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Climate change impacts on peak river flows: Combining national-scale hydrological modelling and probabilistic projections

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ABSTRACT

Potential future increases in flooding due to climate change need to be taken into consideration when designing flood defences or planning new infrastructure or housing developments. Existing guidance on climate change allowances in Great Britain was based on research that developed a sensitivity-based approach to estimating the impacts of climate change on flood peaks, which was applied with catchment-based hydrological models. Here, the sensitivity-based approach is applied with a national-scale grid-based hydrological model, producing modelled flood response surfaces for every river cell on a 1 km grid. This provides a nationally consistent assessment of the sensitivity of flood peaks across Britain to climatic changes. The flood response surfaces are then combined with the most recent climate change projections, UK Climate Projections 2018 (UKCP18), to provide location-specific information on the potential range of impacts on floods across the country, for three flood return periods, three future time-slices and four emissions scenarios. An accompanying web-tool provides a convenient way to explore the large amount of data produced. Consideration is now being given to how to use the latest work to update guidance on climate change and flood peaks, including a workshop held to gather stakeholder views.

1. Introduction

One of the ways in which climate change may particularly impact on society and the natural environment is through changes in river flows, especially extreme high or low flows. Floods are a significant risk globally, and the potential for climate change to increase the magnitude and frequency of flood events is a major concern (Klijn et al., 2015). The few global studies available suggest that flood hazard will increase over about half the globe, but with significant spatial variability (Jiménez Cisneros et al., 2014). In Britain, the general conclusion is that flooding is likely to increase in future (Bell et al., 2012, 2016; Kay et al., 2015; Collet et al., 2018b). Indeed, there is some evidence that recent flood events have already been influenced by climate change (Kay et al., 2011, 2018). Thus in Britain there is specific guidance available to both flood management authorities and local planners, which aims to help them allow for the potential impacts of climate change when managing flood risk (Reynard et al., 2017).

Often, data from climate models are used to drive hydrological models to assess potential impacts on river flows (e.g. Roudier et al.,

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2016; Arnell and Gosling, 2016; Bell et al., 2016); the so-called top-down approach. However, the increasing availability of large climate model ensembles makes the impact modelling process more time-consuming, and it needs to be repeated whenever new climate projections are produced. A number of studies have instead taken a bottom-up, sensitivity-based approach to impact assessment (e.g. Wetterhall et al., 2011; Bastola et al., 2011; Whateley et al., 2014; Culley et al., 2016; Fronzek et al., 2019; Sauquet et al., 2019). Such an approach typically produces so-called response surfaces, illustrating the sensitivity of a certain impact measure to a plausible range of climatic changes. Response surfaces can then be readily combined with climate projections to estimate potential future impacts, even for large ensembles.

Prudhomme et al. (2010) developed a sensitivity framework for estimating the impacts of climate change on flood flows in Great Britain. This was used to model 154 catchments, from which nine ‘flood response types’ were identified (Prudhomme et al., 2013a), each with a representative (average) ‘flood response surface’ illustrating the sensitivity of flood peaks to climatic changes (Supplementary Section 1). Prudhomme et al. (2013b) then developed ‘decision trees’, which enabled estimation of a catchment’s flood response type from its physical catchment properties. Uncertainty from this approach was also investigated (Kay et al., 2014c). The decision trees were applied (after minor modification; Kay et al., 2014a) to estimate the flood response type of the 1000+ gauged catchments in England and Wales listed in the National River Flow Archive (NRFA; nrfa.ceh.ac.uk), and improved decision trees were developed and applied for NRFA catchments in Scotland (Kay et al., 2014b). The UKCP09 probabilistic climate projections for river-basin regions (Murphy et al., 2009) were then used, along with the representative flood response surfaces and the number of NRFA catchments of each type in the region, to estimate regional risk (Kay et al., 2014a, 2014b). The existing guidance on climate change allowances for peak river flows in Britain is based on the above research (Reynard et al., 2017; EA, 2016a, 2016b).

One limitation was that the decision trees could not be applied to estimate the response type of ungauged catchments (as one of the properties found to be useful is only readily available for gauged catchments), meaning that location-specific impact estimates were only possible for gauged catchments. Thus the guidance subsequently derived for flood management authorities and flood risk assessments in England (EA 2016a,b) only provided regional average allowances, as did guidance similarly derived by the devolved administrations for Wales (Welsh Government, 2016, 2017) and Scotland (SEPA, 2016, 2019). Application of regional average values means that there is a risk of over- or under-adaptation, as the impact of climate change will inevitably vary between catchments within a region (sometimes significantly, depending on the response type of individual catchments relative to the dominance of alternative types within a region) (Reynard et al., 2017; Broderick et al., 2019).

The aim of this study is to enable an update to existing guidance on the potential impacts of climate change on flood peaks in Britain, by

- applying the sensitivity framework with a national-scale grid-based hydrological model, allowing a consistent assessment of the sensitivity of flood peaks to climate change across Great Britain;
- applying the most recent climate change projections for the country, UK Climate Projections 2018 (UKCP18; Lowe et al., 2018), for three future time-slices and four emissions scenarios; and
- providing a web-tool enabling exploration of the large amount of data produced.

The methods are described in Section 2, with results, discussion and conclusions in Sections 3–5. Section 4 includes a short report from a workshop held by the Environment Agency (EA) with the aim of gathering stakeholder views on how best to use the latest work to update guidance on climate change allowances for peak river flows.

2. Methods

2.1. Hydrological model and driving data

The Grid-to-Grid (G2G) is a national-scale runoff-production and routing model that provides estimates of river flows on a 1 km grid across Great Britain (Bell et al., 2009). G2G is used within the Flood Forecasting Centre (England and Wales; Price et al., 2012) and the Scottish Flood Forecasting Service (Maxey et al., 2012), and has been used previously to assess the impact of climate change on floods (Bell et al., 2012, 2016) and droughts (Rudd et al., 2019). The model operates at a 15-minute time-step (for stability of the routing scheme). An optional snow module is applied here (Bell et al., 2016). G2G is able to represent a range of hydrological regimes due to use of spatial datasets of soil, terrain and land cover (Bell et al., 2009), and has been shown to perform well for a wide range of catchments across GB (Bell et al., 2009, 2016; Rudd et al., 2017; Formetta et al., 2018), particularly those with a relatively natural flow regime; the river flow estimates produced by the model are natural flows and do not take into account artificial influences like surface or groundwater abstractions.

G2G requires gridded time series of precipitation and potential evaporation (PE), plus temperature (T) for the snow module. Daily 1 km precipitation, from CEH-GEAR (CEH Gridded Estimates of Areal Rainfall; Tanguy et al., 2016), are divided equally over each time step. Monthly 40 km estimates of PE for short grass, from MORECS (Met Office Rainfall and Evaporation Calculation System; Hough and Jones, 1997), are copied to each of the corresponding 1 km grid boxes of the hydrological model grid and divided equally over each time step. Daily 5 km minimum and maximum T (Perry et al., 2009), are interpolated through the day using a sine curve and downscaled to 1 km using a lapse rate (0.0059 °C/m) and elevation data from the IHDTM (Integrated Hydrological Digital Terrain Model; Morris and Flavin, 1990).

While the model simulates flows for every 1 km grid cell, the threshold area for use of model outputs is here set at 100 km^2; no results are output for 1 km grid cells with catchment drainage areas below this threshold, as it is considered that the results will not be reliable for smaller catchments given the daily temporal resolution of the driving precipitation data. The modelling thus covers Great Britain excluding smaller islands where catchments are too small to be included. Hereafter, 1 km grid cells with catchment areas of at least 100 km^2 are termed 1 km river cells.

2.2. The sensitivity framework: definition

The sensitivity framework approach to climate impacts involves the definition of a sensitivity domain comprising a large number of plausible, typically regularly-spaced, scenarios of climatic change. Modelling is then used to define the change in a given indicator for each scenario of the sensitivity domain, producing a 'response surface' (e.g. Wetterhall et al., 2011; Bastola et al., 2011; Broderick et al., 2019).

The sensitivity domain applied here is essentially that developed in Prudhomme et al. (2010). It uses a single-harmonic function to represent the monthly pattern of changes in precipitation and temperature, allowing the dimensionality of the domain to be greatly

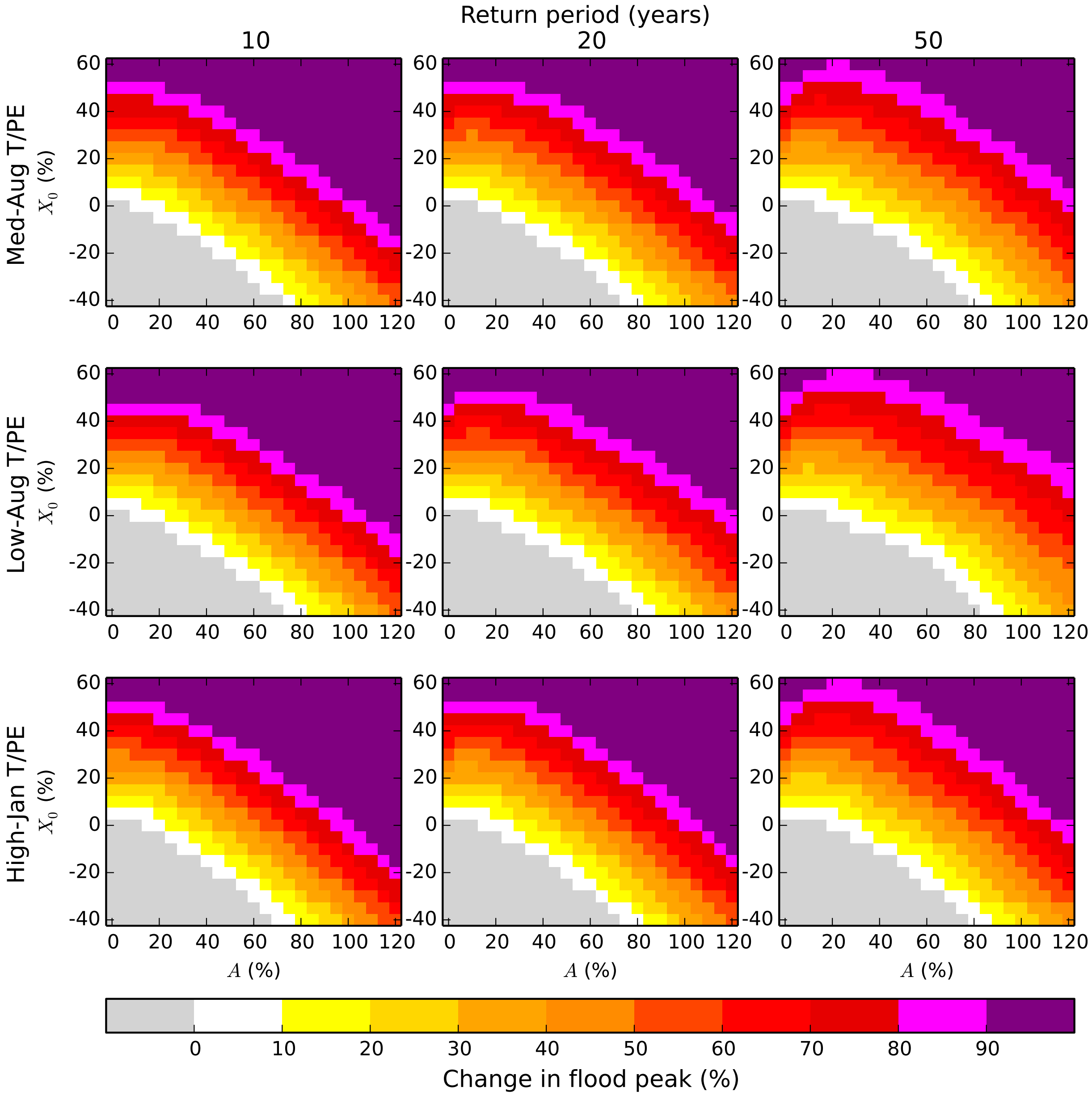


Fig. 1. Example set of flood response surfaces for a single 1 km river cell. Response surfaces are shown for three return periods (10, 20 and 50 years; left to right) and three T/PE scenarios (Medium-August, Low-August and High-January; top to bottom), with annual mean change X_0 on the y-axis and seasonal amplitude A on the x-axis (see equation (1)).

reduced while maintaining a seasonal variation. The function is given by

$$X(t) = X_0 + A\cos[2\pi(t - \Phi)/12] \tag{1}$$

with $X(t)$ change for month t, annual mean change X_0, seasonal amplitude A (height of peak above mean) and phase Φ (month of peak). For precipitation, the phase Φ was set to 1 (January), so the sensitivity domain involved only two dimensions of precipitation change (X_0 and A), each varied in 5% increments between minimum and maximum values (-40% to $+60\%$ for X_0 and 0% to 120% for A). Temperature changes were treated independently and only eight single-harmonic scenarios were used (Supplementary Section 2.1), as floods in Britain are much less sensitive to temperature than precipitation change (Prudhomme et al., 2013a). Monthly PE changes were derived from monthly temperature changes using the Central England temperature series and the temperature-based PE formula of Oudin et al. (2005). This gave a total of 4200 scenarios in the sensitivity domain; 525 precipitation scenarios for each of 8 T/PE scenarios. The same 525 precipitation scenarios are applied here but, due to computing limitations, only 3 of the 8 T/PE scenarios are applied; the selection is based on consistency with UKCP18 projections and coverage of the variation in response types between the 8 T/PE scenarios of Prudhomme et al. (2010) (Supplementary Section 2.1).

The climatic changes given by the sensitivity domain are then applied to baseline climate time series (Section 2.1) using the change factor method, to provide adjusted driving data for the hydrological model. The change factor method involves the application of monthly changes in a variable to a baseline time series for that variable. The monthly change factors are applied equally to each day of the relevant month, with percentage changes for precipitation and PE, and absolute changes for temperature. The baseline period is set to 1961–2001 (40 water-years).

2.3. *The sensitivity framework: application with G2G*

G2G is run with the baseline driving data (Section 2.1), and with the baseline data adjusted using each precipitation scenario of the sensitivity domain (525) with each of the three T/PE scenarios of the sensitivity domain (Section 2.2); 1576 runs in total. For each run, 1 km grids of the annual maxima (AM) of daily mean flows are saved, for each water-year (October-September).

For each 1 km river cell and for each model run, a flood frequency curve is fitted to the 40 AM, using L-moments and the generalised logistic distribution (Robson and Reed, 1999). The peak flows with return periods of 10, 20 and 50 years are then estimated, and changes in these peak flows between the baseline run and each scenario run are determined. This provides a set of 2-d response surfaces for each 1 km river cell. Each response surface illustrates the percentage change in flood peaks (shown using a colour scale) for the 525 precipitation scenarios (21 annual mean changes X_0 on the y-axis by 25 seasonal amplitudes A on the x-axis), with separate surfaces for each of the three return periods and three T/PE scenarios (Fig. 1).

2.4. *Analysis of response surfaces and types*

It is useful for analysis purposes to classify the modelled response surfaces for 1 km river cells into response types. This classification is based on the nine response types derived by Prudhomme et al. (2013a) (Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive) and their representative response surfaces; the Neutral type shows peak flow changes similar to the precipitation changes, while Damped types shows peak flow changes generally smaller than the precipitation changes, Enhanced types shows peak flow changes often larger than the precipitation changes, and the Mixed and Sensitive types show more variable peak flow changes (Supplementary Section 1). The classification is also useful to enable inclusion of uncertainty allowances (Section 2.7).

Classification is done by comparing each modelled response surface with each of the nine representative response surfaces (for a given return period, and for the main part of the response surface; $A \leq 80$) and selecting the response type for which the root mean squared difference (rmsd) is the smallest (note that rmsd was also the similarity measure used by the clustering algorithm applied by Prudhomme et al., 2013a to delineate the response types). The results of the response surface classification are presented in Section 3.1.

The rmsd values, along with Taylor diagrams, were also used to check whether there were any modelled response surfaces significantly different from all nine of the representative response surfaces, as these may indicate the presence of new response types not seen in the previous catchment-based modelling. The analysis (not shown) suggests that there are no completely new response types.

2.5. *The climate change projections*

Similar to UKCP09, UKCP18 provides probabilistic projections, consisting of N sets of changes in a number of climate variables (where N is 3000 for UKCP18 but was 10000 for UKCP09). Both are available for river-basin regions (Supplementary Section 2.2). UKCP18 uses four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, 8.5; van Vuuren et al., 2011) as well as SRES A1B emissions (IPCC, 2000), whereas UKCP09 only used SRES emissions. The UKCP18 data are available as time-slice mean changes for each month from three different baseline periods. The river-basin region data (Met Office Hadley Centre, 2018) are used here as time-slice mean changes from a 1961–1990 baseline for the same three non-overlapping future 30-year time-slices used for UKCP09—2020s (2010–2039), 2050s (2040–2069), 2080s (2070–2099)—and for each emissions scenario (with SRES A1B only used for comparison with UKCP09).

The UKCP18 probabilistic projections present a broad range of potential future climate changes, and the relative likelihoods within these ranges, consistent with information from existing climate model ensembles plus the effects of natural climate variability. But they are dependent on both the input data and choices made within the statistical methodology applied, and are not fully spatially and temporal coherent (Murphy et al. 2018).

2.6. *Application of climate change projections*

The probabilistic climate change projections are applied by overlaying on the modelled response surfaces for each 1 km river cell, and extracting the change in flood peaks corresponding to each projection.

To do the overlaying, a single-harmonic function (Section 2.2) is fitted to each set of monthly precipitation changes for the required region, emissions scenario and time-slice. Two precipitation harmonic parameters (mean X_0 and amplitude A) determine the position of each projection on the sensitivity domain, with the phase Φ of the precipitation harmonic ignored as the response surfaces assume a peak change in January. Checks were performed to ensure the sensitivity domain extents and assumptions for precipitation changes are valid for the UKCP18 projections (Supplementary Section 2.3.1).

The impact corresponding to each climate change projection is then extracted, to produce a cumulative distribution function (cdf) of the percentage changes in flood peaks resulting from the set of climate projections. The extraction uses bi-linear interpolation of the response surface values (only available at 5%x5% intervals; Section 2.2) to give a smoother cdf. Fig. 2 presents an example showing a set of climate projections overlaid on a modelled response surface, and the resulting cdf of change in flood peaks. Any required percentiles of change in flood peaks can be read from the cdf. Sets of impacts are presented in Section 3.2, comparing impacts from UKCP18 projections across time-slices (2020s, 2050s, 2080s) and emissions scenarios (RCP2.6, 4.5, 6.0, 8.5). Only impacts from 20-year return period flood peaks are shown here.

Only the precipitation projections are used for overlaying; variations in temperature changes are much less important for changes in flood peaks in Britain (Prudhomme et al., 2013a), so the results presented here (and in the web-tool) only use the response surfaces for the Medium-August T/PE scenario – the most consistent with UKCP18 projections (Supplementary Section 2.3.2).

Note that application of climate change projections derived as changes from a particular baseline period (1961–1990; Section 2.5) with response surfaces derived from a slightly different (but overlapping) baseline period (1961–2001; Section 2.2), is not strictly consistent. However, the use of a longer baseline in the hydrological modelling was deemed necessary to allow estimation of changes in higher return period peak flows, whereas shorter baselines are preferable for the climate change projections in order to maximise the climate change signal and so that any changes during the baseline period itself can be considered negligible.

2.7. *Sensitivity framework uncertainty*

In the previous work, two main sources of uncertainty were assessed and incorporated in the results (Reynard et al., 2009; Kay et al., 2014a, 2014b). These were

- representation of catchment response surfaces by a set of response types each with representative (average) response surfaces (i.e. there were not modelled response surfaces for every catchment across Britain; Section 1), and

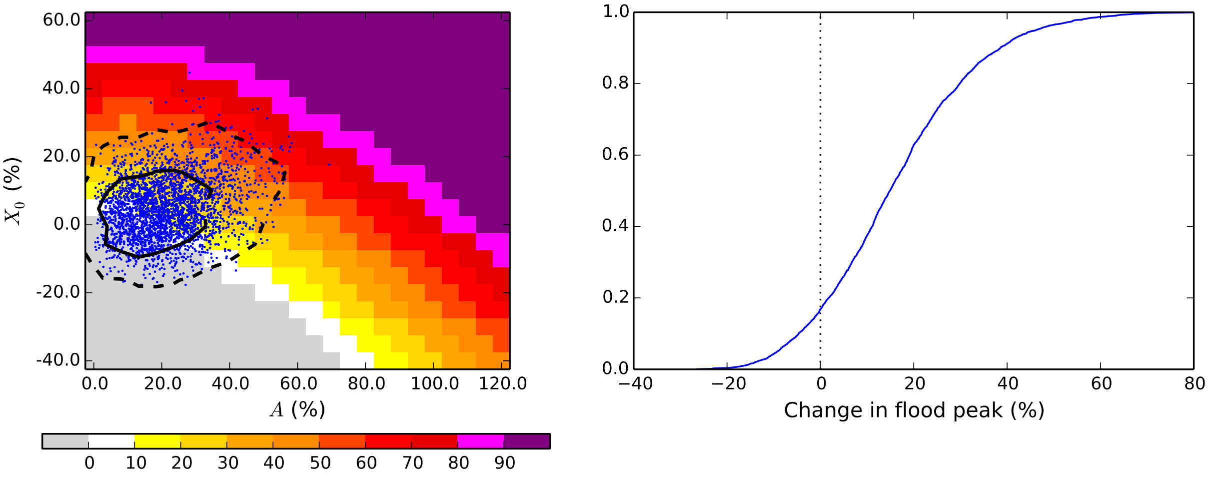


Fig. 2. Example of overlaying UKCP18 climate change projections on a modelled response surface (left). Blue dots show each of the 3000 projections for one river-basin region (North Highland), emissions scenario (RCP8.5) and future time-slice (2080s). The black contours delineate densities of 5 and 50 projections per 5%x5% sensitivity domain square. Also shown is the cdf of the percentage changes in flood peaks extracted from the response surface using the projections (right). In this case the percentage changes are for 20-year return period flood peaks for a location in north-west Scotland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

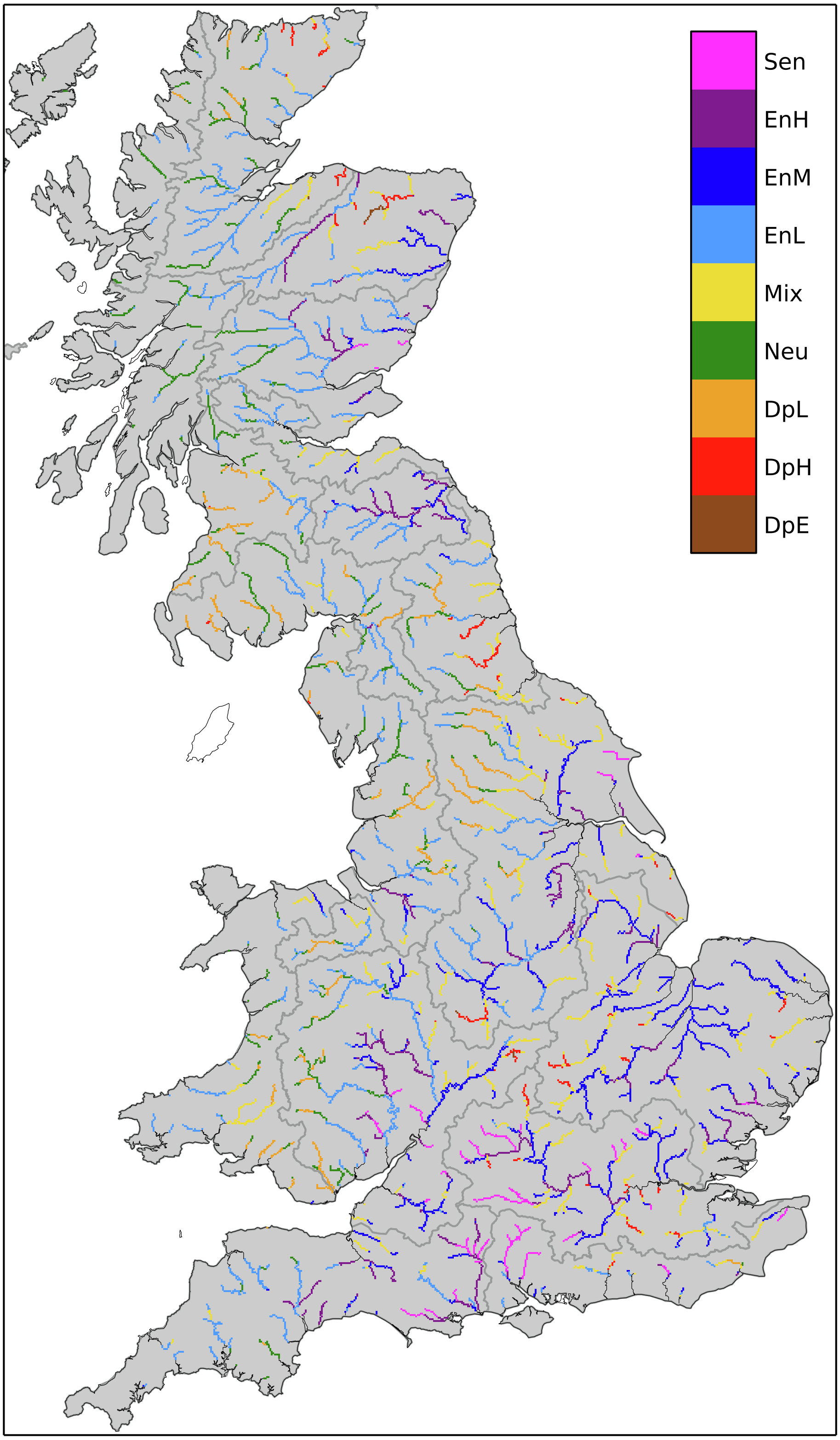


Fig. 3. Map showing the response type of the modelled response surface for each 1 km river cell in GB, for changes in 20-year return period flood peaks using the Medium-August T/PE scenario. The response types are Damped-Extreme (DpE), Damped-High (DpH), Damped-Low (DpL), Neutral (Neu), Mixed (Mix), Enhanced-Low (EnL), Enhanced-Medium (EnM), Enhanced-High (EnH), Sensitive (Sen) – see Supplementary Section 1.

- the assumptions/simplifications necessary to develop/implement the sensitivity-based approach.

The former was addressed by the use of standard deviation surfaces alongside the representative response surfaces, but the availability here of modelled response surfaces for every 1 km river cell means they are no longer required. However, uncertainty from the sensitivity framework assumptions is still present and can be addressed as previously; by adding extra uncertainty allowances derived for each response type and return period (Supplementary Section 2.4).

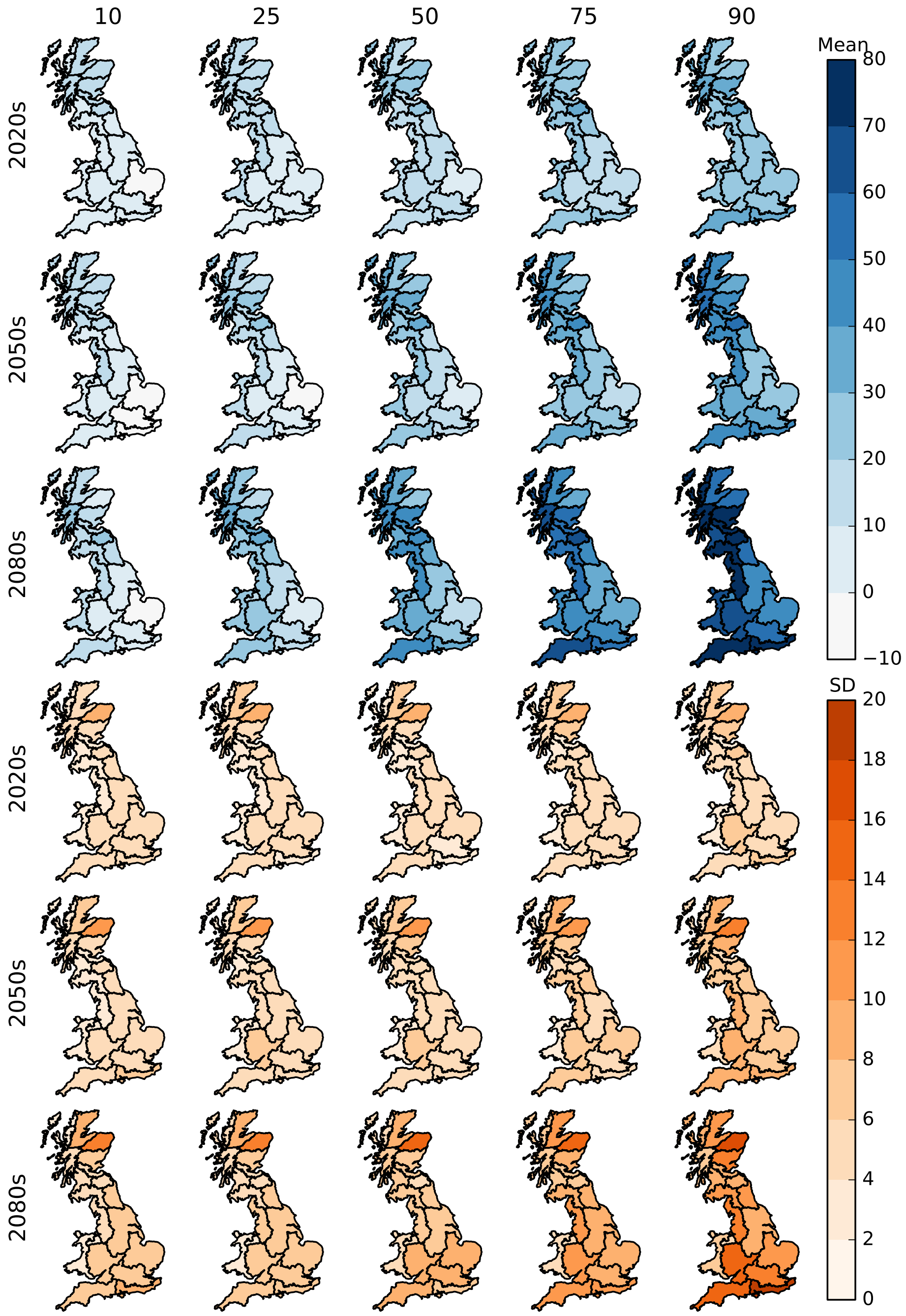


Fig. 4. Maps showing the regional means (top) and standard deviations (SD; bottom) of five percentiles of percentage change in 20-year return period flood peaks (10th, 25th, 50th, 75th and 90th; left to right) for three time-slices (2020s, 2050s and 2080s) under RCP8.5 emissions (Medium-August T/PE scenario).

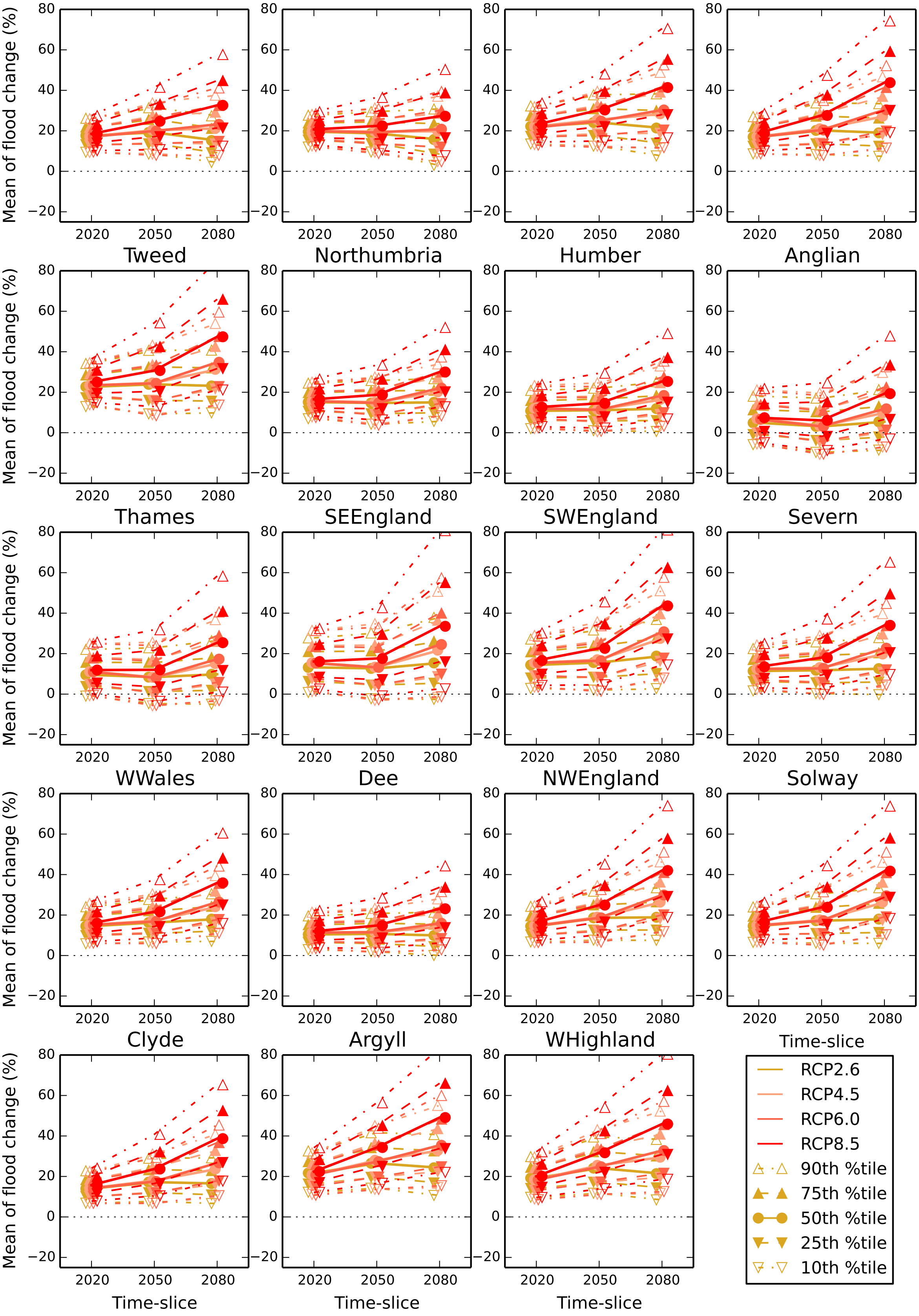

Mean of flood change (%)
80
60
40
20
0
−20
2020
2050
2080
Tweed
Northumbria
Humber
Anglian
Thames
SEEngland
SWEngland
Severn
WWales
Dee
NWEngland
Solway
Clyde
Argyll
WHighland
Time-slice
RCP2.6
RCP4.5
RCP6.0
RCP8.5
90th %tile
75th %tile
50th %tile
25th %tile
10th %tile

Fig. 5. Plots comparing the regional means of changes in 20-year return period flood peaks using UKCP18 probabilistic projections for three time-slices (2020s, 2050s and 2080s) under four emissions scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) (Medium-August T/PE scenario). Each plot shows five percentiles of change (10th, 25th, 50th, 75th and 90th).

(caption on next page)

3. Results

3.1. Response types

The G2G modelled response types are mapped in Fig. 3 for changes in 20-year return period flood peaks under the Medium-August T/PE scenario. There is significant variability in response types across the country, but with typically more Neutral/Damped types in the north/west and more Enhanced/Sensitive types in the south/east, while the Mixed type can be seen in almost all parts of the country (similar patterns as for the previous work; Reynard et al., 2009; Prudhomme et al., 2013a). The variation between river-basin regions can be seen in bar-charts summarising the balance of response types in each region (Supplementary Section 3.1). Response type maps for other return periods and T/PE scenarios (not shown) are generally similar, with high Spearman's rank correlations (Supplementary Section 3.1).

3.2. Impacts from the UKCP18 projections

An example map of flood peak changes for 1 km river cells shows significant spatial variation, with impacts typically higher in the west than the east (Supplementary Section 3.2). However, the scale required for good visualisation of 1 km rivers means that it is not possible to show all combinations of percentile of change, time-slice, emissions scenario and return period in this way. Here, some results are summarised using the regional mean and standard deviation of the change in flood peaks, for each of the 19 UKCP18 river basin regions. Note that all subsequent results include the extra uncertainty allowances (Section 2.7).

Maps of regional means for five percentiles of change in 20-year return period flood peaks, for three future time-slices under RCP8.5 emissions (Fig. 4 top), generally show increases in flood peaks, which are typically higher for later time-slices. The maps show clear differences between regions, with regional mean changes generally smaller in the south-east than in the north-west for the lower percentiles, although the differences become less pronounced for higher percentiles. Some regions show decreases in flood peaks for lower percentiles, and these can either increase or decrease for later time-slices.

The maps of regional standard deviations (SDs) (Fig. 4 bottom) generally show higher SD for later time-slices and higher percentiles, but with less clear spatial variation than for the regional means. However, North East Scotland shows higher SD for all percentiles and time-slices, and southern Britain shows higher SD for the 90th percentile in the 2080s. These regional differences are related to the range of response types in each region; a region with both damped and enhanced/sensitive types will have a higher SD, especially for the higher percentile changes and when the climate projections cover more of the sensitivity domain.

Plots comparing the regional means of changes in flood peaks across three time-slices for the four emissions scenarios (Fig. 5) show that the effect of climate modelling uncertainty (i.e. the percentile range for a given emission scenario) is greater for later time-slices, as is the effect of emissions scenario uncertainty (i.e. the range covered by different emissions scenarios for a given percentile of change).

A comparison of results using the new grid-based hydrological modelling with UKCP18 and UKCP09 projections (A1B emissions) shows relatively little difference, especially for the 50th percentile impact, although the UKCP18 range is often wider than from UKCP09 (Supplementary Section 3.3.1). The impacts derived using UKCP18 projections and national-scale grid-based hydrological modelling are similar to the existing guidance (based on UKCP09 projections and catchment-based modelling plus decision trees), although with differences in some eastern regions probably related to the previous use of decision trees to estimate response types of gauged catchments (Supplementary Section 3.3.2).

4. Discussion

By applying the sensitivity framework of Prudhomme et al. (2010) with a national-scale grid-based hydrological model, this study has provided a nationally consistent assessment of the sensitivity of flood peaks across Great Britain to climatic changes (Section 3.1). It has also applied the most recent climate projections, UK Climate Projections 2018 (UKCP18), to produce an up-to-date assessment of the potential impacts of climate change on flood peaks across the country (Section 3.2). Application of a grid-based model provides modelled response surfaces for every 1 km river cell (catchment area $\geq$ 100 km^2) across the country. This removes a number of steps from the previous approach (use of average response surfaces for each of nine response types, and decision trees to estimate a catchment's response type from its catchment properties), thus removing the additional sources of uncertainty resulting from those steps.

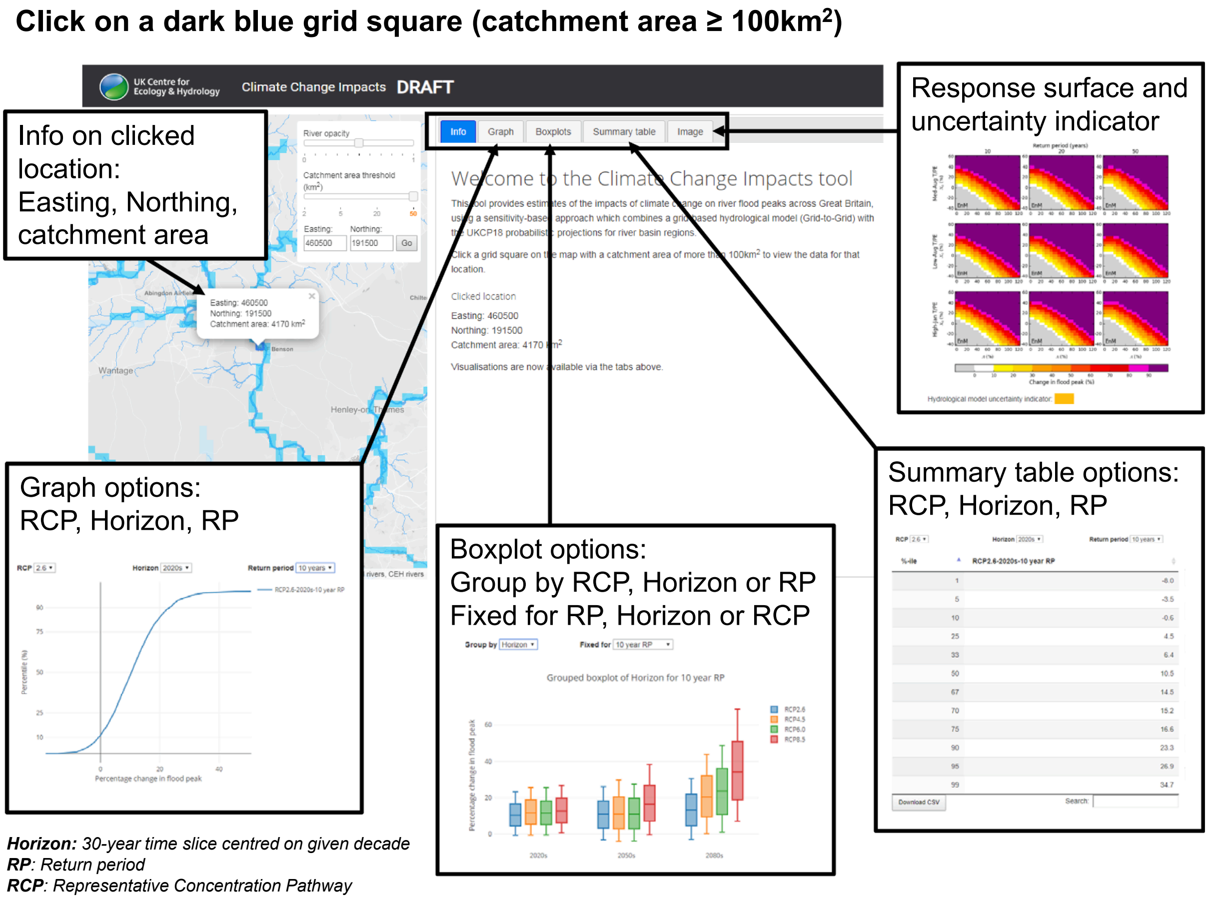
The UKCP18 probabilistic climate projections are applied by overlaying them on the modelled response surfaces, to provide probabilistic impacts on 10-, 20- and 50-year return period flood peaks for any 1 km river cell (gauged or ungauged), for a range of future time-slices and emissions scenarios. Thus impact ranges are location-specific, in contrast to previous results which provided regional average impact ranges. The range of impact uncertainty resulting from overlaid climate projections is large, as the climate projections cover a broad range of changes.

4.1. Web-tool

The overall method produces a considerable amount of data, due to the high number of 1 km river cells in GB (over 12000), the large ensembles of climate projections (3000 for UKCP18), the number of combinations of future time-slice (2020s, 2050s and 2080s) and emissions scenario (RCP2.6, 4.5, 6.0 and 8.5), the number of flood return periods included (10-, 20- and 50-year), and the use of three temperature / potential evaporation (T/PE) scenarios. A prototype interactive web-tool has been developed to allow exploration of the results. The web-tool is not yet publically available, but has undergone some testing with stakeholders (Section 4.2).

A 1 km river cell (catchment area $\geq$ 100 km^2) can be selected from a map of Great Britain, and then corresponding information and figures are shown on five tabs (Fig. 6):

1. **Info tab** – provides a brief introduction to the tool, with instructions on selecting a grid square with a catchment area $\geq$ 100 km^2. It then gives the Easting, Northing and catchment area of the selected river cell (or a message asking the user to choose an alternative cell, if a cell without data has been selected).
2. **Graph tab** – shows the cumulative distribution function of the percentage change in flood peaks for the selected river cell, for a choice of four emissions scenarios (RCP2.6, 4.5, 6.0, 8.5), three time horizons (2020s, 2050s, 2080s) and three return periods (10-, 20- and 50-years).
3. **Boxplot tab** – allows comparison of the range of percentage changes in flood peaks for the selected river cell, for different emissions scenarios, time horizons and return periods.
4. **Summary Table tab** – provides a data table with key percentiles of change in flood peaks for the selected river cell, which can be downloaded as a .csv file.
5. **Image tab** – shows the modelled response surfaces (with response types) for the selected river cell, for the three return periods and three T/PE scenarios. A hydrological model uncertainty indicator (green/amber/red) for the selected river cell is also shown.



Click on a dark blue grid square (catchment area ≥ 100km^2)

Info on clicked location: Easting, Northing, catchment area

Response surface and uncertainty indicator

Graph options: RCP, Horizon, RP

Boxplot options: Group by RCP, Horizon or RP Fixed for RP, Horizon or RCP

Summary table options: RCP, Horizon, RP

Welcome to the Climate Change Impacts tool

This tool provides estimates of the impacts of climate change on river flood peaks across Great Britain, using a sensitivity-based approach which combines a grid-based hydrological model (Grid-to-Grid) with the UKCP18 probabilistic projections for river basin regions.

Click a grid square on the map with a catchment area of more than 100km^2 to view the data for that location.

Clicked location

Easting: 460500
Northing: 191500
Catchment area: 4170 km^2

Visualisations are now available via the tabs above.

RCP 2.6 ▾ Horizon 2020s ▾ Return period 10 years ▾

%-ile	RCP2.6-2020s-10 year RP
1	-8.0
5	-3.5
10	-0.6
25	4.5
33	6.4
50	10.5
67	14.5
70	15.2
75	16.6
90	23.3
95	26.9
99	34.7

Horizon: 30-year time slice centred on given decade
***RP**: Return period*
***RCP**: Representative Concentration Pathway*

Fig. 6. Components of the prototype climate change impacts web-tool.

Only the impacts under the Medium-August T/PE scenario are provided via the web-tool, but impacts are provided for all three flood return periods. This means that, if required (for example, to get an idea of the changes that may apply for higher return period flood peaks), a user can investigate whether the impacts on flood peaks at their location of interest seem to vary with return period. The web-tool also only provides the impacts *including* the extra uncertainty allowances (Section 2.7). However, information on the response type of each 1 km river cell is available via the web-tool, so the interested user can apply this information together with Supplementary Table 2 to see what value has been added.

4.2. Towards deriving updated guidance

A workshop was held by the Environment Agency (EA) in December 2019 to gather stakeholder views on how to use the latest research to update guidance on climate change allowances for peak river flows in England (EA, 2016a, 2016b). In particular, the EA wanted opinions on

- Scale: Whether to obtain allowances from the tool directly for each location or provide updated allowances based on river-basins or other 'scaled up' geography. The former option provides allowances that do not 'mask' variability within a river-basin, so reduces the risk of over- or under-adaptation, but identifying the correct allowance is more labour intensive than the current river-basin approach. The latter option would be simpler than using the web-tool, but finding a balance between an easy-to-apply regional scale and the risk of over-/under-adaptation would not be easy.
- Incomplete coverage: How to obtain allowances where there is no information in the web-tool (e.g. catchments with area < 100 km^2).
- Simplicity vs complexity: How to ensure that the approach is pragmatic and reasonable when considering application for FCERM schemes (EA, 2016a), as well as Flood Risk Assessment and Strategic Flood Risk Assessment (EA, 2016b).
- Consequences: What are the likely (intended or unintended) consequences of any choices?

About 20 invitees, representing EA regional staff, local authorities and water-industry consultants, were given a brief overview of the work and a demonstration of the web-tool. Following some initial discussions, invitees were split into three groups, each with a facilitator, and allowed to experiment with the web-tool. Feedback from this participatory session included

- The need for simple, clear instructions on which climate change allowances are required for a location of interest (e.g. prescribing the return period, RCP and percentile) and how to access them (e.g. web-tool user guidance).
- The potential for information on the 100-year return period flood as well as the 50-year return period flood.
- Concerns about how to select the correct 1 km cell (or how to ensure it has been correctly selected by developers submitting a flood risk assessment for a planning application). This could be a particular issue near confluences (where values between neighbouring cells can differ significantly), or where the flood plain extends beyond the 1 km river cells.
- Concerns regarding what allowances should be used in smaller catchments with no directly available data. Options include advice on choosing a downstream cell or a cell on a neighbouring tributary, or the provision of a regional value to use in these circumstances.

The EA are considering the feedback collected, and work is ongoing on updating the guidance on climate change allowances for peak river flows. The updated guidance is expected in the near future.

4.3. Sources of uncertainty

The sensitivity framework developed in Prudhomme et al. (2010), applied here and in Kay et al. (2014a, 2014b), relies on two key methods/assumptions:

1. A single-harmonic (cosine) function representing the monthly pattern of precipitation and temperature changes.
2. The change factor method; monthly (percentage or absolute) changes in a climate variable are applied to a baseline time series of that variable, to produce modified time series.

The former allows the dimensionality of the sensitivity domain to be greatly reduced, making the analysis tractable, and the latter allows the consistent application of the sets of climatic changes represented by the sensitivity domain (Section 2.2). However, the analysis of Kay et al. (2014c), comparing impacts derived from overlaying climate projections on response surfaces with impacts derived from direct top-down modelling, showed that these simplifications led to some underestimation of impacts on flood peaks, which varied by response type. Extra uncertainty allowances (Section 2.7) were designed to correct the mean impact, but no attempt was made to alter the uncertainty ranges, which were typically found to be broader from direct impact modelling.

While use of the change factor method enables consistency of application (Singh et al., 2014; Sauquet et al., 2019), it gives perturbed climate series that are inevitably similar to the baseline in terms of event ordering and relative sizes (Vormoor et al., 2017), and assumes that changes in extremes follow those of the monthly mean (Singh et al., 2014). Kay and Jones (2012) showed that the range of impacts from ensemble projections was broader when full time series methods were employed (i.e. direct use of RCM data or weather generator data) rather than the change factor method, although the median impacts were similar from each method. However, Broderick et al. (2019), who apply a similar sensitivity framework in the Republic of Ireland, note that "…small catchments with a shorter memory and more linear rainfall-runoff response are also more likely to be affected by changing patterns at (sub-)daily scales, particularly for extreme events."

Vormoor et al. (2017) developed a technique to test the influence of temporal sequencing of events on response surfaces. They make a small set of alternative baseline time series by scaling future RCM time series to allow for mean changes, then use each baseline with the change factor method to make a set of alternative response surfaces representing changes in mean, low and high flows. Their analysis of differences in response surfaces suggests that temporal sequencing makes little difference for mean flows, is slightly more important for high flows (mean of annual maxima), but makes the most difference for low flows (mean of 7-day annual minima). However, their sensitivity domain only includes changes in annual mean precipitation and temperature, so the influence of precipitation seasonality changes is included in their alternative response surface range. Here, the single sensitivity domain includes changes in the seasonality of precipitation, hence a lower influence would be expected for remaining temporal sequencing effects. Vormoor et al. (2017) also only modelled one catchment in Norway, with a mixed snowmelt/rainfall regime; the effect in Britain could be quite different.

Keller et al. (2018) developed this type of analysis further by looking at how response surfaces of changes in the mean annual maximum flood differed between three methods, for a catchment in Switzerland. The three methods were i) the RCM-scaling approach of Vormoor et al. (2017), ii) weather generator data and quantile mapping, and iii) incorporating changes in precipitation seasonality using a harmonic function (as applied here). The results showed that changes in annual maxima were typically larger from the former two methods than the latter. They recommend combining several sensitivity-based methods, as each has strengths and weaknesses, but the alternative methods are more reliant on RCM data to define certain aspects/parameters, making them less general for subsequent application.

Weather generator data can be used within a sensitivity-based approach applied with catchment-based models, but application with a national-scale model is difficult as weather generators are typically designed for single-site (or occasionally multi-site) application rather than to produce spatially coherent gridded data across large regions (Peleg et al., 2017). Furthermore, it is not straightforward to assess a priori what parameters of a weather generator should be modified to produce time series with the required statistics to represent a sensitivity domain, although inverse approaches may help (Guo et al., 2017; Culley et al., 2019). Also, if an ensemble of weather generator runs (or one very long run) is used for each point on the sensitivity domain (e.g. Steinschneider et al., 2015; Kim et al., 2018; Broderick et al., 2019) then this considerably extends the hydrological model run time required, or if a single weather generator run is used for each point (e.g. Bastola et al., 2011; Whateley et al., 2014) then this is likely to produce 'noisy' response surfaces due to natural variability between runs at different points.

Although it is typically considered that the climate models provide the main source of uncertainty when projecting future changes in river flows, especially high flows (e.g. Gosling et al., 2011; Kay et al., 2009), recent research has shown that hydrological model uncertainty can still be significant (Steinschneider et al., 2015; Broderick et al., 2019). Here, an investigation of response surfaces generated for a limited set of catchments using different hydrological models (not shown) was used to provide a simple green-amber-red indicator of possible hydrological model uncertainty, which is provided on a tab in the web-tool.

Another potential source of uncertainty is the time-step of the analysed river flows. Here, the flood frequency analysis was based on annual maxima of simulated daily mean flows (Section 2.3), but it is possible that sub-daily peak flows may respond differently to climate change than daily peak flows. Kim et al. (2018) used a sensitivity-based approach for a 484 km^2 catchment in South Korea and found that use of daily peak flows underestimated the effect of climate change compared to use of hourly peak flows.

An important point is that, while there is substantial uncertainty associated with the potential impacts of climate change on flood peaks, derived from a range of sources, the corresponding uncertainty in flood extents could be less due to physical and topographic constraints (Collet et al., 2018a).

5. Conclusions

The application of the sensitivity framework with a national-scale grid-based hydrological model, and overlaying the resulting response surfaces with the UKCP18 climate projections, has provided a nationally consistent and up-to-date assessment of the sensitivity and vulnerability of flood peaks across Great Britain to climate change.

Further work could include the options below, but most would significantly increase the computational demands of the sensitivity-based approach. Initial analyses could use a small but representative sample of catchments across Britain, with a catchment-based hydrological model (or models), to assess the relative importance of different factors for estimating the impacts of climate change on flood peaks.

- Assess the importance of temporal sequencing within the applied sensitivity framework: Adapt the RCM-scaling approach of Vormoor et al. (2017) to allow for the seasonality changes included in the sensitivity domain applied here.
- Apply multiple different sensitivity-based methods: Apply a range of different ways to derive time series corresponding to each point of the sensitivity domain (e.g. RCM-scaling or a weather generator, as in Keller et al. 2018).
- Develop a more complex sensitivity domain: Perhaps introduce additional dimensions, e.g. allowing precipitation changes to vary with intensity. This may be particularly important to capture intensification of summer storms (Kendon et al., 2014), but presentation of the response surfaces would be more difficult.
- Further investigate the potential level of hydrological modelling uncertainty: Apply a range of hydrological models and assess differences in modelled response surfaces versus differences in model structure and baseline performance.

- Use baseline hourly rainfall data and look at changes in hourly peak flows: A 1 km gridded hourly precipitation dataset has recently been produced, covering 1990–2014 (CEH-GEAR1hr; Lewis et al., 2018). Although it covers a much shorter period than daily CEH-GEAR, it could be used to investigate potential differences in response of hourly versus daily peak flows in different types of catchment or different parts of the country.
- Extend the assessment to flood damages: Assess the relative contribution of various sources of uncertainty to estimates of flood damage, not just flood peaks, as done by Keller et al. (2019) for a catchment in Switzerland.
- Extend the assessment to include land-use change: The hydrological modelling system could be adjusted to allow estimation of the impacts of land-use change as well as climate change (e.g. Singh et al., 2014). Sensitivity-based approaches can also be applied with other models and include a range of climate, land-use and socio-economic changes to investigate a wide range of impacts (e.g. Fronzek et al., 2019).

Implementing some of the above may provide more information on the robustness of the results to various assumptions/simplifications, and guidance on the prioritisation of future developments. While there is always more research that could be done, the work reported here provides significantly more information on the potential impacts of climate change on peak flows in Britain than was available previously. The next step is to decide how to incorporate this information into updates of the existing guidance on climate change allowances.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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