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Translating UKCP09: FCERM-specific projections

Report – SC080004/SR/FCERM Projections

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Miranda Kavanagh

Director of Evidence

Executive summary

The UK Climate Projections, UKCP09, represent a step-change in the availability of climate change information to UK decision makers. The increased sophistication of the science has made much more information available on climate change projections, bringing with it added challenges in ensuring that the projections are used appropriately by staff in the Environment Agency and its partner organisations.

This report presents climate change impacts projections for peak flows in river catchments, making use of UKCP09 information. The work reported here builds on and extends the scenario-neutral approach to understanding the impacts of climate change on flood flows developed in the Defra research project FD2020. The analysis makes use of the UKCP09 Sampled Data outputs and compares this with modelling approaches based on other UKCP09 products.

Whilst confirming the value of the scenario-neutral sensitivity approach, the work also illustrates the scope for using other approaches with a range of UKCP09 outputs. Although the results are most directly applicable to flood risk management, this report also explains different approaches to using some of the more complex UKCP09 products. It is potentially useful for anyone thinking about modelling other aspects of river flow, such as mean or low flows, and probably other variables that require an intermediate impacts model to understand the impacts of projected climate change.

The report forms a part of a set of products developed under the Environment Agency Evidence Project SC080004 *Translating UKCP09*. The project aims to help the Environment Agency to use UKCP09 appropriately and consistently, to support better decision making and to enable the Environment Agency and its partners to communicate climate change effectively with external stakeholders. The methods and results presented in this document include reference to outputs from UKCP09 that are discussed further in other material produced as part of SC080004, including user guidance, training materials, analysis of key messages about the UKCP09 projections and a set of case studies.

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1 Introduction

1.1 Context

This report forms a part of a set of products developed under the Environment Agency Evidence Project SC080004 *Translating UKCP09*. The project aims to help staff to use UKCP09 appropriately and consistently, to support better decision making and to enable the Environment Agency and its partners to communicate climate change effectively with external stakeholders.

The methods and results presented in this document include reference to outputs from UKCP09 that are discussed further in other material produced as part of SC080004, including user guidance, training materials, analysis of key messages about the UKCP09 projections and a set of case studies.

1.2 Changes in flood risk

1.2.1 Historical trends

The UKCP09 report on recent trends in the UK climate (Jenkins *et al.* 2008) concludes that there has been sea level rise around the UK over the past century, and that over the last half century more of the winter rain has fallen during intense wet spells. Seasonal rainfall is highly variable. It seems to have decreased in summer and increased in winter, although winter amounts have changed little in the last 50 years and annual totals appear not to have changed significantly since records began in 1766.

Some of the changes in rainfall might reflect natural variation; however the broad trends are in line with projections from climate models (Environment Agency, 2011). There is enough confidence in the climate modelling for the Environment Agency to say that we should plan for changes in flood risk. Greenhouse gas levels in the atmosphere are likely to cause higher winter rainfall in future. Past greenhouse gas (GHG) emissions mean some climate change is inevitable in the next 20 to 30 years.

It is difficult to detect the influence of climate change on high river flows in part because of background variability and also because of the influence of other factors, in particular catchment land management. In an attempt to control for these factors, Hannaford and Marsh (2008) applied trend tests to high-flow and flood records from a network of catchments in the UK that were judged to be relatively undisturbed by anthropogenic influences. The study found evidence of more protracted high flow conditions in northern and western areas from the 1960s or 1970s up to 2003, but trends in flood magnitude were less prevalent. Few compelling trends were found in the English lowlands. The observed trends seemed consistent with some climate change projections for extreme rainfall. When placed in the context of longer hydrometric records, there was little evidence for trend in the longer time series, consistent with the findings of Robson (2002), which found no statistical evidence of a long-term trend in flooding over the last 80 to 120 years. It is important to note that this evidence does not rule out the possibility that climate change has affected river flooding, or that it could do so in future. Rather the evidence from direct analysis of flood records does not provide proof of a long-term trend when set against the variability of river flow records.

Detection of changes in flood-producing weather related to long-term climate change is also difficult because of the inherent background variability in the data. Even so, Fowler and Wilby (2010) have concluded from analysis of an ensemble of climate model outputs that for 10-day accumulations of winter precipitation at a 1/10 annual probability level, formal detection of change (in the sense of statistical tests) could be possible by the 2020s if the climate follows model projections. For other conditions, such as shorter duration summer ‘flash flood’ storms, detection is much more uncertain and so an adaptation to changes in risk will have to be planned without formal knowledge that change is already occurring.

1.2.2 Risk management

Flood risk is generally considered as a combination of the probability and consequences of the flooding. This report is concerned fluvial flood risk, and more specifically potential changes in the frequency, or probability, of high river flows that could cause flooding. It does not consider the consequences of flooding in terms of measures such as flooded area, economic damages or social and health impacts. These factors may also change in the future, depending on development patterns and how river systems are managed, and hence affect society’s vulnerability to flooding. In order to manage flood risk now and for the future, climate change is therefore considered within strategies and plans for flood risk management.

Given the substantial uncertainty about future climate, flood risk management plans and decisions may not deliver the most effective adaptation if they are based on a narrow projection of future flood risk. Instead it is important to consider the range of plausible futures, especially for decisions that are long lived, where there is a high vulnerability to flooding or the options are very expensive. For the management of fluvial flood risk, there is therefore a need to understand how climate change projections, and the uncertainty in those projections, translate into potential changes in flood flows.

1.3 Projections for peak river flows

This report presents climate change impacts projections for river catchments specific to flood risk management, making use of UKCP09 information. It was produced as part of the Environment Agency evidence project SC080004 *Translating UKCP09*.

The work reported here builds on and extends the scenario-neutral approach to understanding impacts of climate change on flood flows developed in the Defra research project FD2020 (Reynard *et al.* 2009). Rather than simply making a direct, ‘forward’ simulation of the impacts of climate change scenarios, the scenario-neutral FD2020 approach separates the changes in climate variables from the catchment’s response to change. This approach allows for flexibility in how climate change projections, and their uncertainty, are represented. In particular, it is practical to carry out analysis based on the UKCP09 Sampled Data product. The UKCP09 sampled data provides 10,000 equi-probable samples of future climate projections, each of which represents climate change at a single location, for a single emissions scenario and for a single 30-year future time period. Further explanation is given in other reports produced under this project (User Guidance, SC080004/SR/User Guidance, Section 2.13.7).

In this report, the full UKCP09 Sampled Data outputs have been applied within the FD2020 approach. The work also compares other modelling approaches based on the UKCP09 Weather Generator and Regional Climate Model (RCM) outputs.

Whilst confirming the value of the scenario-neutral sensitivity approach, the work also illustrates the scope for using other modelling approaches and some of the technical decisions that have to be made. Although the results are most directly applicable to flood management, this report also explains different approaches to using the more complex of the UKCP09 outputs and as such is useful for anyone thinking about modelling other aspects of river flow, and other variables that require an intermediate impacts model.

2 Demonstration of the application of a range of UKCP09 products to investigate changes in flood peaks

Project FD2020 'Regionalised impacts of climate change on flood flows' (Reynard *et al.* 2009) provided a methodological framework designed to enable the quick estimation of the impact of a set of climate change scenarios on the flood flows of a catchment. This report uses the modelled response patterns for nine of the FD2020 catchments, combined with the UKCP09 Sampled Data, to obtain a probabilistic estimate of the impacts of climate change on flooding at four return periods (2-, 10-, 20- and 50-years). It then compares this set of estimated impacts with those obtained by direct catchment modelling using various UKCP09 products.

Some background to FD2020 is given in Section 2.1. The hydrological model applied and the catchments modelled are presented in Section 2.2, and the methods used with the UKCP09 products are described in Section 2.3. The results are presented and discussed in Section 2.4.

2.1 FD2020 – Background

FD2020 used a scenario-neutral approach, based on a broad sensitivity analysis to determine catchment response to changes in climate. The method separates the climate change that a catchment may be exposed to (the hazard) from the catchment response to changes in the climate (the sensitivity, in terms of change in peak flows). The sensitivity of each of the project's 154 catchments was characterised through the use of a sensitivity framework of changes to the mean and seasonality of precipitation and temperature (Table 2.1) and modelling the response of each catchment within this fixed framework. The framework was chosen to more-than encompass the range of possible changes suggested by climate models available at the time. The modelled response was then presented graphically in a 'response pattern', an example of which is shown in Figure 2.1. By combining current understanding of climate change likelihood (hazard, e.g. from UKCP09) with the vulnerability of a given catchment (response pattern), it is then possible to evaluate the risk of flood flow changes.

Table 2.1 The FD2020 sensitivity framework for changes in precipitation, temperature and PE.

	Phase	Mean annual change	Seasonality	Scenarios
Precipitation	January	-40% to 60%	0 to +120%	All combinations by increments of 5% Total: 525 scenarios
Temperature	January and August	1.5° 2.5° 4.5°	1.2° 0.8° 1.6°	Low-Jan and Low-Aug Medium-Jan and Medium-Aug High-Jan and High-Aug
	None	0.5°; 4.5°	0°	Low-/High-Non-Seasonal (NS) Total: 8 scenarios
Potential evaporation (PE)	One scenario corresponding to each of the temperature scenarios			Total: 8 scenarios

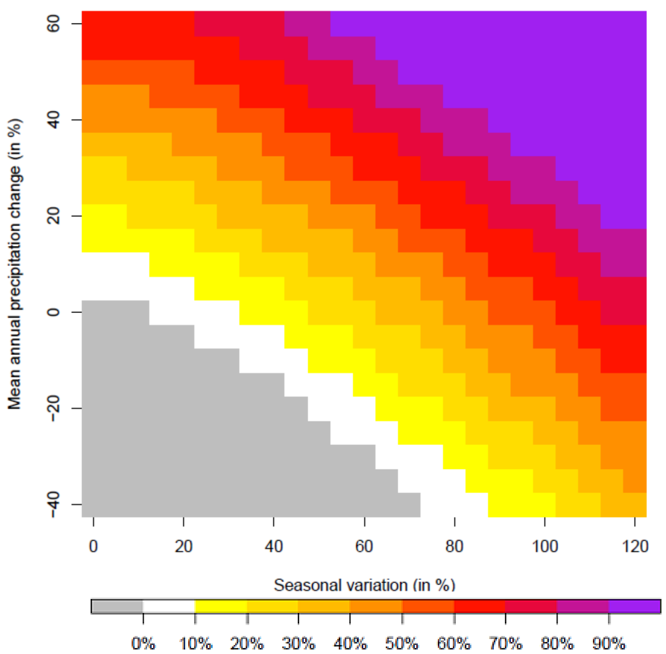


Figure 2.1 Example flood response pattern for changes in 20-year flood peak for the Helmsdale @ Kilphedir with the Medium-Aug temperature/PE scenario (maximum rainfall change in January).

To enable estimation of the risk for unmodelled, or even ungauged, catchments, FD2020 analysed the similarity of the responses of the 154 modelled catchments, and grouped them into nine response types (Figure 2.2), each with a representative (key) response pattern at four return periods (2-, 10-, 20- and 50-years). A subset of these types was then characterised according to catchment properties, enabling the estimation of a catchment's response, and so its risk (when combined with a particular hazard), from its properties. The small number of catchments with a Damped-Extreme type meant that it could not be characterised, and some of the other types were merged at higher return periods, for reasons discussed in Prudhomme *et al.* (2009b). In addition, an uncertainty analysis suggested extra uncertainty allowances, according to response type and return period (Table 2.2).

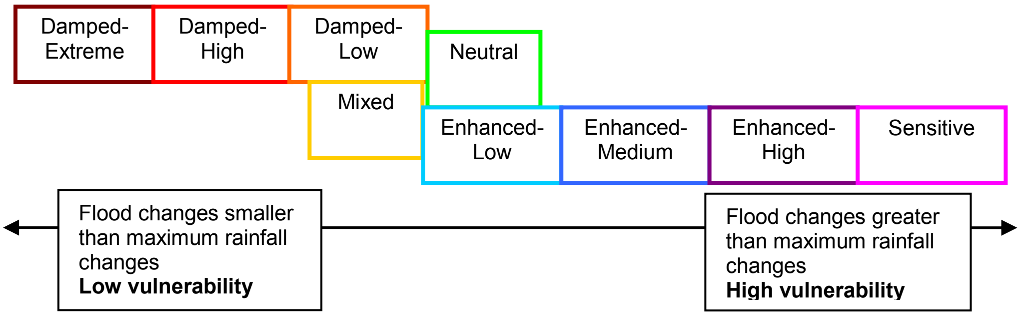


Figure 2.2 Schematic of the nine flood response types from FD2020.

Table 2.2 Suggested FD2020 extra uncertainty allowances by response type and return period (and multiplication factors for larger catchments).

Flood response type:	Return period			
	2-year	10-year	20-year	50-year
Damped-Extreme	10	11	11	11
Damped-High	**8**	11	12	16
Damped-Low	**8**	**6**	**7**	**8**
Neutral	**3**	**3**	3	3
Mixed	**16**	**13**	**11**	**10**
Enhanced-Low	**7**	**6**	7	**8**
Enhanced-Medium	**12**	**12**	15	18
Enhanced-High	**14**	**12**	**9**	6
Sensitive	**20**	**20**	**20**	**20**
If Area > 2000km^2	x1.0	x1.3	x1.7	x2.1

Numbers in bold are those to be used with (merged) key response patterns, when a catchment's response type is estimated from catchment properties. Note that, where flood response types are merged (outlined squares), the middle uncertainty allowance is applied. Numbers not in bold are only required for use with modelled catchment response patterns.

It is the modelled catchment, rather than key, response patterns which are used here, as it is specific FD2020 catchments which are being studied (Section 2.2). Only one temperature/PE scenario (Medium-August; Table 2.1) is used in order to simplify the results, which is reasonable as there are much smaller differences between the response patterns across the 8 temperature scenarios for a catchment than for catchments of different response types (Figure 4.7 of Reynard *et al.* 2009).

2.2 Catchments and hydrological modelling

The hydrological model applied is the PDM (Moore 1985, 2007), a lumped, conceptual rainfall-runoff model widely applied in the UK. This is used along with a simple temperature-dependent snowmelt module (Bell and Moore 1999), which essentially delays the input of water if temperatures are low. This combination of (a simplified version of) the PDM and the simple snowmelt module, when run at a daily time-step, requires daily time-series of catchment-average precipitation and PE, along with a time-series of mean daily temperature, the altitude to which the temperature relates, and information on the area of the catchment within different elevation zones.

The model combination was calibrated for 120 catchments in Britain (76 at a daily time-step) as part of project FD2020 (Crooks *et al.* 2009). Nine of these catchments were used for the uncertainty analysis in that project (Kay *et al.* 2009), chosen to be representative of the nine flood response types (Table 2.3 and Figure 2.3). It is these nine catchments which are used here with various UKCP09 products.

For each catchment, the simulated river flows are used to produce flood frequency curves, using the peaks-over-threshold method (Crooks *et al.* 2009). The impacts of climate change on peak flows are then calculated by looking at the difference between baseline and future simulated flood frequency curves. The analysis is done for peak flows with 2-, 10-, 20- and 50-year return periods, as these were the four flood indicators studied in FD2020. It is these impacts which are presented for each of the nine catchments, using each of the UKCP09 products and methods described in the next section.

Table 2.3 The nine catchments and their FD2020 flood response type.

Catchment number	River name	Location	Flood response type
07002	Findhorn	Forres	Damped-Extreme
02001	Helmsdale	Kilphedir	Damped-High
14001	Eden	Kemback	Damped-Low
47007	Yealm	Puslinch	Neutral
34003	Bure	Ingworth	Mixed
54008	Teme	Tenbury	Enhanced-Low
21023	Leet Water	Coldstream	Enhanced-Medium
43005	Avon	Amesbury	Enhanced-High
38003	Mimram	Panshanger Park	Sensitive

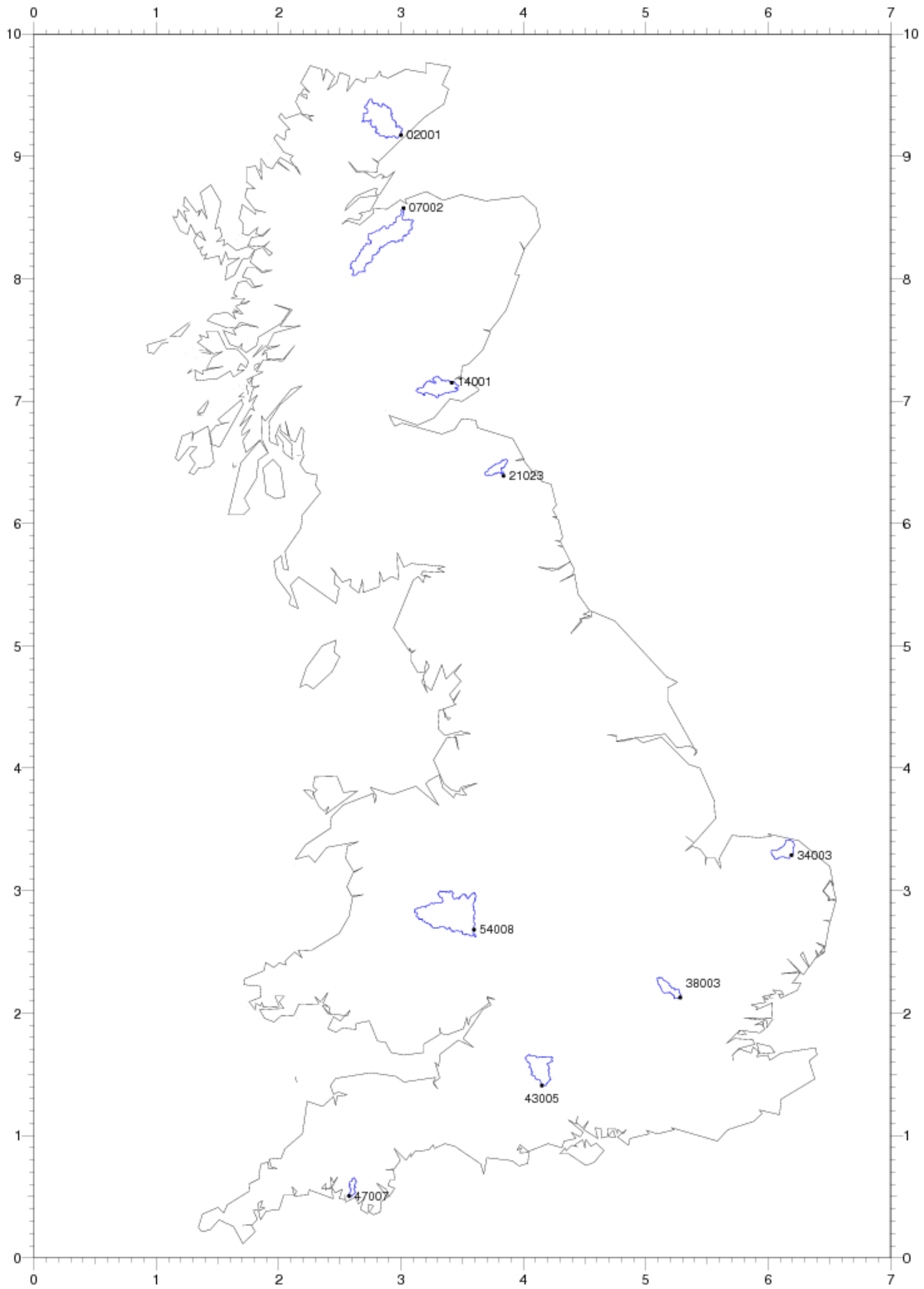


Figure 2.3 Boundaries and outlet locations of the nine catchments.

2.3 UKCP09 products

The UKCP09 products and variables applied are:

1. **Sampled Data**: 10,000 'change factors' for monthly precipitation and temperature (Murphy *et al.* 2009, Section 4);
2. **Weather Generator time-series** of daily precipitation, minimum and maximum temperature and PE (Jones *et al.* 2009);
3. **Regional Climate Model (RCM) time-series** of daily precipitation, mean temperature and PE for the 11-member ensemble (Murphy *et al.* 2009, Section 5).

UKCP09 generally provides information for seven over-lapping 30-year time-slices (2010-2039, 2020-2049, 2030-2059, 2040-2069, 2050-2079, 2060-2089 and 2070-2099), often named by their centre decade (2020s, 2030s, …, 2080s), and three emissions scenarios (High, Medium and Low, corresponding to IPCC SRES (IPCC 2000) scenarios A1F1, A1B and B1 respectively; Murphy *et al.* 2009, Annex 1). However, this Section only uses the 2080s time-slice (2070-2099) and the Medium (A1B) emissions scenario. See Section 3 for some results using other time-slices and emissions scenarios. Note that the RCM time-series data are only available for the A1B emissions scenario.

2.3.1 Methods of application

Each of the three different types of UKCP09 data listed above is applied here:

Sampled Data are applied in two ways:

- **1a. Sampled Data change factors and FD2020 response patterns.**
- **1b. Sampled Data change factors and hydrological model.**

Weather Generator data are only applied in one way:

- **2. Weather Generator time-series and hydrological model.**

RCM ensemble data are applied in three ways, each comparable to one of the above three methods:

- **3a. RCM-derived change factors and FD2020 response patterns** (cf. Method 1a).
- **3b. RCM-derived change factors and hydrological model** (cf. Method 1b).
- **3c. RCM time-series and hydrological model** (cf. Method 2).

Each of these six methods of applying UKCP09 data is summarised below, with some of the choices within each application described in Section 2.3.2.

1. **Sampled Data** (sets of 10,000 'change factors');
   a. **Sampled Data change factors and FD2020 response patterns:** Harmonic functions are fitted to each of the 10,000 sets of monthly changes in precipitation. For each fitted harmonic, two of its parameters (the mean and the amplitude) are used to extract an estimate of the impact on flood peaks from the modelled catchment flood response patterns produced in FD2020. The extra uncertainty allowances developed in FD2020, specified by response type and return period, are also added.
   b. **Sampled Data change factors and hydrological model:** Each of the 10,000 sets of monthly changes in precipitation and temperature are used to adjust their respective observed baseline time-series. Also, because this UKCP09 product does not directly provide changes in PE, the baseline (observed) and adjusted temperature time-series are used to estimate monthly changes in PE using a simple temperature-based PE formulation. These derived changes in PE are then applied to the baseline PE time-series (from MORECS, Thompson *et al.* 1982). The sets of baseline (observed) and adjusted time-series are then used to run the PDM hydrological model for the catchment, and the set of impacts on flood peaks calculated.

2. **Weather Generator time-series and hydrological model:** The UKCP09 Weather Generator can be used to produce a specified number of (stationary) daily time-series of a given length. These are representative of the baseline time-slice (1961-1990) and a given future time-slice under a given emissions scenario, for certain variables (the relevant ones here being precipitation, minimum and maximum temperature and PE). The minimum and maximum temperatures on each day are averaged to produce a daily time-series of mean temperature. The sets of daily time-series of precipitation, mean temperature and PE can then be used to drive the same PDM hydrological model as above, and the set of impacts on flood peaks calculated.

3. **RCM ensemble data**;
   a. **RCM-derived change factors and FD2020 response patterns:** Equivalent to Method 1a, where harmonic functions are fitted to monthly changes in precipitation, except here the change factors are derived from RCM time-series data. However, rather than calculating just one set of monthly changes for each RCM ensemble member, based on the change between 30-year baseline and 30-year future time-slices, sets of monthly changes are derived from every combination of 20-year sub-periods within the 30-year time-slices (as per the method developed for project FD2020, Prudhomme and Reynard 2009). The harmonic function is then fitted to the median change for each month. Using this method improves the fit of the harmonic function, and gives some allowance for natural variability in the RCM time-series data.
   b. **RCM-derived change factors and hydrological model:** Equivalent to Method 1b, except here the median monthly changes derived in Method 3a above are used to adjust the baseline time-series, and the resulting time-series used to run the PDM hydrological model for the catchment.
   c. **RCM time-series and hydrological model:** The actual RCM time-series for the baseline (1961-1990) and future (2070-2099) time-slices are used to run the PDM hydrological model, and the set of impacts on flood peaks calculated by comparing the two runs for each ensemble member separately.

Note that the standard change-factor methodology (as applied in FD2020; Prudhomme *et al.* 2009a) is applied for Methods 1b and 3b; the delta-changes specified for a particular month are applied equally to each and every day of that month. That is, the monthly percentage changes given for precipitation are applied to each day of the corresponding month in the observed precipitation time-series, and the monthly absolute changes given for temperature are added to each day of the corresponding month in the observed temperature time-series. See Section 3 for an investigation of the use of an enhanced change-factor method, which takes some account of changes in rainfall intensity as well as monthly rainfall amount.

2.3.2 Choices

Using each of the three different types of UKCP09 data listed above involves choices about exactly what to apply and how. Some of these choices are discussed below, along with details on what has been done here and why.

1. **Sampled Data** (Methods 1a and 1b);
   i. Sub-samples of the full Sampled Data can be requested, based on either random selection (with replacement) or through specifying Sample Ids. However, the full set of 10,000 has been used here for completeness.
   ii. The Sampled Data for any location in the UK can be obtained for a) boxes on an approximately 25km x 25km grid (that of the RCM, for those boxes categorised as 'land'), b) 16 administrative regions or c) 23 river-basin regions (Murphy *et al.* 2009, Figure 1.2). Sampled Data for river-basin regions have been used here (see below).
   iii. When applying the Sampled Data, it is important to note that they are not spatially consistent (Murphy *et al.* 2009, Annex 4). That is, the first set of change factors for a given grid box cannot be considered to coincide with the first set of change factors for any neighbouring grid box, the second does not necessarily coincide with the second, etc. This means that, for a lumped catchment model, it is not possible to average the Sampled Data across all grid boxes covering a catchment to obtain an average set of Sampled Data for the catchment. Similarly, a catchment cannot be modelled with a (semi-)distributed hydrological model in such a way that different change factors are applied to the inputs for different parts of the catchment. In either case, a single set of Sampled Data has to be chosen for the catchment (e.g. that from a single grid box or from the appropriate river-basin region). Here a lumped catchment model is used, and the single set of Sampled Data applied are those from the river-basin region containing the catchment. See Section 3 for a comparison of this with the use of Sampled Data from the grid box containing the catchment centroid, and an investigation of the effect of the choice of grid box.
   iv. When applying the Sampled Data, it is also important to note that the variables have been processed for UKCP09 in two separate batches and that data are not coherent between these batches (see Murphy *et al.* 2009, Annex 4). That is, the first set of changes for a variable in batch 1 cannot be considered to coincide with the first set of changes for a variable in batch 2, the second set does not coincide with the second, etc. One consequence of this is that formulations of PE requiring surface radiation data, such as the often-used Penman-Monteith formulation, cannot be applied as the short wave and long wave flux terms are in batch 2 whereas temperature is in batch 1 (see Murphy *et al.* 2009, Table A.2). Formulations using relative humidity and/or cloud as well as temperature could be applied though, as these variables are all in batch 1. Here though, for simplicity, a purely temperature-based formulation (that of Oudin *et al.* 2005) has been applied in order to estimate percentage changes in PE corresponding to each line of Sampled Data. These PE change factors have then been applied to

MORECS (Thompson *et al.* 1982) baseline data for the catchment in order to derive future PE data for input to the hydrological model.

2. **Weather Generator data** (Method 2);
   i. The Weather Generator is set-up on a 5km x 5km grid over Britain and, similar to 1iii above, separate runs for neighbouring squares are not spatially consistent so cannot be used to provide spatially variable inputs for a (semi-) distributed model. However, the weather generator does allow the selection of multiple adjoining squares (up to an area of 1000 km^2, or 40 squares), for which it can be run to produce a single set of time-series. As stated in the weather generator report (Jones *et al.* 2009, Section 5.3), "Care must be taken in the interpretation of this series however, as it still corresponds to a single point but one which is representative, on average, of the region. The weather generator variables in the series are not areal-averaged values". Here, for the lumped catchment model, a number of adjoining 5km x 5km squares have been chosen to cover each catchment. Then, for each catchment the weather generator time-series produced for the chosen region have been used directly to drive the PDM hydrological model for the catchment. This seems to be the best way to get the input time-series required by the PDM, although ideally the weather generator would be capable of producing spatially consistent time-series.
   ii. The Weather Generator can be used to produce a specified number of runs (N). Generally, the N runs correspond to a random choice of N of the 10,000 change factors (*with* replacement). Ideally perhaps, it would be possible to get 10,000 weather generator runs — one run for each of the 10,000 change factors. However, N is limited to a maximum of 1000 (to limit the volume of data produced), and a minimum of 100 (considered the smallest number of samples allowable to maintain the probabilistic nature of the data). Here, the minimum of 100 time-series are used for each catchment, as tests suggested that the error introduced in the impacts by using this factor of 10 reduction from the maximum number possible is rather less than the range of impact uncertainty. However it should be noted that re-running the weather generator to produce 100 more runs for the same location will generally produce quite different time-series (unless the same initial seed is specified), and thus a different set of impacts. Note that time-series can also be requested for specific, rather than randomly selected, change factors if required (sampling by sample id), although re-running without specifying the same initial seed would still lead to different results.
   iii. The Weather Generator can be used to produce (stationary) daily time-series of length L, where L can be a minimum of 30 years and a maximum of 100 years, or any multiple of 10 within this range. Here, only runs of 30 years have been applied, as this is the standard time-slice length. See Section 3 for an investigation of the use of longer time-series.
   iv. Only a single baseline (based on a simulation using observed time-series data) is available for use with the sets of 10,000 change factors. However, the Weather Generator gives a set of N possible baselines (representing the presence of natural variability) as well as N possible futures (representing uncertainty in various aspects of the climate as well as the presence of natural variability). Thus the question arises of what baseline to use with each future, when calculating the impacts. Keeping baseline i of N with future i of N, for i in (1,…,N), is perhaps the natural choice (and has been applied here), but this is not really necessary since the baseline ensemble is purely a natural variability ensemble – none of the parameters of the Weather Generator have been changed (this is in contrast to the RCM baseline ensemble, see discussion in 3iv below). Another possibility is to use hydrological model runs

from the baseline ensemble to calculate a mean baseline, and calculate the changes for each of the future runs from this mean baseline.

3. **RCM ensemble data** (Methods 3a, 3b and 3c);
   i. Where sets of monthly changes are derived from RCM time-series data (Methods 3a and 3b), for the lumped hydrological model applied here the monthly changes are taken from the grid box containing the catchment centroid. The difference when using change factors derived from the RCM data (Methods 3a and 3b) compared to the Sampled Data (Methods 1a and 1b) is that for the RCM data the change factors from neighbouring grid boxes are spatially consistent. They thus could be used to apply different changes to inputs in different parts of a large catchment modelled with a (semi-)distributed model.
   ii. Where the actual RCM time-series for the baseline (1961-1990) and future (2070-2099) time-slices are used to run the hydrological model (Method 3c), it is necessary to produce time-series of catchment-average precipitation and PE data from the gridded data of the RCM. This is done here using the method of Kay *et al.* (2006), whereby the catchment boundary is overlaid on the RCM grid and area-weighting used (in combination with SAAR-weighting for precipitation). The temperature time-series applied is simply that for the grid box containing the catchment centroid, which is applied in the snowmelt module along with information on the average altitude of the grid box from the RCM orography file.
   iii. The only PE time-series data available directly from the RCM are open-water PE. These can be transformed into an estimate of PE from vegetation using some other variables available from the RCM (Bell *et al.* 2011).
   iv. Where the actual RCM time-series are used to run the hydrological model (Method 3c), the baseline time-slice and future time-slice pair for each ensemble member should be kept together when calculating the impacts, since both are perturbed parameter as well as natural variability ensembles and there could be different biases for different ensemble members. Some form of bias-correction could be applied, but such correction has to be developed very carefully as a simple comparison of the RCM baselines with observations neglects the fact that the RCM baselines include natural variability, and as such they are not meant to reproduce the baseline period exactly but are simply meant to be *possible* baselines. Thus over-correction and the use of inappropriate corrections for future periods are distinct possibilities, if bias-correction is based on such a direct comparison of RCM baseline and observations. Ideally, bias-correction would be based on either an ERA-driven run of each RCM ensemble member (as these runs, driven at the boundaries by ‘observations’ rather than the equivalent GCM run as in UKCP09, are meant to closely reproduce the actual baseline period) or perhaps on an initial condition ensemble for each perturbed-parameter ensemble member, so that any bias due to deficiencies in the RCM can be more clearly distinguished from differences simply due to natural variability. No bias correction has been applied here, as data to develop an appropriate bias-correction method were not available.

2.4 Results

Figure 2.4 shows the results for the Neutral example catchment (47007), in terms of percentage changes in flood peaks (x-axis) at four flood return periods. Plotted on each graph are: histograms (Figure 2.4a) and cumulative distribution functions (cdfs; Figure 2.4b) showing the range of results for Method 1a (Sampled Data change factors and response patterns), Method 1b (Sampled Data change factors and hydrological model) and Method 2 (Weather Generator time-series and hydrological model), and crosses, marked close to the x-axis, showing the results for Method 3a (RCM-derived change factors and response patterns), Method 3b (RCM-derived change factors and hydrological model) and Method 3c (RCM time-series and hydrological model). Also shown on Figure 2.4b is a second version of each cdf for Method 1a, where the extra uncertainty allowance derived in FD2020, dependent on return period and response type (Table 2.2), has been added.

The cdfs of the results for the other eight catchments (Table 2.3) are shown in

Figure 2.5, and the results for all nine catchments, for Methods 1a, 1b and 2, are summarised in the box-and-whisker plots in Figure 2.6. These show that, for most catchments, there is a reasonable correspondence between the results from each of the methods. That is, there is generally considerable overlap between the cdfs/boxes, with the median values for a catchment generally within 10% or so of each other.

a) Histograms b) Cdfs

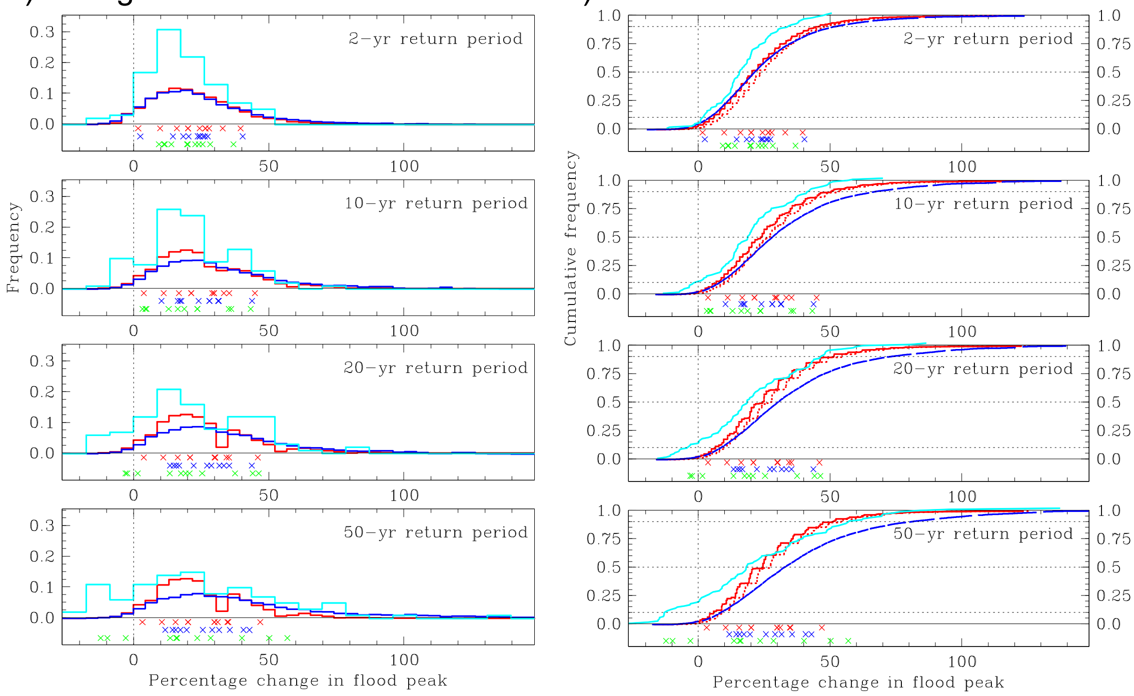


Figure 2.4 Histograms (left) and cdfs (right) of the results for catchment 47007 (Neutral), as percentage change in flood peaks at four return periods, for Method 1a (red line; dotted for cdfs including extra uncertainty allowances), Method 1b (blue line) and Method 2 (cyan line). Also shown are the results for:

Method 3a (red crosses), Method 3b (blue crosses) and Method 3c (green crosses).

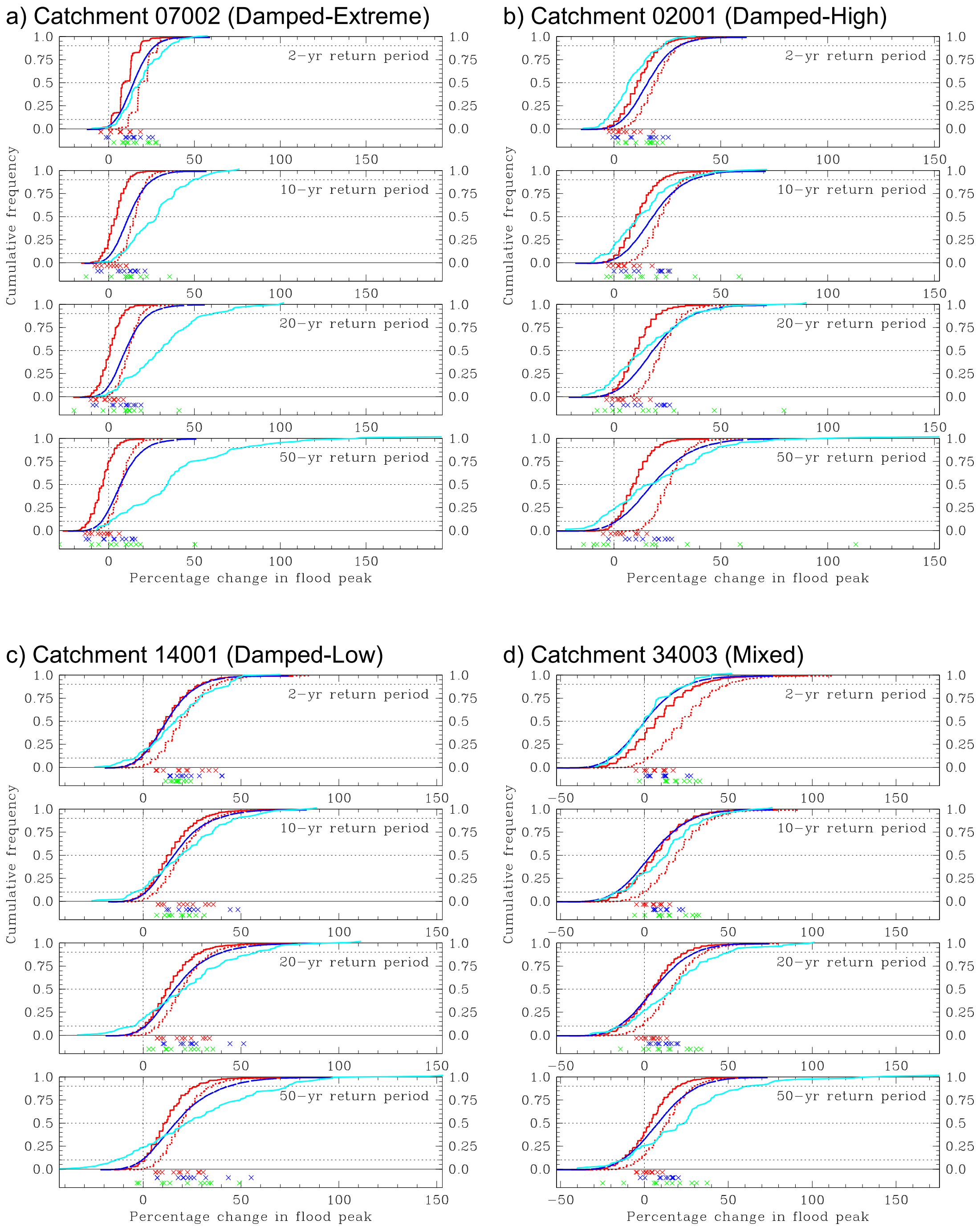
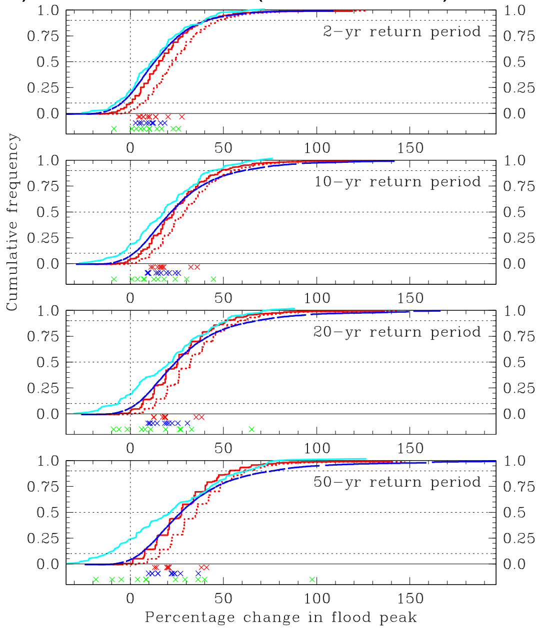
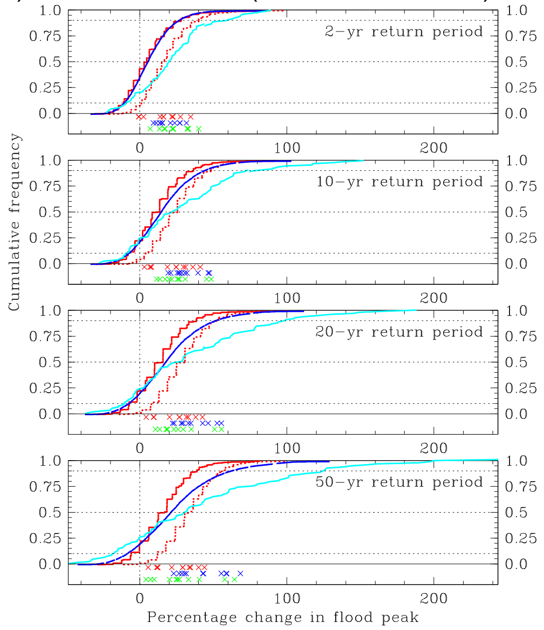


Figure 2.5 Impact cdfs as in Figure 2.4b, but for the other eight catchments (see Table 2.3). Note the differing x-axes between catchments. Figure continued on next page.

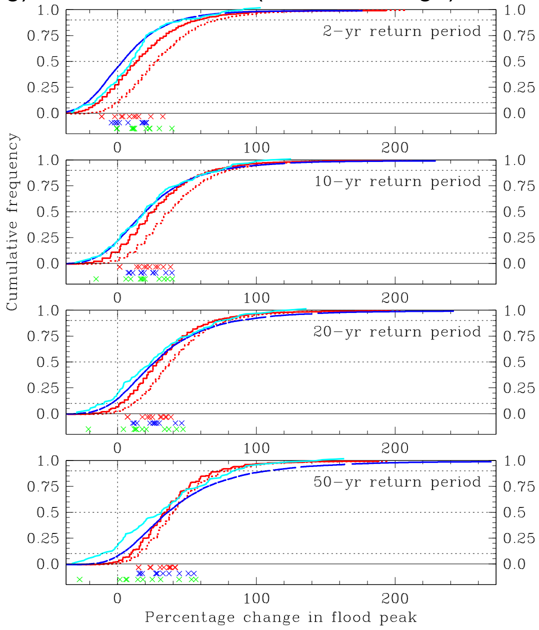
e) Catchment 54008 (Enhanced-Low)



f) Catchment 21023 (Enhanced-Medium)



g) Catchment 43005 (Enhanced-High)



h) Catchment 38003 (Sensitive)

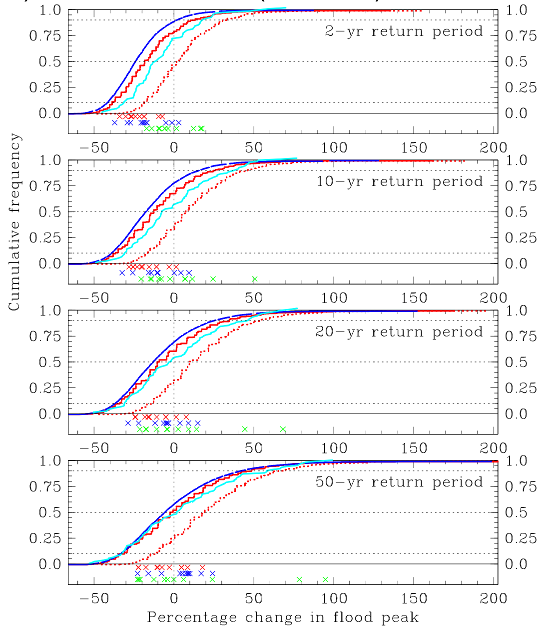


Figure 2.5 continued.

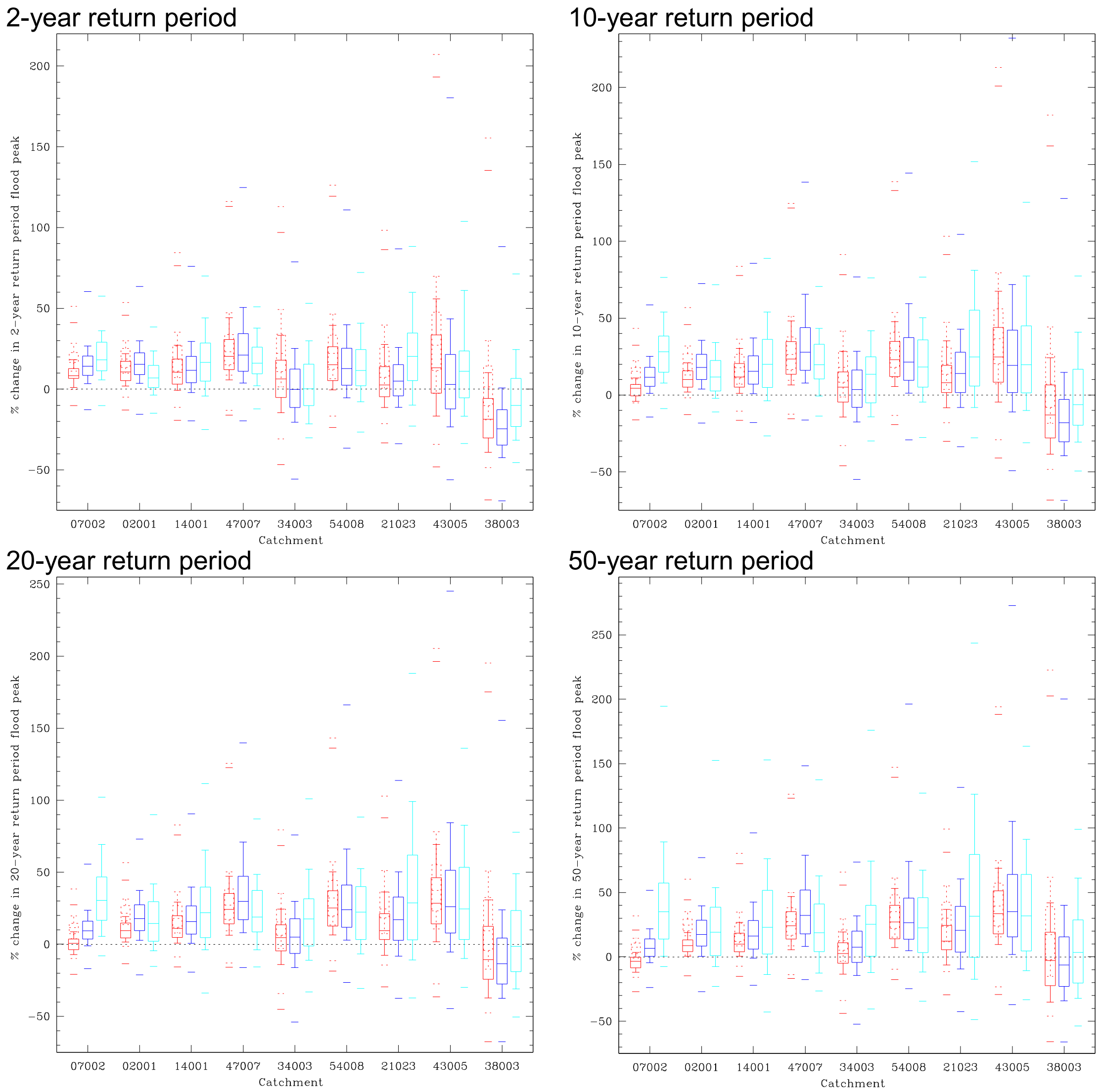


Figure 2.6 Box-and-whisker plots summarising the results for each catchment: Method 1a (red, dotted when including extra uncertainty allowances), Method 1b (blue), Method 2 (cyan). In each case, the boxes indicate the middle 50% of results (25th to 75th percentiles), with the median (50th percentile) shown by the line dividing the box. The whiskers on each box indicate the 10th and 90th percentiles, with additional markers outside the whiskers indicating the minima and maxima.

The main exception to this is catchment 07002 (Damped-Extreme) where, at least above the 2-year return period, the central range of results from Method 1a (Sampled Data change factors and response patterns) sits lower than that for Method 1b (Sampled Data change factors and hydrological model) which is in turn lower than that for Method 2 (Weather Generator time-series and hydrological model). Initially it was thought that these differences related to threshold effects in the snowmelt modelling when using the Weather Generator data, but this proved incorrect since re-running the hydrological model for this catchment without the snowmelt module led to very little difference in the set of impacts. Thus the reasons for these differences remain unclear, but are obviously related to the Weather Generator outputs since the results using the RCM time-series data (Method 3c) are similar to those using change factors (Methods 1a, 1b, 3a and 3b).

For some catchments, the bias-correction of the results from Method 1a, using the FD2020 extra uncertainty allowances (Table 2.2), is a significant improvement (e.g. 07002 and 02001) or slight improvement (e.g. 14001 and 21023) on the un-corrected results. For other catchments there is possibly an over-correction, as the use of the allowances shifts the results from Method 1a to a position with a median impact above that for Method 2 (e.g. 54008, 43005 and 38003). The difference is particularly marked for catchment 38003 (Sensitive), which has the largest extra uncertainty allowance. However, the FD2020 extra uncertainty allowances were based on comparisons between a larger set of alternative methods, including use of time-series data from the UKCP09 RCM ensemble. It is the latter which led to the large allowance for catchment 38003 (see Figure 3.2ix of Kay *et al.* 2009). This difference in impacts for catchment 38003 when RCM time-series data are applied (Method 3c) can be seen in

Figure 2.5h, where two of the RCM ensemble members give impacts located in the extreme tail of the range of impacts from Methods 1a, 1b or 2 at higher return periods. An in-depth comparison of RCM time-series data, Weather Generator time-series data, and baseline data would be required in order to assess any underlying reasons for the differences in impacts between the different methods, and whether or not the differences are real or simply due to sampling issues.

In general, the results from Method 1a and Method 1b have a narrower range for catchments with a Damped response type and a wider range for catchments with an Enhanced response type, which is consistent with the change in vulnerability with response type (Figure 2.2). At higher return periods, the results from Method 1a generally have a narrower range than those from Method 1b, which are in turn generally narrower than those from Method 2. This suggests that the higher percentile impacts for higher return periods may be under-estimated by the methodology of Method 1a, even if the median impact is reasonably estimated, and that perhaps a further correction factor is necessary for higher percentiles. The fact that the results from Method 2 (Weather Generator time-series) generally show a wider range compared to the Sampled Data change factor results at higher return periods might be expected given the restrictions of change factor methods in terms of changes in variability.

3 Investigation of alternative application of some UKCP09 products

This section investigates the alternative application of some of the UKCP09 products, with respect to some of the choices made in Section 2, to look at changes in flood peaks for:

1. Multiple time-slices / emissions scenarios;
2. Changes in short duration, intense rainfall;
3. Larger catchments;
4. Longer recurrence intervals.

3.1 Multiple time-slices / emissions scenarios

For catchments 43005 (Enhanced-High response type) and 47007 (Neutral response type), both in the SW England river-basin region, five different sets of UKCP09 Sampled Data have been applied;

- 2080s time-slice under the A1B (Medium) emissions scenario (as used in Section 2);
- 2050s time-slice under the A1B (Medium) emissions scenario;
- 2020s time-slice under the A1B (Medium) emissions scenario;
- 2080s time-slice under the A1F1 (High) emissions scenario;
- 2080s time-slice under the B1 (Low) emissions scenario.

That is, the three non-over-lapping time-slices (2020s, 2050s and 2080s) are applied to assess transient changes in peak flows for the A1B emissions scenario, and all three emissions scenarios (B1, A1B and A1F1) are applied for the 2080s time-slice, to assess emissions uncertainty. Each is applied under Method 1a (Sampled Data change factors and FD2020 response patterns) and Method 1b (Sampled Data change factors and hydrological model) of Section 2.

Figure 3.1 shows Method 1a graphically, by presenting the information from each set of UKCP09 Sampled Data overlaid (as contours) on the modelled catchment flood response patterns for the 20-year return period flow (for FD2020's Medium-August temperature/PE scenario; Table 2.1). This clearly shows how the same hazard set (here from the UKCP09 Sampled Data for SW England) can have a very different impact on two catchments because of their differing levels of vulnerability (FD2020 response type). It also shows that there is a greater difference between the positioning of the contours for the three time-slices (under the A1B emissions scenario) than between those for the three emissions scenarios (even for the 2080s time-slice).

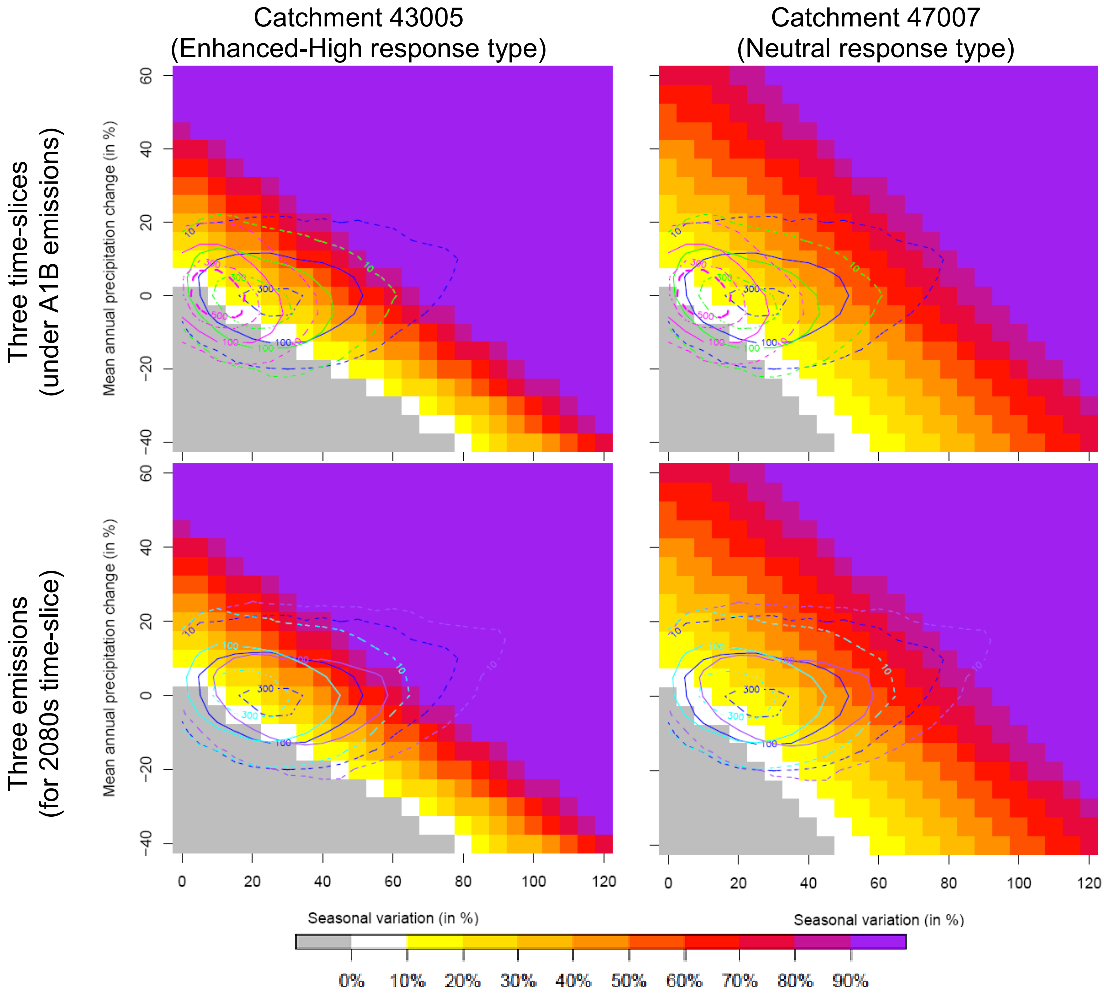


Figure 3.1 FD2020 modelled response patterns (coloured grids; key at bottom) for catchments 43005 and 47007 (at the 20-year return period under the Medium-August temperature/PE scenario) overlaid with contours based on various UKCP09 Sampled Data sets for the SW England river-basin region: Blue – 2080s A1B (common to all four plots); Green – 2050s A1B (top two plots); Magenta – 2020s A1B (top two plots); Purple – 2080s A1F1 (bottom two plots); Cyan – 2080s B1 (bottom two plots). The contours indicate the approximate number of the 10,000 UKCP09 scenarios falling within each 5%x5% box of the response pattern grid.

Figure 3.2 shows the cdfs of the impacts extracted from the overlaid hazard and vulnerability sets shown in Figure 3.1 (Method 1a, without the extra uncertainty allowances added), and compares them with the equivalent cdfs for Method 1b. The pattern of change with time-slice / emissions scenario is similar for the two methods of application of the same Sampled Data. That is, the impact is greater, with a wider range of uncertainty, for later time-slices than for earlier time-slices. Likewise the impact is greater, with a wider range of uncertainty, for higher emissions scenarios than for lower emissions scenarios.

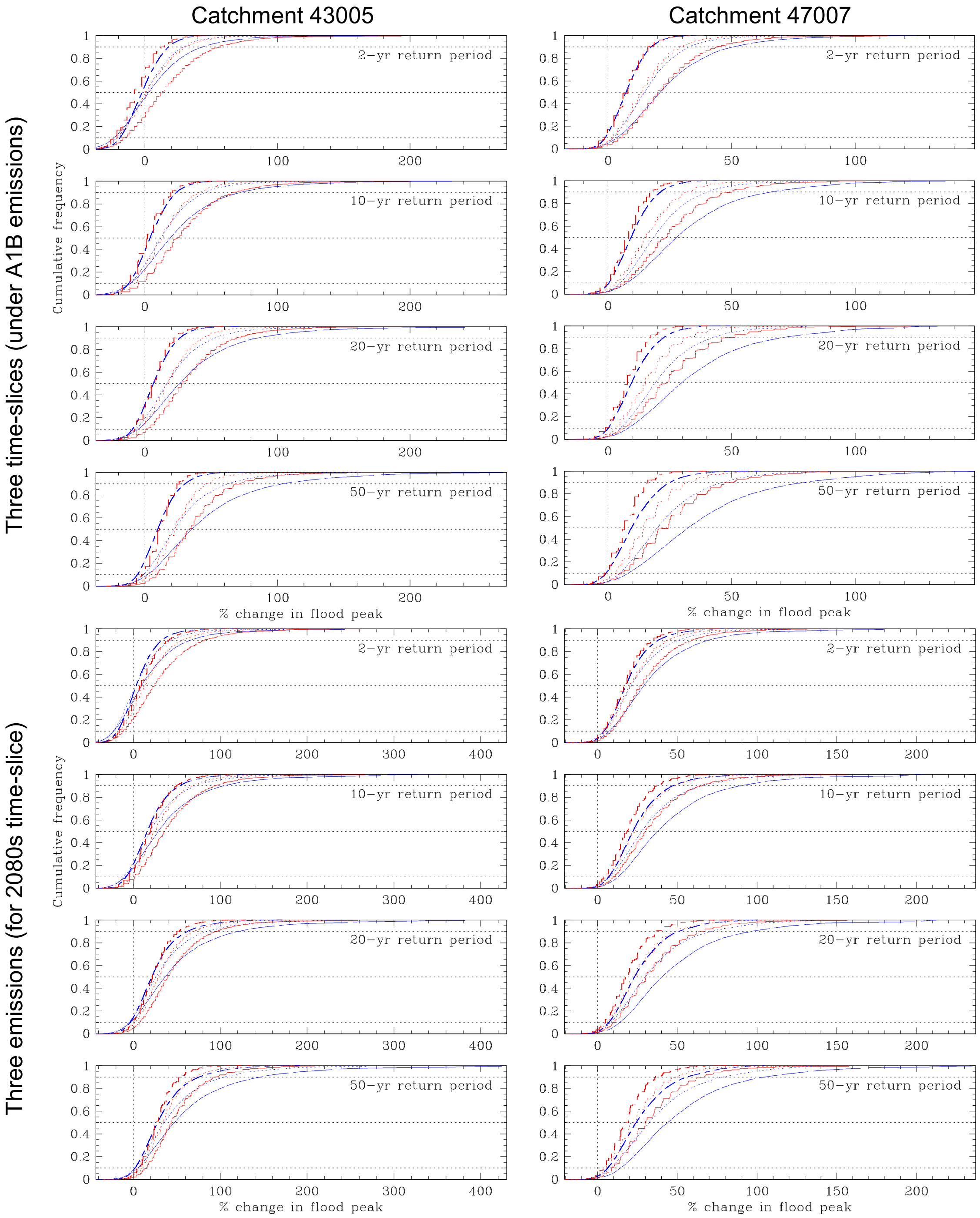


Figure 3.2 Impact cdfs for flood peaks at four return periods, under Method 1a (red) and Method 1b (blue) for catchments 43005 (left) and 47007 (right). Top eight plots: 2020s (dashed), 2050s (dotted) and 2080s (solid) time-slices under the A1B emissions scenario. Bottom eight plots: B1 (dashed), A1B (dotted) and A1F1 (solid) emissions for the 2080s time-slice. Note the differing x-axes between catchments/scenario sets.

3.2 Changes in short duration, intense rainfall

The standard proportional delta-change method used in Section 2 and project FD2020 is simple and easy to understand, but does not allow for changes in rainfall intensity, as it applies the proportional change in rainfall for a month equally to every day of that month. This could be a particular concern if the projected proportional change in rainfall for a month was negative, but daily rainfall of a specific return period was projected to increase. Project W5-032 'Impact of climate change on flood flows in river catchments' (Reynard *et al.* 2004) devised an 'enhanced proportional' delta-change method, which used proportional change in combination with rain day changes and storm enhancement depending on an indicator of change in 20-year return period daily rainfall for each season (see Reynard *et al.* 2004 Section 4.2.1). A version of this 'enhanced proportional' delta-change method is applied here, for catchment 28039 (the Rea at Calthorpe Park; one of the catchments modelled in Reynard *et al.* 2004), and the results compared to those from use of the standard delta-change method. Catchment 28039 is located in the Humber river-basin region.

UKCP09 does not provide Sampled Data on changes in 20-year return period daily rainfall, but does provide information on changes to 'Precipitation on the wettest day' (seasonally) consistent with the changes to mean daily precipitation and temperature (monthly). It is considered that 'precipitation on the wettest day', for the 30-year time-slices, is close enough to '20-year return period daily rainfall' that it can be used directly to define the required indicator of change in intensity (Table 3.1, cf. Table 4.1 of Reynard *et al.* 2004). Thus the requirements from each line of Sampled Data are: twelve monthly mean precipitation (and temperature) changes and four seasonal changes to precipitation on the wettest day. These are used to apply a version of the 'enhanced proportional' delta-change method (Table 3.2, cf. Table 4.2 of Reynard *et al.* 2004) for each set of Sampled Data. Note that, due to the much greater number of UKCP09 scenarios compared to the UKCIP02 scenarios used by Reynard *et al.* (2004), and the consequent increase in the possible combinations of rainfall changes within scenarios, the 'enhanced proportional' delta-change method summarised in Table 3.2 is broader than that used by Reynard *et al.* (2004).

Table 3.1 Indicator values for the percentage changes in the 20-year return period daily rainfall.

Percentage change in 'precipitation on the wettest day'	Indicator value
> 5	1
-5 to +5	0
-20 to -5	-1
< -20	-2

Table 3.2 Summary of the 'enhanced proportional' delta-change method for each category of rainfall change.

Scenario percentage change in rainfall	Indicator value	Method of change
Positive	1	Winter: sliding scale (*P1*) between 100% proportional and 100% rain day change depending on average winter percentage change. Other seasons: increase added to wettest day in month if this is > *P2*, otherwise as winter.
Positive	0	Rain day change (increase added equally to every third day where rainfall < *P3*).
Positive	-1 or -2	Maximum daily rainfall in month decreased by 20% and this amount added to the monthly increase. Then rain day change.
Negative	1	If wettest day in month > 25.0mm: days with rainfall < *P4* changed to dry and this gained amount minus the monthly decrease added to the wettest day. Otherwise: proportional decrease.
Negative	0	Summer: days with rainfall < 5.0mm changed to dry and, for remaining days (up to monthly decrease), $R_t = R_t*R_t/R_{max}$ (where R_t is rainfall on day *t* and R_{max} is maximum rainfall in baseline period for that month). Other seasons: days with rainfall < 10.0mm changed to dry (up to monthly decrease).
Negative	-1	Summer: the average decrease (decrease for month divided by number of days in the month) subtracted from daily rainfall (not < 0.0). Any deficit carried forward to next day and at end of month to corresponding month of following year. Other seasons: proportional decrease.
Negative	-2	Summer: As for indicator of -1 but daily rainfall decreased by 25% if this was more than the average decrease (up to monthly decrease). Other seasons: proportional decrease.

Parameter key:
P1 - the percentage of the change to be achieved by the proportional method;
P2 - a threshold daily rainfall above which the frequency is likely to increase (approximately given by the 1-year return period rainfall for autumn);
P3 - a threshold daily rainfall for creating new wet days (e.g. 0.2mm);
P4 - an initial threshold daily rainfall for creating new dry days (e.g. 3.0mm), which may be increased during the model run.

Figure 3.3 shows the impact cdfs for catchment 28039, using the Humber river-basin region Sampled Data under Method 1b (Sampled Data change factors and hydrological model) for the standard and enhanced proportional delta-change methods, in comparison to the results for Method 3c (RCM time-series and hydrological model). This shows that there are relatively small differences between the distributions, although the standard proportional delta-change method may under-estimate the higher percentile impacts in comparison to the enhanced proportional delta-change method at higher return periods. However, it should be noted that the enhanced proportional delta-change method is still limited by the occurrence and sequencing of events in the baseline time-series of a catchment, albeit to a slightly lesser extent than the standard proportional delta-change method.

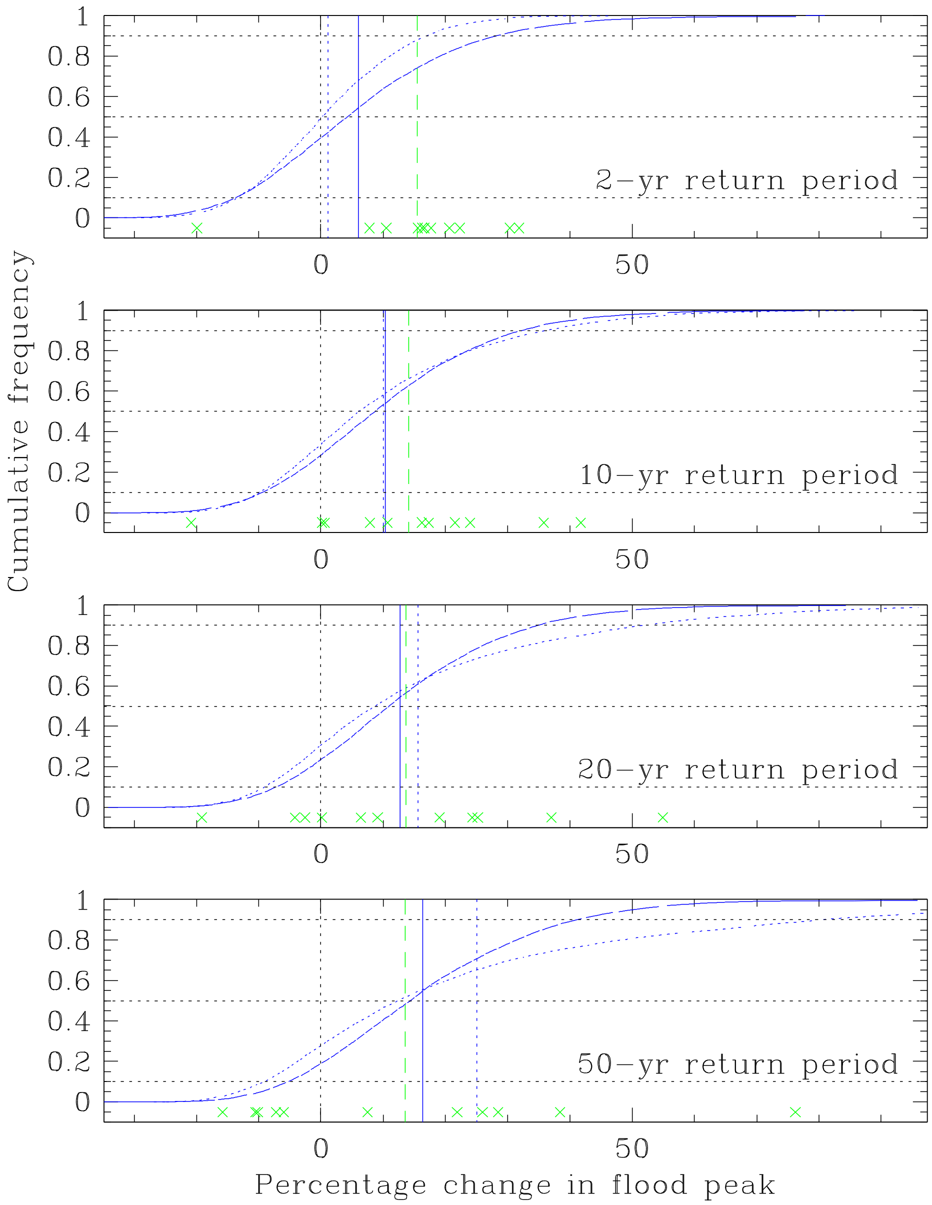


Figure 3.3 Impact cdfs for flood peaks at four return periods, for catchment 28039 under Method 1b for the standard (blue solid) and enhanced (blue dotted) proportional delta-change methods, using Sampled Data from the Humber river-basin region, and impacts from direct use of the 11-member ensemble of RCM time-series data (Method 3c: green crosses), for the 2080s time-slices under the A1B emissions scenario. Each method has its corresponding mean impact marked with a vertical line.

3.3 Larger catchments

For two of the larger catchments used in Section 2 (02001 and 54008; see Table 2.3), the results using Sampled Data from the appropriate river-basin region (as in

Section 2) are compared to the use of Sampled Data from several grid boxes over the catchment. In addition a much larger catchment, the Thames at Kingston (catchment 39001), is modelled using CLASSIC (a semi-distributed model; Crooks and Naden 2007) with the Sampled Data from the Thames river-basin region, and the results compared to use of (spatially consistent) time-series from the 11-member RCM ensemble.

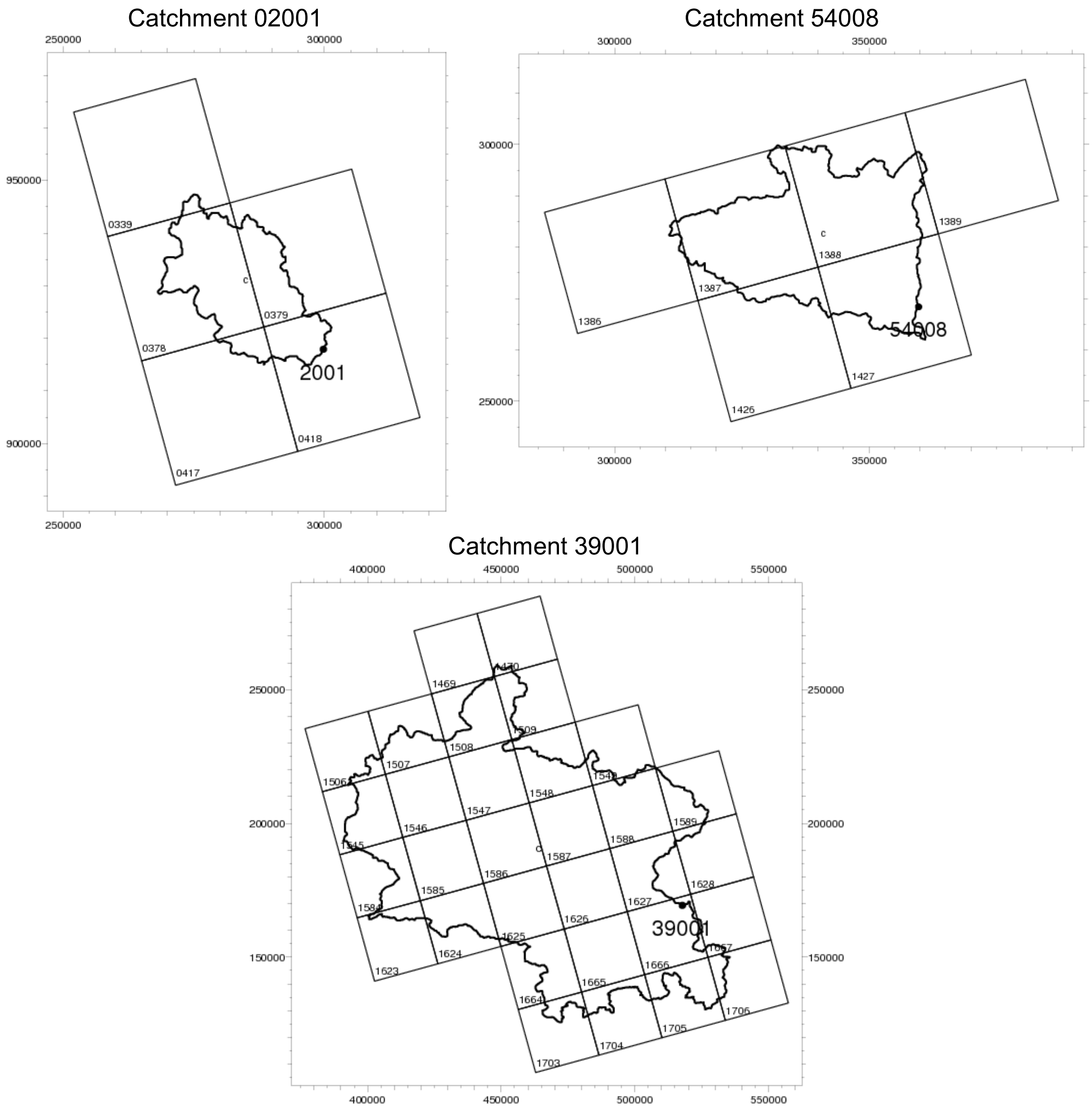


Figure 3.4 Catchments 02001, 54008 and 39001 overlaid with their 25km UKCP09 grid boxes (numbered in the bottom-left corners). The location of the centroid of each catchment is indicated by the small letter ‘c’.

Figure 3.4 shows catchments 02001, 54008 and 39001 overlaid with their UKCP09 grid boxes. For catchment 02001, within the North Highland river-basin region, grid box 0378 is the main grid box (containing the catchment centroid) whilst grid boxes 0379 and (to a lesser extent) 0418 could be appropriate alternatives. For catchment 54008, within the Severn river-basin region, grid box 1388 is the main grid box (containing the catchment centroid) whilst grid boxes 1387 and 1427 could be appropriate alternatives.

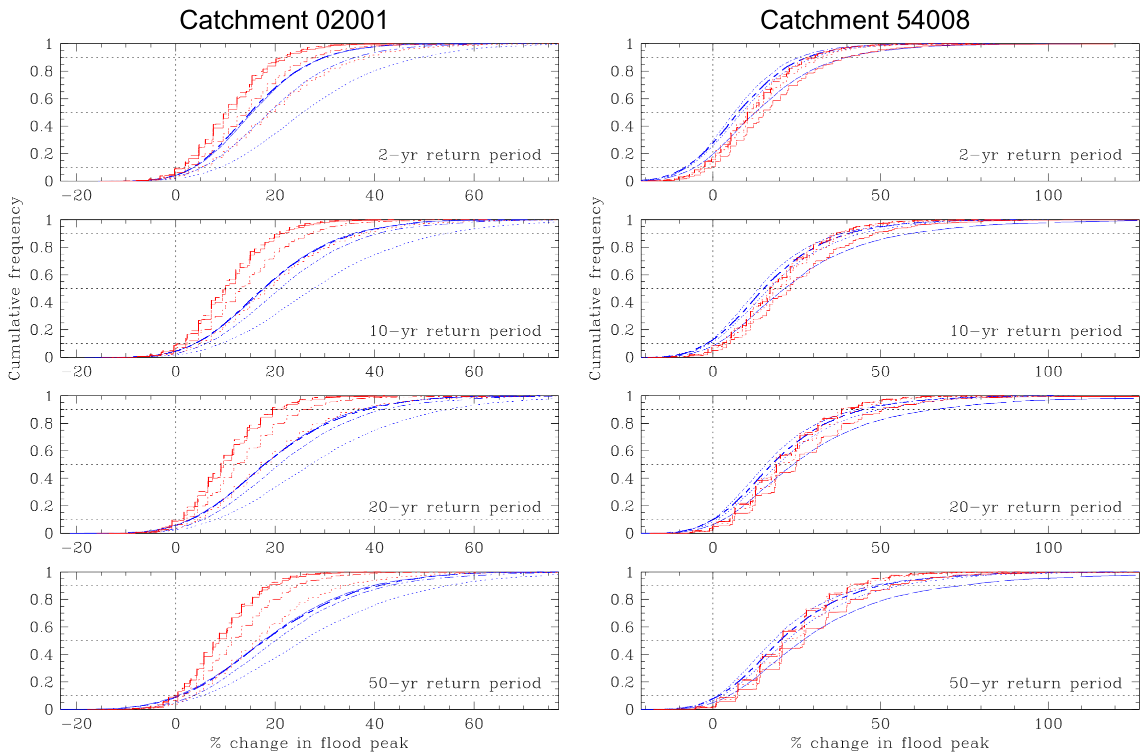


Figure 3.5 Impact cdfs for flood peaks at four return periods, under Method 1a (red) and Method 1b (blue) for catchments 02001 (left) and 54008 (right), using Sampled Data from the appropriate river-basin region (solid), from the grid box containing the catchment centroid (long-dashed) and from two alternative grid boxes over the catchment (short-dashed and dotted) for the 2080s time-slices under the A1B emissions scenario.

Figure 3.5 shows the impact cdfs for catchments 02001 and 54008, for various sets of Sampled Data under Method 1a (without the extra uncertainty allowances added) and Method 1b. They show that, at least for these catchments, using Sampled Data from different grid boxes over the catchment, or using that from the appropriate river-basin region, makes little difference to the results when considered in terms of the overall range of impacts including climate change uncertainty and natural variability. In general it is not thought that the use of river-basin region Sampled Data as against 25km grid-box Sampled Data will make a big difference to the estimate of risk for a catchment. However, there is obviously more chance of differences within a large river-basin region (e.g. Humber) and less chance of differences within a small river-basin region (e.g. Dee).

Figure 3.6 shows the impact cdfs for catchment 39001, using the Thames river-basin region Sampled Data under Method 1a (without and with the extra uncertainty allowances added) and Method 1b, in comparison to the results for Method 3c (RCM time-series and hydrological model). This shows that there are relatively small differences between the distributions from Method 1a without the extra uncertainty allowances and Method 1b, although the former may under-estimate the higher percentile impacts in comparison to the latter at higher return periods. With the extra uncertainty allowances (including the multiplication factors for larger catchments; Table 2.2), Method 1a may over-estimate the lower and median percentile impacts in comparison to Method 1b. However, as discussed in Section 2.4, the FD2020 extra uncertainty allowances were based on comparisons between a larger set of alternative methods, including use of time-series data from the UKCP09 RCM ensemble.

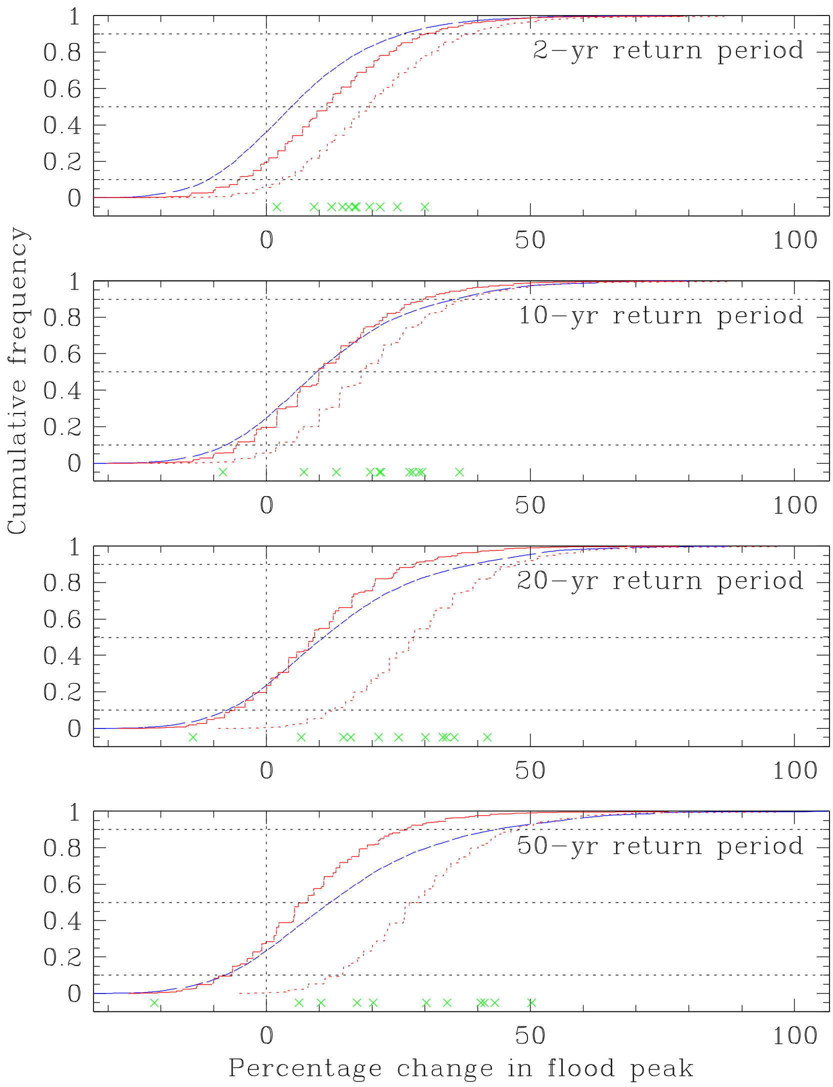


Figure 3.6 Impact cdfs for flood peaks at four return periods, for catchment 39001 under Method 1a (red; dotted when including FD2020 extra uncertainty allowances) and Method 1b (blue) using Sampled Data from the Thames river-basin region, and impacts from direct use of the 11-member ensemble of RCM

time-series data (Method 3c: green crosses), for the 2080s time-slices under the A1B emissions scenario.

The use of the spatially-consistent time-series data from the 11-member RCM ensemble to drive the semi-distributed hydrological model for catchment 39001 has not resulted in an overall impact range much different to that seen from the use of Sampled Data. If the 11-member RCM ensemble can be considered as representative of the Sampled Data, then it might be expected that the results from one member would lie below the 10th percentile of the cdf and that those from another member would lie above the 90th percentile of the cdf, with the rest lying somewhere in between. This is almost precisely what is shown in Figure 3.6 for the RCM results with-respect-to the cdf for Method 1b for catchment 39001. However, it might also be expected that the impact for approximately half of the 11 RCM ensemble members would lie below the 50th percentile with the other half above the 50th percentile. This is not the case for the RCM results with-respect-to the cdf for Method 1b, but is closer to being true for the RCM results with-respect-to the cdf for Method 1a with the extra uncertainty allowances. That is, the FD2020 extra uncertainty allowances were based on the positioning of mean impacts from various alternative methods, rather than on the positioning of the higher or lower percentiles. In general though, the range from the 11-member RCM ensemble should not be considered as representative of the range from the full set of Sampled Data. This is demonstrated for changes in seasonal precipitation and temperature in Figure 3 of the UKCP09 report on Spatially Coherent Projections (Sexton *et al.* 2010).

3.4 Longer recurrence intervals

For two of the catchments used in Section 2 (47007 and 38003), progressively longer time-series from the UKCP09 Weather Generator are applied to test the effect on estimation of changes in flood peaks at higher return periods.

As discussed in Section 2.3.2, the UKCP09 Weather Generator can be requested to generate between 100 and 1000 runs, with a length of between 30 and 100 years (or any multiple of 10 within this range). Runs are produced both for the baseline time-slice and for a future representing a given time-slice and emissions scenario, for a given set of connecting 5x5km grid squares. Here, 100 runs each of 100-year length have been generated for an area covering each catchment, and the resulting time-series used to drive the hydrological model. The simulated flows have then been analysed, by fitting flood frequency curves to different lengths of the series; 30, 50, 70 and 90 years, counted from after the 5th year of each flow series (to allow a generous run-in period). The differences between (baseline and future) pairs of fitted flood frequency curves have then been calculated, at four return periods; 10, 50, 100 and 200 years. The distributions of these impacts from the 100 runs for each catchment, at each return period and for each length of data series, are shown in Figure 3.7.

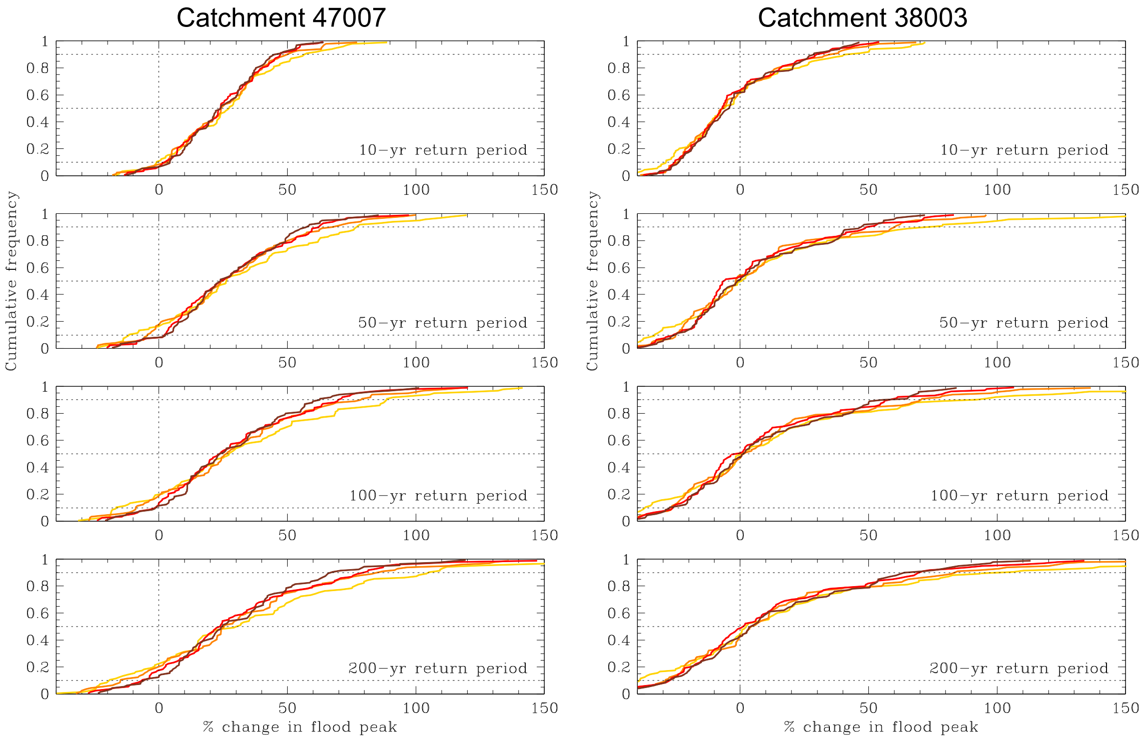


Figure 3.7 Impact cdfs for flood peaks at four return periods (10-, 50-, 100- and 200-years), using sub-series of increasing length from each of 100 Weather Generator time-series (each 100 years long) for the 2080s time-slices under the A1B emissions scenario: sub-series of length 30 years (gold), 50 years (orange), 70 years (red), 90 years (brown).

The results show that the use of longer time-series of Weather Generator data leads to a slight reduction in the range of simulated impacts for these two catchments, especially at higher return periods, but with very little difference in the median impact for either catchment. This suggests that the use of the standard 30-year time-series length may lead to a slight over-estimation of higher percentile impacts (those unlikely to be exceeded) and a slight under-estimation of lower percentile impacts (those almost certain to be exceeded) at higher return periods (compare yellow lines with brown lines in
Figure 3.7), but without affecting the estimation of the median impact significantly.

4 Discussion

This report has compared the use of three UKCP09 products (Sampled Data, Weather Generator time-series and RCM ensemble data), applied in different ways to estimate the impacts of climate change on flood frequency in Britain. The main aim (Section 2) was to compare the results from the use of the FD2020 response pattern method using Sampled Data with the more complex and time-consuming methods requiring specific hydrological modelling. This showed reasonable correspondence between the methods, suggesting that the simple FD2020 response pattern method provides a useful way of estimating the potential impacts of climate change on flood frequency. The method's strength is that alternative sets of scenarios, based on new sets of projections that may be produced at some point in the future or on projections for alternative time-slices and emissions scenarios, can be quickly and easily applied, without the need for a significant new modelling study. However, it is recommended that further hydrological modelling is carried out in some cases, for example for very vulnerable situations or where significant investment is planned, as in these cases the chance of greater impacts than those estimated by the FD2020 response pattern method may be of critical importance.

More generally, climate impact studies should not necessarily rely on the application of a single UKCP09 product, as each product has different strengths and weaknesses. The data requirements of different impact applications must also be borne in mind. While the Sampled Data currently provide the fullest coverage of climate modelling uncertainty, the range of impacts modelled using these data will not necessarily encompass the range modelled using other methods, particularly those using time-series.

This report also discusses various choices that have to be made when applying the different UKCP09 products (Section 2.3.2), which might be of use to other users considering how best to apply the data, potentially even for very different applications than modelling the impacts on flooding. In addition, alternative applications of some of the products are investigated (Section 3), illustrating the effect that some of the choices may have on the results.

Finally, it is important to note that any results using the UKCP09 projections are conditional on available data and resources. That is, the probabilities given by UKCP09 represent "the relative degree to which each possible climate outcome is supported by the evidence available, taking into account our current understanding of climate science and observations, as generated by the UKCP09 methodology." (Murphy *et al.* 2009, Section 1.1.1). Thus decision-making processes should be based around flexible options, allowing for future changes to projections and their application.

References

Bell, V.A, Gedney, N., Kay, A.L., Smith, R., Jones, R.G. and Moore, R.J. 2011. *Estimating potential evaporation from vegetated surfaces for water management impact assessments using climate model output.* Journal of Hydrometeorology, in press.

Bell, V.A. and Moore R.J. 1999. *An elevation-dependent snowmelt model for upland Britain.* Hydrological Processes, **13**, 1887-1903.

Crooks, S.M., Kay, A.L. and Reynard, N.S. 2009. *Regionalised impacts of climate change on flood flows: hydrological models, catchments and calibration.* Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, November 2009, 59pp.

Crooks, S.M. and Naden, P.S. 2007. *CLASSIC: a semi-distributed modelling system.* Hydrology and Earth System Sciences, **11**(1), 516-531.

Environment Agency, 2011. Preliminary Flood Risk Assessment (PFRA) - Annexes to the final guidance, Report GEHO1210BTHF-E-E, Environment Agency, Bristol.

Fowler, H. J., and R. L. Wilby, 2010. Detecting changes in seasonal precipitation extremes using regional climate model projections: Implications for managing fluvial flood risk, Water Resour. Res., 46, W03525, doi:10.1029/2008WR007636

Hannaford, J. and Marsh, T.J. 2008. High flow and flood trends in a network of undisturbed catchments in the UK. International Journal of Climatology, 28 (10), 1325 – 1338. 10.1002/joc.1643

IPCC, 2000. *Special report on emissions scenarios (SRES): A special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 599 pp.

Jenkins, G. J., Perry, M. C., and Prior, M. J., 2008. The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, UK.

Jones, P.D., Kilsby, C.G., Harpham, C., Glenis, V., Burton, A. 2009. *UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator.* University of Newcastle, UK.

Kay, A.L., Crooks, S. and Prudhomme, C. 2009. *Regionalised impacts of climate change on flood flows: Uncertainty analysis.* Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, November 2009, 71pp.

Kay, A.L., Reynard, N.S. and Jones, R.G. 2006. *RCM rainfall for UK flood frequency estimation. I. Method and validation*. Journal of Hydrology, 318, 151-162.

Moore, R.J. 1985. *The probability-distributed principle and runoff production at point and basin scales.* Hydrolog. Sci. J., **30**, 273-297.

Moore, R.J. 2007. *The PDM rainfall-runoff model.* Hydrology and Earth System Sciences, **11**(1), 483-499.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A. 2009. *UK Climate Projections Science Report: Climate change projections.* Met Office Hadley Centre, Exeter.

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andreassian, V., Anctil, F. and Loumagne, C. 2005. *Which potential evapotranspiration input for a lumped rainfall-runoff model?: Part 2 - Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling*. Journal of Hydrology, **303**(1-4): 290-306.

Prudhomme, C, Crooks, S.M. and Kay, A.L. 2009a. *Regionalised impacts of climate change on flood flows: Identification of flood response types for Britain.* Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, 47pp.

Prudhomme, C., Crooks, S., Kay, A.L. 2009b. Regionalised impacts of climate change on flood flows: Regionalising the flood response types in Britain. Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, November 2009, 48pp.

Prudhomme, C. and Reynard, N.S. 2009. *Regionalised impacts of climate change on flood flows: Rationale for definition of climate change scenarios and sensitivity framework*, Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, 34pp.

Reynard, N.S., Crooks, S.M. and Kay, A.L. 2004. *Impact of climate change on flood flows in river catchments.* Report to Department for Environment, Food and Rural Affairs and the Environment Agency, Technical Report W5-032/TR, CEH Wallingford, March 2004, 99pp.

Reynard, N.S., Crooks, S., Kay, A.L. and Prudhomme, C. 2009. *Regionalised impacts of climate change on flood flows.* Report to Department for Environment, Food and Rural Affairs, Technical Report FD2020, CEH Wallingford, November 2009, 113pp.

Robson, A. 2002. Evidence for trends in UK flooding, Phil. Trans. R. Soc. Lond. A 2002 360, 1327-1343, doi: 10.1098/rsta.2002.1003.

Sexton, D.M.H., Harris, G. and Murphy, J. 2010. *UKCP09: Spatially coherent projections*. *UK Climate Projections additional product report.* Met Office Hadley Centre, Exeter, November 2010, 19pp.

Thompson, N., Barrie, I.A. and Ayles, M. 1982. *The Meteorological Office Rainfall and Evaporation Calculation System: MORECS* (July 1981). Hydrological Memorandum No. 45, Met Office, Bracknell.
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