Risk Management R&D Programme

Regionalised Impacts of Climate Change on Flood Flows:

Rationale for Definition of Climate Change Scenarios and Sensitivity Framework

R&D Milestone Report FD2020/MR2

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

Milestone report 2 – Project FD2020

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Statement of use
The primary objective of FD2020 ‘Regionalised impacts of climate change on flood flows’ was to assess the suitability of the October 2006 FCDPAG3 guidance on climate change. This guidance requires an allowance of 20% to be added to peak flows for any period between 2025 and 2115 for any location across Britain. This guidance was considered precautionary and its derivation reflected the evidence available at that time. FD2020 has been designed to increase this evidence base and the research findings suggest that regional, rather than national, guidelines for changes to peak flows due to climate change might be more appropriate.

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Executive summary

The primary objective of FD2020 ‘Regionalising the impacts of climate change on flood flows’ was to assess the suitability of current FCDPAG3 guidance given the advances in climate change science since its publication. PAG3 requires an allowance of 20% to be added to peak flows for any period between 2025 and 2115 for any location across Britain. This guidance was considered a precautionary value and its derivation reflected the evidence available at that time. FD2020 has been designed to increase this evidence base, and it is anticipated that the research will lead to the development of regional, rather than national, guidelines for changes to peak flows due to climate change.

A **scenario-neutral** approach based on a broad sensitivity analysis to determine catchment response to changes in climate as chosen for FD2020. The method separates the climate change that a catchment may be exposed to **(the hazard)** from the catchment response (change in peak flows) to changes in the climate **(the vulnerability)**. By combining current understanding of climate change likelihood (the ‘hazard’) with the vulnerability of a given catchment, it is possible to evaluate the **risk** of flood flow changes. The vulnerability of a catchment is to be characterised in two steps: first, the response of a set of catchment’s to a range of climatic changes are modelled, then analysed for similarity, and characterised according to catchment properties. This is done by defining a sensitivity framework of changes to the mean and seasonality of precipitation and temperature and modelling the response of each catchment within this fixed framework.

To properly understand the relationship between catchment properties, climate changes and changes in flood flows, it is essential that the considered scenarios capture the range of potential climatic changes expected to occur in Great Britain, including the large GCM (Global Climate Model) uncertainty. This means the vulnerability assessment (or the conclusions of the modelling exercise and regionalisation study) will be as robust as possible, and provide a sound science-base for subsequent policy guidance to the flood management community.

This project report describes the rationale and the development of the climate change scenarios used in the project FD2020. The objective of this module of work was to develop a methodology to conceptualise how a catchment’s **vulnerability** (in terms of change in its flood regime under climate change) could be evaluated. This requires the identification of a range of climate change scenarios to be used in a comprehensive yet manageable evaluation of future river flood flows, which was guided by, but not limited to, current predictions of future climatic changes. This methodology is also designed to characterise the climatic change **hazard**, so that it can be compared with the catchments vulnerability to changes.

Previous climate change studies relied only on projections from a few global (GCM) and regional climate models (RCMs), 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 have been 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.

Current GCMs provide information on monthly mean changes, but the range of projections is wide and varies by region, and impacts on flood flows are therefore also varied. In order to separate the variation in the response due to catchment properties from that due to climate drivers (specifically precipitation, temperature and potential evapotranspiration), it is necessary to impose the same climate driver changes to a range of catchments over Great Britain. This is best achieved through a sensitivity framework. Due to the importance of seasonality in the hydrological cycle, seasonal variation must also be considered in addition to mean annual changes. Considering a comprehensive range of monthly changes in the three variables of interest would be very complex, and lead to a 12x3 dimension sensitivity space. This report evaluates how to reduce the dimensionality of the sensitivity space without losing important details, and leads to the concept of using a harmonic function as a description of the seasonal pattern of future climate change scenarios.

Projections from 17 GCMs, following 3 emission pathways, from the IPCC-AR4 were analysed for all land cells over Britain, and harmonic function parameters identified. The monthly changes in precipitation almost always show a peak in winter, while for temperature the peak might fall in either the winter or the summer. A final eight scenarios for temperature were selected. They are associated with a two-dimensional sensitivity space describing 525 precipitation scenarios built on the results obtained across Great Britain. This sensitivity space defines changes in precipitation varying between an annual reduction of 40% to an annual increase of 60%, combined with an additional seasonality of change between 0 and 120%.

The selected domain of the new scenarios is larger than the current limit of the IPCC-AR4 factors of change. It is 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 of this project should thus provide robust, long-lasting guidance to help identify changes in flood risk.

This project presents a novel approach that deals with some of the limitations involved in scenario development listed above. Within a sensitivity analysis framework, all of the project’s catchments 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.

Contents

1. Introduction

This milestone report for project FD2020 ‘Regionalised impacts of climate change on flood flows’ describes the rationale for the definition of climate change scenarios. In particular, it defines the changes in precipitation and temperature to be explored in a comprehensive sensitivity analysis of responses of British catchments to changed climate. A background on previous practices used for investigating climate change impacts on high flows, and their limitations, is given in Section 2, followed by the rationale for this new approach (Section 3). Section 4 describes the new methodology, Section 5 summarises the results obtained in Great Britain and Section 5.4 presents how changes in Potential Evapotranspiration are evaluated. The implementation of the methodology and the definition of the sensitivity domain are provided in Section 6, followed by its limitations (Section 6.3). Section 6.4 summarises the report.

1.1 Project Context

Current Defra / Environment Agency guidance (PAG3 supplementary note) requires all flood management plans to allow for climate change by incorporating, within a sensitivity analysis, an increase in river flows of up 20% over the next 50 years. This guidance is the same for all of England and Wales, making no allowance for regional variation in climate change or catchment type. This is because the underpinning science has not been able to resolve the spatial distribution of climate change impact on flood flows with enough confidence to set such policy regionally. The recommendation for a 20% allowance was first raised in 1999 for MAFF and subsequently reviewed following the release of the UKCIP02 scenarios.

Defra and the Environment Agency have procured this project (FD2020) to provide more rigorous science evidence to consider whether the guidance within the PAG3 supplementary note can be revised. Although the 20% figure is a memorable target, there is the risk that it leads to a significant under- or over-estimating of future flood risk, and as yet there is not the confidence in the science evidence to support significant investment in adapting to future river flows above the current sensitivity approach. Ultimately, this may lead to the country being under-prepared for the future, a situation that must be quickly addressed if we are to put in place the measures to reduce the impact of river flooding driven by climate change.

The objectives of the FD2020 project are:

- Investigate the impact of climate change on a number of British catchments to assess the suitability of the PAG3 20% climate change allowance for river flows, given scientific developments since 2002;
- Investigate catchment response to climate change to identify any potential similarities such that the PAG3 nationwide allowance could be regionalised (the term regionalised is not limited here to location and could equally be a function of any catchment characteristic);

- Investigate the uncertainty in understanding changes to river flows from climate change

1.2 Context for this Project note

The objectives of the work presented in this project note are:

- To develop an approach for the representation of climate change such that the dynamics of the relationship between climate change and peak river flows can be fully explored;
- To develop an approach that has longevity beyond the length of this project, or the lifetime of the latest generation of climate model results.

This project report describes the rationale and the development of the climate change scenarios used in the project FD2020. The objective of this module of work was to develop a methodology to conceptualise how a catchment's **vulnerability** (in terms of change in its flood regime under climate change) could be evaluated. This requires the identification of a range of climate change scenarios to be used in a comprehensive yet manageable evaluation of future river flood flows, which was guided by, but not limited to, current predictions of future climatic changes.

2. Background, previous methodology and limitations

Current Defra/Environment Agency guidance (FCDPAG3) requires all flood management strategies and schemes to be tested through the application of a sensitivity analysis allowing for climate change by incorporating an increase in peak flows of up to 20% over the next 50 years [and beyond to 2115]. This guidance is applied uniformly 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 in a simple methodological framework such as reported in Reynard et al. (2004).

This simple methodological framework is as follows. First, scenarios describing future climate are derived either using climate model outputs directly (typical when RCM outputs are used), or downscaled using empirical (delta or factor of change methods, whether using proportional or more sophisticated techniques) or statistical approaches, both designed to correct the errors in the climate projections. Second, these scenarios are run through a continuous river flow simulation model to provide estimations of ‘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. 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 Benefits

Traditional impact studies are an important source of information for policy makers, specifically:

- Climate change impact studies provide **in-depth analysis of the response of the considered catchments to some climate change scenarios**, ideally using the methodology most appropriate locally;
- The methodology is clear, well tested, and uses referenced climate model outputs. **Results provide legitimacy and traceability to potential resulting decisions.**

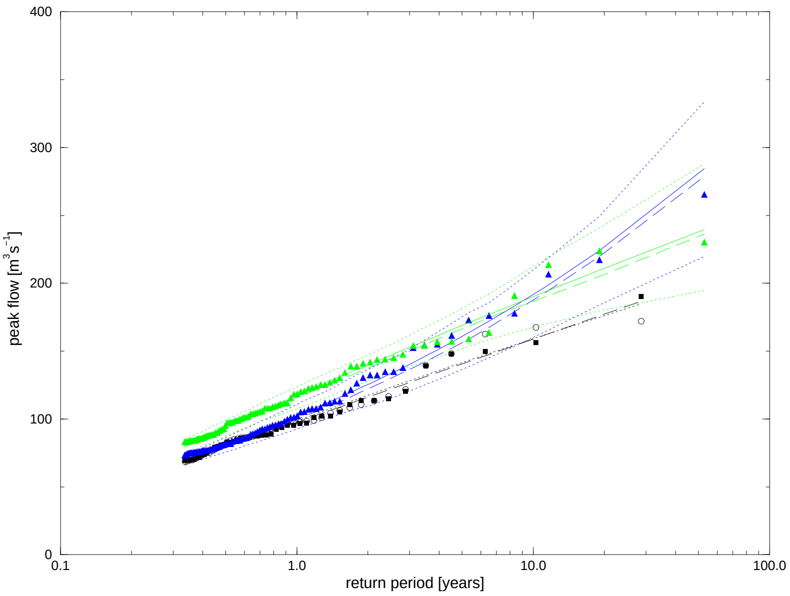

Figure 2.1 Example of flood frequency curves (Halladale @ Halladale) derived from observed flows (dotted black) and modelled flows from 1985-2001 observed series (dashed black), from 1961-1990 RCM series, median and 90% confidence band from resampling (resp. solid, dashed and dotted blue), and from 2071-2100 RCM series, median and 90% confidence band from resampling (resp. solid, dashed and dotted green) from Reynard et al. (2004)

2.3 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). In the UK, standard practice usually relied on UKCIP02 or preceding UKCIP98 scenarios, based on a single GCM. However, the recent IPCC AR4 has made available outputs from 17 GCMs. Despite the large variations in their projections, they are all considered by the IPCC to be equally plausible. **Only considering a few GCMS cannot, therefore, capture the all existing GCM uncertainty;**
- Because of the limited number of scenarios, associated changes in peak flows 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 gases 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 socio-economic development, and are likely to be revised in the future, **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, or slower evolution, thus time-dependant results are to be treated with caution, (ii) decision-makers may have a different time frame than the fixed 2020s; 2050s and 2080s traditionally used by the IPCC, and (iii) the emergence of continuous transient projections of the IPCC-AR4 (representing a 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;**
- **Impact studies are usually undertaken for a small number of catchments, each run with different climate change scenarios**. While this ensures the regional variation in climate change scenarios are taken into account, **this procedure limits a rigorous investigation of catchment/climate dynamics** and in particular whether catchment properties play a major role in the response to climate change drivers.

3. Project’s aim and rationale for new approach

3.1 Aim of the project

As described in section 1.1, this project will explore the dynamics of the relationships between climate change impacts on peak flows and catchment characteristics. To achieve this, 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 so that the resulting impacts on peak flows are characterised by the catchment properties. In other words, the project will explore the sensitivity of a 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 change in peak flows based on where the scenario lies 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, delivering evidence to support, or not, changes to the current guidelines on climate change for flood management.

3.2 Rationale for the new approach

The novel approach being developed for this project is designed to limit the six risks described in Section 2.3, through a sensitivity analysis framework. The framework is explained in more detail in the next section, but some key advantages are summarised here:

- The sensitivity domain covers more than the entire spectrum of the latest IPCC-AR4 GCM outputs (17 GCMs), as well as other projections such as outputs from the PRUDENCE project, **thus encompassing the full range of uncertainty as described by currently available GCM and RCM outputs;**
- The sensitivity domain includes extra values at both ends of the ‘IPCC’ spectrum to plan for potential new ‘extreme’ projections. **This means that results from FD2020 are likely to remain appropriate even with future development and improvement in global climate modelling capability;**
- **The sensitivity domain is compatible with a probabilistic framework** as it enables an assessment of the conditional likelihood and probability of any results obtained within the domain;
- The sensitivity domain covers 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 up to and including 2100**

- The choice of the sensitivity domain remains compatible with potential revisions in future greenhouse gas emissions, **thus conclusions will remain valid even when new emission assumptions are used;**
- 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 considered, thus **placing the conclusions and resulting policy guidance at the forefront of research into changing flood risk under climate change**.

4. Proposed methodology

To achieve the stated objectives, the project needs to provide a comprehensive assessment of a wide range of catchment impacts from a spectrum of plausible climatic changes. It will also allow the identification of critical thresholds beyond which catchment responses to climate change might become a serious management problem, thus allowing for better preparedness. In this context, the sensitivity domain for the analysis should capture as much as possible different change patterns (seasonal and those due to GCM variability).

4.1 IPCC-AR4 climate projections: range and uncertainty

The IPCC-AR4 Data Distribution Centre provides outputs from 17 GCMs for a range of 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 gas 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);
- For the initial exploratory analysis, locations have been selected as examples of the contrasting projections in the 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 the north of the 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).

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[1] Latest download in November 2007

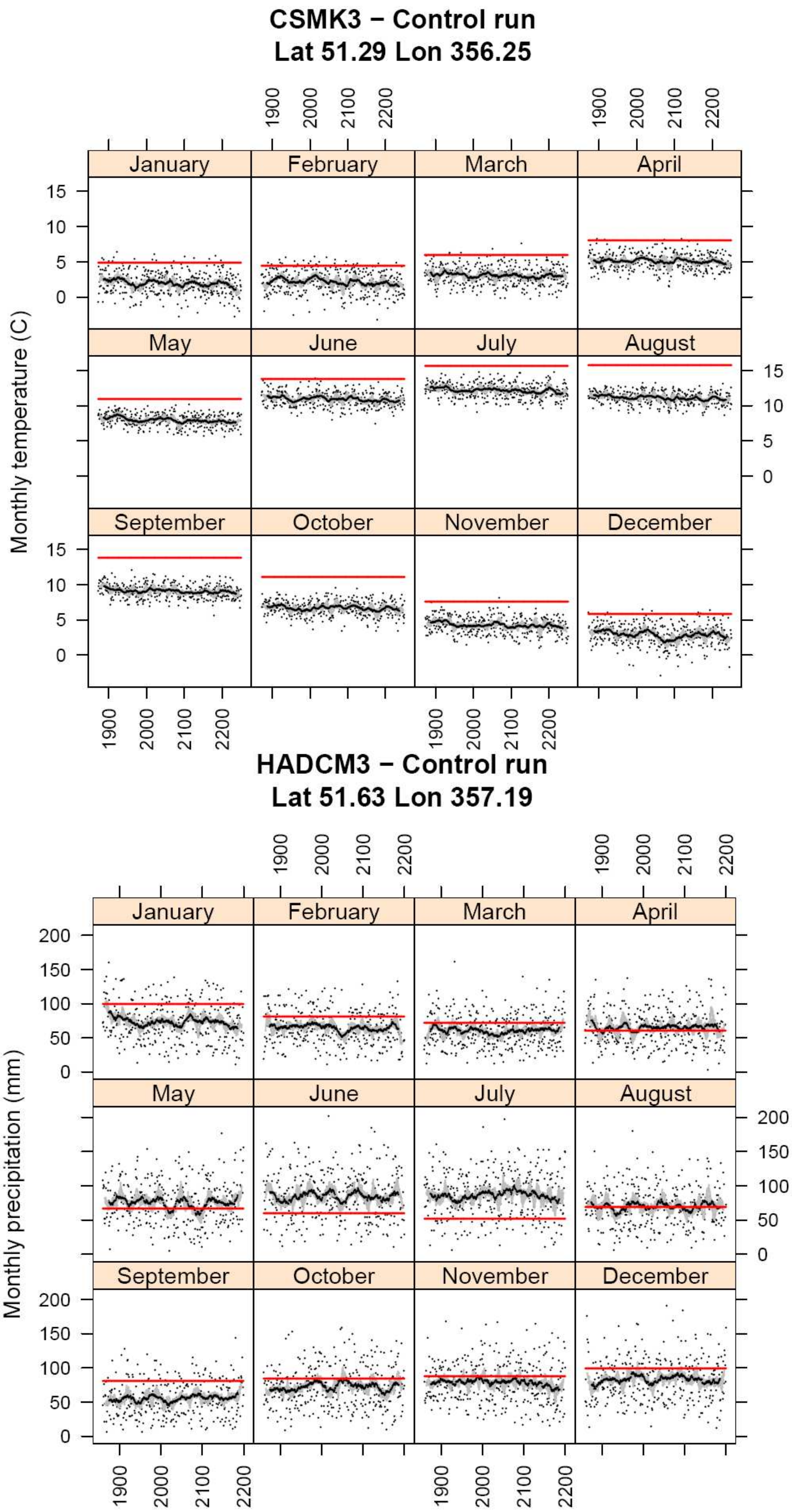

Figure 4.1 Examples of GCM monthly temperature (top) and rainfall (bottom) control series for two cells, and corresponding running averages (30-year: black; 10 to 40 years: grey) with the CRU climatology 1961-1990 (horizontal red line)

4.2 Definition of monthly factors of change

Due to GCM biases, the direct use of GCM output is not considered appropriate. For this 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 the baseline as for the 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). The delta change method is one of the most widely used techniques in climate change studies to-date, and is consistent with both the UKCIP02 and UKCP09 scenarios.

Three assumptions underline the definition of factors of changes:

- **Definition of the baseline period**: most studies assume the baseline 1961-1990 as a reference. However, this period does not necessarily cover the observation period, which can include data from the 1950s or 1990s.
- **Definition of the future period**: to be comparable with the baseline period, the future analysis period must be the same length. Previous climate factors of change, such as UKCIP02, or derived from IPCC-TAR, are based on the fixed periods 2011-2040; 2041-2070; 2071-2100.
- **Length of the period of reference**. World Meteorological Organization suggests a 30-year period as a 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 the reference value might 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 an indication as the models are not intended to reproduce exactly the observed events and their precise dates[2]. Any choice of a 30-year reference period is, therefore, also 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

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[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.

periods resampled from within the control run within [1951-2000]. This 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), first and third quartiles of the differences (boxes, in percent for rainfall and degrees for temperature); the bars outside the boxes show 1.5 times the interquartile range; the extra circles represent the full extent of the data. The range in the factors varies from month to month, and can exceed 20%. In 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 (i.e. the dotted line is outside the box), and does not incorporate any information on the uncertainty in defining the factors of change.

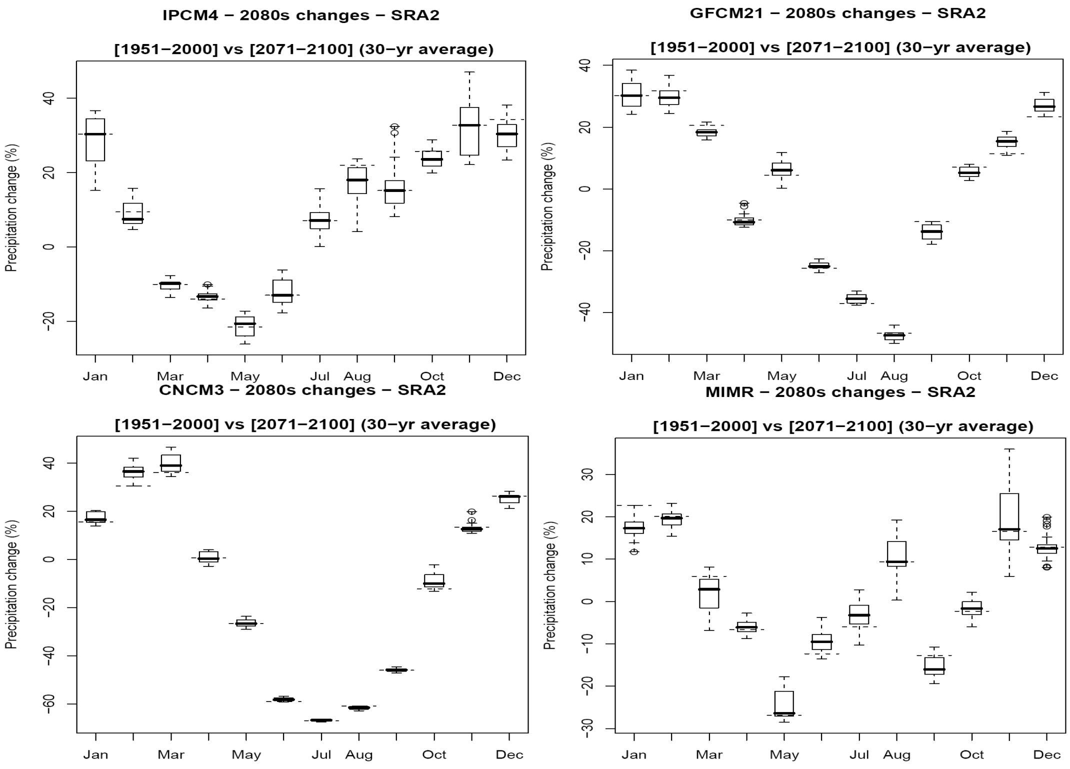


Figure 4.2 Factors of change for outputs for a Northern cell (top) and a Southern cell (bottom) based on 30-year average for the 2080s: [2071-2100] compared to [1961-1990] (dotted back line) or any 30-year resampled from within [1951-2000] (box plots and circles: first, second and third quartiles: rectangle; 1.5 times interquartile range: whiskers; outliers: circles). See Table 5.2 for a description of the GCMs shown.

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] (with future period [2081-2090]) show an even larger variability illustrating the natural variability (Figure 4.3).

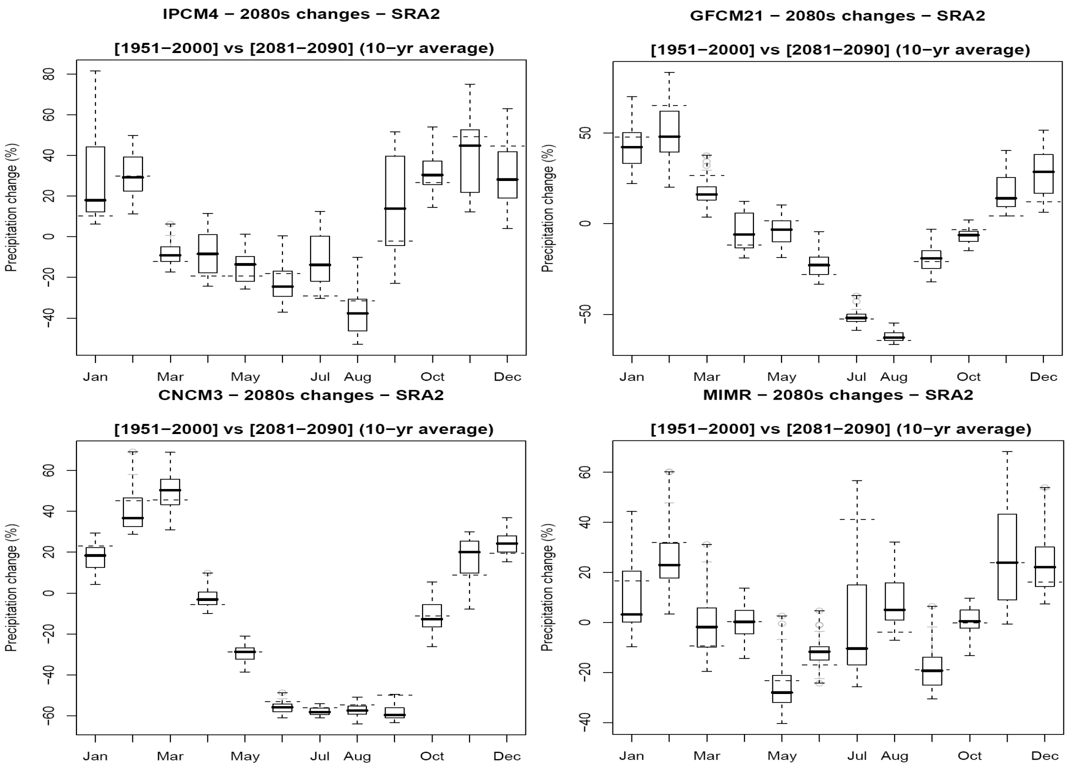


Figure 4.3 As Figure 4.2 but with 10-year averages, with future as [2081-2090]. The dashed line is based on the [1971-1980] average

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 as it allows for climate variability both from baseline and future time horizons, which was otherwise not possible, and was hence 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 of these being randomly resampled, with replacement. Ranges in factors of change are larger than those of Figure 4.2 as uncertainty is accounted for in the mean climate of both baseline and future.

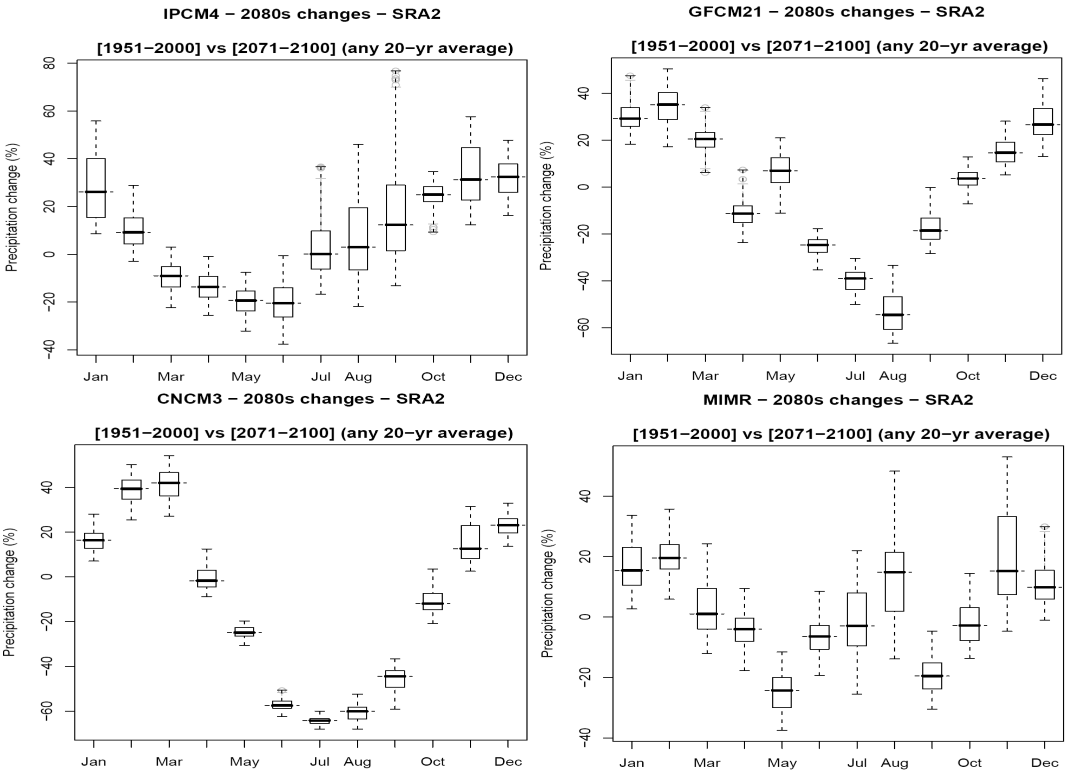


Figure 4.4 As Figure 4.2 but for 20-year averages for any baseline within [1951-2000] and any future within [2071-2100]

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 Factors of change defined through a harmonic function

Harmonic analysis is commonly applied to study periodic variations and was applied herein to the monthly factors of change to synthesise and smooth out the signal due to the large intra-annual variations caused by natural variability.

The expression of a harmonic function is:

$$X = X_0 + \sum_{i=1}^{N/2} A_i \cos\left(\frac{2\pi it}{P} - \Phi_i\right)$$

with N the number of observations, $M = N/2$ the maximum number of harmonics applied, X_0 the arithmetic mean, A_i the semi-amplitude of harmonic *i*, Φ_i the phase of harmonic *i* (in radians), P the period of observation, and X is the value of the series at time t (Wilks, 2006). In our case, P equals 12 months, and X is the median of the factors of change derived from the resampled 20-year average incorporating both control and future variability.

The type of variation dominating the curve is revealed by the comparative size of the amplitudes A_i, where a large first harmonic suggests a strong annual variation. The phase angle Φ_i indicates the time of the year the maximum or minimum of a given harmonic occurs (Kirkyla and Hameed, 1989) and was converted to months.

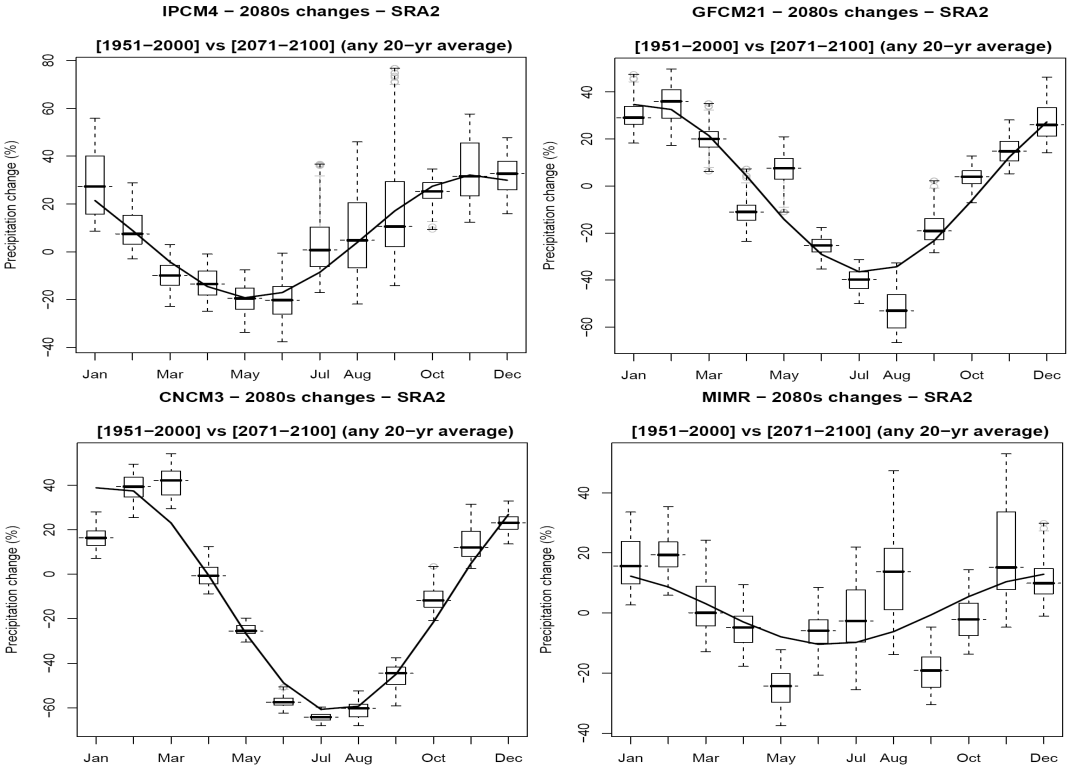


Figure 4.5 Same as Figure 4.4 but with a single harmonic function fitted to describe the factors of change

4.4 Sensitivity analysis framework

Factors of change vary seasonally as well between GCMs: all GCM outputs show seasonal patterns in the changes in 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 for the seasonal distribution of soil moisture, and in turn, the capacity for a catchment to either absorb some of the rainfall or, alternatively, to be close to saturation with the potential to generate quicker and 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) dimension matrix, which would be extremely difficult to analyse and interpret. Instead, the seasonal pattern of change factor is described here by a harmonic function (see 4.3). Figure 4.5 shows, for different

GCMs, a single 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 with a single harmonic has only three parameters: the maximum amplitude of the sinusoid (A_1), the deviation from the annual mean change (X_0), and the delay in the peak change from January (Φ_1). It is an efficient representation of the 12 monthly change factors, as it is a generally good fit with the possible change factors of most months, as represented by the box-and-whiskers plots in Figure 4.5 above.

With this single harmonic function describing the monthly change factors, the sensitivity domain that needs to be considered is reduced to a 3 (parameters) x 3 (variables) dimension matrix – only 9 dimensions, compared with the 36 dimensions required if the 12 monthly factors were used individually.

5. National domain definition

5.1 Climate change projections

Monthly time series of precipitation and temperature for 17 GCMs were downloaded, and time series were extracted for all the land cells over the UK. A summary of the GCMs characteristics is given in Table 5.2. Coupled Ocean-Atmosphere Global Climate Models (AOGCM, or GCM hereafter) as used for the IPCC AR4 consider the surface as either ocean or land via a land mask. The surface energy and water balance is described differently by atmospheric and ocean models, and in particular land-surface interaction processes (including vegetation feedbacks) are modelled only in land cells. To avoid any bias due to an ocean grid-box describing the atmosphere over land, only simulations from land-cells are considered, following Vidal and Wade (2008). Only time series simulated over land cells (or where more than 50% of the cell was attributed to land) were therefore extracted (Table 5.2).

The IPCC has developed different pathways describing the future evolution of global CO_2 emissions, depending on assumptions about the social and economic development, generally referred to as 'SRES emission scenarios' (IPCC, 2000). The pathways are known as 'emission scenarios' and labelled according to the assumptions made. In addition to simulations assuming greenhouse gas concentrations observed during the 20th century (control run 20C3M), future simulations for three emission scenarios were obtained (Table 5.1).

Table 5.1 Emission scenarios considered. More detail in IPCC (2000)

Emission scenario	Detail	No GCM exp.
20C3M	Climate of the 20th Century experiment. Generally runs from ~1850 to present. Control run for SRES emission scenarios A1B, A2 and B1 experiments	17
SRA1B	Future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. SRES A1B assumes a balance across all sources of technology (fossil intensive and non-fossil energy source). Experiments run from conditions from the end of 20C3M until 2100, then with fixed CO2 levels to 720 ppm and continue to run to 2200	16
SRA2	Very heterogeneous world. The underlying theme is self-reliance and preservation of local identities, with continuously increasing of global population. Technological changes are slower and more fragmented that in other storylines. Experiments use the end of the 20C3M experiment as their initial condition.	17
SRB1	Convergent world with the same population projection as A1, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity but without additional climate initiatives. Experiments run from conditions from the end of 20C3M until 2100, then with fixed CO2 levels to 550 ppm and continue to run to 2200	14

Table 5.2 Models used in this study. For more details, see http://www-pcmdi.llnl.gov. GCM grid-boxes with less than 50% land were excluded. No re-gridding was performed.

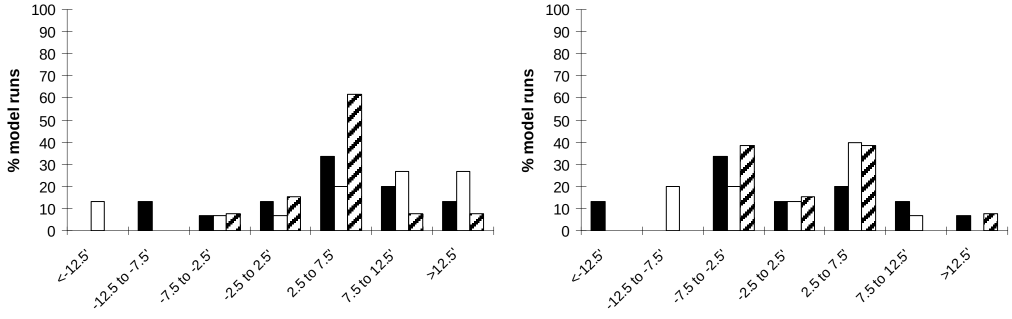
Model	CERA	Modelling Group	Country	Spatial Resolution		
	Acronym			Mesh (Lon x Lat)	~ km over UK	No. GB Land cells
BCCR-BCM2.0	BCM2	Bjerknes Centre for Climate Research	Norway	Gaussian – 128 x 64	280 x 280	5
CCSM3	NCCCSM	National Centre for Atmospheric Research	USA	Gaussian – 256 x 128	140 x 140	15
CGCM3.1 (T47)	CGMR	Canadian Centre for Climate Modelling & Analysis	Canada	Gaussian – 96 x 48	375 x 375	4
CNRM-CM3	CNCM3	Météo-France / Centre National de Recherches Météorologiques	France	Gaussian – 128 x 64	280 x 280	4
CSIRO-Mk3.0	CSMK3	CSIRO Atmospheric Research	Australia	Gaussian – 192 x 96	190 x 220	10
ECHAM5/ MPI-OM	MPEH5	Max Planck Institute for Meteorology	Germany	Gaussian – 192 x 96	190 x 220	10
ECHO-G	ECHOG	Meteorological Institute of the University of Bonn, KMA meteorological inst., and M & D group	Germany / Korea	Gaussian – 96 x 48	375 x 375	3
GFDL-CM2.0	GFCM20	Geophysical Fluid Dynamics Laboratory	USA	Regular – 144 x 90	250 x 200	8
GFDL-CM2.1	GFCM21	Geophysical Fluid Dynamics Laboratory	USA	Regular – 144 x 90	250 x 200	7
GISS-ER	GIER	NASA / Goddard Institute for Space Studies	USA	Regular – 72 x 46	500 x 390	1
INM-CM3.0	INCM3	Institute for Numerical Mathematics	Russia	Regular – 72 x 45	500 x 400	3
IPSL-CM4	IPCM4	Institut Pierre Simon Laplace	France	Regular – 96 x 72	375 x 250	4
MIROC3.2 (medres)	MIMR	National Institute for Environmental Studies, and Frontier Research Centre for Global Change	Japan	Gaussian – 128 x 64	280 x 280	3
MRI-CGCM2.3.2	MRCGCM	Meteorological Research Institute	Japan	Gaussian – 128 x 64	280 x 280	5
PCM	NCPCM	National Centre for Atmospheric Research	USA	Gaussian – 128 x 64	280 x 280	2
UKMO-HadCM3	HADCM3	UK Met. Office	UK	Regular – 96 x 73	375 x 250	4
UKMO-HadGEM1	HADGEM	UK Met. Office	UK	Regular – 192 x 145	190 x 125	14

5.2 Implementation and results of the analysis

The harmonic analysis described in Section 4 was applied to the factors of change derived from the differences between any 20-year period in the future and baseline simulations from each GCM. This was done for two locations: one centred on the Cairngorms in Scotland; one centred on London. The change factors and harmonic functions, for precipitation and temperature, were applied to GCM results for all land cells over the two points of interest. The histograms of each of the parameters of the fitted harmonic functions are shown below (for precipitation Figure 5.1-Figure 5.3, for temperature Figure 5.6-Figure 5.8), with the three emission scenarios shown separately.

5.2.1 Precipitation results

Mean annual change in precipitation varies from decreases greater than 12.5% to increases greater than 12.5% (Figure 5.1). In Scotland, most of the GCM experiments suggest a mean annual increase in precipitation of more than 2.5 %, while near London, the majority of changes are between -7.5% and +7.5%.

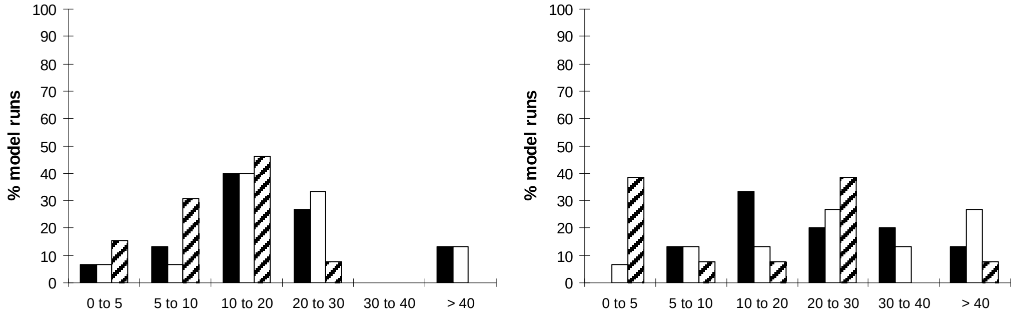


North (Scotland)

South (near London)

Figure 5.1 Histograms of precipitation mean annual change (X_0, in %) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

For the north, around 30% of the experiments are associated with a strong seasonal pattern (maximum seasonal variation greater than 20%), while the proportion reaches more than 50% in the south and very large seasonality was attributed to experiments only for the southern region (Figure 5.2).



North (Scotland)

South (near London)

Figure 5.2 Histograms of precipitation maximum seasonal variation (semi-amplitude of first harmonic A_1, in %) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

Precipitation increase is **largest in winter for nearly all experiments**, **regardless of the region** (Figure 5.3). This is consistent with the increase of winter rainfall reported for the UKCIP02 and PRUDENCE scenarios (see Haylock et al., 2006).

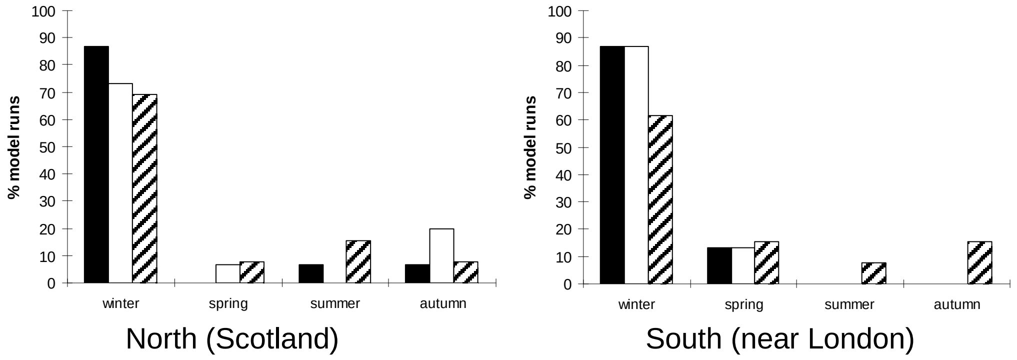


Figure 5.3 Histograms of precipitation season of maximum change (phase of the first harmonic Φ_1) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

An alternative illustration of the prevalence of winter peaks in precipitation change scenarios is shown in Figure 5.4 where the harmonic functions (with a single harmonic) fitted on all available GCM experiments (SRA2 and SRB1) are plotted for all land cells in Great Britain. They are coloured according to the season of maximum change: blue for winter, green for spring, yellow for summer and brown for autumn. Note that even when the peak occurs in the autumn, the maximum is reached in November, which is close to beginning of the definition of winter (December, January, February). Also note that for SRB1 scenarios, where some scenarios have the maximum precipitation in spring or summer, the corresponding seasonal variation is small (relatively flat curves, reflecting little change in seasonality).

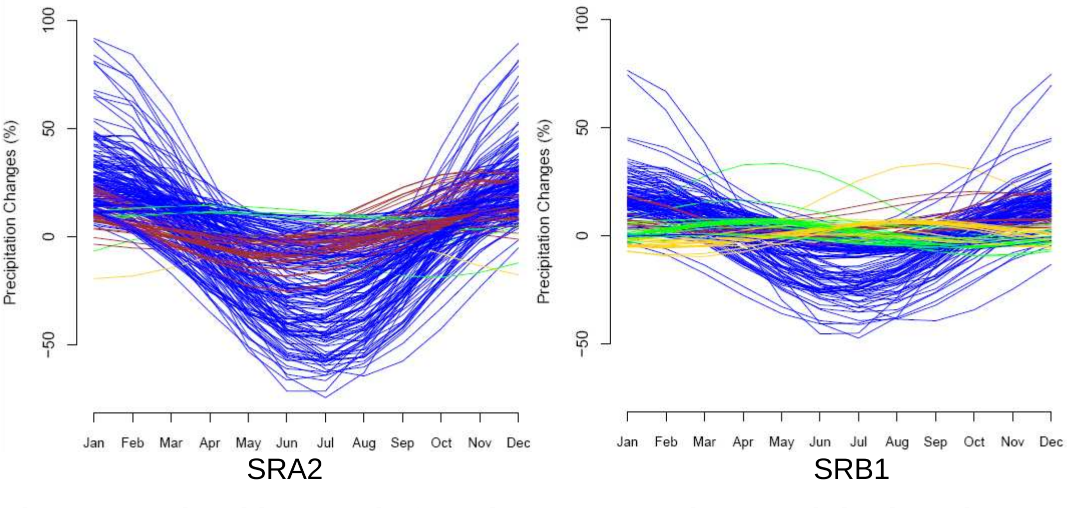


Figure 5.4 Fitted harmonic functions on monthly precipitation changes (in %) from all available GCM experiments for land cells in Great Britain under SRA2 and SRB1. Season of maximum change: blue - winter (DJF); green - spring (MAM); yellow - summer (JJA); brown - autumn (SON)

The **secondary peak** is seen to occur primarily in autumn, and for the southern cell, also in winter (Figure 5.5, bottom) but is **always of low amplitude** (Figure 5.5, top). **No strong regional difference in the shape of the harmonic function (mean annual change, seasonality range and phase) emerges from the analysis.**

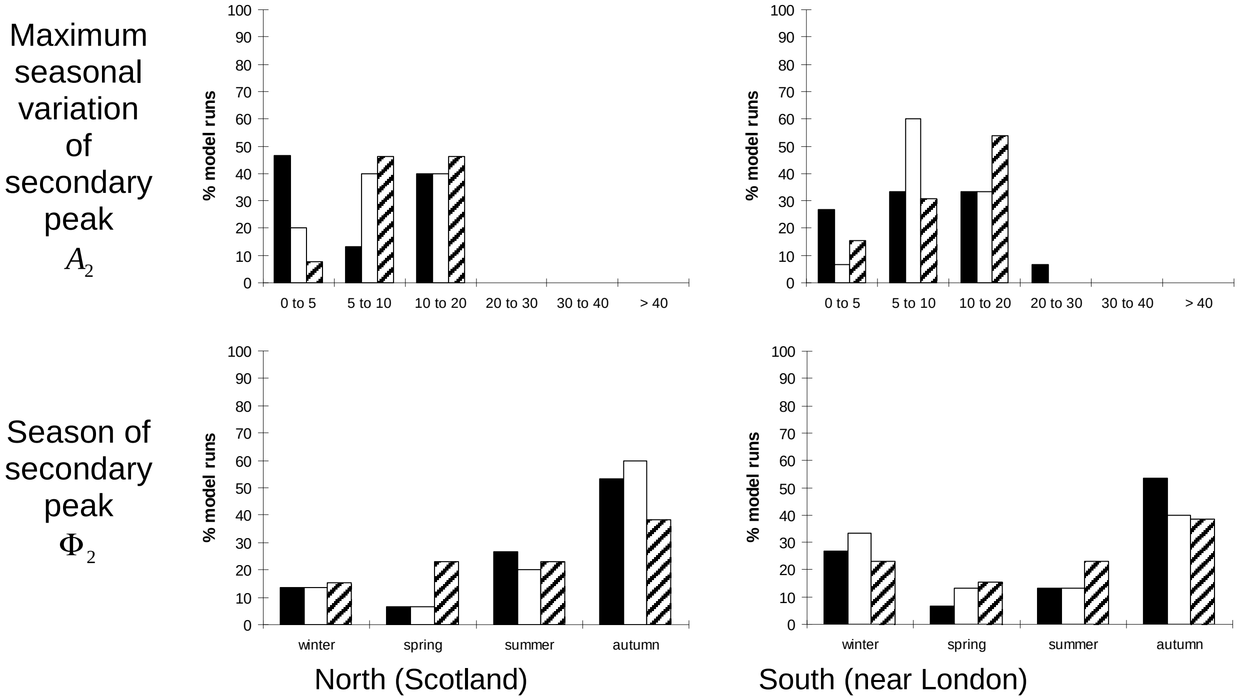


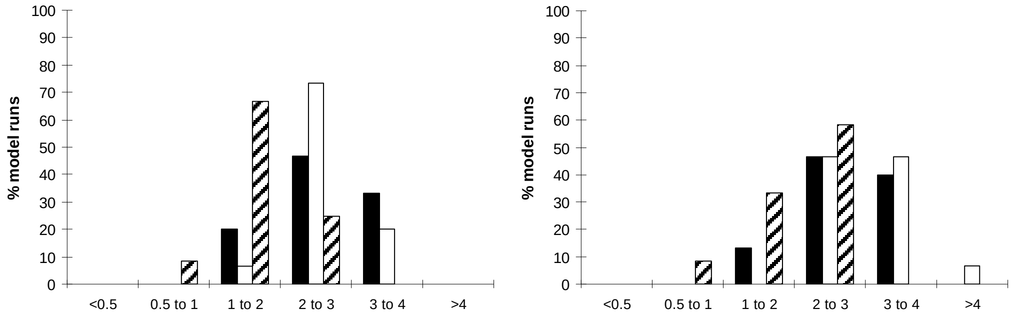
Figure 5.5 Histograms of precipitation second order seasonal variation (semi-amplitude of second harmonic A_2, in % top) and season of second order maximum change (phase of the second harmonic Φ_2 bottom) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

Differences due to the emission scenarios are not important: the range in mean annual changes and seasonal pattern for both regions is similar regardless of the emission scenario. This suggests that the decadal variability uncertainty is greater than the emission scenario uncertainty. Perhaps the most consistent feature can be found for the emission SRB1 (hashed bars) where results are not as extreme as for SRA1B (black) and SRA2 (white): the majority of experiments suggests a mean annual change in precipitation of no more than 7.5%, with an additional seasonality component of less than 30 % in Scotland and generally less than 30% near London.

5.2.2 Temperature results

In terms of temperature, the suggested annual warming is between 2 and 3ºC, with 50% of experiments in this class for both regions (Figure 5.6), and 100%

and 98% of experiments in the north and the south, respectively, within the class spanning a warming of between 1 and 4ºC

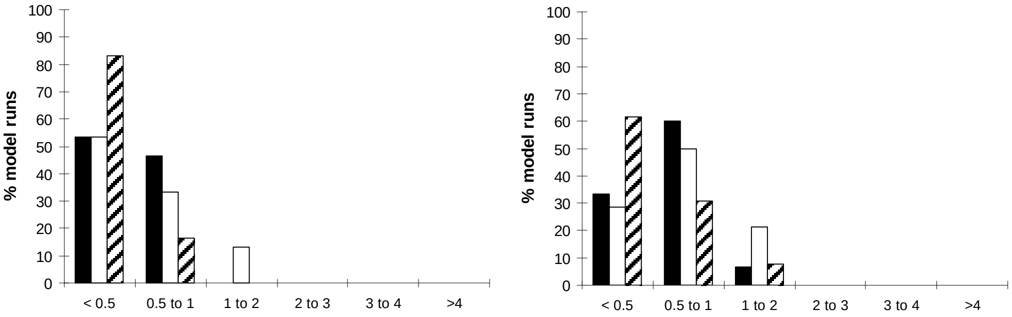


North (Scotland)

South (near London)

Figure 5.6 Histograms of temperature mean annual change (X_0 , in degree Celsius) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

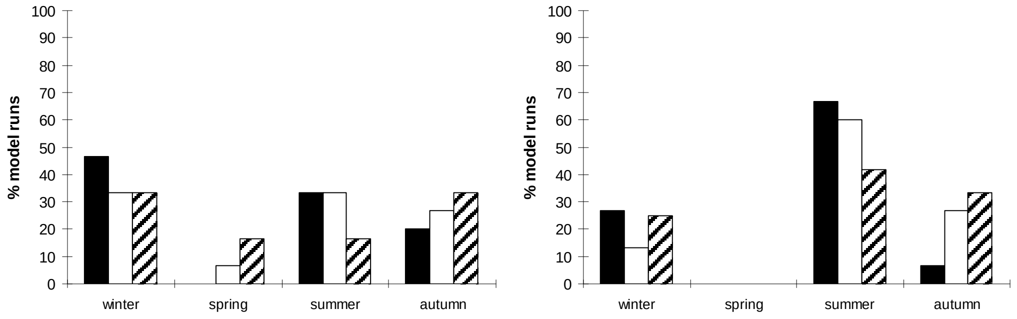
There is a **weak seasonal pattern in the warming** (maximum seasonal variation is less than 1ºC), marginally stronger in the south (Figure 5.7), and, on average, greater warming is expected in **winter** and autumn in the north, and in **summer** in the south (Figure 5.8).



North (Scotland)

South (near London)

Figure 5.7 Histograms of temperature maximum seasonal variation (semi-amplitude of first harmonic A_1, in degree Celsius) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

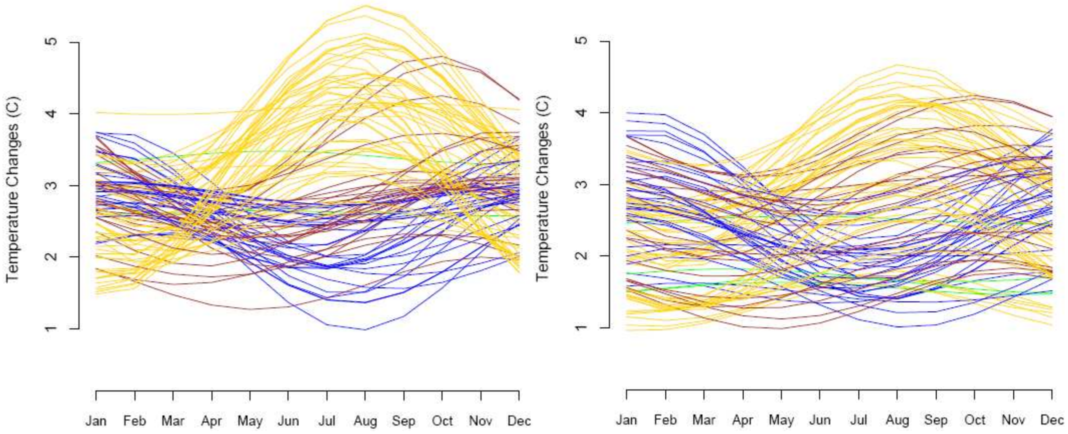


North (Scotland)

South (near London)

Figure 5.8 Histograms of temperature season of maximum change (phase of the first harmonic Φ_1) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

The mixture of summer and winter maxima is also illustrated in Figure 5.9 where the harmonic functions (with a single harmonic) fitted on all available GCM experiments (SRA2 and SRA1B) for all land cells in Great Britain are plotted, and coloured according to the season of maximum change.



SRA2

SRA1B

Figure 5.9 Fitted harmonic functions on monthly temperature changes (in degree Celsius) from all available GCM experiments for land cells in Great Britain under SRA2 and SRB1. Season of maximum change: blue - winter (DJF); green - spring (MAM); yellow - summer (JJA); brown - autumn (SON)

The effect of the emission scenario on the range of projected mean annual warming is more pronounced in the south, where the warmest trend is indicated by SRA2 (white) with a warming starting at 2ºC while for SRB1 (hashed) the suggested range would be 0.5 to 3ºC, (Figure 5.6 right). Both emission scenarios however show the majority of experiments have a warming of 2 to 3ºC. In Scotland (Figure 5.6 left), this difference in the range is weaker.

The effect of the emission scenarios is also discernable for the season of the second order maximum change within the year (season associated with the second harmonic) where emission SRA1B and SRA2 generally have the second peak in spring, while for the emission SRB1, the second peak is most often in summer in the north, and in no particular season in the south (Figure 5.10, bottom). However, these changes are not significant in view of the very small amplitude associated with this secondary peak (less than 0.5 ºC; Figure 5.10, top).

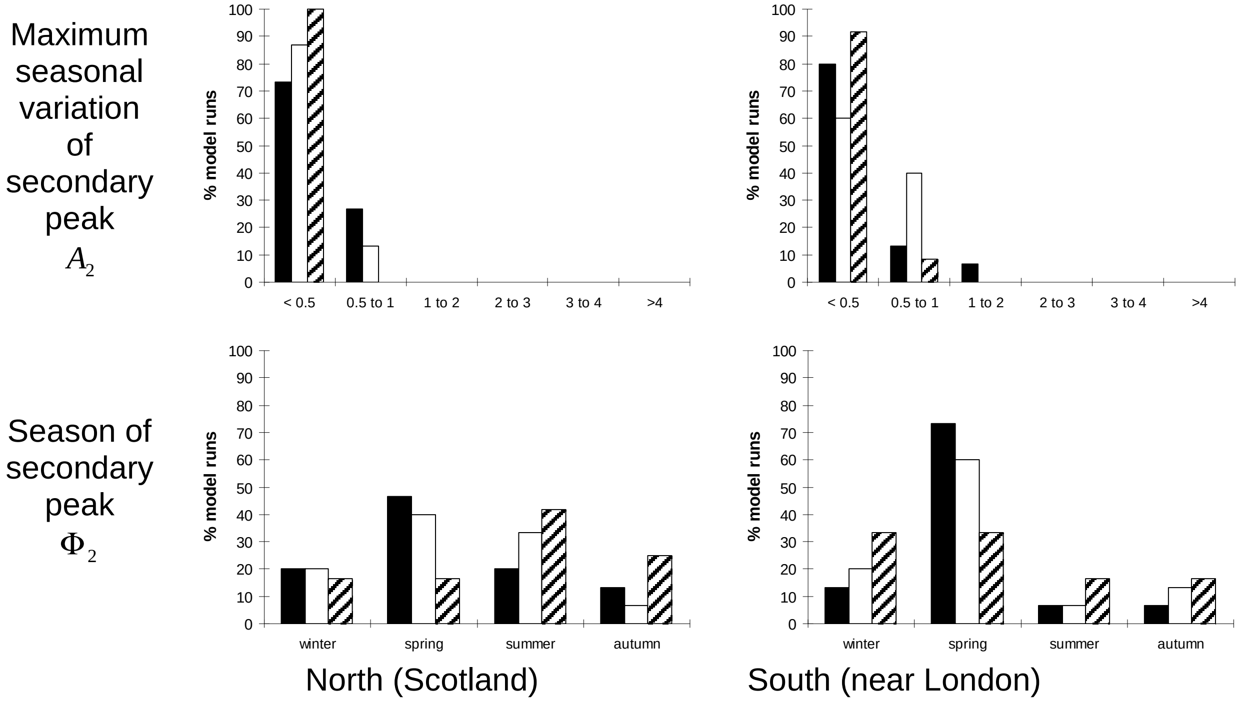


Figure 5.10 Histograms of temperature second order seasonal variation (semi-amplitude of second harmonic A_2 in degree Celsius, top) and season of second order maximum change (phase of the second harmonic Φ_2 bottom) from all available GCM experiments. Black: SRA1B; White: SRA2; Hashed: SRB1

5.3 Dependence between changes in precipitation and temperature

Dependence in the seasonal patterns of expected changes in precipitation and temperature are assessed from scatter graphs of the three parameters of the single harmonic function (Figure 5.11). For both mean annual change and maximum seasonal variation (top graphs), no clear relationship emerges from the plots. As already discussed, winter peaks prevail for precipitation, associated equally to maximum warming in summer or winter (bottom graph). This means that precipitation and temperature changes can be considered independent.

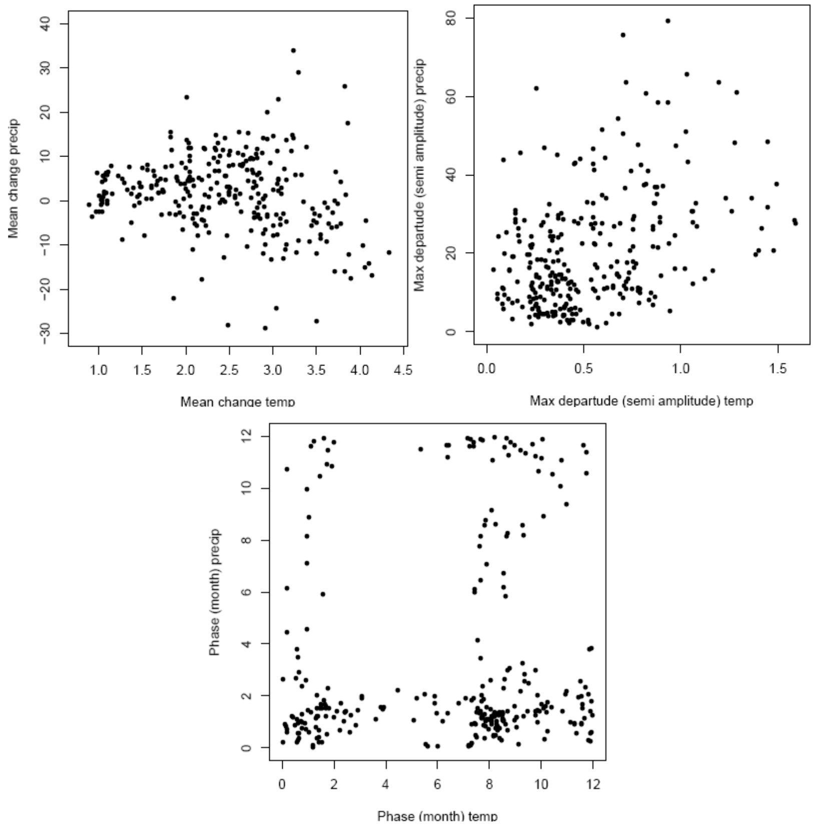


Figure 5.11 Scatter plots of precipitation (x-axis) vs temperature (y-axis) mean annual change (top left), seasonal variation of changes (top right) and season of maximum increase (bottom) for all scenarios in all GB land cells for the 2080s

5.4 Potential evapotranspiration

The catchment average potential evapotranspiration PE used for the hydrological modelling for this project is estimated 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 baseline) GCM-PE, for example the Penman-Montieth method (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 and more simple PE-estimation equations exist that are based only on the variation of the temperature. The use of these methods has previously been verified for use in hydrological modelling by Oudin et al. (2005). Moreover, if the sensitivity domain for PE is large enough, it is likely it would also include any potential changes that would have been derived using Penman-Montieth GCM-PE.

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

- Encompassing the full range IPCC-AR4 GCMs, 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 easier interpretation of the results

To estimate changes in PE, we have used the Central England Temperature series (http://www.cru.uea.ac.uk/~mikeh/datasets/uk/cet.htm) as the baseline, and applied temperature changes to derive a number of alternative temperature series (see §6.2). PE was calculated for both baseline and perturbed series using the equations from Oudin et al. (2005) and the corresponding monthly changes calculated to provide a number of sets of changes in PE.

6. Implementation of the sensitivity analysis

6.1 Analysis of the factors of change

Following the analysis of factors of changes and harmonic functions fitted on all available GCM projections in Great Britain, we conclude that:

- Inter-annual variation of the factors of change is **satisfactorily represented by a single phase harmonic function;**
- **For precipitation**, the peak change occurs (almost always) in **winter;**
- **For temperature**, peak change can occur in **winter** or **summer;**
- There is **little regional difference** in the properties of the harmonic functions;
- Changes in precipitation and temperature can be considered as **independent;**
- Representation of change in PE can be achieved by using a **temperature-based method for calculating PE**, where temperature changes are defined by a harmonic function.

6.2 Sensitivity domain definition

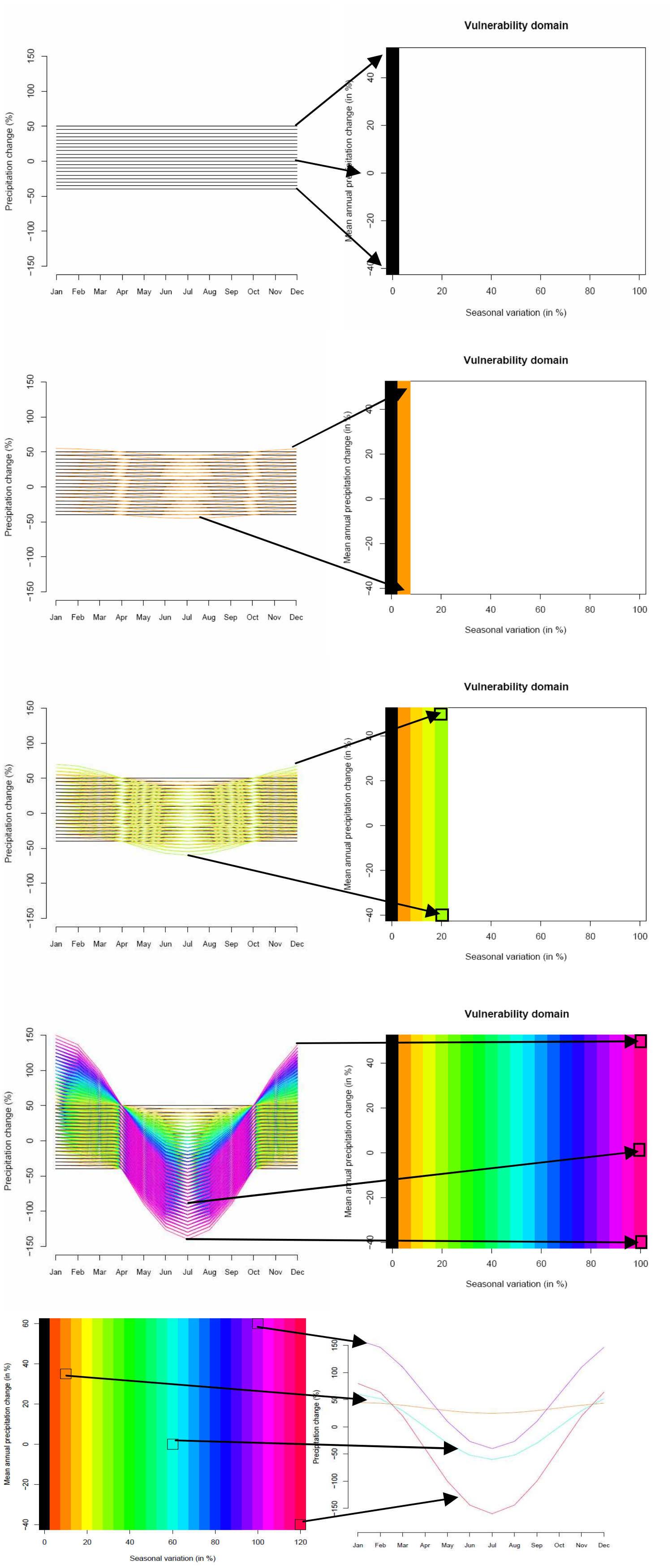
The above analysis was conducted in order to define a space of climate change factors representative of the latest IPCC-AR4 projections, but also be large enough to encompass possible future projections, such as, for example, the UK Climate Impact Programme next set of scenarios (UKCP09). Under this framework, for any catchment of the UK, the space of the sensitivity domain will be the foundation for climate change impact studies, **where the impact of a regular set of scenarios within the domain will be calculated**. For the method to be manageable and the computing load realistic, it is necessary to constrain the scenario space. Several important simplifications have been made for this purpose:

- **The same domain will be considered everywhere in the UK**. It will be defined to include all possible regional variations;
- **The main sensitivity space refers to changes in precipitation**. While changes in PE do have an impact on the river flows, it is not as large as the impact of changes in rainfall for flood flows. Changes in temperature can impact snow pack formation and snow melt, but flood-generation mechanisms in Great Britain are rarely purely snow-melt based, and are either generated from precipitation only (for the majority of catchments) or from a mixture of snow-melt and precipitation events in the mountain ranges and northern catchments of Great Britain;
- **The highest peak of change in precipitation is fixed to occur in January**. The analysis of the GCM-simulated monthly changes in rainfall for Great Britain has shown the greatest changes in precipitation were projected to occur in winter for all GCMs and emission scenarios anywhere in the country. To reduce the sensitivity domain for precipitation to two-

dimensions, the timing of the greatest changes was fixed to occur in January (the middle winter month);

- **The mean annual change in precipitation varies between a reduction of 40% and an increase of 60%.** The uncertainty in the direction and quantity of GCM-simulated change in precipitation in Britain is captured by this range of changes. Note the variation is much wider than suggested from the AR4-GCMs, and these changes are in fact well above any current projections (from GCMs or RCMs) for GB;
- **The additional change above/below the mean annual change (reflecting the inter-annual variability of projected changes) varies between 0 and 120%**. An additional change of 0% represents a uniform change in precipitation equal to the mean annual change. This is equivalent to the sensitivity study of Jones et al. (2006). An additional change of 120% represents a maximum additional increase of 120% to the mean annual change in January, and a reduction of 120% from the mean annual change in July. For example, if the mean annual change is +40%, the change in January will be +160% and the change in July will be -80%. Note that when the mean annual change suggests an overall reduction of precipitation, some summer months will have a reduction in precipitation of 100% (i.e. no rainfall). Also note that increases in precipitation in the summer is included within the sensitivity domain: for example a mean annual change of 40% combined with a additional change of 20% represents a variation of precipitation change of +20% in July to +60% in January;
- **The sensitivity domain space for precipitation is sampled at increments of 5%.** This means that the total number of combinations defining the entire domain space is 21 (mean annual changes) x 25 (additional seasonal change) = 525 scenarios;
- **Changes in temperature are considered from eight scenarios taken to capture the IPCC range** (Figure 5.6 and Figure 5.7)**, all considered in conjunction with the entire precipitation sensitivity domain**. Changes in precipitation are assumed independent of changes in temperature, as suggested by the analysis in two locations of GB;
- **The eight temperature scenarios (and corresponding PE scenarios) are defined as follows:** Six scenarios (three with highest changes in January and three in August) are defined as mean annual increases of 1.5º and 1.2º additional seasonal change (low scenario); 4.5º mean annual change and 1.6º additional seasonal change (high scenario) and 2.5º mean annual change with an additional seasonal change of 0.8º (medium scenario); a further two scenarios, without any seasonality change, are also included, corresponding to an increase of 0.5º and 4.5º. Note than in the low scenarios, cooling occurs in some months of the year;
- **For each scenario of the domain, a complete impact study will be undertaken, and the changes in river flood indicators calculated**. For each catchment, this represents a total of 525x8 = 4200 scenarios.

Each scenario of the domain will be applied to the input time series (precipitation, temperature and PE) and run through the hydrological models to provide changes in river flow time series. Changes in flood peak indicators associated with each of the scenarios will be calculated, and mapped into a two-dimensional diagram. A schematic of the diagram with the associated scenarios shown in different colours is illustrated bellow showing how the vulnerability domain is built up from left to right:



- Left hand side of domain: uniform scenario, no seasonality in the changes
- Lower part of domain mean annual precipitation decrease
- Higher part of diagram: mean annual precipitation increase
- Increase in the seasonality towards the right hand side
- Mean annual change and seasonal variation are incremented by 5%
- Each scenario corresponds to one square in the domain
- The higher the seasonality, the greater the difference between winter and summer changes
- Increase as well as decrease in summer precipitation are captured by the range of 525 scenarios
- Selected scenarios for different part of the sensitivity domain are showed as example

6.3 Limitations

The construction of the sensitivity space is not free from assumptions and these constrain the space primarily to limit the number of runs of the hydrological models, which is **4200 for each catchment**. These assumptions are listed below:

- winter peak in change to precipitation
- winter peak always centred on January
- symmetry between summer and winter variance from mean, no change to inter-monthly rainfall pattern
- no consideration of extreme events outside of the data used in calibrating hydrological models (due to the use of the perturbation method)
- precipitation is greater driver of change in peak flows than temperature, so the temperature domain change is limited to eight scenarios only
- sample extreme of temperature space to ensure that resulting impacts capture full range of possible values

The effects of some of these limitations on the resulting impacts are assessed in the uncertainty analysis, undertaken on a limited number of catchments, and reported in Kay *et al* (2009).

6.4 Summary

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 patterns of change in climatic variables are described by a single harmonic function. This allows a sensitivity analysis to be undertaken that analyses the response of catchments to a change of climate, which includes the large uncertainty due to GCM outputs, but also captures the seasonal variability in the changes.

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