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Regionalised impacts of climate change on flood flows: rationale for climate change scenarios definition

FD2020 project note

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Executive summary

The climate change scenarios to be used within the project must capture the range of potential climatic changes expected to occur in the UK, including the large GCM uncertainty. This will allow the conclusions of the modelling exercise and regionalisation study to be as robust as possible, and provide a sound, science-base for subsequent guidance to advise policy makers.

Previous climate change studies relied only on projections from a few global (GCM) and regional (RCM) climate models, and thus could only capture a very limited part of the GCM uncertainty. The IPCC AR4 now provides data from 17 GCMs, all considered equally plausible representations of future climates. Outputs from all 17 will be incorporated in the novel methodological framework developed specifically for this project.

In addition to the limited number of GCMs, results obtained in previous studies are very closely linked to the specific version of each GCM, to the assumed greenhouse gas emission scenarios, and to the time horizons of the projections. This is very limiting because such a 'deterministic' approach does not allow for progress made in the formulation and parameterisation of the GCMs, their spatial resolution, or in the emission scenarios, to be incorporated in a straight, forward manner. New impact studies would be necessary for every new model version, an inefficient use of time and resources.

The definition of the factors of change, up to now considered as trivial, is in fact arbitrary and could show a potentially large variability. Relying on one single definition of the factors, such as the difference between [2071-2100] and [1961-1990] is therefore a risk, as it ignores an important uncertainty in climate change projections, resulting from natural climate variability. Scenarios of change for this project will be described through a harmonic function that represents the seasonal patterns of future changes in rainfall and temperature and smooths the variability due to the specific definition of reference and future climate averages when computing the change factor.

The selected domain of the new scenarios will be larger than the current limit of the IPCC-AR4 factors of change. It will be defined to be able to include changes that *may* be projected by new versions of the existing models, or from runs assuming different emission scenarios. The conclusions obtained at the end of the project should thus provide robust, long-lasting guidance to help identifying changes in flood risk.

This project presents a novel approach that deals with some of the limitations involved in scenarios development listed above. Within a sensitivity analysis framework, all catchments of UK will be driven by the same climate change scenarios, so that the variation in their response will only be due to differences in the catchments characteristics. The sensitivity framework will incorporate ranges shown from all IPCC AR4 GCM outputs available to date from the IPCC Data Distribution Centre, and for all time horizons and emission scenarios.

Contents

Executive summary iii
1. Introduction 1
2. Background, previous methodology and limitations 3
   2.1 Previous methodology 3
   2.2 Limitations 4
   2.3 Aim of the project 4
3. Rationale for new approach 7
4. Proposed methodology 9
   4.1 IPCC-AR4 climate projections: range and uncertainty 9
   4.2 Definition of monthly change factors 11
   4.3 Sensitivity analysis framework 14
5. Implementation of the sensitivity analysis 17
6. Next step 19
7. References 21

1. Introduction

This note, for the project FD2020 ‘Regionalised impacts of climate change on flood flows’, describes the progress to date on the definition of climate change scenarios to be considered for a comprehensive sensitivity analysis of responses of UK catchments to changed rainfall and temperature. A background on previous practices for flood impact and their limitations is given in Section 1, followed by the rationale for a new approach (Section 2). Section 3 describes the new methodology and Section 4 summarises its implementation.

2. Background, previous methodology and limitations

Current Defra/EA guidance requires all flood management strategies and schemes to allow for climate change by incorporating an increase in peak flows by up 20% over the next 50 years. This guidance applies across England and Wales, making no allowance for possible regional variation in climate change or catchment type.

2.1 Previous methodology

The study underpinning the national upper limit of a 20% increase of peak flood by 2050 relied on outputs from a limited number of catchments, and a limited number of global (GCM) and regional (RCM) climate model outputs used within a simple methodological framework (Reynard et al., 2004).

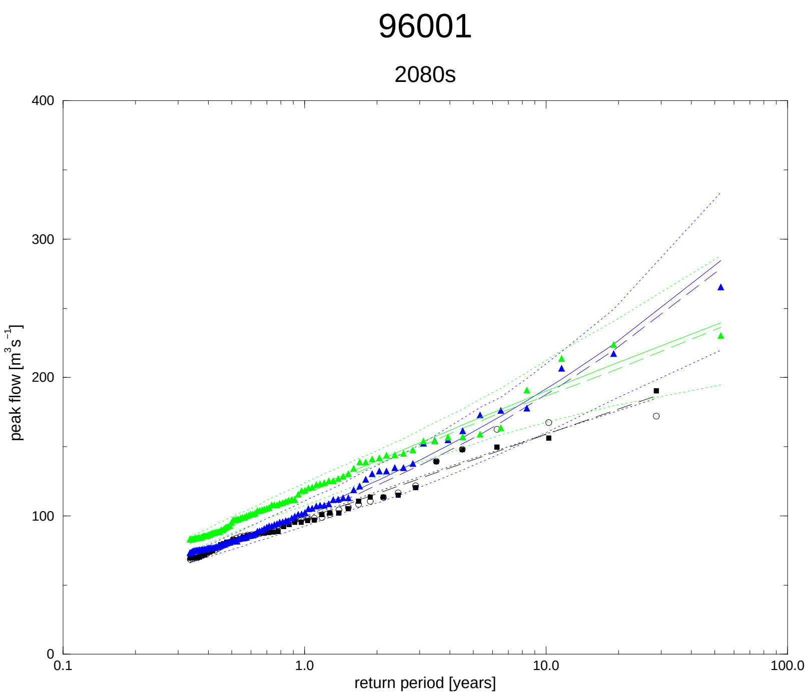

Figure 2.1 Example of flood frequency curve (Halladale @ Halladale) derived from observed flows (black) and modelled flows from 1961-1990 observed series (dashed black), from 1961-1990 RCM series, median and 90% confidence band from resampling (resp. solid, dashed and dotted blue), and from 2080s RCM series, median and 90% confidence band from resampling (resp. solid, dashed and dotted green) (from Reynard et al., 2004)

This simple methodological framework is as follows. First, scenarios describing future climate are derived either using climate model outputs directly (typically when considering RCM outputs), or downscaled using empirical (delta or factor of change methods, whether using proportional or more sophisticated techniques) or statistical approaches (such as statistical downscaling), both designed to correct the errors in the climate projections. Second, these scenarios are run through a continuous flow simulation model to provide 'future' flow series. The corresponding flood quantiles derived from these 'future' flow series are compared to the same quantiles derived from 'baseline' flow series to define the change in these quantiles. Uncertainty could be captured through resampling techniques to provide confidence bands associated with each individual scenario (e.g. Figure 2.1). This practice is still common in many climate change impacts studies (e.g. Fowler and Kilsby, 2007)

2.2 Limitations

This 'traditional' approach has a number of limitations that could be considered as 'risks' when guiding new policy, summarised below:

- Each calculated change in flood peak is tied to a single (or few) GCM output(s). However, the recent IPCC AR4 has made available outputs from 20 GCMs. Despite the large variations in their projections, they are all considered by the IPCC to be equally plausible. **Only considering a few cannot capture the known existing GCM uncertainty**
- Because of the limited number of scenarios, associated changes in peak flood are often misinterpreted as 'deterministic projections'. But in reality, they only illustrate a few possible representations of the future, **inconsistent with a probabilistic risk framework**
- Results depend on SRES greenhouse gases emission scenarios (i.e. how much CO_2 equivalent will be emitted to the atmosphere) used for the GCM runs. However, emission scenarios are highly uncertain as they are based on assumptions on global economy and societal changes, and are likely to be revised in due course, **thus making obsolete any results from earlier assumptions**
- Results are provided for fixed time horizons (i.e. when the associated changes are projected to happen). But (i) revised emissions scenarios could show faster/slower evolution, thus time-dependant results are to be avoided, (ii) decision makers may have a different time framework than the fixed 2020s; 2050s and 2080s of the IPCC, and (iii) the emergence of continuous transient projections of the IPCC-AR4 (great improvement from the time-slice and pattern-scaling approach of IPCC-TAR scenarios) is not fully exploited
- Each year, new climate scenarios are developed by climate research centres and universities, from up-to-date climate models incorporating the latest improvements in parameterisation and spatial resolution. **Studies relying on currently available GCM and RCM outputs may become obsolete each time a newer version of the climate models is developed**

2.3 Aim of the project

The FD2020 project will explore the dynamics of the relationships between climate change impacts on peak flows and the catchment characteristics. To achieve that aim, it is necessary to move away from individual climate-driven scenarios (linked to specific climate model projections and locations), and employ a generic technique for any catchment expected to be impacted by similar climatic changes, so that the resulting impacts on flood peaks are really characterised by the catchment properties. In other words, the project will explore the sensitivity of a whole range of catchments to a changing climate. This will be achieved not simply by undertaking a large, multi-catchment, multi-scenario climate change impact analysis, but in a ‘scenario neutral’ way.

Results will provide a wealth of information that can afterwards be reconsidered from the perspective of the individual, or multiple GCMs / RCMs. Specific scenarios can then be used to provide a policy maker with a potential “probability” of that change in flows occurring based on where the scenario sits within the wider “surface” of change indicated by the sensitivity analysis. This will inform decisions on issuing new policy statements or allowances for the management of these types of catchments under climate change.

Such a sensitivity analysis-type methodology will provide a more robust science base than previous methodologies, so that such regional policy can be developed.

3. Rationale for new approach

The novel approach developed is designed to limit the four risks described in Section 2.2 through a sensitivity analysis framework. The framework will be explained in more detail in the next part, but its key advantages are summarised here:

- The sensitivity domain will cover over the entire spectrum of the latest IPCC-AR4 GCM outputs (17 GCMs) (and possibly RCM data from PRUDENCE) **thus encompassing the full range of uncertainty as described by available GCM and RCM outputs**
- The sensitivity domain will include extra values at both ends of the ‘IPCC’ spectrum to plan for potential new ‘extreme’ projections. **This will ensure results from FD2020 comply with any future climate modelling progress**
- **The sensitivity domain is compatible with a probabilistic framework** as it enables to attach conditional likelihood and probability to any results obtained within the domain
- The sensitivity domain will cover climate projections associated with the full range of greenhouse gases emissions for which IPCC-AR4 scenarios are available to date (including the 2080s time horizon where changes are the greatest) **thus capturing any changes expected to occur at any time horizon prior to 2100**
- The choice of the sensitivity domain will remain compatible with potential revisions in future greenhouse gases emissions, **thus conclusions will remain valid even when new emission assumptions are made**
- Limited, carefully chosen case studies within the sensitivity domain will assess changes from a range of GCM and emission scenarios that no other research study on floods and climate change to date has ever considered, thus **placing the conclusions and resulting policy guidance at the forefront of research into changing flood risk under climate change**.

4. Proposed methodology

The project's objective is to provide a fuller description of a whole range of catchment's impacts from changes to a range of different plausible climates. It will also allow identify critical thresholds for which catchment's response becomes a serious management problem, thus allowing better preparedness. In this context, the sensitivity domain for the analysis should capture as much as possible different change patterns (seasonal and due to GCM variability).

4.1 IPCC-AR4 climate projections: range and uncertainty

The IPCC-AR4 Data Distribution Centre provides outputs of 17 GCMs for different climate variables, including rainfall and temperature[1]. Two families of multi-decadal runs are available for each GCM, one corresponding to greenhouse gases concentrations observed in the 19th and 20th centuries (control run) and one corresponding to greenhouse gases concentration as described by some SRES emission scenarios (IPCC, 2000) (future run).

To undertake the sensitivity analysis, sets of scenarios need to be chosen:

- For the impact of changes due to catchment characteristics to be comparable from one catchment to another, it is necessary to input the same drivers, i.e. the sensitivity domain should be identical for all catchments in the UK
- Some GCM and RCM projections (e.g. UKCIP02 scenarios) show a distinct pattern of changes between the north and the south of UK. In particular, the sign of changes in summer rainfall is different: increase in the north and decrease in the south. Within smaller regions, it is the magnitude, and not the sign of changes, that varies (Hulme et al., 2002)
- Two distinct sensitivity domains have been selected as examples of the contrasting projections in North and South of the UK.

GCMs are notorious for not being able to reproduce average rainfall and temperature patterns at regional scales. Figure 4.1 shows examples of control run outputs for north of UK, compared to the 1961-1990 monthly mean values from the observed climatology of the Climate Research Unit (CRU) (New et al., 1999).

Each panel represents a calendar month, with monthly GCM projections for the entire control run (dots), and running averages (30-year: black curves; 10 to 40 years, grey curves). The red horizontal line shows CRU monthly climatology. The uncertainty due to the length of the running average (spread of the grey lines) is much smaller than the bias in the models (departure from the CRU line in red).

[1] Latest download in November 2007

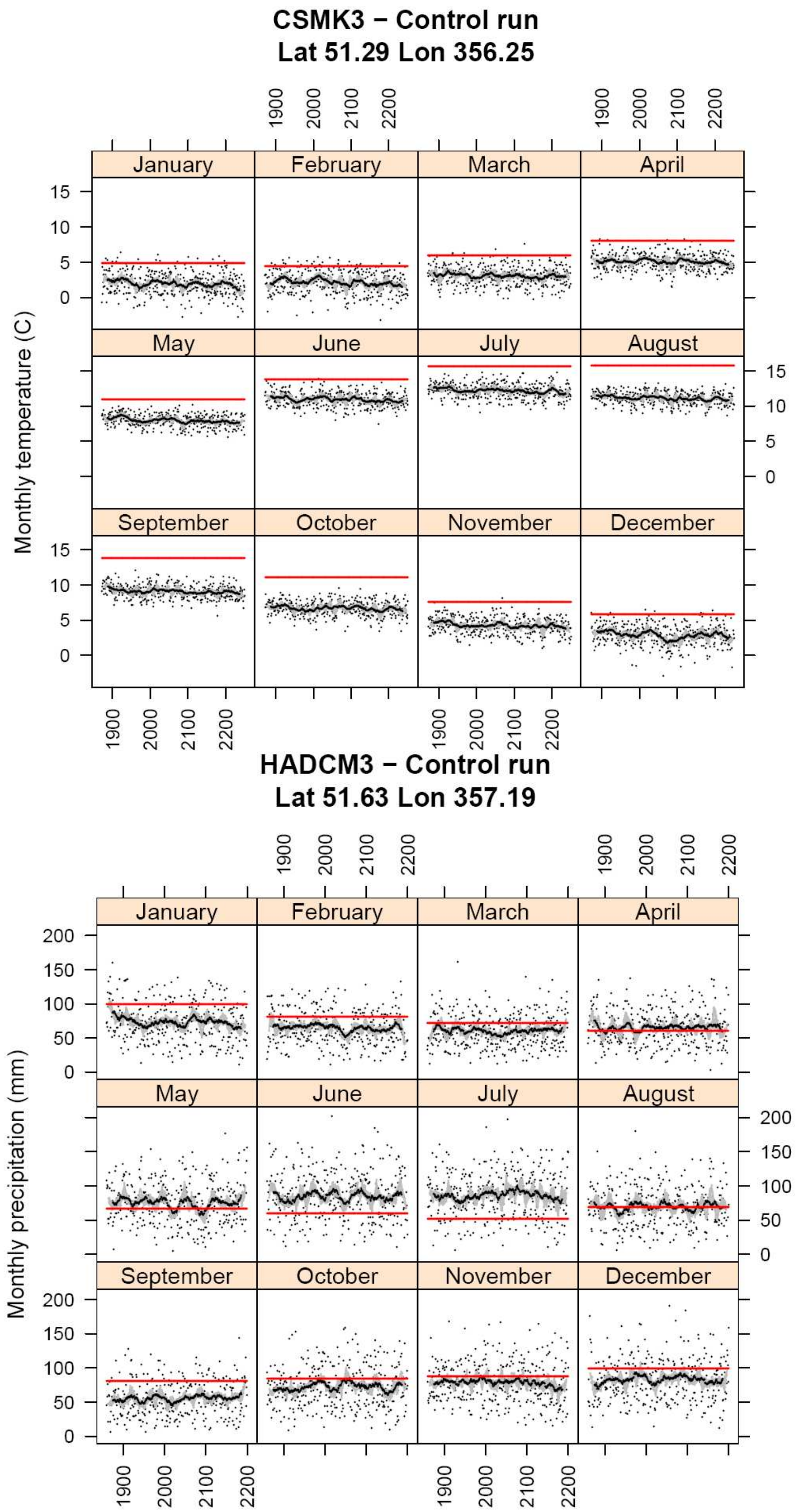

Figure 4.1 Examples of GCM monthly temperature (top) and rainfall (bottom) control series for two cells, and corresponding running averages (30-year: black; 10 to 40 years: grey) with the CRU climatology 1961-1990 (horizontal line)

4.2 Definition of monthly factors of change

Due to GCM biases, the direct use of GCM output is inappropriate. For that reason, techniques to generate synthetic climate series, conditioned from GCM outputs, have been developed. Our approach is adapted from the simple delta (or factor) change method, as a benchmark for the rest of the study. Its main assumption is that biases in the calculation of the climate are of the same order of magnitude for baseline as well as future climates, and thus changes in GCM outputs for different time horizons are representative of the evolution of the climate, and are without bias. More sophisticated techniques, such as statistical or dynamical downscaling, provide local bias correction but depend on the GCM run, and are inconsistent with the region-based sensitivity study approach developed here. Recent attempts to construct probabilistic climate change scenarios for hydrological impact assessments are based on a relatively small sample of downscaled GCMs (Wilby and Harris, 2006). Delta change method is one of the most widely used technique in climate change study to-date, and is consistent with UKCIP02 scenarios as well as the forecoming UKCIP08 scenarios.

Three assumptions underline the definition of factors of changes

- **Definition of the baseline period**: most studies assume the baseline 1961-1990 as reference. However, this period does not necessarily cover observation periods that can include measures from the early 1950s or the late 1990s.
- **Definition of the future period**: to be comparable with the baseline period, it must be of same length. Previous climate factors of change, such as UKCIP02, or derived from IPCC-TAR, are based on the fixed periods 2011-2030; 2041-2060; 2071-2100
- **Length of the period of reference**. WMO suggests a 30-year period as reference climate, as it is expected to contain enough of the natural variability to provide a robust estimate of the mean climate

As seen from Figure 4.1, the value of a 30-year average varies with the period of reference (shown by the variability of the black line): the choice of 1961-1990 as reference value could be considered as arbitrary. Moreover, GCMs are designed to represent the average climate and not the weather (i.e. the inter-annual variation that exists in climatic variables such as rainfall). The years associated with the control run outputs are only provided as indication, but the models are not intended to reproduce exactly the observed events and their date[2]. Any choice of a 30-year reference period is therefore arbitrary.

Because of the large inter annual variability, especially in rainfall totals, the range in factors estimated from different periods can be significant. For example, Figure 4.2 shows rainfall changes calculated as the difference between the fixed [2071-2100] period of the future run, and each of the 30-year periods resampled from within the control run within [1951-2000]. This

[2] Some GCM produce control run outputs referring to dates outside the 20th century: eg. GFCM21 control is from year 000 to year 500 and MIMR control run is from 2300 to 2800.

reference [1951-2000] was chosen as it includes most of the recording periods of river flow series used in climate change impact studies. For each month, the box plot shows the median (thick grey line), second and third quartiles of the differences (in percent for rainfall, and degree for temperature); the bars outside the boxes show 1.5 times the interquartile range, the extra circles representing the full extent of the data. The range in the factors varies from one month to the other and can exceed 20%. As comparison, the dotted black line shows the factor defined strictly as IPCC-TAR, i.e. [2071-2100] minus [1961-1990]. It is sometimes outside the 50% band around the median of all the other factors (dotted line outside the box), and does not incorporate any information on the uncertainty in defining the factors of change.

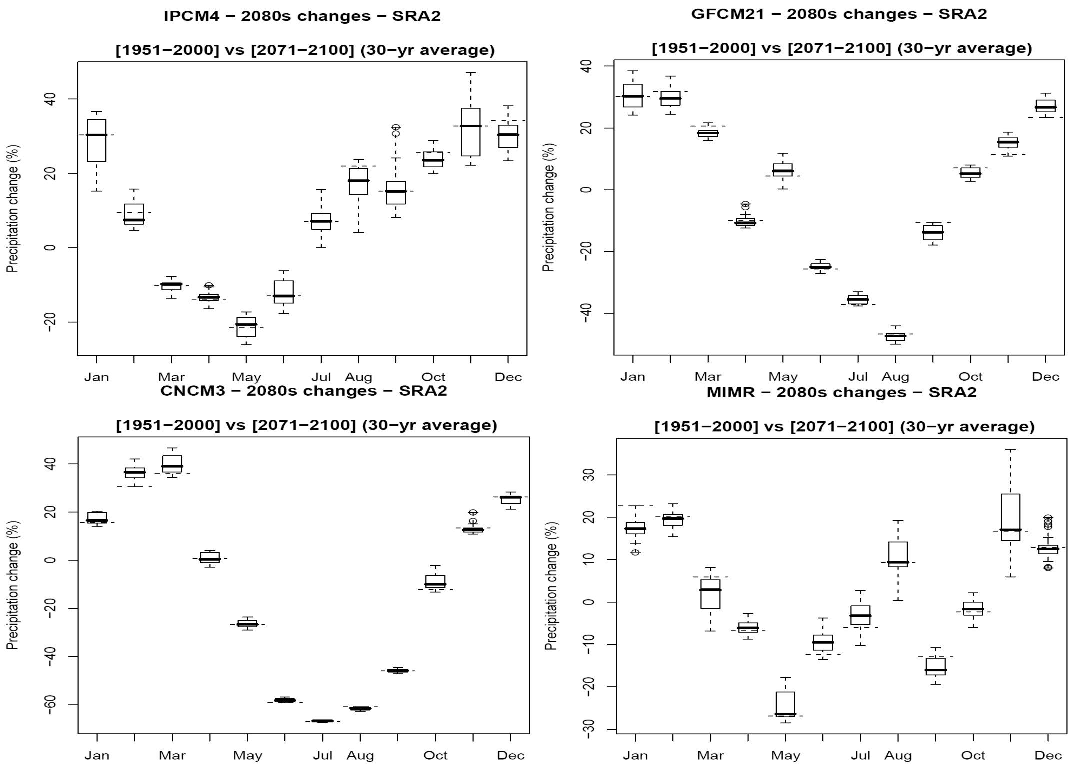

Figure 4.2. Factors of change for outputs for a Northern cell (top) and a Southern cell (bottom) based on 30-year average for the 2080s: [2071-2100] compared to [1961-1990] (dotted back line) or any 30-year resampled from within [1951-2000] (box plots and circles: first, second and third quartiles: rectangle; 1.5 times interquartile range: wiskers; outliers: circles).

A shorter reference period of 10 years is more consistent with the length of observations generally available for hydrological modelling, and thus could be considered as a more appropriate reference. Factors derived from 10-year averages within [1951-2000] (the future period is [2081-2090]) show an even larger variability illustrating the natural variability (Figure 4.3).

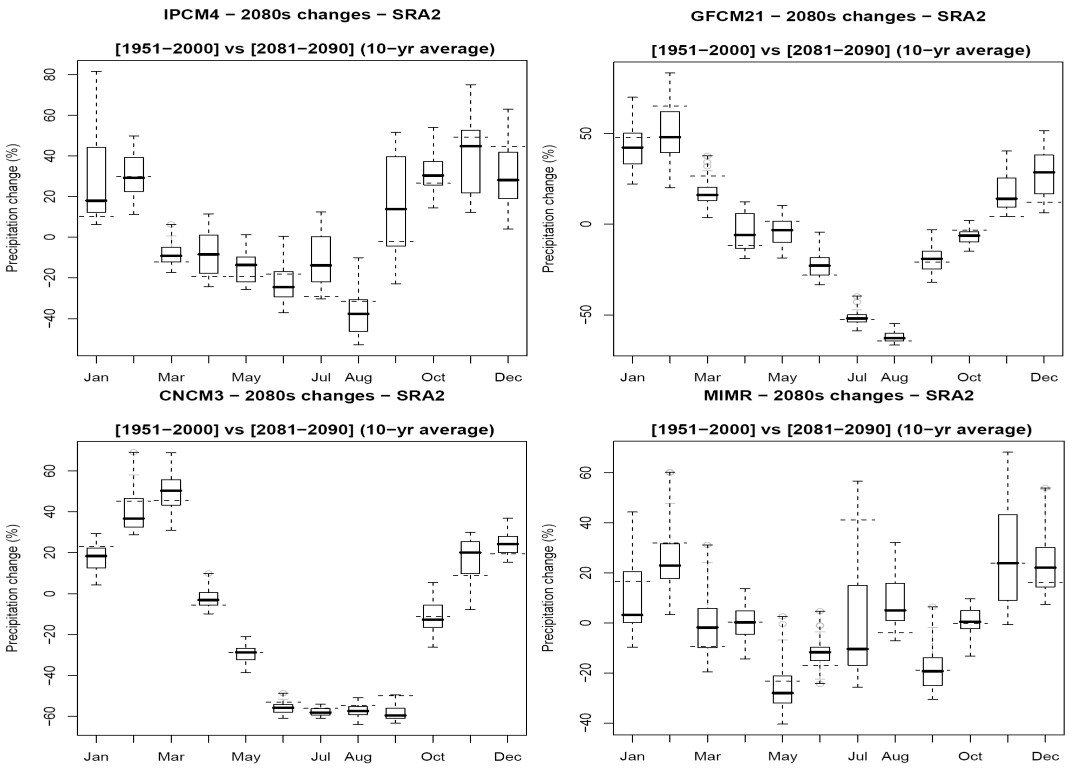

Figure 4.3. as Figure 4.2 but with 10-year averages, with future as [2081-2090]. The dashed line is based on the [1971-1980] average

The dependence of factors of change on the selected averaging period also exists for the future. In a context of non-stationarity, spanning over a longer period than 30 years (e.g. 2061-2100) to sample different future 30-year averages would risk mixing natural variability with the climate change signal. It is generally considered that up to 30 years, the climate signal is too small compared to natural variability to introduce a bias in the calculation of the average. Shorter periods, such as a 10-year period would only integrate a very weak climate change signal, but would be too short to capture natural variability. A 20-year period provides a good compromise and was considered here. Figure 4.4 shows the range in factors when calculated from a 20-year period, as the difference between any 20-year period within [1951-2000] and any 20-year period within [2071-2100], all these randomnly resampled with replacement. Ranges in factors of change are larger than those of Figure 4.2 as uncertainty in the mean climate of both baseline and future is accounted for.

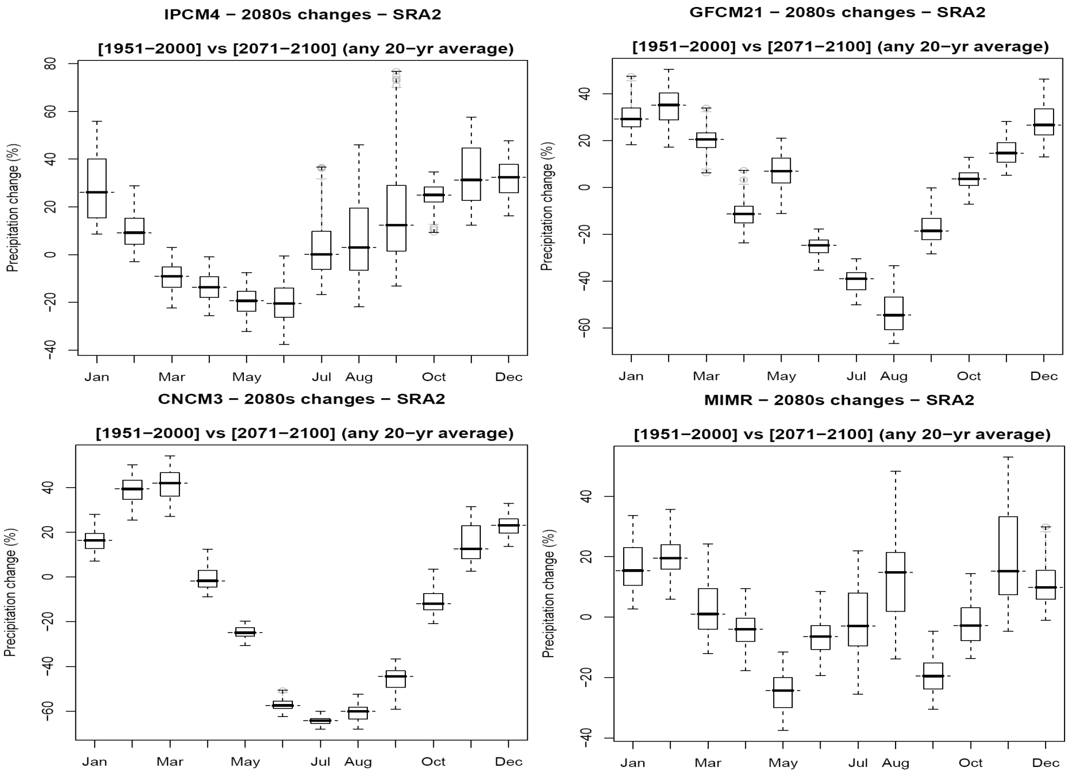

Figure 4.4. As Figure 4.2 but for 20-year averages for any baseline within [1951-2000] and any future within [2071-2100]

The definition of the factors of change, up to now considered as trivial, is in fact arbitrary and could show a potentially large variability. Relying on one single definition of the factors, such as the difference between [2071-2100] and [1961-1990] is therefore a risk, as it ignores an important uncertainty in climate change projections, resulting from natural climate variability. Any factor of change within the boxes presented in Figure 4.4 would be equally valid, and legitimate to use in a climate change impact study.

4.3 Sensitivity analysis framework

Factors of change vary seasonally as well between GCMs: all GCM outputs show seasonal patterns in the changes in rainfall and precipitation. A sensitivity analysis such as implemented by Jones et al. (2006), which relies on mean annual changes, would hide very important changes in the hydrological cycle. A shift in the rainfall season, or a lengthening of dry season, could have important consequences in the seasonal distribution of the soil moisture, and in turn, on the capacity for a catchment to absorb rainfall or alternatively, to be saturated and generate larger floods.

Considering monthly changes in the sensitivity study for our variables of interest (precipitation, temperature and evapotranspiration) would lead to a 12 months x 3 variables = 36 dimension matrix, extremely difficult to analyse and interpret. Instead, the seasonal pattern of change factor is described here by a harmonic function. Figure 4.5 shows, for different GCMs, a harmonic function fitted on the median of change factors derived from 20-year averages incorporating natural variability for both baseline and future time horizons (e.g. similar to Figure 4.4). The harmonic function has only three parameters: the maximum magnitude in the sinusoid, the deviation from the annual mean change, and the delay in the peak change from January. It is an efficient representation of the 12 monthly change factors, as it generally goes through the possible change factors of most months, as represented by the box-and-wiskers plots. With a harmonic function describing the monthly change factors, the sensitivity function domain that needs to be considered is reduced to a 3 parameters x 3 variables = 9 dimension matrix.

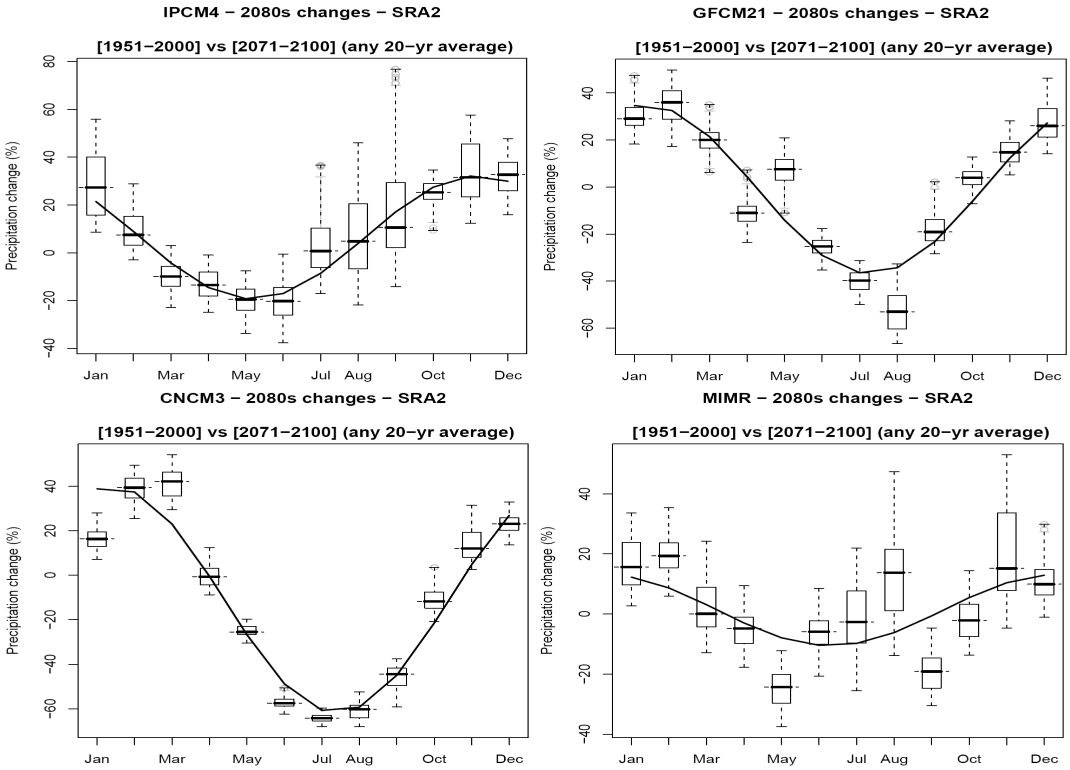

Figure 4.5. Same as Figure 4.4 but with a harmonic function fitted to describe the factors of change

5. Implementation of the sensitivity analysis

Potential evapotranspiration PE is usually estimated in the UK from the MORECS monthly time series (Thomson et al., 1981). To be consistent with observed time series used in the hydrological modelling, it would be preferable to use a similar approach to calculate future (and control) GCM-PE, such as for example the Penman-Montieth formula (Allen et al., 1994). However, variables necessary for estimating Penman-Montieth PE are not all available from all GCMs. Temperature, on the other hand, is a reliable GCM output. Some more simple PE estimation equations exist, only based on the variation of the temperature, and could be used as alternative from Penman-Montieth derived PE formula. If the sensitivity domain of PE is large enough, it is likely it would also include potential changes that could be estimated from Penman-Montieth GCM-PE.

Changes derived from simple temperature-based equations for PE have the advantage of:

- Encompassing the full range of IPCC-AR4, rather than only a small sub-selection
- Avoiding the large errors in some GCM climate variables necessary for physically-based PE estimation
- Reducing the sensitivity study to a 3 parameters x 2 variables = 6 dimension matrix, facilitating the interpretation of the results

6. Next steps

This project note provides the background for the development of a new generation of climate change scenarios. Instead of defining monthly change factors, as it is traditionally done, seasonal pattern of change in climatic variables are described by a single harmonic function. This allows undertaking a sensitivity analysis of the response of catchments to a change of climate, that includes the large uncertainty due to GCM outputs, but also captures the seasonal variability in the changes.

The next step will be to define a sensitivity domain that captures all the uncertainties for rainfall and temperature. This domain will be used as benchmark to perturb catchment climate series, prior to the hydrological modelling under changed conditions.

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