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LETTER

Hydrological impacts from transient high-impact low-likelihood climate scenarios for Great Britain

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Abstract

Information about the potential for progression of climate change outside the range of conventional climate projections could be crucial for appropriate adaptation planning, particularly for water-related hazards like floods and droughts. The development and application of plausible high-impact low-likelihood (HILL) climate scenarios aims to address this. Here, a recently developed set of transient HILL climate scenarios for the UK is used with a grid-based hydrological model to assess the potential impacts on river flows across Great Britain and how these differ from those under conventional climate projections. Changes in seasonal mean flows and 10 year return period high and low flows are investigated. The results vary, both between the five transient HILL scenarios applied, and for different flow indices and regions of the country. Some of the flow impacts from conventional climate projections are at least partially ameliorated under some HILL scenarios, but made worse under others. For example, high flow increases in the north are ameliorated under 'Stronger Arctic Amplification' but worsen under 'Collapse of Sub-Polar Gyre'. The most concerning HILL scenario is possibly 'Collapse of AMOC', which could cause substantial changes in seasonal mean and high flows to the north of Britain, related to increased snow. Studies such as this should add impetus to mitigation efforts, to reduce the chance of occurrence of HILL scenarios, as well as aiding adaptation planning, particularly for critical infrastructure.

1. Introduction

The occurrence of unprecedented water-related hazards can lead to severe impacts, particularly where flood defences and water supply systems, and associated plans and risk assessments, were made with reference to historical ranges of variability, which tend to be limited by relatively short records (e.g. Watts *et al* 2012, Bertola *et al* 2023). Climate change is likely to exacerbate this issue. Furthermore, conventional climate projections may not fully represent the potential range of impacts of climate change, because climate sensitivity or feedbacks are greater than expected or tipping points are crossed (Hanlon *et al* 2021, Wood *et al* 2023, Arnell *et al* 2025a).

Methods have been developed to try to understand how extreme events could be, both in the current climate and in future climates under global warming. These include use of large climate model ensembles (e.g. Bevacqua *et al* 2023, Kay *et al* 2024), 'storylines' describing how observed events could have unfolded differently (e.g. Chan *et al* 2022), and 'credible maximum' or 'H++' scenarios, which are plausible but unlikely high-end weather or climate scenarios (e.g. Wade *et al* 2015, Reynard *et al* 2017). Such methods are crucial to enable better planning and preparedness for events, and are considered for major UK infrastructure projects for example (Environment Agency 2016, Office for Nuclear Regulation 2022).

A project was commissioned within the UK Climate Resilience programme (www.ukclimateresilience.org/) to derive a set of scenarios representing plausible high consequence but low probability future climates for the UK (Arnell *et al* 2025a, 2025b)—often called high-impact low-likelihood (HILL) climate scenarios. Both 'transient' and 'extreme anomaly' scenarios were described. The transient HILL scenarios describe plausible changes in climate and sea level to 2100 which are outside the range of changes from conventional climate projections (i.e. those produced using standard climate model setups and emissions scenarios). The extreme anomaly HILL scenarios describe plausible extreme monthly and seasonal anomalies in temperature, rainfall and windspeed. Note that these HILL scenarios are described in terms of low-likelihood drivers (e.g. changes in atmospheric or oceanic conditions) that may have high impact in the UK, but HILL scenarios can also be derived in terms of outcomes (e.g. changes in river flows) with high impact (Arnell *et al* 2025a). Note also that, while these HILL scenarios are considered low-likelihood, they are not assigned quantitative likelihoods (Arnell *et al* 2025a).

Here, the transient HILL climate scenarios that affect precipitation or temperature are applied, alongside the latest set of conventional climate projections for the UK, with a national-scale grid-based hydrological model. The potential impacts of these HILL climate scenarios on river flows across Great Britain (GB) are assessed, and how these differ from the impacts under the conventional climate projections alone. Since impacts on the water cycle are one of the main ways that climate change will affect both society and the environment (www.un.org/en/climatechange/science/climate-issues/water), having an understanding beyond climate to hydrology is critical for appropriate adaptation planning, as well as aiding the argument for stronger mitigation action.

2. Methods

2.1. The hydrological model and base climate impact data

The grid-to-grid (G2G) is a grid-based hydrological model run at a 15 min time-step on a 1 km grid across GB (Bell *et al* 2009). It requires daily 1 km gridded time-series of precipitation and potential evaporation (PE), plus daily min and max temperature for the snow module (Bell *et al* 2016). Flow simulations perform well for a wide range of catchments (e.g. Rudd *et al* 2017, Formetta *et al* 2018, Kay and Brown 2023). G2G has been used for a range of climate impact applications across GB, including floods (Kay *et al* 2021b) and droughts (Rudd *et al* 2019), and is used for operational flood forecasting (Cranston *et al* 2012, Price *et al* 2012).

Data from the Regional component of UK Climate Projections 2018 (UKCP18; Murphy and Harris *et al* 2018) are used to drive G2G in order to produce a base dataset of future hydrological impacts to which HILL scenario impacts are compared. UKCP18 Regional comprises a 12-member perturbed-parameter ensemble (PPE) of regional climate model (RCM) simulations for the UK (under RCP8.5 emissions), processed onto a 12 km grid aligned with the GB national grid (Met Office Hadley Centre 2018). The UKCP18 projections are used as the base because (i) they are the standard scenarios used for adaptation planning in the UK and (ii) Arnell *et al* (2025a, 2025b) developed the HILL climate scenarios with specific reference to UKCP18.

The UKCP18 Regional ensemble directly provides time-series of precipitation and temperature, with PE estimated from other variables, and the 12 km data are then processed onto the 1 km G2G grid. Briefly, precipitation is bias-adjusted using a simple monthly correction against observations then downscaled using historical rainfall patterns, temperature is downscaled using a lapse rate with elevation, and PE is simply copied down to the 1 km grid. This processing was shown to provide reasonable performance against observed flows in the baseline period (Kay 2021).

The UKCP18 Regional PPE shows spatially varying temperature increases of roughly 1 °C–4 °C in winter and 2 °C–7 °C in summer by 2061–2080 (Murphy and Harris *et al* 2018 figure 4.8(a) and (b)), alongside spatially varying precipitation decreases of roughly −60% to 0% in summer and increases of roughly 0%–40% in winter, although summer increases of up to 10% and winter decreases of −10% or more are shown in parts of northern Scotland by some ensemble members (Murphy and Harris *et al* 2018 figure 4.8(c) and (d)).

2.2. HILL scenarios: definition and application

Arnell *et al* (2025a, 2025b) describe six transient HILL scenarios for the UK. They were chosen following an extensive literature survey, and their specifications were '…based on a combination of observed and historical experience, model simulations and theory', as well as discussions with stakeholders (Arnell *et al* 2025a). Only four of the scenarios are applied here, although one has two variants: HILL-1 (Enhanced Warming), HILL-2 (Reduced Aerosols), HILL-4 (Stronger Arctic Amplification), HILL-5a (Collapse of Atlantic Meridional Overturning Circulation (AMOC)), HILL-5b (Collapse of Sub-polar Gyre (SPG)).

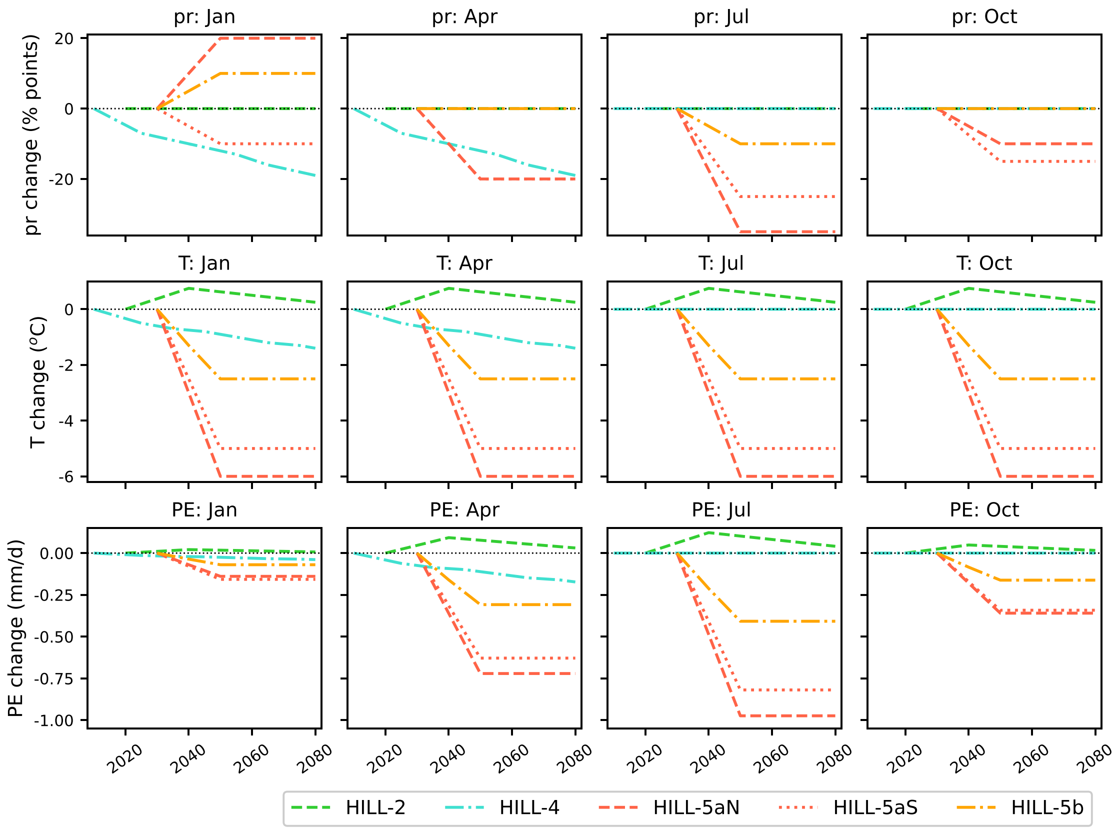

Figure 1. The time-series of changes in precipitation (*pr*; top row), temperature (*T*; middle row) and PE (bottom row) for January, April, July and October (left-to-right) under each HILL scenario (except HILL-1). Plots for all months are in supp. figure 1.

The remaining two scenarios are HILL-3 (Volcanic cooling), which is not applied as the effects are relatively short-term (5 years), and HILL-6 (Enhanced sea level rise), which is not applied as only sea-level rise is specified.

Table 1 summarises the five scenarios used here, and how they are applied with the hydrological model. The scenarios were specifically designed to be simple to apply, including as input to impact models. Most specify additional future changes in climate (precipitation and/or temperature) that are considered to apply on top of future changes in conventional climate projections like UKCP18. HILL-1 is the exception; this is considered as extreme changes across UKCP18 under RCP8.5 emissions (i.e. taking the impact from the PPE member with the greatest impact on the variable of interest at each grid cell, even though this member will vary between grid cells—see section 2.3.1). The additional future changes in climate for the other HILL scenarios are given as national values (i.e. not spatially varying), except for HILL-5a where different changes are given for Northern and Southern regions (table 1). The transient HILL scenarios thus ‘provide a high-level picture of how future UK climate could be different to that implied by conventional UKCP18 climate projections’ (Arnell *et al* 2025b).

2.2.1. The additional changes in climate variables for each HILL scenario

For each HILL scenario applied (except HILL-1), the additional precipitation, temperature (T) and PE changes for one month in each season are plotted in figure 1 (with plots for all months and tables of values given in Supp. Mat.). Note that the precipitation changes are provided as percentage points, whereas the T changes are provided as °C. The derivation of PE changes (as mm d^{-1}) from T changes is described in section 2.2.2. Most of the HILL scenarios have T and precipitation changes which vary by month as well as future year, except for HILL-2 where the T changes are the same in each month and there are no changes in precipitation (although the PE changes still vary by month). HILL-2 and HILL-4 vary for each future year up to 2100, but the HILL-5 variants (involving abrupt ocean circulation changes) vary linearly from zero in 2030 up to a maximum effect in 2050 (i.e. the full ocean change is assumed to take 20 years), with the 2050 values then applying up to 2100.

These additional changes have been applied to the UKCP18 Regional PPE gridded time-series for each variable for each corresponding year, then used to drive the G2G hydrological model. Adjustments

Table 1. The five transient HILL scenarios applied with the G2G hydrological model, with brief information on the provided precipitation (*pr*) and temperature (*T*) changes, and the method of application with G2G.

Scenario	Summary of climate changes and how applied
HILL-1 Enhanced warming	• Using prior G2G runs driven by the UKCP18 RCM PPE, extract values pixel-by-pixel from the member with 'the largest increase/decrease as appropriate'; in practice, extract both min and max flow changes, rather than deciding *a priori* which is most appropriate for each flow index. • On pixel-by-pixel basis the selected member will vary, but still calculate regional means for both min and max. • Use 12 original PPE members.
HILL-2 Reduced aerosols	• Only *T* change specified (no *pr* change); same change for each month in year. • Estimate monthly PE changes from *T* changes. • Changes apply from 2020, peak in 2040 and reduce to zero in 2100—linearly interpolate to get transient changes for each year in 2020–2080. • Apply monthly *T* and PE changes to UKCP18 RCM PPE grids (12 original members).
HILL-4 Stronger arctic amplification	• Winter (Nov–Apr) *T* and *pr* changes specified; no changes for other months. • Estimate monthly PE changes from *T* changes. • Changes given for 2020s to 2080s—assume these apply mid-decade and linearly interpolate from zero in 2010 to get transient changes for each year in 2010–2080. • Apply monthly *pr, T* and PE changes to UKCP18 RCM PPE grids (12 original members).
HILL-5a Abrupt ocean circulation change: collapse of AMOC	• Monthly *T* and *pr* changes specified for 'Northern UK' and 'Southern UK', where these are defined in terms of UKCP18 administrative regions (Fung *et al* 2018). • Region definition: Northern UK; NW and NE England, Yorkshire and Humber, Scotland and Northern Ireland. Southern UK; Wales, England up to and including West and East Midlands. These are converted to UKCP18 river-basin regions (Fung *et al* 2018) for application with G2G (table 2). • Estimate monthly PE changes from *T* changes. • Changes given for 2030, 2040, 2050 (zero in 2030)—linearly interpolate to get transient changes for each year in 2030–2050, then apply 2050 values for 2050–2080. • Apply monthly *pr, T* and PE changes to UKCP18 RCM PPE grids (12 original members).
HILL-5b Abrupt ocean circulation change: collapse of SPG	• Monthly *T* and *pr* changes specified. • Estimate monthly PE changes from *T* changes. • Changes given for 2030, 2040, 2050 (zero in 2030)—linearly interpolate to get transient changes for each year in 2030–2050, then apply 2050 values for 2050–2080. • Apply monthly *pr, T* and PE changes to UKCP18 RCM PPE grids (12 original members).

are made to the additional percentage point changes for precipitation to allow for their application with future precipitation time-series (section 2.2.3). Note that the absolute changes in PE are not allowed to result in PE itself being negative—any such values are reset to zero.

2.2.2. Derivation of PE changes from temperature changes

For application with G2G, PE changes are also required. These are derived from the provided *T* changes using the Oudin *et al* (2005) temperature-based PE estimation method, so that

$$\partial \mathrm{PE} = \frac{R_{\mathrm{e}}}{\lambda\rho}\frac{\partial T}{100} \tag{1}$$

where R_{e} is extraterrestrial radiation (MJ m^{-2} d^{-1}; dependent on latitude and day-in-year only), λ is latent heat flux (MJ kg^{-1}) and ρ is the density of water (1 kg mm^{-1} m^{-2}). This gives an absolute change in PE (mm d^{-1}) from the absolute change in T (°C), for each month and year (using the middle day for each month). Since R_e depends on latitude, equation (1) should give monthly PE changes that vary with latitude as well as month, but for ease of application a fixed latitude has been used here to give a single set of monthly PE changes for each set of monthly T changes. The latitude has been set at 53.5° N for all scenarios except HILL-5a, where a latitude of 55.5° N is used for the Northern variant and 52.0° N is used for the Southern variant.

The use of fixed latitudes makes very little difference to the PE change derived, particularly for Spring to Autumn. For example, for the largest decrease in T of −6 °C, using a latitude for the more southerly parts of the country (51° N) gives a difference in δPE of only up to 3.5% of typical daily PE values for Mar–Oct in southern GB (much less than 1% in summer), compared to the 53.5° N applied. Similarly, using a latitude for the more northerly parts of the country (58° N) gives a difference in δPE of only up to 9% of typical daily PE values for Mar–Oct in northern GB (less than 1.5% in summer) compared to the 53.5° N applied. Percentage differences in δPE are larger in winter, but PE itself is very low in winter, and much lower than rainfall, so it makes little difference to the water balance or flow response.

2.2.3. Application of precipitation percentage point changes

Arnell *et al* (2025b) specify that the additional precipitation percentage point changes for the HILL scenarios should be added to the precipitation percentage changes from UKCP18: 'if a UKCP18 projection has a change in summer rainfall of −23% in 2050 (relative, for example, to a 1981–2010 baseline), then add the change from table HILL5-1 (e.g. −25 percentage points for southern England for 2050) to produce a change of −48%.' The precipitation percentage point changes thus cannot be applied directly to UKCP18 RCM PPE precipitation time-series for future periods, as this would under-do decreases and over-do increases. For example, if UKCP18 gives a summer decrease of −20% from 100 mm, and a HILL scenario gives a further −20% point summer decrease, this should be an overall decrease of −40% to 60 mm, but applying the further −20% point decrease to a future precipitation of 80 mm (i.e. already decreased by 20%) would give 64 mm.

Instead, the additional precipitation changes for each month and year are adjusted using

$$\frac{Y_{\mathrm{A}}(i,g)}{100}=\frac{Y_{\mathrm{HS}}}{100+X(i,g)} \qquad (2)$$

where Y_{A} is the adjusted percentage change, Y_{HS} is the original percentage point change for the HILL scenario, and X is the percentage change for grid box g of UKCP18 Regional PPE member i. Since X varies by ensemble member i and grid box g as well as time, so does Y_{A}, even though Y_{HS} has a single value across GB (for each month and year) and is independent of the UKCP18 PPE member with which it is applied.

Kay *et al* (2021a) derived transient grids of percentage changes in precipitation for each UKCP18 Regional PPE member. This involved deriving grids of changes for each month and year, using multiple future 30 year time-slices moving on one year at a time, relative to a fixed baseline time-slice (Dec 1980–Nov 2010); the monthly change factors for a specific year were calculated from the mean change over the 30 years centred on that year. These transient grids of percentage changes in monthly precipitation are applied here to adjust the HILL scenario precipitation percentage point changes as in equation (2).

2.3. Analysis of simulated river flows

For all of the HILL scenarios except HILL-1, the G2G output of gridded time-series of monthly mean flow, annual maxima of daily mean flow, and annual minima of 7 d mean flow have been used to investigate impacts on seasonal mean river flows (for winter, spring, summer and autumn), 10 year return period high flows, and 10 year return period low flows (derived as in Kay 2025).

For each flow index, percentage changes are calculated from a baseline time-slice of Dec 1980–Nov 2010 (Oct 1981–Sep 2010 for high flows, using water years), to future time-slices of 30 years (29 years for high flows) moving forward by 5 years at a time, up to a final time-slice of Dec 2050–Nov 2080 (Oct 2051–Sep 2080 for high flows). The small differences in time-slices for high flows are due to the use of water years. These moving window changes are calculated for each river pixel (non-sea, non-tidal 1 km G2G grid cells with a drainage area of at least 50 km^2), then regional average changes are calculated, as the mean across each of four regions of GB (table 2 and figure 2).

2.3.1. Calculation of regional means for HILL-1

HILL-1 is defined by Arnell *et al* (2025a, 2025b) as the most extreme impact (i.e. largest magnitude increase or decrease), for each grid-cell separately, from across the UKCP18 PPE. Here, the min and

Table 2. The definition of Northern and Southern regions by UKCP18 river-basin regions (for HILL-5a application), also divided by West and East (for summarising results over four regions—NW, NE, SW,SE; figure 2).

	West	East
North	West Highland Argyll Clyde Solway NW England	North Highland NE Scotland Tay Forth Tweed Northumbria
South	West Wales Dee Severn SW England	Humber Anglian Thames SE England

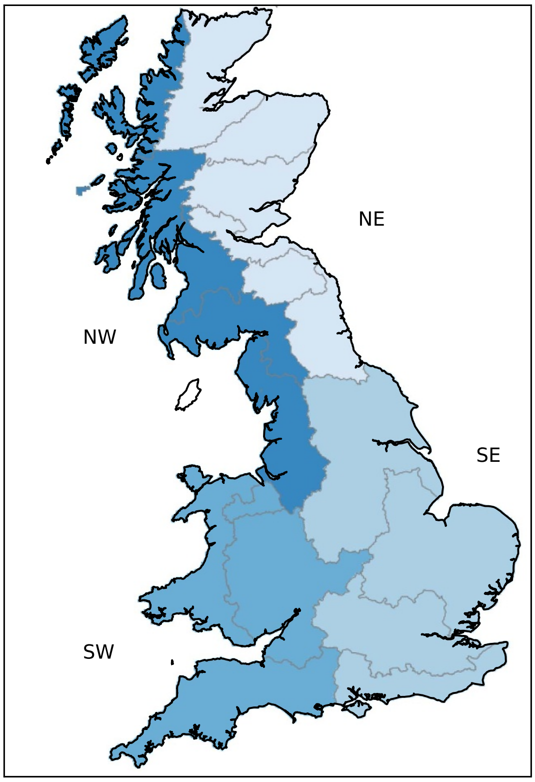

Figure 2. The NW, NE, SW and SE regions (groupings of UKCP18 river-basin regions) used for summarising flow changes.

max change across the UKCP18 PPE is calculated for each river pixel, for each flow index. The regional means of the min and max are then calculated. Taking regional averages of the most extreme pixel-based changes regardless of ensemble member could be considered to give improbable regional impacts, since they may not be spatially coherent, but does give the broadest idea of the potential range.

3. Results

The transient changes in seasonal mean flows, 10 year return period high flows and 10 year return period low flows for the four regions of GB are shown in figure 3 for HILL scenarios 1 and 2, and figure 4 for HILL scenarios 4, 5a and 5b, each alongside those derived from the UKCP18 Regional PPE.

Unsurprisingly, HILL-1 (Enhanced Global Warming; derived as the regional means of pixel-by-pixel min and max changes across the UKCP18 Regional PPE) shows flow changes much more extreme than UKCP18 Regional (figure 3). There are larger increases in winter mean flows in the north, larger decreases in summer and 10 year return period low flows right across the country, and larger decreases

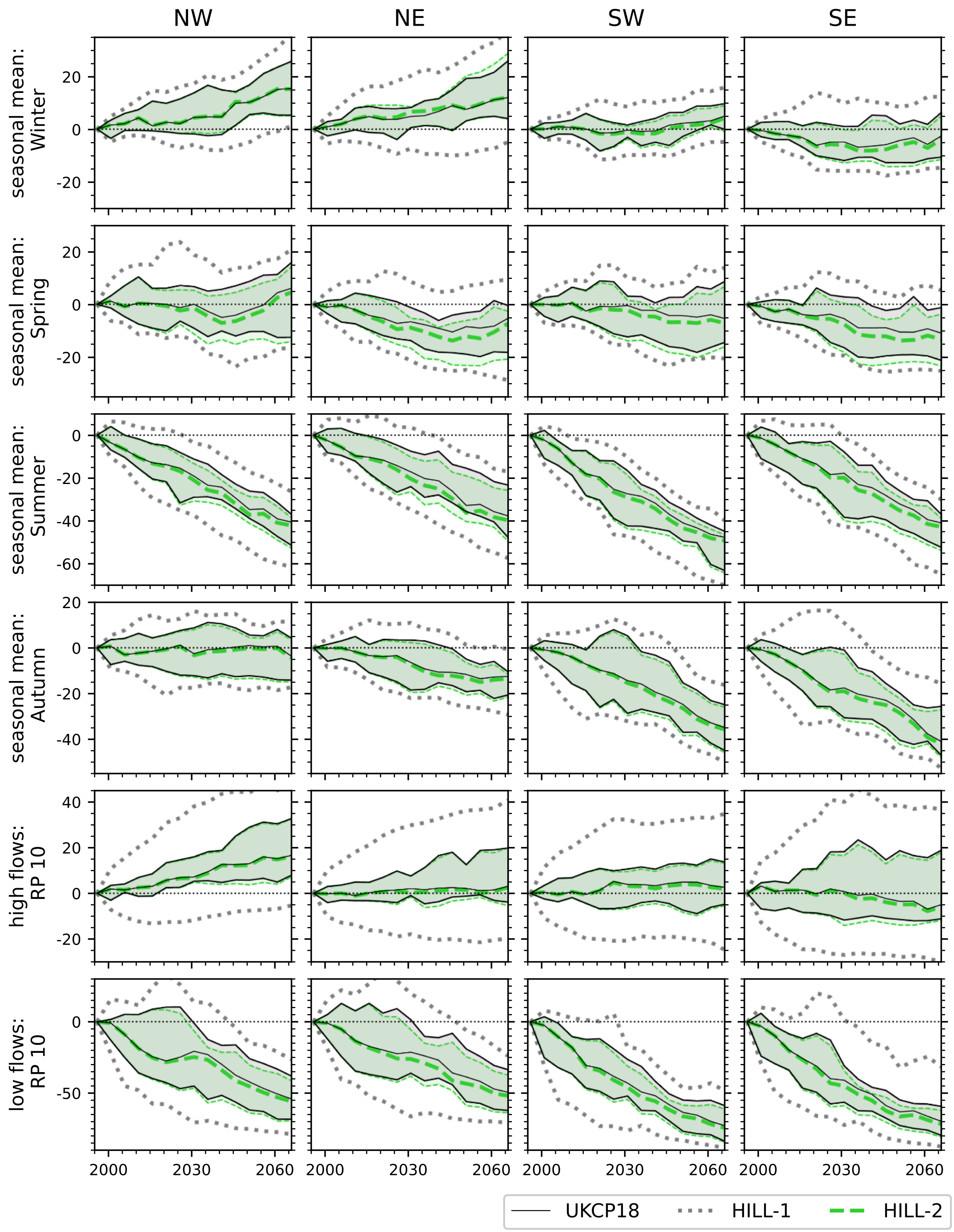

Figure 3. Transient changes in seasonal mean flows, 10 year return period high flows and 10 year return period low flows (top to bottom) for four regions of GB (left to right) for HILL scenarios 1 and 2, alongside those derived from UKCP18 Regional. The shading for UKCP18 and HILL-2 shows the range across the 12 ensemble members, excluding the largest and smallest changes. For HILL-1 two lines are shown, one which takes the pixel-by-pixel minimum flow changes from across the UKCP18 Regional PPE and averages them across the region, and one that does the same but for the pixel-by-pixel maximum flow changes.

in autumn flows in the south. There is a particularly broad range for changes in 10 year return period high flows, encompassing both much larger increases and decreases.

HILL-2 (Reduced Aerosols) has no change in precipitation but an increase in T and PE relative to UKCP18 Regional (figure 1). It shows very similar changes in flows to UKCP18 Regional, with slightly larger decreases in Spring–Autumn flows and 10 year return period low flows (figure 3).

HILL-4 (Stronger Arctic Amplification) has large decreases in precipitation and a decrease in T and PE relative to UKCP18 Regional for Nov–Apr, but no change for the rest of the year (figure 1). It shows greater decreases in Autumn-Spring mean flows than UKCP18 Regional (figure 4). Differences are small

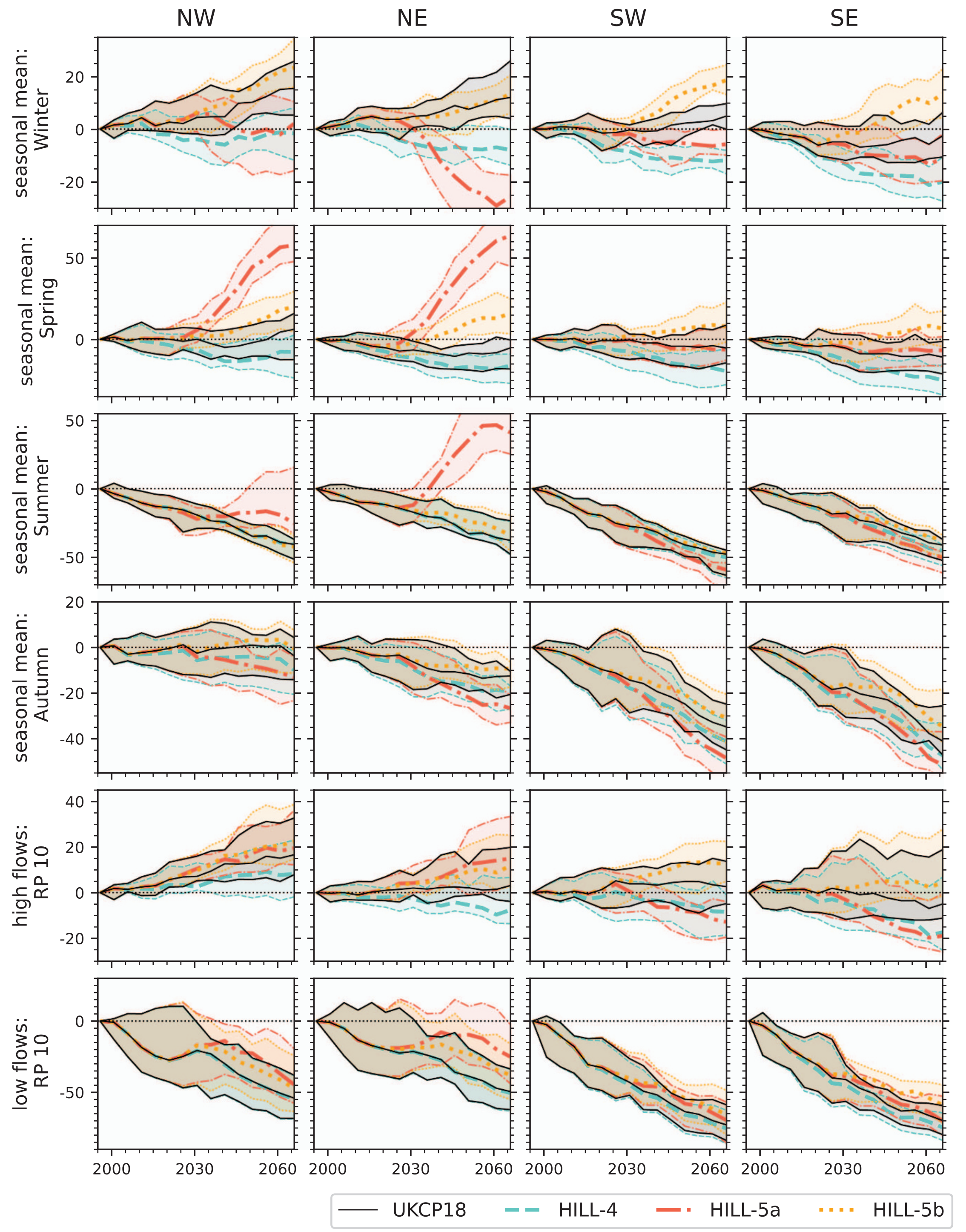

Figure 4. Transient changes in seasonal mean flows, 10 year return period high flows and 10 year return period low flows (top to bottom) for four regions of GB (left to right) for HILL scenarios 4, 5a, 5b, alongside those derived from UKCP18 Regional. The shading for each shows the range across the 12 ensemble members, excluding the largest and smallest changes.

for summer flows and 10 year return period low flows. For 10 year return period high flows, HILL-4 shows smaller increases or larger decreases relative to UKCP18 Regional, depending on the time-slice and region.

HILL-5b (Collapse of SPG) has winter (Dec–Feb) increases and summer (Jun–Aug) decreases in precipitation (with no change in spring or autumn) and T and PE decreases throughout the year (figure 1), relative to UKCP18 Regional. It shows greater increases or smaller decreases in seasonal mean flows, low flows and high flows relative to UKCP18 Regional. Differences are particularly pronounced for spring flows, and for winter flows in the south, but small for summer and autumn flows (figure 4).

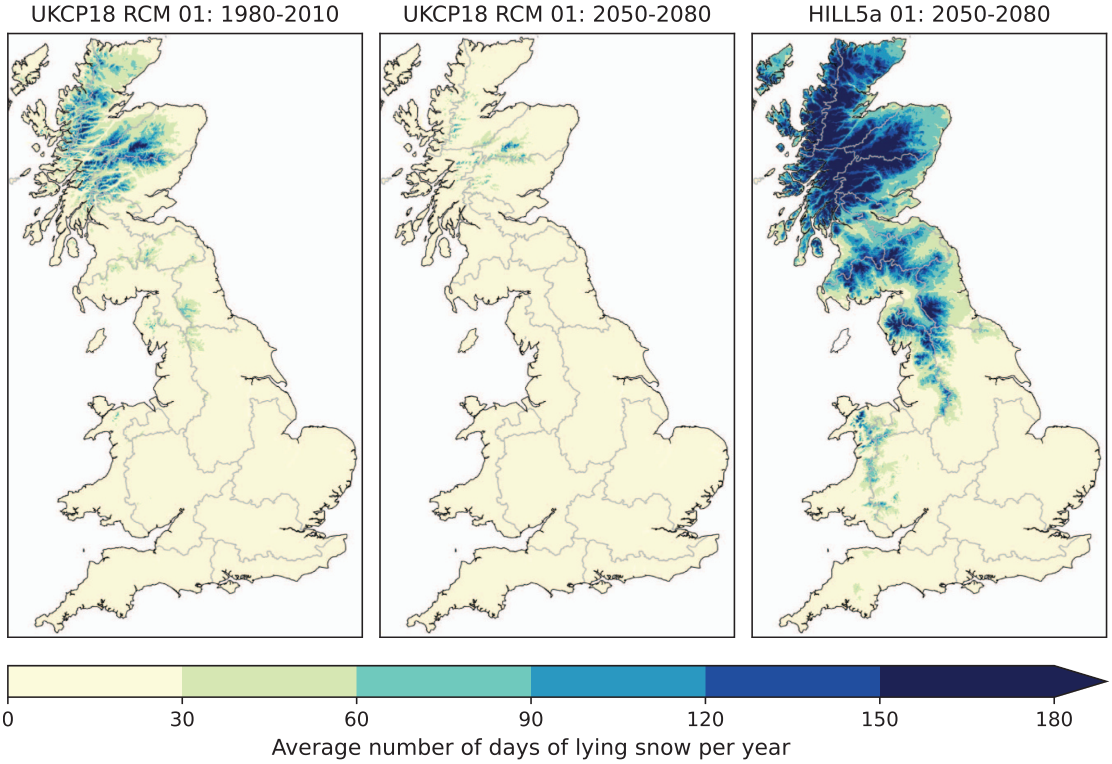

Figure 5. The average number of days of lying snow per year simulated by G2G for the first and last 30 year time-slices using UKCP18 Regional PPE member 01 (left and middle), compared to the number in the last 30 year time-slice under HILL-5a (right).

HILL-5a (Collapse of AMOC) in the NW and NE (HILL-5aN) has patterns of precipitation change relatively similar to, but much more extreme than, HILL-5b (including decreases extending from summer into several spring and autumn months), with much larger T and PE decreases throughout the year (figure 1), relative to UKCP18 Regional. It shows flow changes that are more variable relative to both UKCP18 Regional and HILL-5b, with significantly reduced winter flows and increased spring flows (and summer flows in the NE; figure 4). In both the NW and NE, decreases in 10 year return period low flows under UKCP18 Regional are somewhat ameliorated under HILL-5aN, but at the expense of slightly larger increases in 10 year return period high flows.

The patterns of change in seasonal mean flows in HILL-5a in the north are due to increased snowfall under the significantly colder and wetter winters given by HILL-5aN, with more accumulation of snow in winter leading to lower flows, and snowmelt leading to increased spring flows. Figure 5 shows the average number of days of lying snow simulated by G2G under HILL-5a in the far-future period vs UKCP18 Regional for baseline and far-future periods (ensemble member 01), where a lying snow day has been defined as one where the total (wet plus dry) snow water equivalent is greater than 5 mm at midnight. There is a clear increase in lying snow days in the future under HILL-5a but a decrease otherwise. Note that this definition of lying snow gives quite a high number of days, but for many the snow is likely to be highly transient, melting by the morning as temperatures rise.

HILL-5a in the SW and SE (HILL-5aS) has decreases in precipitation similar to HILL-4 but extending through the whole year, with greater decreases in T and PE than HILL-4 (although not as great as HILL-5aN) also extending throughout the year (figure 1). It shows flows changes similar to HILL-4, but with less difference from UKCP18 Regional in winter and spring, slightly greater difference from UKCP18 Regional in summer and autumn, and slightly lesser reductions in 10 year return period low flows (figure 4). Changes in 10 year return period high flows show slightly greater reductions relative to HILL-4 and UKCP18 Regional in the SE, and reductions rather than a small increase relative to UKCP18 Regional in the SW.

4. Discussion

The publication of a set of transient HILL climate scenarios for the UK, including additional changes in precipitation and temperature for future years beyond those from conventional climate projections, has enabled the application of a grid-based hydrological model to assess potential HILL impacts on river flows across GB. Most of the transient HILL climate scenarios are given as single nationally-applicable values for each month and year (except for HILL-5a where different changes are given for Northern and Southern regions, and HILL-1 which is defined as extreme changes across the UKCP18 PPE).

The relative simplicity of the HILL climate scenarios necessitated a similarly simple application with the hydrological model. In particular, the required PE changes were derived from T changes using a simple T-based PE formula and assuming a fixed latitude. Changes in PE are also affected by factors other than temperature (e.g. humidity), and if these could be incorporated they could lead to some differences in flow changes from hydrological modelling (e.g. Kay and Davies 2008), but changes in temperature have been shown to be the main driver of changes in PE across Britain (Robinson *et al* 2017). The broad-scale additional delta changes to precipitation, T and PE were applied to spatio-temporal data from existing UKCP18 Regional projections, and used to drive the G2G model (with adjustments to the additional percentage point changes for precipitation to enable their application with future precipitation time-series, and ensuring that PE did not become negative when the absolute value of the PE change was applied). While the UKCP18 Regional projections were used as the base dataset of 'conventional climate projections' here, their reliance on a single climate model structure means that they may not fully represent the potential range of impacts; projections based on multi-model ensembles could potentially be used (e.g. EuroCORDEX-UK; Barnes *et al* 2024, Kay 2025). Alternative hydrological models could also be applied.

The flow outputs from each HILL climate scenario were compared to flow outputs from runs driven directly by the UKCP18 Regional PPE, and assessed in terms of regional means of changes for seasonal mean flows and 10 year return period high and low flows. The use of just four regions (NW, NE, SW, SE) simplified the comparison of the results across the multiple scenarios and flow indices. Future work could look in more detail at spatial differences, particularly if further information enabled the development of HILL climate scenarios with greater spatial definition.

HILL-1 (Enhanced Global Warming) gives some much more extreme flow changes relative to those from the UKCP18 Regional PPE, particularly for high flows. But its derivation as the regional means of pixel-by-pixel min and max flow changes across the UKCP18 Regional PPE means that the combined changes are likely not spatially coherent. The resulting ranges may be improbable, but are not necessarily unrealistic, hence fit the requirement of a HILL scenario.

HILL-2 (Reduced Aerosols) is the only scenario giving even higher T increases (and therefore further PE increases) relative to UKCP18. But the increases are relatively modest (and there is no change in precipitation), so the additional effect on flows is small. However, it does result in already large decreases in summer and low flows under the UKCP18 Regional PPE being made worse, which could exacerbate impacts on aquatic ecology and make dealing with future hydrological and water resource droughts even more difficult (e.g. Rudd *et al* 2019).

HILL-4 (Stronger Arctic Amplification) ameliorates the increases in winter and high flows in the north seen under the UKCP18 Regional PPE, but worsens the decreases in spring flows across GB, which could have implications for both river ecology and agriculture.

HILL-5a (Collapse of AMOC) could cause significant problems with snow in some areas, with consequent large changes in the seasonal pattern of river flows, but with possibly relatively little direct effect in the south. However, the spatial application of this scenario, with large differences in precipitation changes between the north and south, gives a hard boundary which is likely to be somewhat artificial—in reality there is likely to be more spatial gradation in the climate impacts, and thus in the effect on flows.

HILL-5b (Collapse of SPG) is a less extreme version of HILL-5a in the north but applies across the whole country. It could have a large effect in the south in particular, with greater increase in winter and high flows, which could increase the cost of flood adaptation measures.

The most concerning transient HILL scenario, in terms of flow impacts, is possibly HILL-5a (Collapse of AMOC), which could cause substantial changes in seasonal mean and high flows to the north of Britain, alongside increased disruption directly from snow. This would be a stark contrast to the decreases in snow seen over recent decades, and further decreases in future from conventional climate projections (Kay 2016). Hanlon *et al* (2021) similarly suggest UK impacts from increased magnitude and duration of snowfall if AMOC were to collapse, although they state that 'reduced river flow … could moderate future flooding impacts'. In contrast, here the specific simulation and analysis of river flows under AMOC collapse suggests higher increases in 10 year return period high flows in the north. This could be related to rapid spring snowmelt and/or rain-on-snow events, which have led to several major historical flood events in Britain (e.g. Macdonald 2012, Marsh and Harvey 2012).

Ritchie *et al* (2020) suggest significant impacts of AMOC collapse on UK agriculture, particularly related to water deficits, but no other studies have specifically modelled the potential impacts of AMOC collapse on UK river flows. Recent research has suggested that AMOC is unlikely to collapse this century (Baker *et al* 2025), but longer climate model runs suggest that AMOC shutdown after 2100 is far from improbable, and is even possible under lower emissions scenarios (Drijfhout *et al* 2025). According to Rahmstorf (2024) 'A full AMOC collapse would be a massive, planetary-scale disaster. We *really* want to prevent this from happening. In other words: we are talking about risk analysis and disaster prevention. This is not about being 100% or even just 50% sure that the AMOC will pass its tipping point this century; the issue is that we'd like to be 100% sure that it will not'.

While the transient HILL scenarios were here applied singly, it is entirely possible that more than one could occur, further complicating potential impacts. Alongside the transient HILL scenarios, Arnell *et al* (2025a, 2025b) provide Extreme Anomaly HILL scenarios for the UK. Three sets of scenarios provide (i) individual extreme months and seasons (hot, cold, wet, dry, windy; which can be combined in any sequence); (ii) persistent extreme anomalies across successive months (strongly cyclonic or anticyclonic for Nov–Apr and May–Oct); (iii) historical analogue extreme months and seasons (based on analyses of observed datasets). All are given as anomalies relative to a historical long-term mean, and can be applied to a future long-term mean from climate projections (conventional, or with the transient HILL scenarios applied here) to assess how extreme future events could be. In particular, compound or sequential events (combinations of weather or climate drivers occurring together or successively) can be investigated. The rarity of such events makes them particularly difficult to assess using historical data alone (Bevacqua *et al* 2023).

5. Conclusion

A set of five transient HILL climate scenarios for the UK has been applied, alongside the conventional UKCP18 Regional climate projections, with a grid-based hydrological model, to assess how potential future impacts on river flows across GB may differ from those under conventional climate projections. The results vary, both between the transient HILL scenarios applied, and for different flow indices and regions of the country. Conventional climate projections already give some potentially highly impactful changes in river flows across Britain, including increases in the magnitude of floods and droughts. While some of these impacts may be at least partially ameliorated under some HILL scenarios, others are made worse. Studies such as this should add impetus to mitigation efforts, to reduce the chance of occurrence of high-impact scenarios, as well as aiding adaptation planning, particularly for critical infrastructure.

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Data availability statement

The data cannot be made publicly available upon publication because the cost of preparing, depositing and hosting the data would be prohibitive within the terms of this research project. The data that support the findings of this study are available upon reasonable request from the authors.

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Author contribution

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Conceptualization (equal), Data curation (equal), Formal analysis (equal), Investigation (equal), Methodology (equal), Visualization (equal), Writing – original draft (equal), Writing – review & editing (equal)

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