCP18 sea level rise scenarios (Met Office Hadley Centre, 2018a). The HILL-5a scenario is applied to the median UKCP18 RCP8.5 projection, shown by the dotted line.

world reaching 4°C above pre-industrial levels by 2100. This illustrative 4°C world scenario was constructed from the UKCP18 global strand RCP8.5 projections by rescaling the UKCP18 changes for an ensemble member by the ratio of the difference in global average temperature in a given year in a 4°C world (actually SSP3-7.0) and in that ensemble member. Figure 1 is illustrative. The conventional change in climate is different across the UK: most significantly, summer rainfall is projected to show less of a reduction in the north and far west than in the south and east. A corresponding figure for northern UK is shown in Figure S1 of Supporting Information S1.

HILL-1 describes an enhanced global warming greater than 4°C above pre-industrial levels by 2100 (causal loop diagram in Figure S2 of Supporting Information S1). This can arise either because emissions are greater than conventionally assumed (stronger forcing), or because climate sensitivity might be at the top end of the estimated range (Forster et al. (2021); stronger response), or because accelerated feedbacks in the carbon cycle (Canadell et al., 2021) such as permafrost degradation or loss of the Amazon rainforest mean that greenhouse gases are released from storage (stronger response). The three potential mechanisms are separate although potentially mutually reinforcing, but in practice would have the same effect on climate in the UK. This storyline is characterized as the most extreme value (largest change) from the UKCP18 RCP8.5 global, regional and local strand projections, and the 95th percentile (or 5th percentile) from the UKCP18 RCP8.5 probabilistic and sea level rise projections. The HILL-1 scenario is based on RCP8.5 simulations primarily because this has future emissions well above current policy scenarios and was described by Riahi et al. (2022) as a useful "high-end, high-risk" scenario. The scenario was not constructed from the subset of UKCP18 climate models with the highest equilibrium climate sensitivity because these do not necessarily produce the most extreme change in climate across the UK (Figure S3 in Supporting Information S1).

HILL-2 describes a storyline where aerosol emissions are reduced much more rapidly than is assumed in the emissions scenarios used to construct current climate projections (Persad et al., 2022): it represents a difference in forcing (causal loop diagram in Figure S4 of Supporting Information S1). This leads to less aerosol cooling, and therefore more warming for the next few decades as underlying greenhouse gas-driven warming is unmasked. There is emerging evidence (Samset et al., 2025) that aerosol emissions are already being reduced more rapidly than assumed in emissions scenarios. The scenario assumes that temperature increases above a conventional climate scenario from 2030, peaking at an additional increase of 0.75°C in 2040 and declining to no additional increase by 2100. The same changes apply across the UK and throughout the year. There are potential mechanisms by which rainfall and windspeed would also be affected across the UK, but the directions of change are uncertain and the changes are likely to be small relative to the uncertainty across climate models. The scenario is based on model simulations using three models and two contrasting aerosol scenarios (Luo et al., 2020: Figure S5 in Supporting Information S1). The scenario is presented as an increment to be applied to UKCP18 temperature projections from any strand, either to a time series or to a time slice representing a given level of warming at a given time.

HILL-3 assumes that a tropical volcanic eruption similar in scale (VEI-7) to Tambora in 1815 leads to a reduction in temperature and rainfall across the UK for up to 5 years (causal loop diagram in Figure S6 of Supporting Information S1). It is based on simulations from Bethke et al. (2017), drawing on the simulation with the largest synthetic explosion (Figure S7 in Supporting Information S1). Temperature is assumed to reduce consistently across the UK by up to 2.5°C below the mean within 9 months of an eruption, and rainfall is assumed to reduce by up to 20%: the effect reduces until it disappears 60 months after the eruption. The scenario can be applied to a time series or time slice of temperature and rainfall from any UKCP18 strand assuming an eruption at any time, with the possibility for multiple eruptions. Like HILL-2, it represents a difference in forcing.

HILL-4 describes a storyline where large increases in temperature in high latitudes—Arctic Amplification—and loss of Arctic Ocean sea ice lead to greater changes in atmospheric circulation than represented in the current generation of climate models. It represents a difference in system response (Figure S8 in Supporting Information S1). There is considerable scientific controversy and uncertainty over the potential effects of enhanced Arctic Amplification (e.g., Francis & Vavrus, 2012; Rantenen et al., 2022; Smith et al., 2022). The storyline here assumes that enhanced Arctic Amplification reduces the strength of the winter jet stream and shifts it southwards (Smith et al., 2022) relative to that projected in most climate models, increasing the frequency of cold weather outbreaks and lowering winter temperature and rainfall. It is based on comparing years in the UKCP18 global strand 15-member ensemble with weak southerly jets with all years (Figure S9 in Supporting Information S1). The scenario here describes a reduction of winter temperature across the UK of 1.5°C and a reduction of winter rainfall of 20% points by 2100, relative to the increase that would otherwise have occurred, and can be applied to any UKCP18 strand (again, a time series or a time slice corresponding to a specific level of warming).

HILL-5 describes an abrupt change in ocean circulation in the North Atlantic Ocean, leading to cooling across western Europe and the UK: it represents a change in system response. One variant (HILL-5a) assumes a collapse in the Atlantic Meridional Overturning Circulation (AMOC), and the other (HILL-5b) assumes a collapse of the sub-Polar Gyre (SPG: causal loop diagram in Figure S10 of Supporting Information S1). Both variants are presented as changes to be applied to any UKCP18 climate projection. HILL-5a is based on hosing experiments described by Jackson et al. (2015) and Mecking et al. (2016), as used by Ritchie et al. (2020): it is very similar to the change in temperature and rainfall projected by van Westen et al. (2024) for London following AMOC collapse. HILL-5b is based on one of the climate models that Swingedouw et al. (2021) found simulated rapid cooling in the SPG (Figure S11 in Supporting Information S1). AMOC and (to a lesser extent) SPG collapse are the most widely cited potential HILL climate scenarios affecting the UK (e.g., Laybourn et al., 2024; Ritchie et al., 2020). Our illustrative quantification assumes collapse begins in 2030, with the maximum effect persisting after 2050. HILL-5a has a maximum reduction in temperature of between 5 and 6°C by 2050 (relative to the temperature that would have occurred under conventional scenarios), a reduction in summer rainfall of between 25% and 35%, and an increase in winter rainfall in northern UK (20% points) and a reduction in winter rainfall in the south (−10% points). The rate of sea level rise is also increased (following Leverman et al., 2005). HILL-5b has a maximum reduction in temperature of 2.5°C, an increase in winter rainfall (10% points) and a decrease in summer rainfall (−10% points), with changes assumed consistent across the UK. Both scenarios can be applied to time series or time slice scenarios.

HILL-6 describes enhanced sea level rise around the UK coast due to accelerated loss of ice from Greenland and, more significantly, Antarctica (causal loop diagrams in Figures S12 and S13 of Supporting Information S1). This HILL scenario is the only one that has been widely used in adaptation and resilience planning, for example, in the US (at national and state level), the Netherlands, France, Belgium and Denmark. In the UK, the H++ sea level rise scenario (Lowe et al., 2009; Ranger et al., 2013) is the designated credible maximum scenario for coastal infrastructure, and has been used for example, in the Thames Estuary 2100 Plan, which provides strategic direction for the continued management of flood risk in the Thames Estuary through to the end of the 21st century and beyond (Environment Agency, 2012). The HILL-6 scenario here is based directly on the high-end sea level storyline in the IPCC AR6 sea level rise projections (Fox-Kemper et al., 2021), and is specifically taken from the 95th percentile from the projections in the NASA IPCC AR6 sea level projection tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool; Garner et al., 2021; Kopp et al., 2023). The rise in sea level varies between 2.0

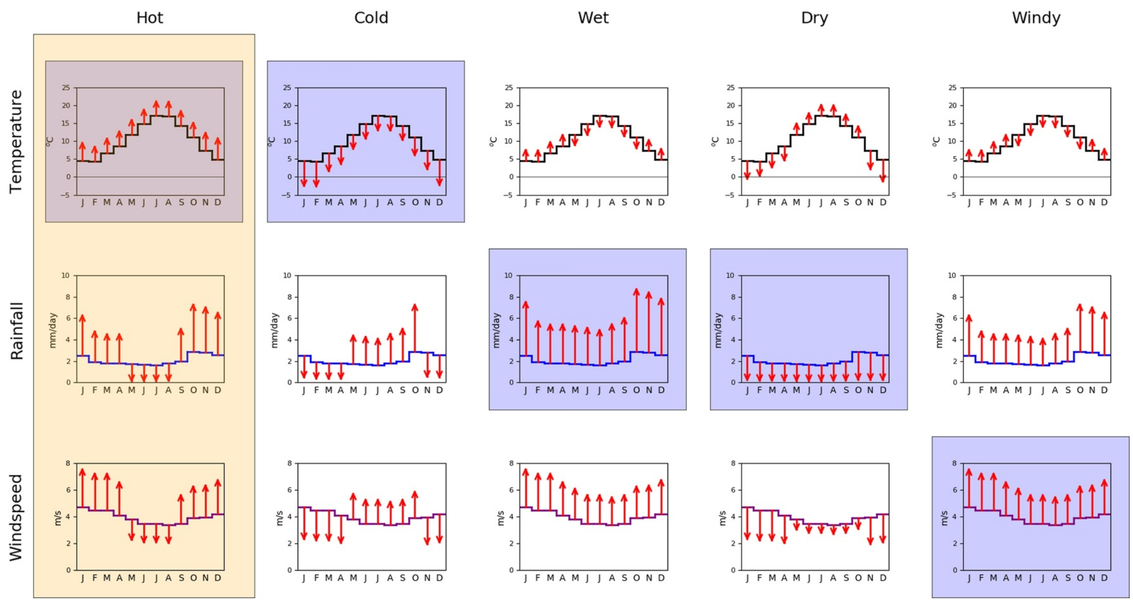

Figure 3. Extreme anomaly scenarios illustrated for a location in southern England. The arrows illustrate the anomaly from the long-term mean. Anomalies in each month can be assumed to be independent. The blue shaded boxes show the core hot, cold, wet, dry and windy anomaly scenarios. The orange shaded box illustrates the compound hot extreme anomaly scenarios.

and 2.2 m by 2100, relative to 1981–2000, around the coast of the UK. Palmer et al. (2024) also defined HILL sea level rise scenarios for the UK: these are slightly lower than the values in HILL-6 because they used a different percentile from the IPCC AR6 distribution.

Other potential storylines for HILL scenarios were considered, but rejected because their direct effects on UK weather, climate or sea level were assessed to be small or within the range of the storylines already defined. These included abrupt changes to the South Asian Monsoon or the El Nino-Southern Oscillation. We also did not explicitly include a storyline describing changes in the North Atlantic jet stream (in contrast to previous characterizations of HILL scenarios for the UK: Slingo (2021), Hanlon et al. (2021), and Harvey et al. (2023)). This largely reflects differences in the starting point for the storylines. In our study, persistent changes to the jet stream are a consequence of the initial storylines—especially HILL-4—rather than a driver. The extreme anomaly scenarios outlined below, however, explicitly describe jet stream characteristics.

4. Extreme Anomaly Scenarios

The extreme anomaly scenarios (Figures 3 and 4 and Tables 2 and 3) describe plausible extreme months and seasons, focusing on temperature, rainfall and windspeed individually and in combination. The scenarios are presented as anomalies from a long-term (ideally 30-year) mean and can be applied to conventional climate projections or the transient scenarios outlined above. The scenarios were informed by an assessment of the drivers generating extreme anomalous months and seasons across the UK (Arnell et al., 2025b). Weather in the UK varies with the direction of the airflow and the characteristics of air masses, which are determined by factors such as large-scale atmospheric circulation patterns strongly influenced by the jet stream, the state of the Atlantic Ocean and the extent of snow and ice cover (Dong et al., 2025). Air masses from the west—usually from cyclonic weather patterns—are typically wet and mild in winter, but wet and cool in summer. Air masses from the east—usually from anticyclonic weather patterns—are usually dry, and typically cold in winter and hot in summer. The drivers of these weather patterns are complex and interconnected. Rather than starting with a narrative storyline as was done with the transient scenarios, the extreme anomaly scenarios were therefore constructed by defining plausible extreme anomalies from observations (HadUK-Grid: Hollis et al., 2019; Met Office et al., 2018), exploring empirical relationships between drivers and extreme anomalies, using model simulations (UKCP18 climate projections) and process understanding, and then adding a *post hoc* "backstory" storyline describing the drivers and conditions that could generate such anomalies. The quantitative scenarios define extreme monthly and

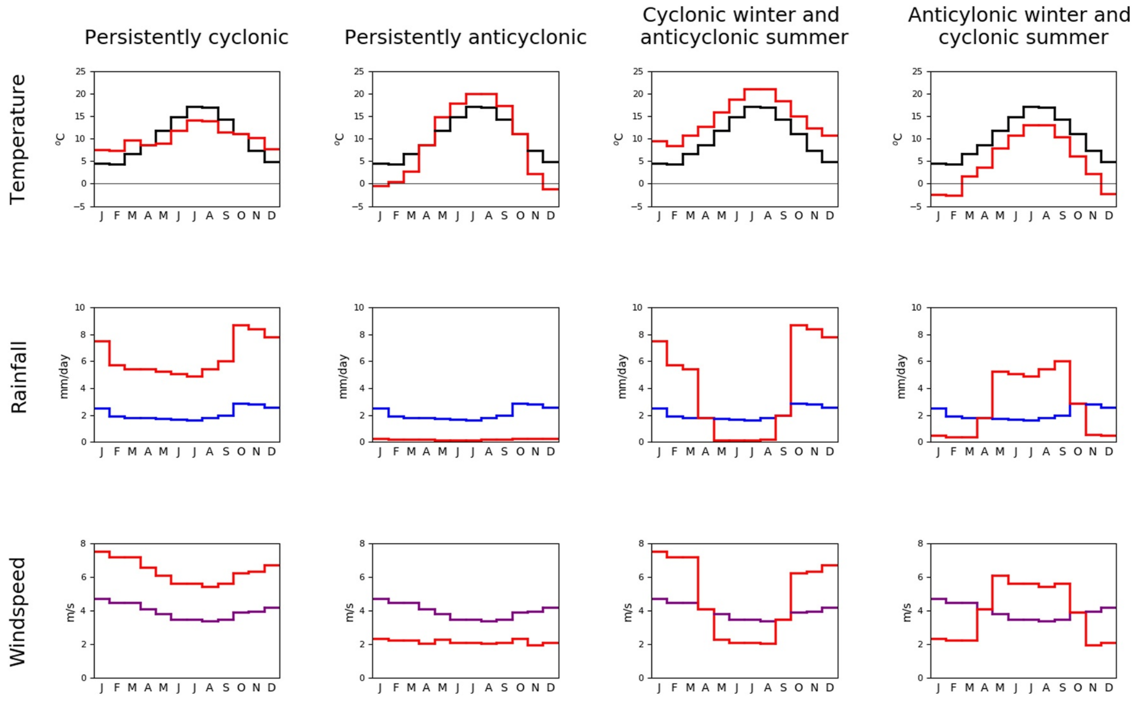

Figure 4. Persistent extreme anomaly scenarios for a location in southern England. The black, blue and purple lines show the long-term mean and the red line shows the maximum persistent anomaly.

seasonal temperature, rainfall and windspeed anomalies, and the narrative storyline allows users to define plausible consistent extremes in other weather variables.

One set of extreme anomaly scenarios characterizes individual extreme months or seasons. The five basic scenarios here are hot, cold, wet, dry and windy. Each of the five basic scenarios also describes plausible

Table 2
High-Impact Low Likelihood (HILL) Extreme Anomaly Scenarios for the UK

Scenario	Description	Compound	Summary storyline
Hot	Average monthly temperatures between 4 and 6°C above the mean	Wet and windy in winter, dry and calm in summer	Winter: strong jet stream and cyclonic conditions, positive North Atlantic Oscillation (NAO) Summer: weak, meandering jet stream, blocking and anticyclonic conditions
Cold	Average monthly temperatures between 4 and 7°C below the mean	Dry and calm in winter, wet and windy in summer	Winter: persistent anticyclonic conditions over Scandinavia with a weak jet stream. Frequent sudden stratospheric warmings and cold air outbreaks. Negative NAO Summer: strong jet stream to the south with frequent windstorms. Strongly cyclonic
Wet	Average monthly rainfall between 2.5 and 3 times the mean	Mild and windy in winter, cool and windy in summer	Strongly cyclonic conditions with a strong jet stream to the south of its average position. Positive NAO
Dry	Average rainfall 10% of the mean (at the regional scale)	Cold and calm in winter, hot and calm in summer	Strongly anticyclonic conditions, with the jet stream to the north and weak with persistent meanders. Negative NAO in winter and positive NAO in summer.
Windy	Average windspeeds 60%–80% higher than the average	Mild and wet in winter, cool and wet in summer	Strong jet stream with strongly cyclonic conditions. Positive NAO

Note. The numbers in the Description column represent anomalies in the regional average.

Table 3
High-Impact Low Likelihood (HILL) Persistent Extreme Anomaly Scenarios for the UK

Scenario	Characteristics	Storyline
Persistently cyclonic	Wet and windy: rainfall 3 times the mean, windspeed 1.6 times the mean, and temperatures 3°C above the mean November to March and 3°C below the mean May to September	Persistent cyclonic conditions bring mild wet air from the west, with high windspeeds and frequent and clustered storms. Strong jet stream. At some point in spring and autumn temperatures will be close to the average
Persistently anticyclonic	Dry and calm: Rainfall 10% of the mean, windspeed 50% of the mean, temperatures 3°C below the mean November to March and 3°C above the mean May to September	Persistently anticyclonic conditions bring dry air from the east and south. Weak meandering jet stream, and persistent blocking. Cold in winter with frequent cold spells; hot in summer with chance of intense convective storms
Cyclonic in winter and anticyclonic in summer	Temperatures consistently 3°C above the mean, wet and windy in winter and dry and calm in summer	Cyclonic conditions bring mild air and wet and windy weather from the west during winter. In spring this flips rapidly to persistent anticyclonic conditions, bringing hot, dry and calm conditions from the east. In autumn conditions flip back to cyclonic
Anticyclonic in winter and cyclonic in summer	Temperatures consistently 3°C below the mean, dry and calm in winter and warm and windy in summer	Anticyclonic conditions bring cold and dry air from the east during winter. In spring this flips rapidly to persistent cyclonic conditions bringing cool, wet and windy weather in summer. In autumn conditions flip back to anticyclonic

Note. The numbers in the Characteristics column represent anomalies in the regional average.

combinations of weather that could occur (e.g., cool summer months can be also wet and windy). A sequence of extreme months or seasons could plausibly be constructed by assuming that each month or season is independent of each other, producing for example, sequences that flip from one extreme to another, or sequences that persist.

A second set of extreme anomaly scenarios (Table 3) is explicitly based on storylines describing persistent anomalous weather continuing for successive months. Four storylines describe two extreme drivers in two seasons: persistently anticyclonic throughout the year (dry), persistently cyclonic throughout the year (wet), anticyclonic in winter and cyclonic in summer (cold in winter and cool in summer), and cyclonic in winter and anticyclonic in summer (mild in winter and hot in summer).

A key assumption behind the extreme anomaly scenarios is that extreme anomalies relative to a long-term mean do not change substantially as the long-term mean changes into the future. Analysis of UKCP18 projections (Figures S14–S16 in Supporting Information S1) shows that this assumption is reasonable for monthly temperature and windspeed anomalies, and for rainfall in winter, spring and autumn. Summer rainfall anomalies, however, increase over time when expressed as a percentage of the mean. This is because "wet" summers continue to occur but become less frequent, so the mean reduces. Anomalies expressed as multiples of the standard deviation are more consistent over time, but are not so useful in practice. Whilst standard deviations of observed or simulated temperature, rainfall and windspeed can of course be calculated from annual time series, standard deviations are not presented in the data portals used by many users (they include multi-year means, but not standard deviations).

The magnitude of an extreme monthly or seasonal anomaly varies with spatial scale, and the finer the spatial scale the more extreme the anomaly. The extreme anomaly scenarios therefore also include adjustments for spatial scale, based on HadUK-grid observations (Hollis et al., 2019) gridded at different scales. For example, extreme temperature anomalies are approximately 1°C more extreme at the local (5×5 km) scale than at the regional scale (13,000–25,000 km^2), and extreme wet rainfall anomalies are approximately 50% larger.

The extreme anomaly scenarios are designed to inform an assessment of risks from extreme months and seasons. They do not define individual short-duration events such as heatwaves, cold spells, rainstorms and windstorms, primarily because the user requirements for such "worst case scenarios" vary considerably between users. The UK's National Security Risk Assessment (HM Government, 2025) presents the reasonable worst case scenarios used for contingency planning in the UK, for example, but other sectors may have more specific needs. Short-duration extremes consistent with the storylines can in principle be constructed from theoretical reasoning,

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analysis of observed or modeled experience, or through the use of simulation experiments conditioned on boundary conditions consistent with the storylines (see Leach et al. (2022), Brogli et al. (2023), Gessner et al. (2023), and Hawkins et al. (2023) for examples of methods). Extreme months or seasons do not necessarily include extreme short-duration events, and extreme short-duration events do not necessarily lead to an extreme month or season.

5. Concluding Comments

We have summarized here two types of HILL climate scenarios for the UK. They are designed to complement existing UK climate projections, to inform decisions around adaptation and resilience and meet an identified need for "worst-case" climate scenarios that can be applied simply. The narrative storylines for each scenario can be used to develop qualitative risk assessments, and the indicative quantifications can be used for more quantitative risk assessments as inputs to impact and risk models. The approach presents a template for application in other areas. We note that the definition and application of HILL climate scenarios implies a definition of "conventional" scenarios, and specifically emissions scenarios used to project future changes.

The scenarios map closely, but not exactly, onto the four categories of HILL scenarios proposed by Wood et al. (2023): compound or unprecedented weather extremes, levels or rates of change above the likely range assessed by the IPCC, crossing tipping points, and the consequences of unexpected human actions. The extreme anomaly scenarios fit within Wood et al.'s (2023) first category. HILL-2 (rapidly reduced aerosols) fits into the fourth category. HILL-4 (enhanced Arctic Amplification), HILL-5 (ocean circulation change) and HILL-6 (enhanced sea level rise) all fit into the third category. HILL-1 (enhanced warming) explicitly fits into the second category, although one of the drivers—very high emissions—falls into the fourth category: it was assumed that for practical purposes drivers in both these categories would have similar effects. HILL-3 (volcanic cooling) does not fit directly into the categorization because although it affects climate risks it is not itself associated with human-induced climate change.

The scenarios describe HILL *drivers* of potential impact, rather than HILL *outcomes*. HILL-1 (enhanced warming) and HILL-2 (rapidly reduced aerosols) would both lead to more extreme changes in UK climate than conventional projections. HILL-4 (Arctic Amplification) and HILL-5 (ocean circulation change) both lead to significant and persistent cooling across the UK. HILL-3 (volcanic cooling) assumes a short-lived cooling. HILL-6 assumes a much larger increase in sea level than conventional scenarios. In practice the additional estimated impacts with some of the transient scenarios (especially HILL-2 and HILL-4) may be small relative to the range under conventional UKCP18 scenarios.

Climate change adaptation and resilience planning is informed by climate scenarios, used in different ways in different communities. The UK Climate Change Committee (2021) introduced 10 principles for good adaptation. One of these recommended "adapt to 2°C and assess the risks for 4°C," and another recommended preparing for "unpredictable extremes." As noted in the introduction, several UK agencies require consideration of "credible maximum scenarios" for investments and development where the consequences of loss or failure would be extreme and so-called "tail risks" are high. The HILL scenarios provided here are directly relevant when adaptation and resilience planning considers tail risks and "preparing for the worst" (Wood et al., 2023). They can also be used within an adaptive pathways approach to adaptation (Haasnoot et al., 2024) where decisions are staged as information and evidence changes over time.

The scenarios are based on current understanding of the potential for HILL climate changes across the UK. This understanding is evolving and may lead to revisions to the plausible changes described here and may identify further storylines and scenarios. The approach developed here provides a framework for updating and expanding the list of plausible HILL scenarios which could be considered for adaptation and resilience planning.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The analysis used UKCP18 climate and sea level projections (Met Office Hadley Centre, 2018a, 2018b, 2018c) and the HadUK-Grid observed climate data set (Met Office et al., 2018). HILL-2 is informed by model simulations conducted by Luo et al. (2020), and HILL-3 is based on model simulations presented by Bethke et al. (2017). HILL-5b is informed by CMIP6 model simulations following Swingedouw et al. (2021). The HILL-6 sea level scenarios are taken from the NASA IPCC AR6 sea level projection tool (Garner et al., 2021; https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool), rescaled to a 1981–2010 reference period. Full quantifications of the HILL scenarios are presented in Arnell et al. (2025a).

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