Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Regionalised Impacts of Climate Change on Flood Flows:

Uncertainty Analysis

R&D Milestone Report FD2020/MR5

Environment
Agency

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Joint Defra/EA Flood and Coastal Erosion Risk
Management R&D Programme

Regionalised impacts of climate change on flood flows: uncertainty analysis

Milestone report 5 – Project FD2020

Produced: August 2009
Revised: November 2009

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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.

Dissemination status
Internal: Released internally
External: Released to public domain

Keywords:
Hydrological modelling; uncertainty; climate change impacts; delta change factors; regional climate models; global climate models

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www.defra.gov.uk/environ/fcd

Executive summary

This milestone report for project FD2020 ‘Regionalised impacts of climate change on flood flows’ describes the analysis undertaken to assess the potential level of uncertainty, due to various assumptions and simplifications necessary to develop the project’s ‘scenario-neutral’ approach to regionalisation. It relies on three previous project milestone reports, describing the hydrological models, the catchments modelled and the model calibration (Crooks *et al*. 2009), the development of the sensitivity framework (Prudhomme and Reynard 2009), and the identification of flood response types (Prudhomme *et al*. 2009a).

The scenario-neutral approach required that the monthly changes in precipitation and temperature suggested by current Global Climate Models (GCMs) were distilled down into a ‘simple’ sensitivity framework, using single harmonic functions (i.e. annual sine-curves with a single peak and trough). These 4200 ‘scenarios’ (525 precipitation x 8 temperature / potential evaporation) were then applied to baseline catchment time-series using the delta change method of downscaling, and run through the catchment hydrological models. This resulted in the production of flood response patterns, representing the response of each catchment to the prescribed sets of changes in precipitation and temperature / potential evaporation in terms of the percentage change in flood peaks at four return periods.

The main aim of the uncertainty analysis is to assess whether values obtained from the flood response patterns will consistently over- or under-estimate the impact of climate change scenarios. The uncertainty analysis thus addresses the following factors:

1. Assumptions made for sensitivity framework development;
2. Use of a fitted harmonic instead of monthly factors;
3. Use of the simple delta change method of downscaling;
4. Natural variability.

Due to the number of factors investigated, the analysis is performed on a small subset of catchments, chosen to be as representative as possible of the nine flood response types found in Great Britain (described as ‘Damped-Extreme’, ‘Damped-High’, ‘Damped-Low’, ‘Neutral’, ‘Mixed’, ‘Enhanced-Low’, ‘Enhanced-Medium’, ‘Enhanced-High’ and ‘Sensitive’). There is one catchment modelled with the PDM hydrological model (at a daily time step) for each of the nine flood response types, for which the full uncertainty analysis is performed. In addition, there are four catchments modelled with the CLASSIC hydrological model (at a daily time step), representing four of the flood response types, for which a subset of the analysis is performed.

The results show that the level of uncertainty from different factors varies significantly between catchments. For some catchments the overall level of uncertainty varies little with return period, whilst for others it increases / decreases with return period. The four CLASSIC catchments show a similar pattern of uncertainty to that for the corresponding PDM catchments. However, each of the CLASSIC catchments has a higher level of uncertainty than the

PDM catchment of the same flood response type. This probably reflects the larger catchment area of the CLASSIC catchments.

Generalising the catchment results to their flood response types suggests that ‘Neutral’ catchments will have the lowest level of uncertainty and ‘Sensitive’ catchments will have the highest level of uncertainty. The different levels of uncertainty for the different catchment types are compatible with the underlying climatological and hydrological differences between their flood response types.

Despite the small number of catchments investigated here, the fact that the results are physically reasonable, and the similarity of the results for comparable PDM and CLASSIC example catchments, gives confidence in the extension of the results to catchment type. The next step is to develop guidance on what level of uncertainty to allow, according to flood response type and return period. The potential effect of catchment area on the level of uncertainty will also have to be borne-in-mind.

Contents

1. Introduction

This milestone report for project FD2020 ‘Regionalised impacts of climate change on flood flows’ describes the analysis undertaken to assess the potential level of uncertainty, due to various assumptions and simplifications necessary to develop the project’s ‘scenario-neutral’ approach to regionalisation. It relies on three previous milestone reports, describing the hydrological models, the catchments modelled and the model calibration (Crooks *et al*. 2009), the development of the sensitivity framework (Prudhomme and Reynard 2009), and the identification of flood response types (Prudhomme *et al*. 2009a).

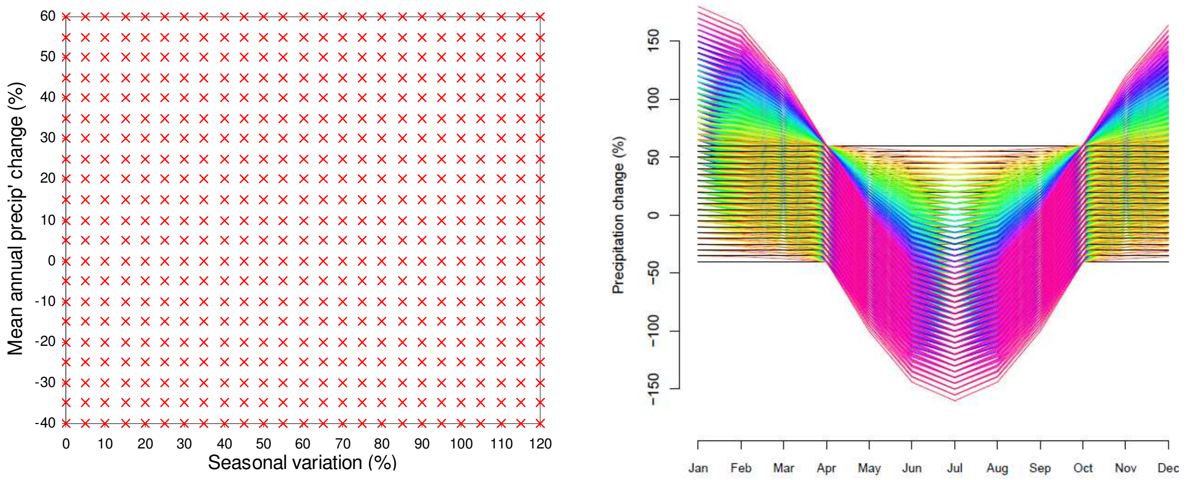
A brief summary of the sensitivity framework approach is given below. Section 2 describes the main factors contributing to uncertainty, and how each factor is addressed in the uncertainty analysis. The results are presented in Section 3, and discussed in Section 4.

1.1 The sensitivity framework and flood response patterns

The scenario-neutral approach taken in project FD2020 meant that the monthly changes in precipitation and temperature suggested by current Global Climate Models (GCMs) had to be distilled down into a ‘simple’ sensitivity framework. This distillation, using single harmonic functions (i.e. annual sine-curves with a single peak and trough), resulted in the set-up of:

- 525 precipitation scenarios, consisting of 21 percentage changes in mean rainfall, at 5% intervals between -40% and +60%, with each of 25 percentage changes in seasonality, at 5% intervals between 0% and 120%, each assuming a peak change in January (Figure 1.1);
- eight temperature (T) scenarios — two non-seasonal scenarios (Low/High-NS), and three seasonal scenarios which are used both with the peak change in January (Low/Med/High-Jan) and with the peak change in August (Low/Med/High-Aug) (Figure 1.2);
- a potential evaporation (PE) scenario corresponding to each of the eight temperature scenarios (Figure 1.3), calculated via the Central England temperature time-series using the temperature-based PE formula of Oudin *et al.* (2005).

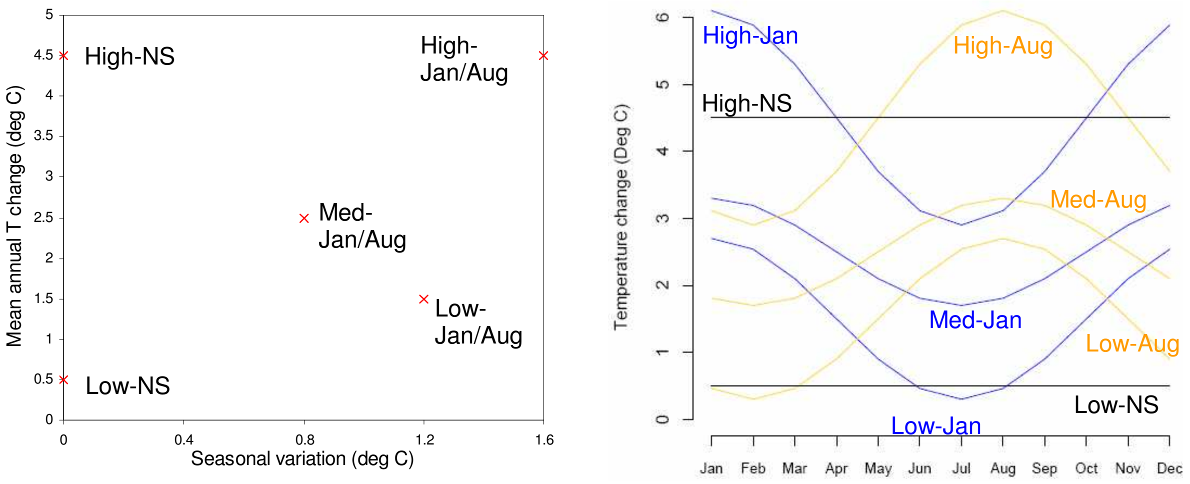
The regular grid of 525 precipitation scenarios is used with each of the eight temperature / potential evaporation (T/PE) scenarios, resulting in a total of 4200 scenarios. This large set of ‘scenarios’, whilst being guided by what current GCMs suggest about future changes in precipitation and temperature, is not limited to those specific sets of changes. See Prudhomme and Reynard (2009) for the detailed rationale behind the development of the framework.



a) Mean changes and seasonal variation

b) Monthly changes

Figure 1.1 The sensitivity framework of 525 precipitation scenarios.



a) Mean changes and seasonal variation

b) Monthly changes

Figure 1.2 The sensitivity framework of eight temperature scenarios.

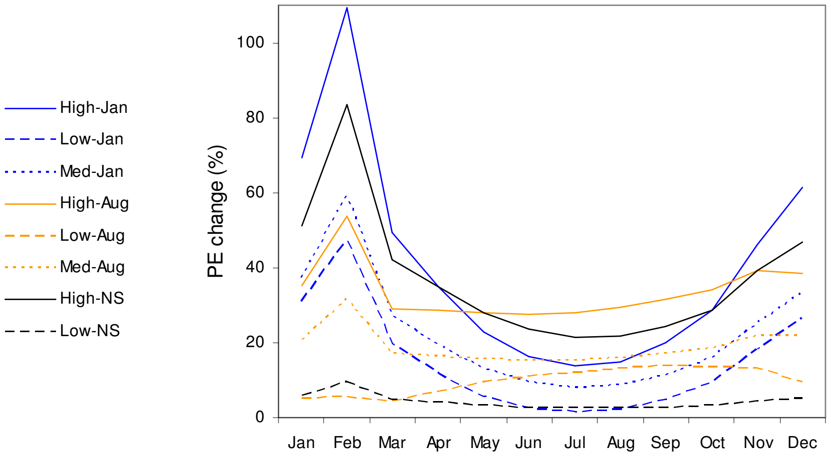


Figure 1.3 The monthly changes for the PE scenarios corresponding to the eight temperature scenarios.

The 4200 scenarios are run for each of the project's 154 catchments across Britain (giving 155 sets of results, as one catchment is run with both of the hydrological models used for the project; PDM and CLASSIC). The results from each set of 525 precipitation scenarios (that is, for each T/PE scenario), are then turned into 'flood response patterns' for specific flood statistics (e.g. the change in the flood peak with a 20-year return period) , where the modelled change under each scenario is colour-coded (see example in Figure 1.4). The four flood statistics of principal interest were chosen as the percentage change in the flood peak (from daily mean flows) at the 2-, 10-, 20- and 50-year return periods, so it is the sets of flood response patterns for these four statistics which are 'regionalised'; see Prudhomme *et al.* (2009a) for details. Points can then be plotted on top of the flood response patterns for a given catchment, to indicate the precipitation scenarios suggested by specific global and regional climate models (GCMs and RCMs). An example of such a flood response pattern, with points representing different GCMs and RCMs, is shown in Figure 1.4. The values corresponding to these points can then be extracted from the datasets of the flood response patterns, as estimates of the impact of each climate model scenario.

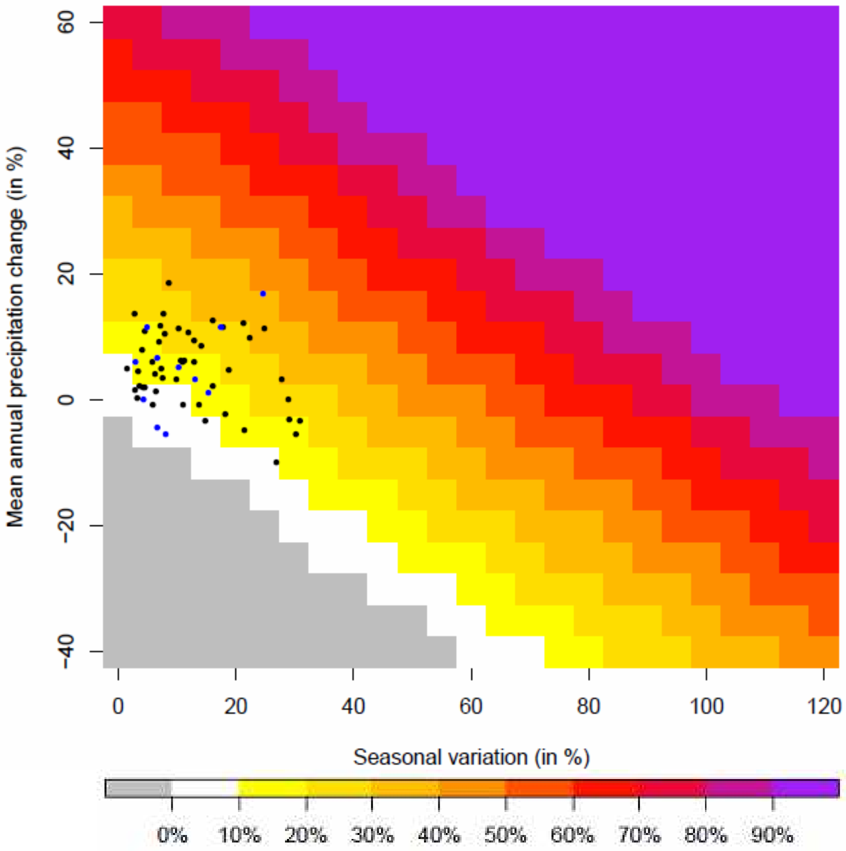


Figure 1.4 Example flood response pattern, showing the percentage change in the flood peak with a 20-year return period for one catchment under one T/PE scenario. Grey areas show scenarios with a decrease in the flood peak, other colours show an increase (in 10% increments). The points plotted on top of the response pattern indicate the locations of particular GCM (black) and RCM (blue) scenarios.

1.2 The aim of the uncertainty analysis

When values are extracted from the flood response patterns to represent the impacts of specific climate model scenarios, a number of simplifications are applied. For data from a given climate model, for a given grid box (chosen according to the catchment location), firstly a set of monthly changes in precipitation is calculated (which can be done in a number of different ways), then a sine-curve (single harmonic function) is fitted to those 12 monthly values. It is two of the parameters of that harmonic function (the mean and the amplitude) which determine the position of the corresponding point on the response pattern. The phase of the fitted harmonic is ignored, as are the exact mean and seasonal amplitude, since the flood response pattern is based on the sensitivity framework harmonics which all correspond to a January peak change in precipitation and have means and seasonal amplitude in multiples of 5% (Figure 1.1). Also ignored is what that particular climate model says about other changes in precipitation, like intensity changes. In addition, no account is taken of how well the single harmonic function fits the 12 monthly values. Similarly, what that particular climate model says about changes in monthly temperature could be ignored, and the values extracted from the flood response patterns corresponding to all eight of the applied T/PE scenarios, or a single harmonic function could be fitted to the 12 monthly temperature changes of the specific climate model scenario and the values only extracted from the flood response pattern of the closest temperature scenario of the eight applied (Figure 1.2). These are some of the factors which are addressed as part of the uncertainty analysis.

Essentially, the uncertainty analysis aims to address the questions:

1. *Due to the assumptions and simplifications necessary for the sensitivity framework methodology, will values extracted from the flood response patterns consistently over- or under-estimate the impact of climate change scenarios?*
2. *If so, can guidance be given on the level of this potential bias, according to catchment type and flood return period?*

2. Approach

The factors addressed in the uncertainty analysis are presented in this section, along with a discussion of how they are investigated. The factors are:

1. Assumptions made for sensitivity framework development;
2. Use of a fitted harmonic instead of monthly factors;
3. Use of the simple delta change method of downscaling;
4. Natural variability.

Due to the number of factors investigated, the analysis is performed on a small subset of catchments, chosen to be as representative as possible of the flood response types identified (see Prudhomme *et al.* 2009a). The selection of this catchment subset is described below. There is also a discussion of potential additional factors which are not specifically addressed within this project.

2.1 Selection of catchment subset for the uncertainty analysis

It was decided to perform the uncertainty analysis on a subset of catchments, chosen to be in some way representative of the nine flood response types (or groups). The flood response types are named 'Damped-Extreme', 'Damped-High', 'Damped-Low', 'Neutral', 'Mixed', 'Enhanced-Low', 'Enhanced-Medium', 'Enhanced-High' and 'Sensitive' (see schematic in Figure 2.1). See Prudhomme *et al.* (2009a) for a full description of the grouping methodology and results.

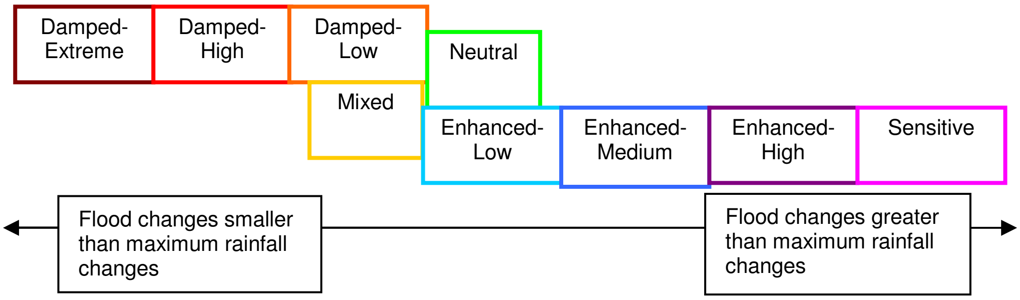


Figure 2.1 Schematic of the nine flood response types.

For each of the nine flood response types, a catchment modelled with the PDM at a daily time step was chosen. Preference was given to daily PDM catchments, rather than choosing catchments modelled with the PDM at an hourly time step or modelled with CLASSIC at a daily time step for some flood response types, in order to maintain as much consistency as possible (in terms of hydrological model and length of data record) across all the flood response types. In general it was possible to pick catchments which were in the same flood response type across all of the four flood indicators (the percentage change in the flood peak at the 2-, 10-, 20- and 50-year return periods), although this was not quite possible for all flood response types (see below). Where several potential daily PDM candidates existed within a flood response type, a choice was made after consideration of the calibration results and of catchment location. A CLASSIC catchment was chosen in addition to the daily PDM catchment where possible (there are not CLASSIC catchments with all flood response types, in particular there are none consistently within any of the ‘Enhanced’ flood response types and none within the ‘Sensitive’ flood response type). The full uncertainty analysis, described later in this Section, is performed for each of the chosen PDM catchments, with a subset of that analysis performed for the chosen CLASSIC catchments, to investigate the effect of some of the sources on uncertainty on larger catchments. The PDM catchments thus selected within each flood response type are given in Table 2.1, with the additional CLASSIC catchments given in brackets. The locations of the catchments are shown in Figure 2.2.

Table 2.1 Chosen PDM (*CLASSIC*) catchments for each flood response type.

Response type	Catchment number	River name	Location
Damped-Extreme	07002	Findhorn	Forres
	(-)		
Damped High	02001	Helmsdale	Kilphedir
	(27009)	*(Ouse)*	*(Skelton)*
Damped-Low	14001	Eden	Kemback
	(*39001*)	(*Thames*)	(*Kingston*)
Neutral	47007	Yealm	Puslinch
	(*76007*)	(*Eden*)	(*Sheepmount*)
Mixed	34003	Bure	Ingworth
	(*33026*)	(*Bedford Ouse*)	(*Offord*)
Enhanced-Low	54008	Teme	Tenbury
	(-)		
Enhanced-Medium	21023	Leet Water	Coldstream
	(-)		
Enhanced-High	43005	Avon	Amesbury
	(-)		
Sensitive	38003	Mimram	Panshanger Park
	(-)		

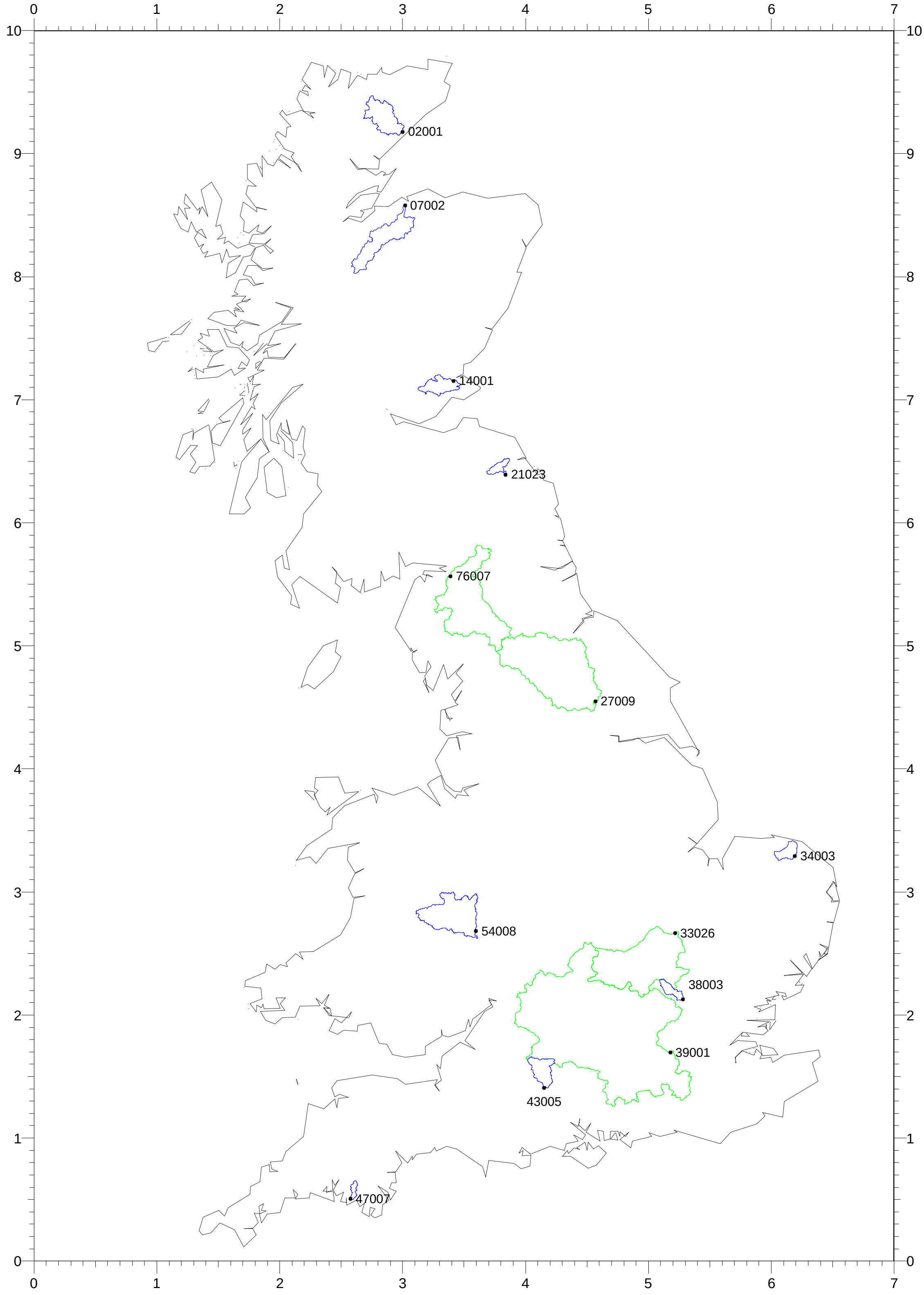


Figure 2.2 Boundaries and outlet locations of the catchments selected for the uncertainty analysis. The full analysis is performed for the daily PDM catchments (blue), while a subset of the analysis is performed for the CLASSIC catchments (green).

The flood response patterns for each of the 13 example catchments, for each of the eight T/PE scenarios and four return periods, are presented in Appendix A. Of the PDM catchments in Table 2.1, it is only catchment 14001 (selected for the ‘Damped-Low’ response type) which is actually classified as the ‘Mixed’ flood response type at the 20-year return period. Of the CLASSIC catchments in Table 2.1, catchment 39001 (selected for the ‘Damped-Low’ flood response type) is classified as the ‘Mixed’ flood response type for the 20- and 50-year return periods, and catchment 27009 (selected for the ‘Damped-High’ flood response type) is classified as the ‘Damped-Low’ response type at the 2-year return period. There are actually minimal differences in the flood response patterns across the return periods for each of these three catchments though (see Appendix A), as the shift is only by one flood response type (Figure 2.1). Thus the selected catchments will be considered, for the purposes of the uncertainty analysis, as representing the flood response types given in Table 2.1 at all return periods.

2.2 Selection of climate change scenarios for the uncertainty analysis

Unless otherwise specified, the tests for the uncertainty analysis are done using two sets of climate scenarios – one based on GCMs and one on RCMs – both of which have data available for baseline and 2080s timeslices, for the A1B emissions scenario. The GCM-based scenarios are from the IPCC 4th Assessment report: BCM2, CGMR, CNCM3, CSMK3, ECHOG, GFCM20, GFCM21, HADCM3, HADGEM, INCM3, IPCM4, MIMR, MPEH5, MRCGCM, NCCCSM, NCPCM (see Table 5.1 of Prudhomme and Reynard (2009) for details). The RCM-based scenarios are those of the perturbed parameter ensemble produced by the Met Office Hadley Centre for UKCP09 (11 runs in total, see Section 2.5.1 for details).

2.3 Factor 1: Assumptions made for sensitivity framework development

The development of the sensitivity approach necessarily meant a number of simplifying assumptions, in order to reduce the dimensionality of the space explored. These assumptions are that:

a) Precipitation is a greater driver of change for flooding than temperature (or PE). Thus only eight temperature scenarios were applied (Section 1.1 and Figure 1.2), chosen towards the centre and the extremes of the temperature change space suggested by current GCMs (Prudhomme and Reynard 2009).
b) The peak change to precipitation occurs in winter (specifically, in January);
c) There is symmetry between summer and winter variance from the mean (that is, a single-harmonic sine-curve is applied);

The testing of each of these assumptions is described below.

The first of these assumptions, resulting in the application of just eight temperature (and corresponding PE) scenarios, could be tested by applying a larger number of scenarios, with different means and seasonal amplitudes, as well as different phases (that is, month of peak change). However, the results using the eight existing scenarios suggest this is unnecessary as there are relatively small differences in the flood response patterns for most catchments across the eight existing scenarios. Certainly the similarity of the results for the eight T/PE scenarios for a catchment is much greater than the similarity between catchments falling in different flood response types (see examples in Figure 2.3, and plots for all 13 example catchments in Appendix A). As most of the tested temperature scenarios were chosen towards the extremes of the likely domain of change suggested by current GCMs, any additional scenario would be intermediate to the existing ones so it is very unlikely that they would result in significantly different flood response patterns. This also justifies the use, later in this analysis, of all eight T/PE scenarios simultaneously, rather than attempting to select the 'best' T/PE scenario for each GCM/RCM for each catchment.

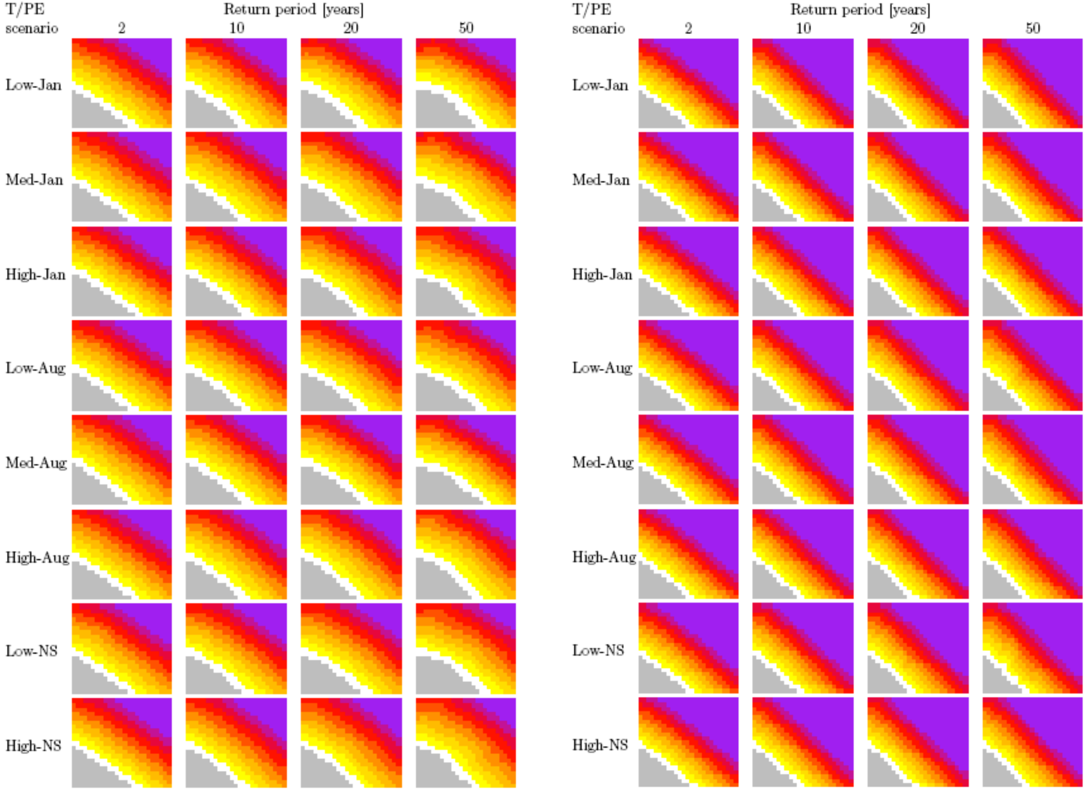
The second of these assumptions, that the peak precipitation change occurs in January, is perhaps the most important. To demonstrate the effect of this assumption, for each catchment in the chosen subset the same 525 precipitation scenarios of the sensitivity framework (in terms of mean change and seasonal amplitude of change) are applied, but with different phases (i.e. the peak change taken to occur in each other month of the year in turn), for each of the eight T/PE scenarios. This generates a set of 11*8 alternative flood response patterns which are compared to the original 8, to demonstrate the range of results when the peak month of precipitation change is varied.

In addition to the alternative flood response patterns above, the single-harmonic fitted to specific GCM and RCM scenarios (for the 2080s under the A1B emissions scenario; see Section 2.2) are applied directly. That is, the monthly precipitation changes given by the fitted single-harmonic are applied to the baseline precipitation series, and run through the catchment hydrological model for each of the eight T/PE scenarios. The resulting changes in flood statistics are then compared to those extracted from the flood response pattern (where a January peak is assumed and the mean change and seasonal amplitude are multiples of 5%; see discussion under Factor 2). .

The effect of the symmetry implicit in the use of a single harmonic is explored through comparison with the use of a double harmonic, which breaks the rotational symmetry of the single harmonic about the mid-point between the peak and the trough. For each catchment, the changes in precipitation given by each harmonic are then applied to the baseline rainfall, and run through the catchment hydrological model for each of the eight T/PE scenarios (see discussion under Factor 2).

a) Catchment 02001 (Damped-High)

b) Catchment 47007 (Neutral)



c) Catchment 21023 (Enhanced-Medium)

d) Catchment 38003 (Sensitive)

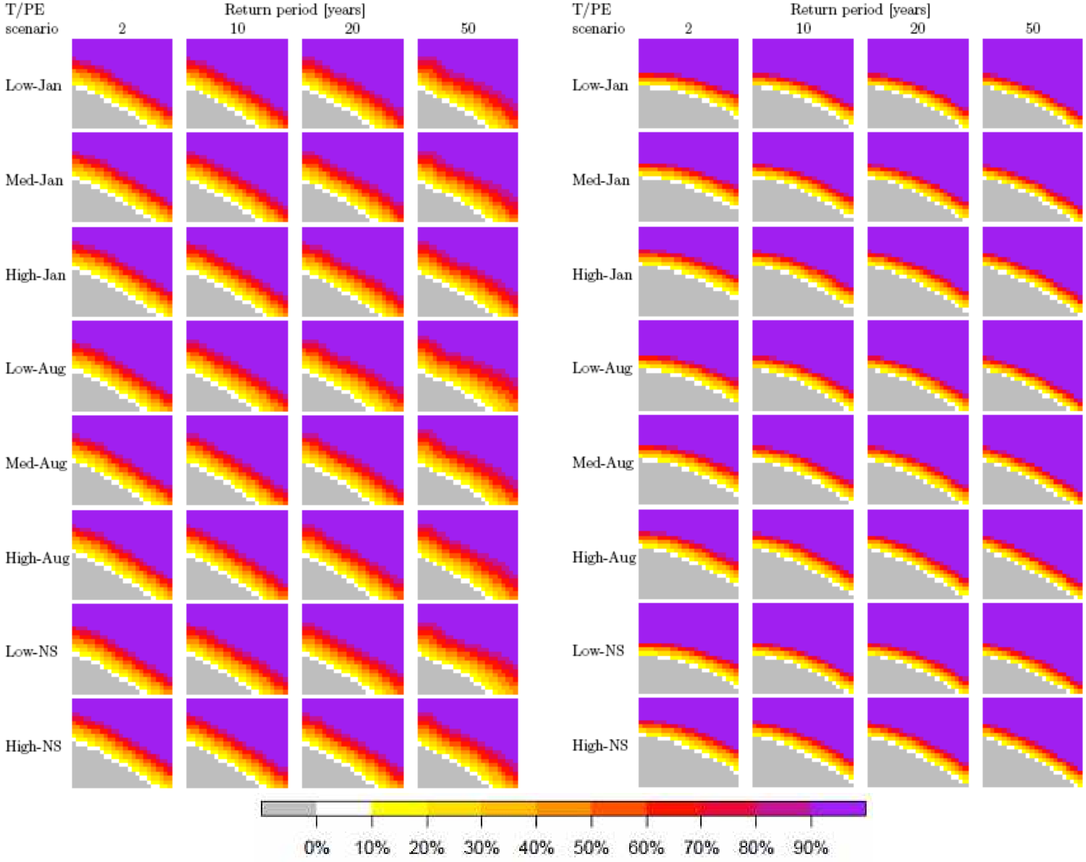


Figure 2.3 Example flood response patterns for four catchments showing the similarity in results across the eight T/PE scenarios (top to bottom), for percentage change in the flood peak at four return periods (left to right).

2.4 Factor 2: Use of a fitted harmonic instead of monthly factors

As well as not taking account of the month in which the peak of the fitted harmonic occurs, extracting a flood change estimate from the flood response pattern for a specific GCM/RCM scenario takes no account of how well the single harmonic fits the GCM/RCM monthly rainfall factors, or of the corresponding changes in temperature suggested by the GCM/RCM. The question thus arises: *How much difference is there between the estimated impact of a given climate model if the derived monthly changes in precipitation are applied directly, alongside their corresponding monthly changes in temperature, compared to the estimated impacts when the monthly changes smoothed by the fitted harmonic are applied, or the impacts extracted from the flood response patterns?*

Additionally, those monthly changes can be derived in different ways, as discussed in the milestone report describing the establishment of the sensitivity domain (Prudhomme and Reynard 2009). The standard way is to express changes between the monthly averages from two 30-year time-slices (one Baseline and one Future). In this project though, multiple sets of monthly changes have been derived, by calculating changes between different 20-year sub-periods in the Baseline and Future time-slices. This method acknowledges the presence of natural variability within the climate model data, and thus the fact that a slightly different sub-period within the Baseline and/or Future time-slice can result in different sets of monthly changes: There is not just one valid set of monthly changes, as is suggested by the use of changes between two fixed 30-year time-slices. The harmonic has then been fitted to the monthly medians from the sets of monthly changes.

The analysis thus compares, separately for GCM- and RCM-based scenarios (see Section 2.2), the values extracted from the flood response patterns (i.e. for a response pattern harmonic) for each flood statistic with:

- The changes if the actual fitted precipitation harmonic (single or double, including its phase) is applied directly to the baseline rainfall data, under each of the eight T/PE scenarios.
- The changes if the monthly median values (to which the precipitation harmonic is fitted) are applied directly to the baseline rainfall data, alongside the corresponding monthly temperature changes applied to the baseline temperature series.
- The changes if each set of monthly values (from which the monthly median values are calculated) is applied directly to the baseline rainfall data, alongside the corresponding monthly temperature changes applied to the baseline temperature series. Here, the median and 95% bounds are then calculated and plotted.
- The changes if the alternative monthly values derived from the standard 30-year time-slices are applied directly to the baseline rainfall data, alongside the corresponding monthly temperature changes applied to the baseline temperature series.

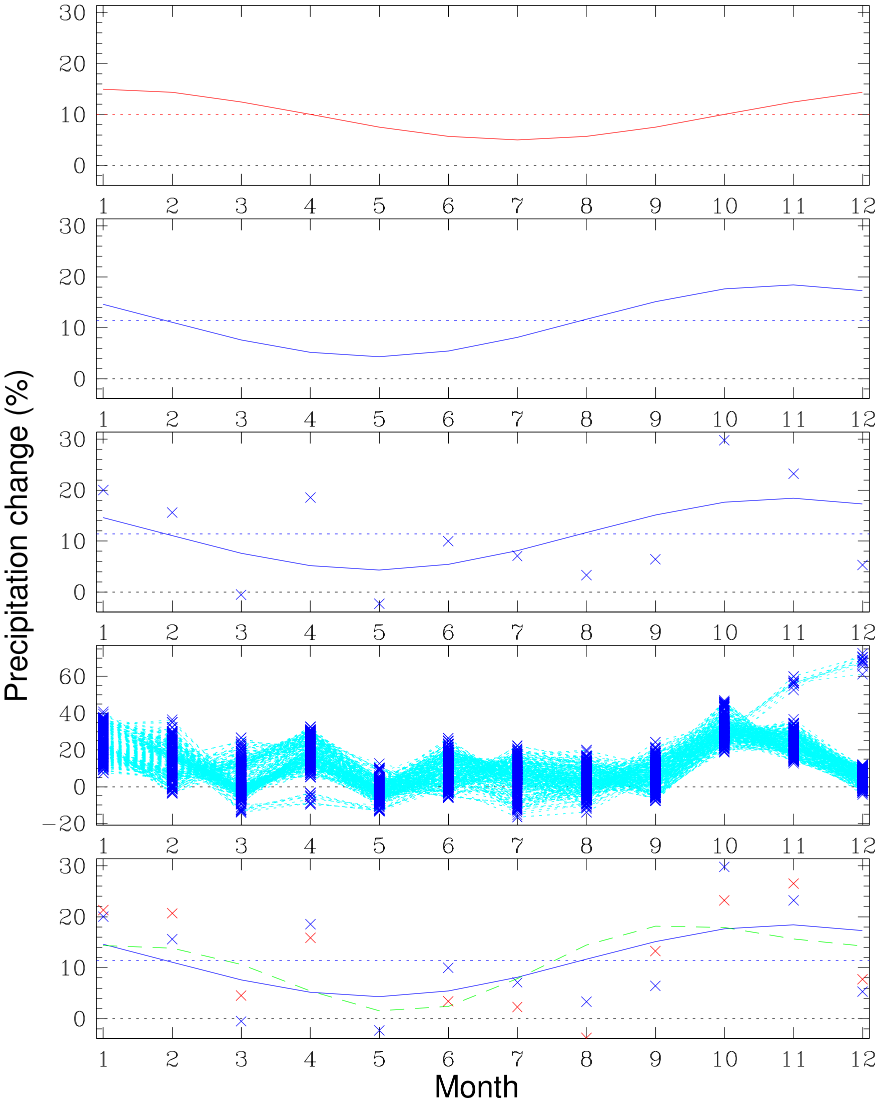
A summary of these alternative delta change methods, for precipitation and for the corresponding temperature and PE, is given in Table 2.2, along with the notation used for the results from the set of GCM scenarios and for the set of RCM scenarios. Note that, through the use of sets of climate scenarios, the range of climate model uncertainty will be demonstrated for each catchment, and any differences in this range according to methodology can be assessed. By comparing the mean values from the different methods (across either set of climate scenarios), any bias according to methodology developed for the project can be assessed.

Examples of how each of the alternative sets of delta changes given in Table 2.2 might compare, in terms of the monthly percentage changes applied to precipitation, are given in Figure 2.4.

Table 2.2 Summary of the alternative delta change methods applied, with the notation used for the results from each set of GCM and RCM scenarios.

Precipitation	Temperature (T) and Potential Evaporation (PE)	Notation for sets of climate model scenarios (2080s, A1B emissions)	
		16 AR4 GCMs	11 UKCP09 RCMs
Response pattern harmonic (multiple of 5% for mean and amplitude; January peak; Figure 1.1)	8 T harmonics (Figure 1.2) and associated PE changes (Figure 1.3)	*gcm_rpat*	*rcm_rpat*
Actual single harmonic (fitted to median monthly changes below)	As above	*gcmharm*	*rcmharm*
Actual double harmonic (fitted to median monthly changes below)	As above	*gcmharm2*	*rcmharm2*
Monthly changes (median of range below)	Associated monthly T and PE changes	*gcm20med*	*rcm20med*
Range of monthly changes (20-year sub-periods in baseline and future time-slices)	As above	*gcm20*	*rcm20*
Alternative monthly changes (fixed 30-year baseline and future time-slices)	As above	*gcm30*	*rcm30*

For the RCM-based analysis, the corresponding monthly changes in PE are derived from the RCM PE data (see Section 2.5.1) and applied to the baseline PE series. However, PE is not available for the GCMs. Instead, a simple temperature-based PE formula (Oudin *et al.* 2005) has been used to estimate changes in PE from changes in temperature. Kay and Davies (2008) showed that this temperature-based PE formulation worked well, producing baseline PE from climate model data which was comparable with observation-based PE data. The derivation of changes in PE involves deriving a temperature-based baseline PE, from the baseline temperature time-series, and a temperature-based scenario PE, from the baseline temperature time-series adjusted according to the GCM-derived changes in temperature. The derived monthly changes in the temperature-based PE have then been applied to the observation-based baseline PE time-series for the catchment.



a) Response pattern harmonic (red line: mean 10%; amplitude 5%; January peak).

b) Actual single harmonic (blue line: mean 11.4%; amplitude 7%; November peak).

c) Monthly changes (blue crosses; median of range from 20-yr sub-periods, below).

d) Range of monthly changes (20-yr sub-periods in baseline and future time-slices).

e) Alternative monthly changes (red crosses: fixed 30-year baseline and future time-slices) and

Actual double harmonic (green dashed line)

Figure 2.4 Examples of how the alternative delta changes listed in Table 2.2 might compare, in terms of the monthly percentage changes applied to precipitation.

2.5 Factor 3: Use of the simple delta change method of downscaling

This point aims to assess the uncertainty due to the use of the simple delta change method of downscaling, where a fixed baseline of observed data is perturbed and where the perturbed series is inevitably similar to the baseline in terms of the relative size and ordering of events.

The assessment involves the use of alternative data sets to drive the hydrological models for the representative catchments; UKCP09 RCM ensemble time-series data. The results are compared to the results from the use of GCM and RCM monthly changes in Factor 2 (Table 2.2).

2.5.1 Application of RCM data

For UKCP09 (Murphy *et al.* 2009), the Met Office Hadley Centre ran a perturbed parameter ensemble of their standard RCM, HadRM3, nested within the equivalent perturbed parameter runs of their GCM HadCM3. This perturbed parameter approach is used to address uncertainty in climate projections, due to the fact that many important physical processes cannot be explicitly resolved by climate models, typically because they occur on a scale smaller than the model grid (e.g. the formation of cloud). There has to be a compromise between the enormous number of possible combinations of parameter values and the available computer resources: Eleven versions of the RCM are used, one unperturbed member (standard HadRM3 in standard HadCM3, called *afgcx*) and ten perturbed versions (called *afixa*, *afixc*, *afixh*, *afixi*, *afixj*, *afixk*, *afixl*, *afixm*, *afixo*, *afixq*). Each should be interpreted as a plausible realisation, and there are no weights attached to any of the ensemble members.

For each ensemble member, the required data were available for two time-slices. The first (Baseline) time-slice runs from 1 January 1961 to 30 December 1990 and the second (Future) time-slice runs from 1 January 2070 to 30 November 2099 and is available for the A1B SRES emissions scenario (IPCC 2000). Note that the length of the RCM year is only 360 days, comprising of twelve 30-day months. The RCM grid box size is approximately 25 km x 25 km over Britain.

For each RCM grid box, hourly precipitation is available directly, and daily PE from the land-surface is derived from daily RCM open-water PE using the method described in Kay *et al.* (2008). Daily minimum and maximum temperature are also available. For the PDM, the required catchment-average rainfall and PE are produced using the method of Kay *et al.* (2006), and the temperature time-series required by the snowmelt module is produced for the grid box containing the catchment centroid. The altitude of that grid box within the orography file of the RCM is also extracted, so that the snowmelt module can then be applied with the temperature from the RCM in a similar way to that with gridded observed temperature data (Crooks *et al.* 2009). For CLASSIC, the RCM grid is overlaid on the CLASSIC modelling grid and grid-box-average rainfall and PE derived in a similar way as catchment-average rainfall and PE for the PDM. Similarly, the temperature time-series (and altitude) are taken from the RCM grid box containing the catchment centroid, and applied across the catchment. This use of temperature data from a single (25km x 25km) RCM grid box is in contrast to the application of (5km x 5km) gridded observed temperature data within the snowmelt module for CLASSIC (Crooks *et al.* 2009), where data from multiple grid boxes were applied for each catchment, but the latter was not thought necessary with RCM data, due to the larger grid size.

When RCM data are used to drive one of the hydrological models, the changes in a given flood indicator are assessed by comparing the results for the Baseline and Future time-slices (assuming stationarity within each time-slice), rather than by comparing the result using the Future time-slice to an observed baseline, as there may be bias in the RCM data. Also, the Baseline and Future time-slices for a given RCM ensemble member are kept together, as any bias may differ between ensemble members.

2.6 Factor 4: Natural variability

A simple and pragmatic method of exploring the effect of natural variability is applied, based on resampling of the baseline rainfall data following the method of Kay *et al.* (2009). That is, resampling is performed in 3-month blocks (to limit the effects of autocorrelation), with replacement, to produce a large number of plausible new rainfall series, of the same length as the original baseline series. This method does not allow for variation in shorter term extremes (e.g. maximum daily rainfall), or for very long-term variations (e.g. multi-decadal natural variability due to the North Atlantic Oscillation) but does allow variation in medium term extremes (e.g. by allowing a wet winter to follow a wet autumn, when this perhaps did not occur much in the original series), so is looking at the natural variability in antecedent conditions.

In Kay *et al.* (2009) only the rainfall series were resampled, with the PE series kept fixed, as PE is not closely related to rainfall. However, a complication in this application is the presence of the snowmelt module, requiring temperature series as input. If the temperature series were kept fixed, as with the PE data, it is possible that, when the rainfall data are resampled, a wet and warm winter becomes a wet and cold winter, thus resulting in a significant accumulation of snow and generating a spring snowmelt flood event. In reality this is unlikely to have occurred, since temperature and rainfall in Britain are correlated in such a way that, in general, winters are either wet and warm or dry and cold. Thus rainfall and temperature are resampled together, to maintain this dependence.

For each chosen catchment, a set of 101 resampled rainfall and temperature series are thus produced, with resampling in 3-month blocks. The model is then run, and the required flood statistics derived, with each new set of input data. The differences between these sets of flood statistics and those derived using the baseline (non-resampled) input series are then calculated. These differences are then ordered, for each statistic, and the median and the upper and lower 95% bounds extracted (that is, the 51st, 3rd and 99th of the 101 ordered values). This range, when compared to values suggested by different scenarios of climate change, helps to put the latter into context, as it can be seen whether climate change is likely to result in changes in flooding within or beyond the potential range of natural variability.

2.7 Discussion of factors which are not specifically addressed

Uncertainty due to the choice of emissions scenario is not covered in the uncertainty analysis, as other research has consistently shown that emissions uncertainty is smaller than GCM uncertainty (e.g. Kay *et al.* 2009, Prudhomme and Davies 2009, Wilby *et al.* 2006, Wilby and Harris 2006, Cameron 2006).

Likewise, hydrological modelling uncertainty, whether from hydrological model structure or parameterisation, is not specifically addressed within the uncertainty analysis as other research has suggested that it is smaller than GCM uncertainty (Kay *et al.* 2009, New *et al.* 2007, Wilby and Harris 2006, Booij 2005). However, the results from the catchment modelled both with the PDM and CLASSIC (catchment 27007, the Ure at Westwick Lock) are discussed below. The similarity in the results for this catchment using two very differently structured and parameterised hydrological models suggests that hydrological modelling uncertainty is unlikely to be a major factor.

Catchment 27007 is classified as the ‘Damped-High’ response type at all four return periods when modelled with the PDM. When modelled with CLASSIC, it is classified as the ‘Damped-High’ response type at all except the 2-year return period, when it is classified as the ‘Damped-Low’ response type. This difference in flood response type at the lowest return period can be seen in the flood response patterns (Figure 2.5). However, because the shift is only by one flood response type (see Figure 2.1), the difference is minimal in terms of the values extracted from specific points on these flood response patterns (e.g. for specific GCM and RCM scenarios).

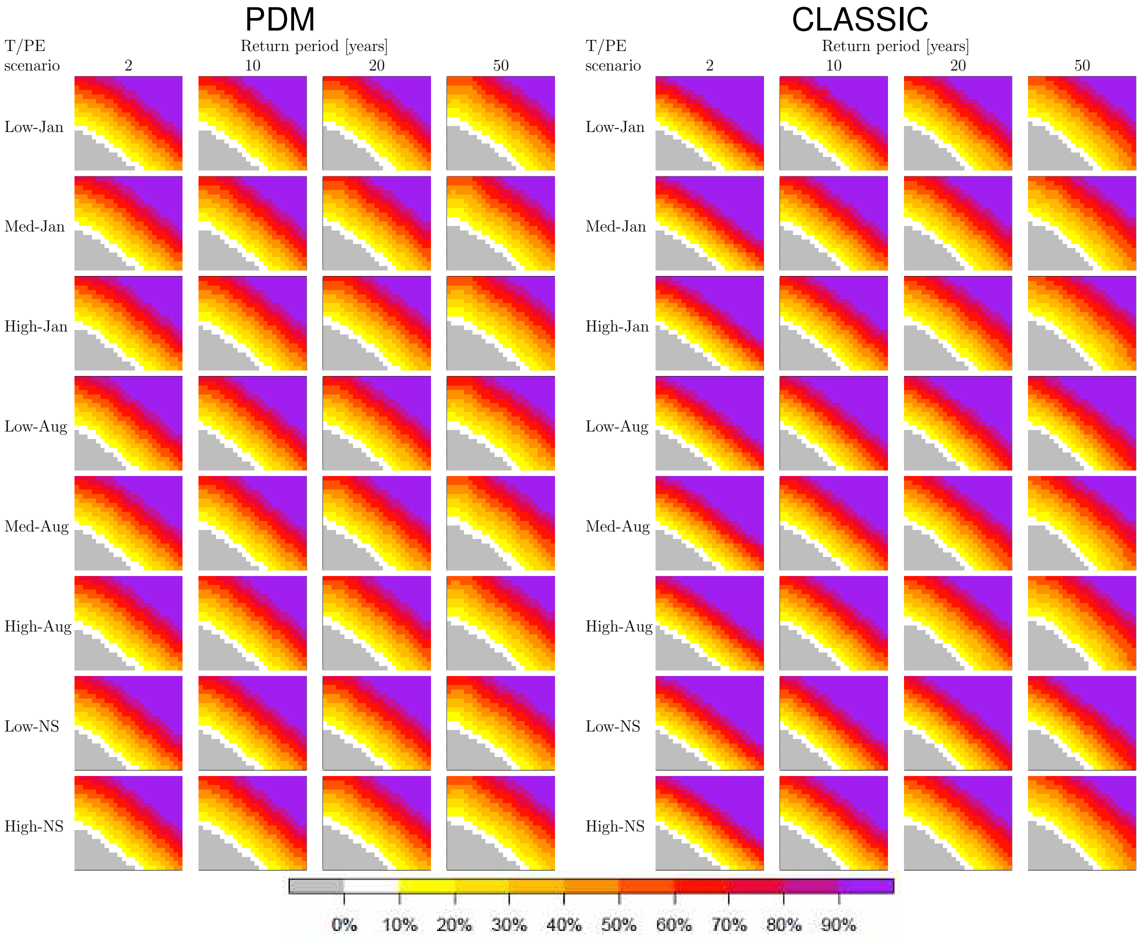


Figure 2.5 Flood response patterns for catchment 27007 (the Ure at Westwick Lock) using the PDM (left) and CLASSIC (right), for each of the four return periods (left to right) under each of the eight T/PE scenarios (top to bottom).

Figure 2.6 compares the values extracted from the flood response patterns (*gcm_rpat* and *rcm_rpat* respectively for the GCM-based and RCM-based scenarios; see Section 2.4) for each hydrological model, at four different return periods. The values extracted from the CLASSIC simulations show a slightly expanded range (at each end) compared to those from the PDM simulations, but the mean values for each set (shown by the black horizontal lines) are very similar. The greatest difference between the mean values occurs at the 2-year return period (i.e. where the flood response type differs) for both the GCM-based results and the RCM-based results, but the difference in terms of the former is greater than that for the latter. Even for the GCM-based results, the difference in the mean impact between the two models is less than 2%, and so is significantly smaller than the range of GCM or RCM uncertainty (which is at least 20%, and over 30% in some cases). The mean values from the CLASSIC simulations are slightly higher than those from the PDM at the 2-year return period, but slightly lower than those from the PDM at each of the higher return periods. However, both models show the same pattern of change with increasing return period: a decrease in the mean change, and indeed in the minimum and maximum changes. This comparison suggests that the results are unlikely to be overly influenced by choice of hydrological model.

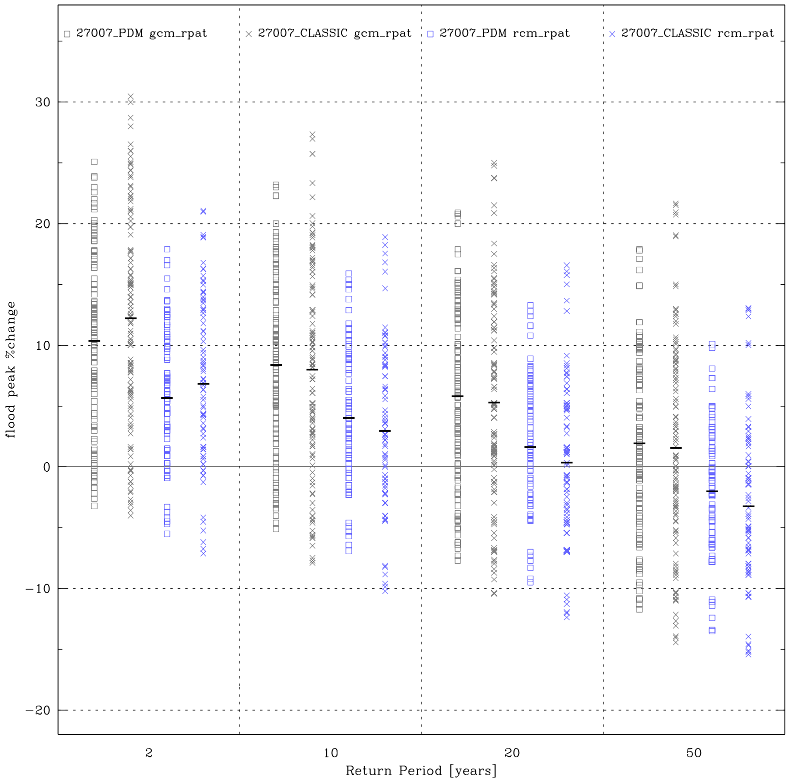


Figure 2.6 Graph comparing the *gcm_rpat* (grey) and *rcm_rpat* (blue) values for catchment 27007 modelled with the PDM (squares) and CLASSIC (crosses), at the 2-, 10-, 20- and 50-year return periods. The mean values for each set are shown by the black horizontal lines.

3. Results

3.1 Factor 1: Assumptions made for sensitivity framework development

Examples of alternative flood response patterns, using the regular grid of 525 mean and seasonal precipitation changes with the phase in each month from January through to December, are shown in Figure 3.1a, for each of the chosen PDM catchments, for the flood peak with a 20-year return period under the Medium-Aug T/PE scenario (Figure 1.2). Appendix B presents these flood response patterns for each of the 8 T/PE scenarios and four indicators (the percentage change in the flood peak at the 2-, 10-, 20- and 50-year return periods). These demonstrate that, when the peak change in precipitation occurs between February and mid-summer, rather than January, the effect on flooding is generally less, whereas if the peak change in precipitation occurs in autumn or earlier in winter the effect can be greater. The exception to this occurs for catchment 07002 (Damped-Extreme), where the impact on flooding is greater if the peak change in precipitation occurs between spring and autumn rather than in winter. This difference is probably mainly due to the effect of snowfall / snowmelt, but also partly due to the distribution of peaks within the baseline.

It must be recalled, when looking at the results in Figure 3.1a and Appendix B, that not all months for peak change in precipitation are equally likely under current scenarios of climate change. As shown in Figure 3.1b, January is the month of peak precipitation change for over 35% of AR4 GCM scenarios, and peaks during the period December-February account for nearly 70% of all precipitation scenarios over Great Britain, while peaks in October and November correspond to 13% of the precipitation scenarios. However, the potential differences in impacts if the peak precipitation change occurs in a month other than January are taken into account later in the project, in order to make the results less dependent on what is currently suggested by GCMs (Prudhomme *et al.* 2009b).

Figure 3.2 shows the minimal difference in results when the actual GCM/RCM fitted harmonics for precipitation are applied versus when the values corresponding to those harmonics (but with a January peak) are extracted from the flood response patterns. Generally the values extracted from the flood response patterns for each T/PE scenario (*gcm_rpat* and *rcm_rpat* in Figure 3.2) are similar to or larger than the values from the use of the fitted single harmonic under each T/PE scenario (*gcmharm* and *rcmharm* in Figure 3.2). It is only for the snow-dominated catchment (07002; Damped-Extreme) that the values extracted from the flood response patterns (*gcm_rpat* and *rcm_rpat*) can be lower than those from use of the fitted single harmonic (*gcmharm* and *rcmharm*), in terms of mean and maximum changes, at least at higher return periods. Differences in the mean changes can be seen more clearly in Figure 3.3, which summarises the average values from the different sets of results in Figure 3.2, colour-coded by catchment / response type.

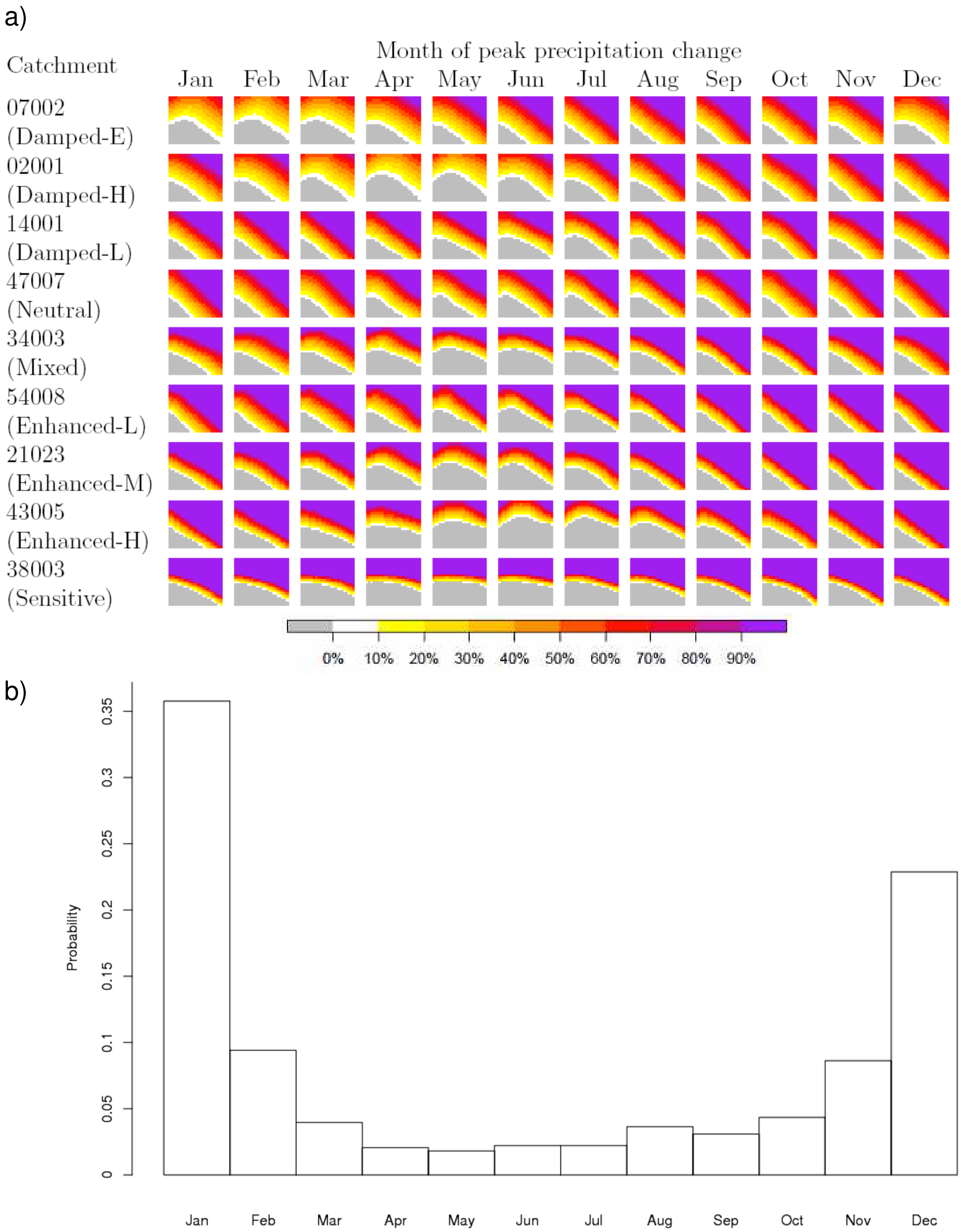


Figure 3.1 a) Example flood response patterns for the nine catchments showing the difference when the peak change in precipitation is taken in each month from January (far left) to December (far right), for percentage change in the flood peak with a 20-year return period (under the Medium-Aug T/PE scenario). b) Likelihood of month of peak precipitation change from current (AR4) GCMs over Great Britain.

Likewise, there are minimal differences in results when the GCM/RCM fitted double harmonic for precipitation is applied (*gcmharm2* and *rcmharm2* in Figure 3.2 and Figure 3.3) versus when the corresponding single harmonic is applied (*gcmharm* and *rcmharm* in Figure 3.2 and Figure 3.3), under each T/PE scenario.

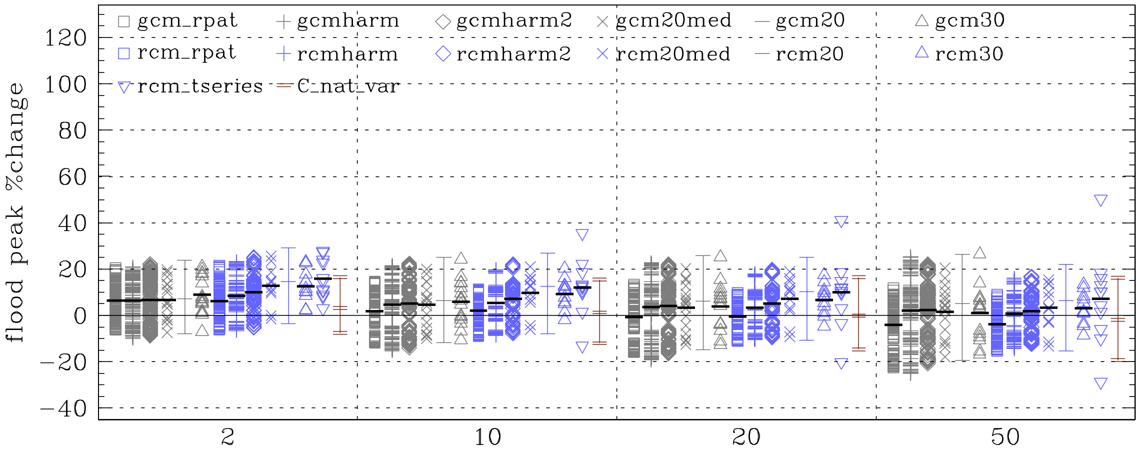
3.2 Factor 2: Comparison of harmonic and monthly factor results

In general, the mean and minimum flood peak percentage changes are greater when the monthly median precipitation changes are used directly (*gcm20med* and *rcm20med* in Figure 3.2 and Figure 3.3) rather than being smoothed out by a single harmonic function (*gcmharm* and *rcmharm* in Figure 3.2 and Figure 3.3). The maximum flood peak percentage change can be smaller in some cases, particularly at lower return periods (resulting in a much smaller range of flood changes, i.e. a narrower range of climate model uncertainty), but is similar or larger in other cases. The largest increases in the maximum flood change, of around 20%, occur at the 50-year return period for catchments 14001 (Damped-Low) and 21023 (Enhanced-Medium), under the RCM-based scenarios. The largest increases in the mean flood change, of around 25-30%, occur at higher return periods for catchment 38003 (Sensitive), under the GCM-based scenarios. Increases in the mean flood change of over 20% also occur at the 2-year return period for this catchment and for catchments 34003 (Mixed) and 43005 (Enhanced-High), under the GCM-based scenarios. The increases in the mean flood change under the RCM-based scenarios are generally smaller than those for GCM-based scenarios.

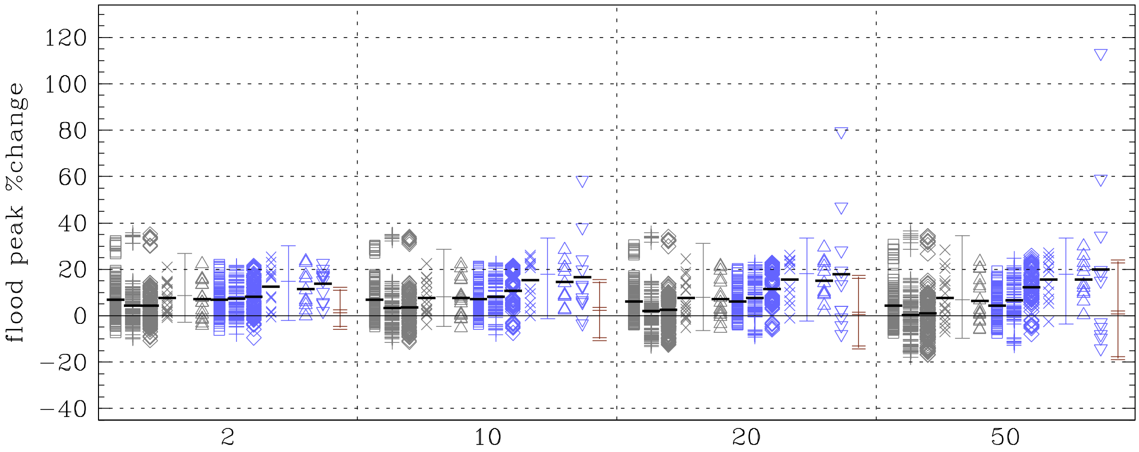
The differences described above are partly due to the use of the actual monthly median values for precipitation changes instead of the values smoothed through the year via the fitted harmonic function. However, they are also due to the use of the actual monthly GCM/RCM temperature/PE scenarios for the catchment, rather than the eight fixed temperature/PE scenarios (from temperature changes smoothed through the year via a harmonic function; Figure 1.2b and Figure 1.3).

When the sets of monthly changes in precipitation and temperature/PE are used for each GCM/RCM scenario (*gcm20* and *rcm20* in Figure 3.2 and Figure 3.3), rather than the median values calculated from these (*gcm20med* and *rcm20med* in Figure 3.2 and Figure 3.3), the 95% bounds of the former encompass the latter, with the median of the former within 5% of the mean of the latter. There is generally an increase at the upper end of the range though, with the largest increase in the upper 95% bound, of around 15%, occurring for catchment 38003 (Sensitive) under the GCM-based scenarios (Figure 3.2).

i) Catchment 07002 (Damped–Extreme)



ii) Catchment 02001 (Damped–High)



iii) Catchment 14001 (Damped–Low)

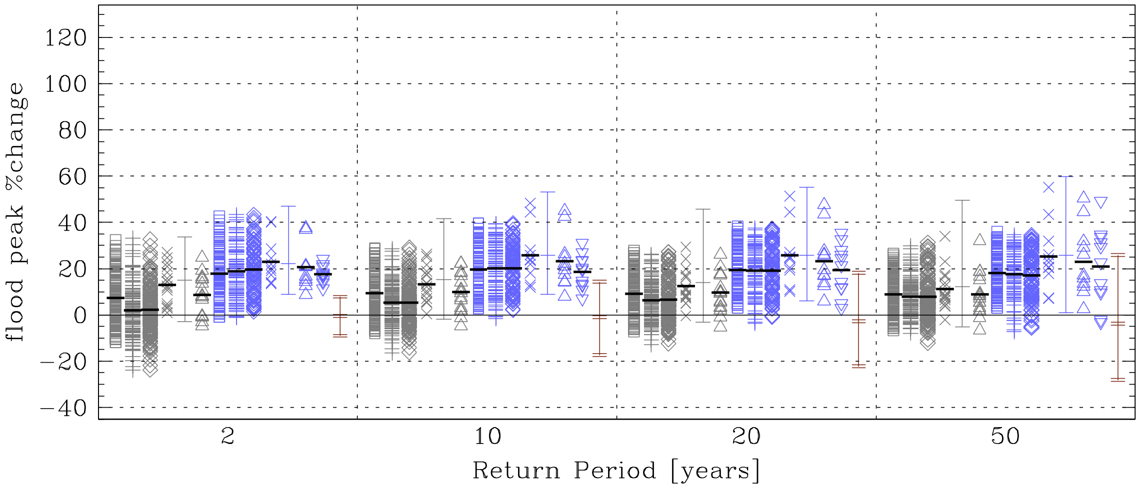


Figure 3.2 Graphs showing, for each chosen PDM catchment, the modelled change in flood peak at the 2-, 10-, 20- and 50-year return period using GCM data (grey) and RCM data (blue). Values extracted from the flood response patterns under each T/PE scenario (*gcm_rpat* and *rcm_rpat*) are compared to: 1) the use of the single harmonic under each T/PE scenario (*gcmharm* and *rcmharm*). 2) the use of the double harmonic under each T/PE scenario (*gcmharm2* and *rcmharm2*). Figure and caption continued on next page.

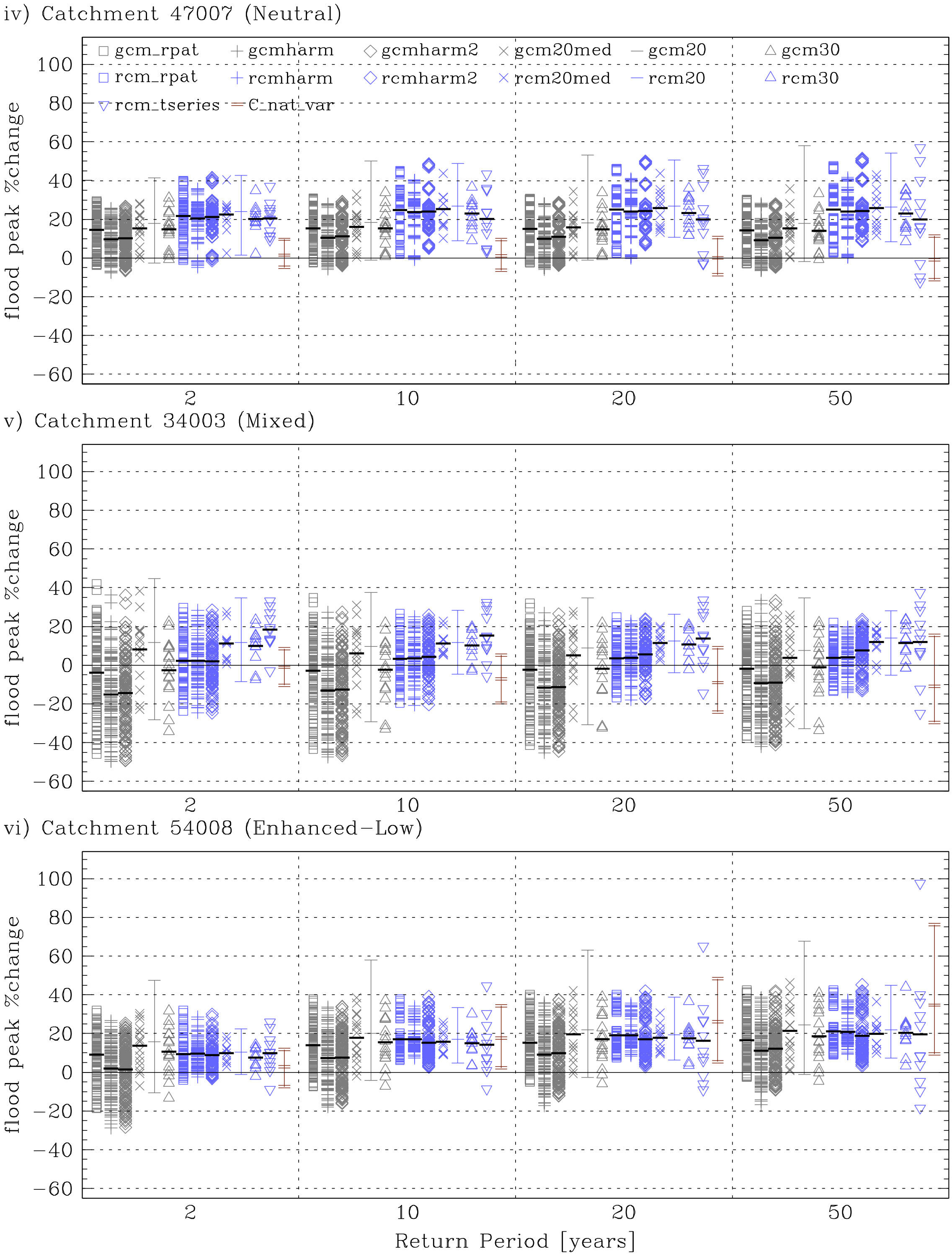
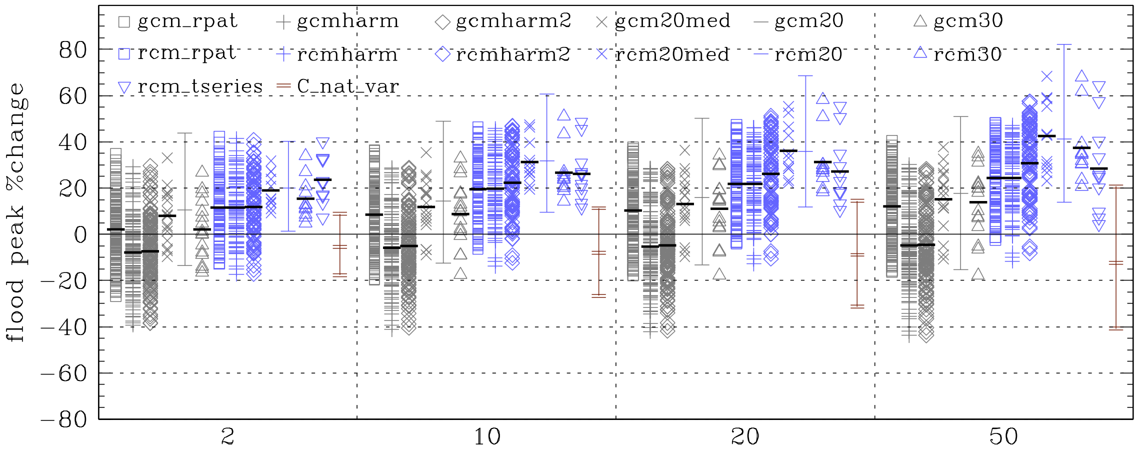
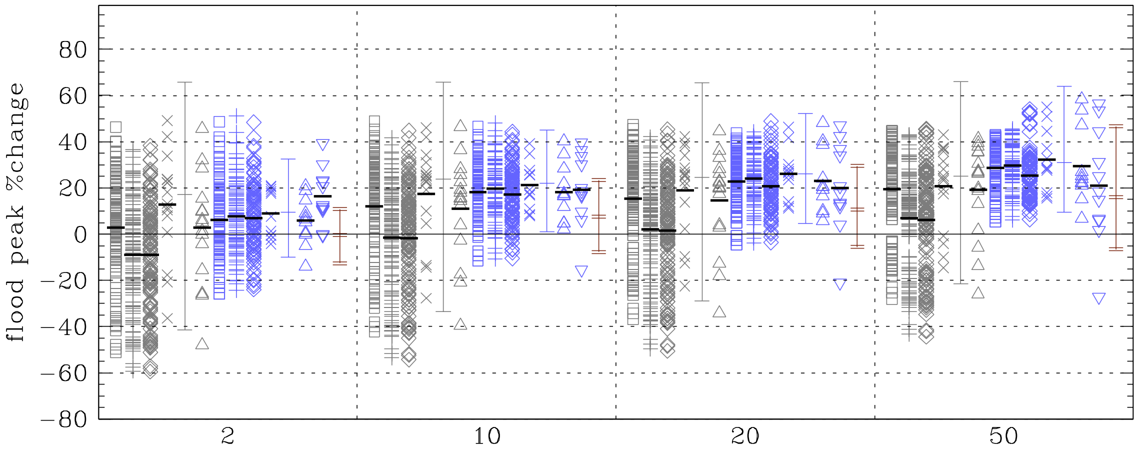


Figure 3.2 continued. 3) the use of the monthly median values that the harmonic is fitted to (*gcm20med* and *rcm20med*). 4) the use of each set of monthly values (*gcm20* and *rcm20*, where the median and 95% bounds are shown). 5) the use of the changes between the standard 30-year time-slices (*gcm30* and *rcm30*). See Table 2.2 (Section 2.4) for explanation of these. Figure and caption continued on next page.

vii) Catchment 21023 (Enhanced−Medium)



viii) Catchment 43005 (Enhanced−High)



ix) Catchment 38003 (Sensitive)

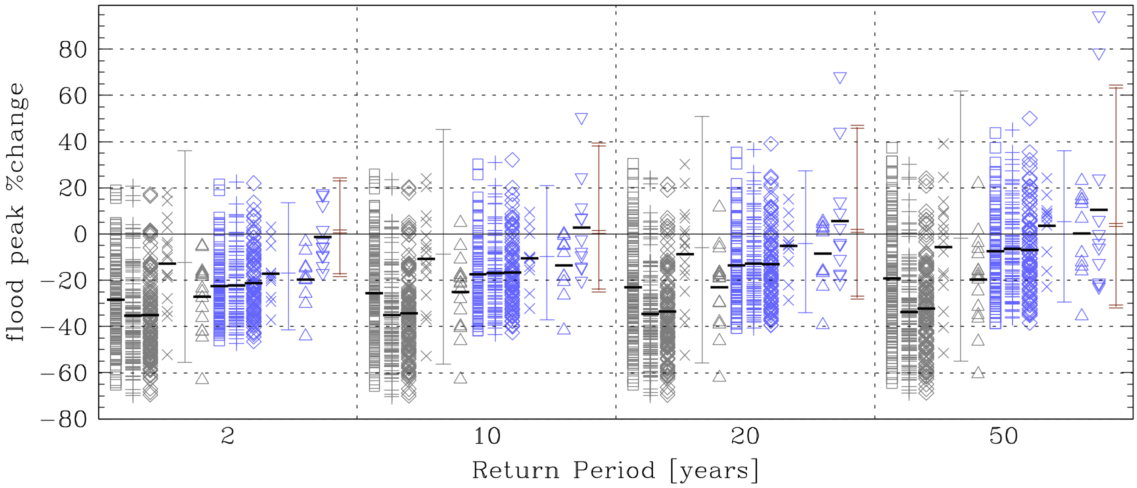


Figure 3.2 continued. Also shown on each graph, for comparison, are results from the direct use of RCM time-series data (*rcm_tseries*; see Section 2.5) and the potential range of current natural variability (*C_nat_var*, where the median and 95% bounds are shown; see Section 2.6). The mean values for each set of points are shown by the black horizontal lines.

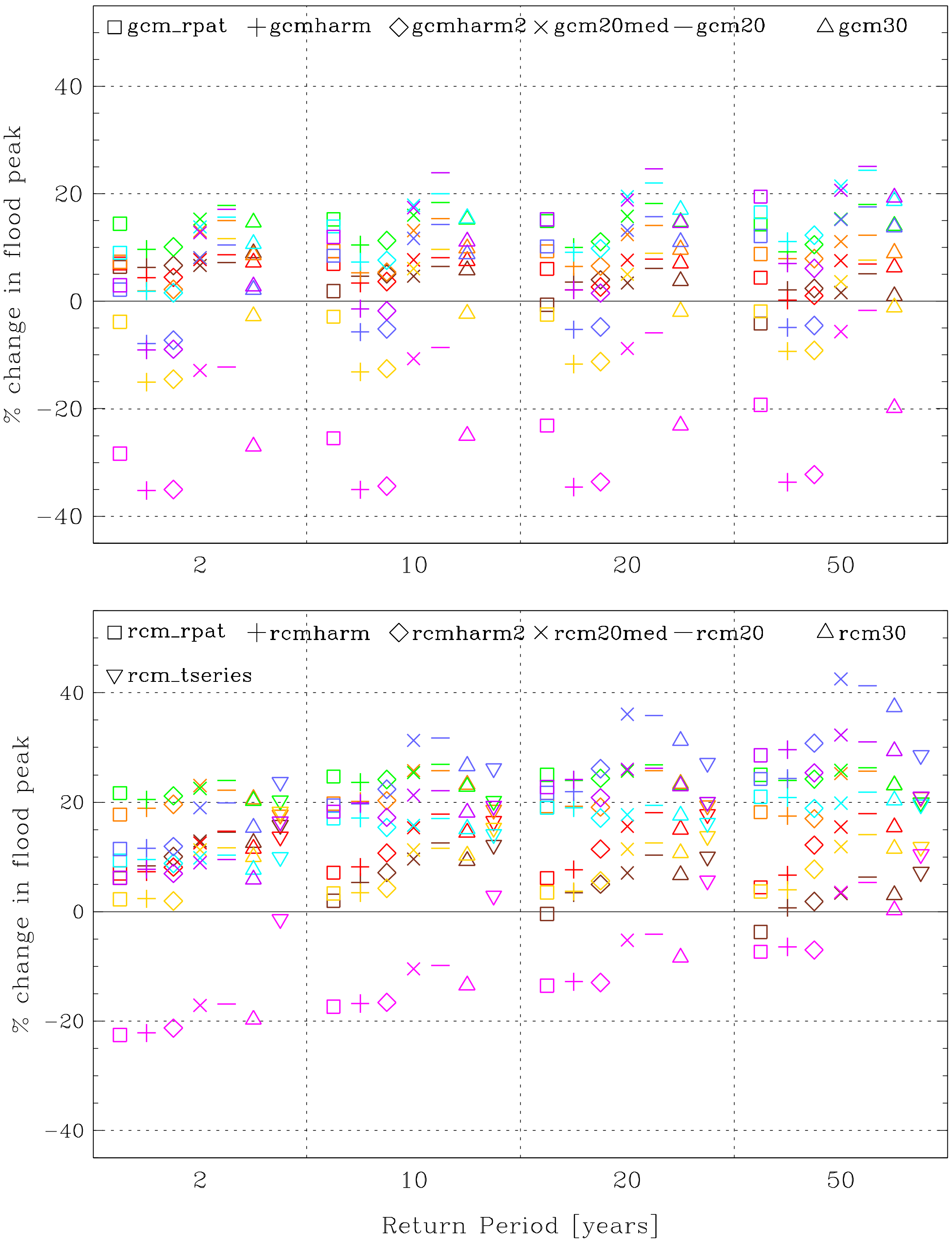


Figure 3.3 Graphs summarising the average (mean or median) values from the different sets of results in Figure 3.2, for GCM-based scenarios (top) and RCM-based scenarios (bottom). The results are coloured by catchment / response type (Table 2.1): 07002 (Damped-Extreme; brown), 02001 (Damped-High; red), 14001 (Damped-Low; orange), 47007 (Neutral; green), 34003 (Mixed; gold), 54008 (Enhanced-Low; cyan), 21023 (Enhanced-Medium; blue), 43005 (Enhanced-High; purple), 38003 (Sensitive; magenta).

The 95% bounds from the use of the sets of monthly changes in precipitation and temperature/PE (*gcm20* and *rcm20* in Figure 3.2) also generally encompass the range of results when the monthly changes from the fixed 30-year time-slices are applied (*gcm30* and *rcm30* in Figure 3.2). There are just a small number of GCM or RCM scenarios which fall very slightly below their corresponding lower 95% bound or above their corresponding upper 95% bound. The median of the former is generally within 5% or so of the mean of the latter (Figure 3.3), except for catchments 34003 (Mixed), 43005 (Enhanced-High) and 38003 (Sensitive), where the mean change using the 30-year time-slices can be over 15% less than the median change from the sets of 20-year time-slices, at least for some (generally lower) return periods and under the GCM-based scenarios.

3.3 Factor 3: Comparison with use of time-series input data

When Baseline and Future time-series of rainfall, PE and temperature, derived for each catchment from the gridded data from the 11 UKCP09 RCM runs (see Section 2.5.1), are used as direct inputs to the PDM (*rcm_tseries* in Figure 3.2 and Figure 3.3), the mean change in the simulated flood peaks (across the 11-member ensemble) is generally similar (at each return period for each of PDM example catchments) to that obtained from the different delta change methodologies using scenarios based on the RCM data (Figure 3.3). The main exception is catchment 38003 (Sensitive), where the mean from direct use of the RCM ensemble data is much larger than the mean from any of the alternatives, especially at lower return periods.

Although the mean values from direct use of the RCM ensemble data are generally similar to the means from the alternative delta change methods, the full range of results from the direct use of the RCM ensemble data is often wider than that from any of the delta change methods (Figure 3.2), especially for higher return periods. However, it is not always the same RCM ensemble member that results in the increased range at either end. For instance, for catchment 02001 it is ensemble members *afixh* and *afixl* which give higher flood changes than every other scenario (at least above the 2-year return period), and no ensemble member gives lower flood changes than every other scenario (although *afixk* gives the lowest of the RCM ensemble members, at least above the 2-year return period). In contrast, for catchment 47007 it is *afgcx* which gives higher flood peak changes than every other scenario and ensemble members *afixh*, *afixk* and *afixm* which give lower flood peak changes than every other scenario at the 50-year return period. Thus *afixh* gives one of the highest changes for one catchment but the lowest for another catchment, in a different location. The ordering of the results from the RCM ensemble members differs not just by catchment, but to some extent by return period too. The Baseline and Future flood frequency curves for four catchments, simulated using data from the Baseline and Future time-slices of each of the 11 RCM ensemble members, are shown in Figure 3.4.

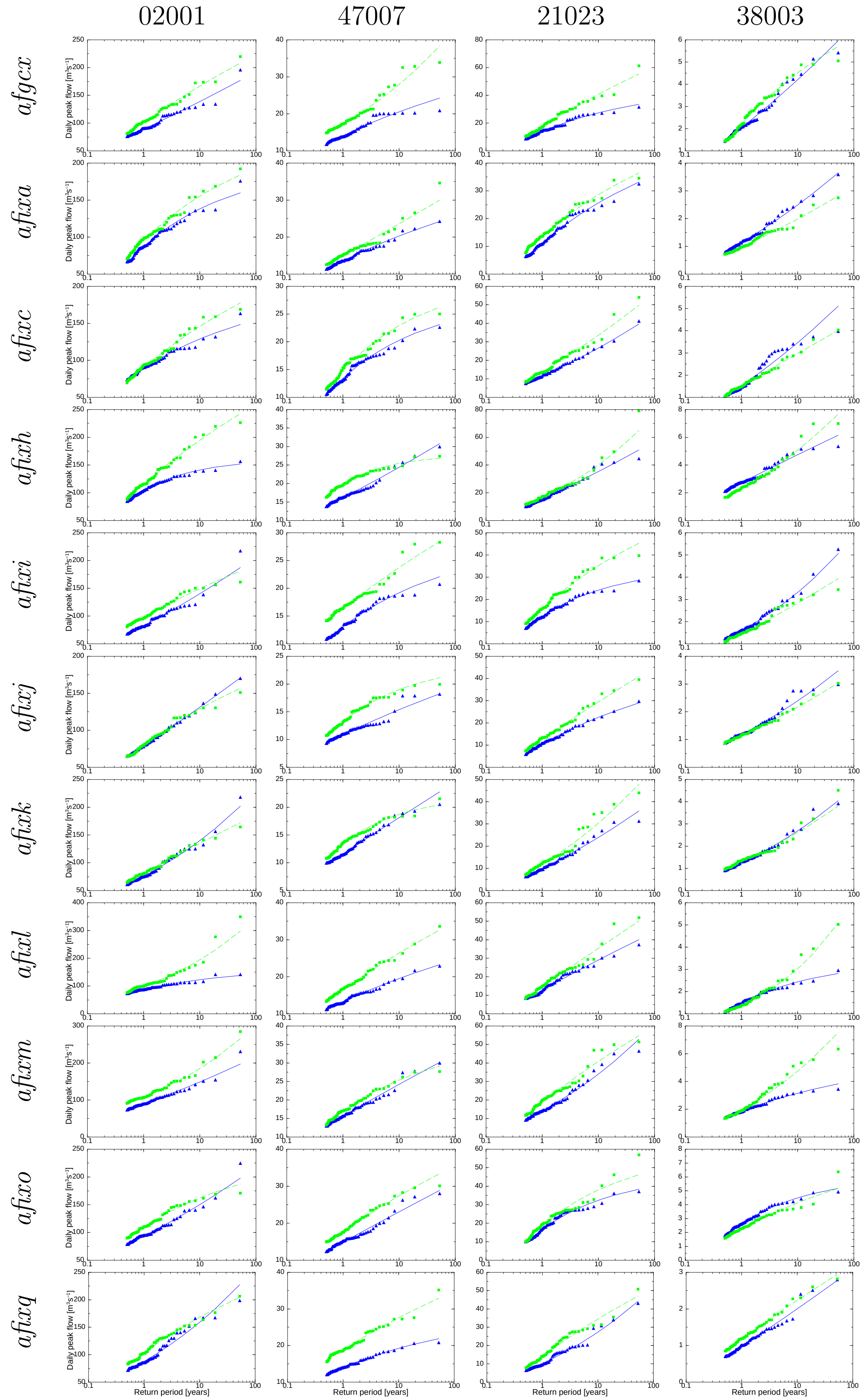


Figure 3.4 Simulated POT and fitted flood frequency curves for Baseline (blue triangles / solid line) and Future (green squares / dashed line) time-slices using the ensemble of RCM time-series data directly, for four of the PDM example catchments. [Note the differing y-axes on these graphs].

The picture is similar for the four example CLASSIC catchments (Figure 3.5), with the use of RCM time-series data leading to a wider range of changes than those extracted from the flood response patterns, at least for higher return periods. The mean flood change from the RCM ensemble is also clearly larger than that from the flood response patterns, although it is possible that this ‘gap’ would be filled to some extent had the alternative delta change methodologies (e.g. *rcmharm* etc.) been tested for the CLASSIC catchments as for the PDM catchments. However, the difference between the mean flood changes at the 50-year return period is nearly 30% for catchments 27009 (Damped-High) and 33026 (Mixed), which is larger than the equivalent difference for any of the PDM catchments (the largest of which is less than 20%, for catchment 38003 (Sensitive)). It is possible that this apparent increased response of the CLASSIC catchments compared to the PDM catchments, when using RCM time-series data as input, is due to the generally larger area of the CLASSIC catchments (see Crooks *et al.* 2009). A larger catchment area means an increased possibility of large accumulations of water reaching the river, and the RCM data could be suggesting greater spatial coherence of rainfall in future (due to wetter winters / drier summers meaning more large-scale, frontal rainfall and less convective rainfall).

Overall, from all 13 example catchments (nine PDM and four CLASSIC) and the four flood indicators, it is only ensemble member *afixa* that never gives the largest or second largest change. Every one of the 11 ensemble members gives the smallest or second smallest change in at least one case. The overall tendency of *afixa* to give smaller changes is probably due to its particular RCM parameter settings, which seem to result in bigger increases in PE than for the other ensemble members (Kay *et al.* 2008). The fact that the other ensemble members do not show any clear tendencies suggests that their particular parameter settings are less important, and perhaps that the natural variability displayed within each time-slice of each ensemble member is the more dominant factor. However, it is difficult to separate this from possible differences in the underlying spatial patterns present in the RCM ensemble data.

Figure 3.4 presents the flood frequency curves simulated using data from the Baseline and Future time-slices of each of the 11 RCM ensemble members, for four of the PDM example catchments. It is the pair of curves for each RCM ensemble member which is used to calculate the percentage differences at the four return periods (Section 2.5.1). Figure 3.4 illustrates the wide range of possible Baseline and Future curves, which can differ in shape as well as position. Often, it is the pairing of differently shaped curves – a flattening baseline curve with an ever-increasing future curve – which leads to very large percentage increases at higher return periods (for example for catchment 38003 under *afixl* and *afixm* and for catchment 02001 under *afixh* and *afixl*). Note that the RCM baselines are not meant to exactly reproduce the climate in the baseline period, but are simply one representation of what could have occurred in that period, just as the Future time-slice is one representation of what could occur in that period (under given assumptions on emissions etc). That is, *both* time-slices are affected by the presence of natural variability. Note also that it is generally not outlier events significantly skewing the fitting of the flood frequency curves, although some curves clearly fit their set of simulated peaks-over-threshold (POT) better than others (Figure 3.4).

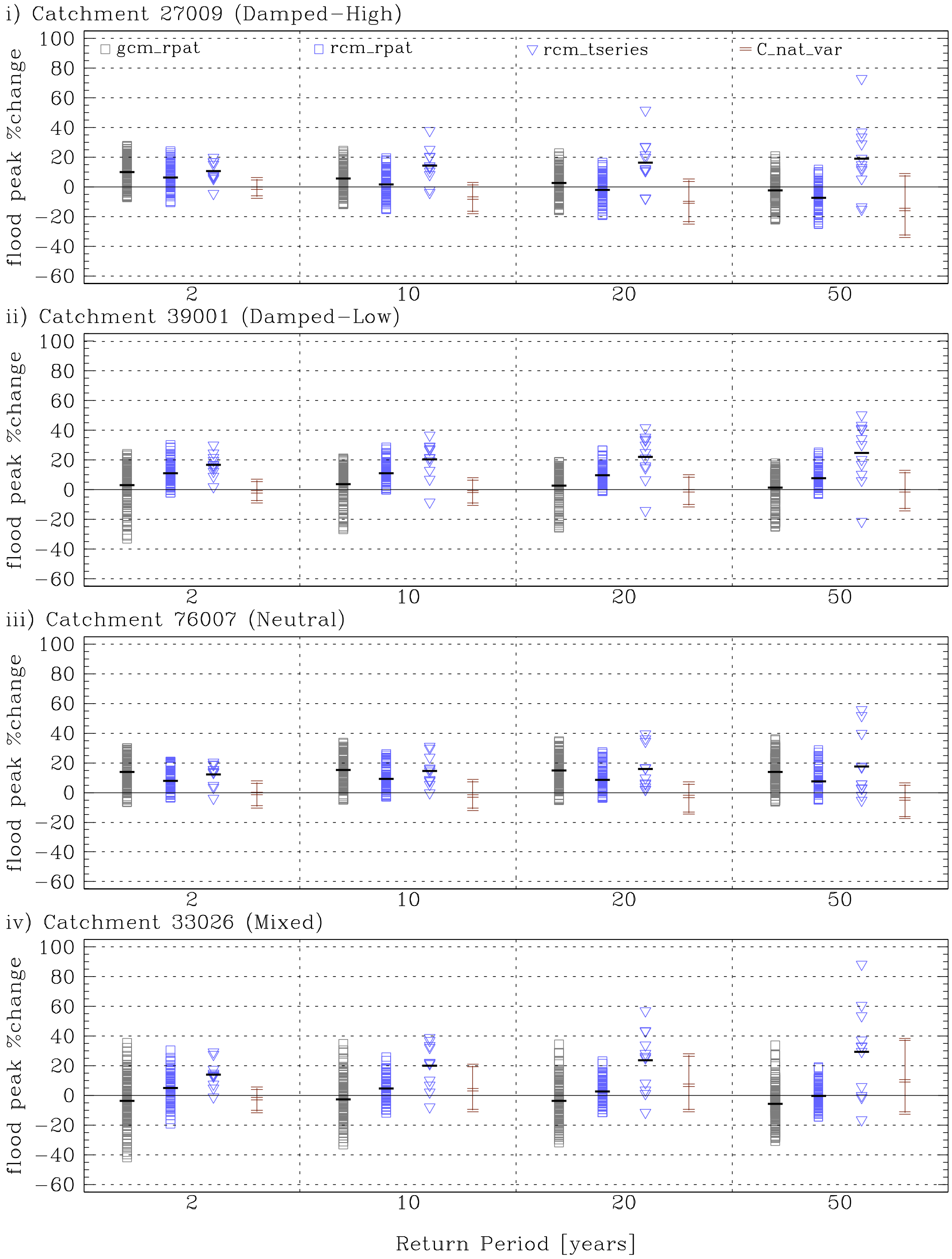


Figure 3.5 Graphs showing, for each chosen CLASSIC catchment, the modelled change in flood peak at the 2-, 10-, 20- and 50-year return period using GCM data (grey) and RCM data (blue). The values extracted from the flood response patterns under each T/PE scenario (*gcm_rpat* and *rcm_rpat*) are compared to results from the direct use of RCM time-series data (*rcm_tseries*; see Section 2.5) and the potential range due to current natural variability (*C_nat_var*, where the median and 95% bounds are shown; see Section 2.6). The mean values for each set of points are shown by the black horizontal lines.

Considering the range of results from the direct use of the RCM time-series ensemble as representing climate change plus natural variability helps to explain their expanded range relative to that from use of the delta change methods (which do not include natural variability). This is because, under a given RCM ensemble member in a given period, natural variability could act in the same direction as climate change, thus reinforcing its apparent effect in that period, or act in the opposite direction, thus reducing its apparent effect in that period (see discussion in Section 2.2 of Murphy *et al.* 2009). Add to this the fact that the Baseline, as well as the Future, RCM time-slice includes natural variability, and it is clear how the range of changes can appear to be much wider using this method. An estimate of the potential range of current natural variability is also shown on the plots in Figure 3.2 and Figure 3.5 (described in the next section). This estimate can be used to help put the RCM time-series ensemble results into context with the delta change results.

3.4 Factor 4: Comparison with the potential range of natural variability

Also shown for each catchment in Figure 3.2 (PDM catchments) and Figure 3.5 (CLASSIC catchments) is the potential range of current natural variability (estimated via the method described in Section 2.6), to help put the potential impacts under climate change into context with the range of flood peaks that could be expected under the current climate. For some catchments the potential climate change impacts on flood peaks (for the 2080s) hardly ever exceed the potential range that could occur just through natural variability of the current climate (e.g. catchments 07002 (Damped-Extreme), 43005 (Enhanced-High) and 38003 (Sensitive) for the PDM and catchment 33026 (Mixed) for CLASSIC). For other catchments there is a distinct upwards shift in impacts under climate change, in comparison to the range of natural variability (e.g. catchments 14001 (Damped-Low), 47007 (Neutral) and 21023 (Enhanced-Medium) for the PDM and catchment 76007 (Neutral) for CLASSIC).

There is considerable similarity in the results, relative to natural variability, between the four CLASSIC catchments and their corresponding (in terms of flood response type) PDM catchments, that is 27009 cf. 02001 (Damped-High), 39001 cf. 14001 (Damped-Low), 76007 cf. 47007 (Neutral) and 33026 cf. 34003 (Mixed) (see Table 2.1). This suggests that this result is a real feature of catchment type that can be carried through to the flood response types, at least for these four flood response types.

However, it cannot be assumed that a catchment is ‘safe’ from the impacts of climate change just because there is not an upward shift relative to natural variability, as the catchment may not be sufficiently protected against natural variability in itself. This could particularly be the case if the potential range of natural variability is very large (e.g. for ‘Enhanced’ or ‘Sensitive’ catchments) or if the observed record for the catchment is not all that representative of what could generally be expected of the catchment. The latter could be the case if a catchment’s period of record covers a so-called flood-poor period, or a period where certain types of flooding simply have not occurred (due to multi-decadal natural variability for example). The possible existence of such issues is shown by the natural variability results presented in Figure 3.2 and Figure 3.5, where the median might be expected to lie close to the zero percentage change line but can actually be some way from that for some catchments. It seems to be a particular issue for catchment 54008, where even the estimated lower 95% bound for current natural variability lies above the zero line, suggesting that the majority of the 101 resampled rainfall time-series are in some way different to the baseline time-series. This could be due, for instance, to a wet winter never having followed a wet summer in the baseline time-series, despite several of both occurring separately, so that many of the resampled series could end up with a wet winter following a wet summer, and so higher flood peaks.

It should also be remembered that the resampling methodology used here to estimate the range of current natural variability is a pragmatic method used to investigate a very complex issue. As such it does not cover the full range of contributing factors, for instance changes in maximum daily rainfall, and thus the full range of natural variability is likely to be larger for all catchments, and perhaps proportionally more so for some types of catchment compared to others. In addition, natural variability may itself alter under climate change.

3.5 Summary

When compared to values extracted from the flood response patterns (*gcm_rpat* and *rcm_rpat* in Figure 3.2 and Figure 3.3), some catchments show greater changes under any of the alternative options than do other catchments. In order to compare the potential levels of uncertainty between the PDM example catchments, at each of the four return periods, the difference between the mean (or median) values for each of the alternative methods (both delta change and using the RCM time-series) presented in Figure 3.3 and the mean of the values extracted from the flood response patterns (*gcm_rpat* and *rcm_rpat* in Figure 3.3) was calculated. Here, the GCM-based and RCM-based results have been kept separate, so that, for instance, the mean of *gcmharm* is compared to the mean of *gcm_rpat* whereas the mean of *rcmharm* is compared to the mean of *rcm_rpat*, etc. The maximum of these differences in each case is given in Table 3.1.

The analyses show that it is catchment 47007 (Neutral) which has the lowest potential uncertainty at all four return periods, with catchments 14001 (Damped-Low) and 54008 (Enhanced-Low) also showing quite low levels of uncertainty. In contrast catchment 38003 (Sensitive) shows the highest potential uncertainty at all except the 50-year return period, where it is equal-highest with catchment 21023 (Enhanced-Medium). Catchment 02001 (Damped-High) also shows quite high levels in uncertainty, especially for higher return periods.

The potential level of uncertainty is very similar across each of the four return periods for some catchments (for example 07002 (Damped-Extreme) and 14001 (Damped-Low)), but increases/decreases with return period for other catchments. For example, the potential level of uncertainty for catchment 34003 (Mixed) is the second highest at the 2-year return period but decreases with return period until, at the 50-year return period, its uncertainty is about average. But for catchment 02001 (Damped-High) the potential uncertainty is below average at the 2-year return period, and increases with return period until it is well above average at the 50-year return period.

A full comparison with the potential level of uncertainty for the example CLASSIC catchments is not possible, both because there are not CLASSIC catchments in each of the nine flood response types and because only the RCM time-series results can be compared to the *rcm_rpat* results for these catchments, as the alternative delta change methods have not been applied with them. However, the available differences (Table 3.2) show a similar pattern to that for the PDM example catchments. That is, catchment 76007 (Neutral) shows the lowest level of uncertainty at all four return periods (cf. PDM catchment 47007 in Table 3.1), with catchment 39001 (Damped-Low) also showing a below-average level of uncertainty (cf. PDM catchment 14001 in Table 3.1). Also, catchment 27009 (Damped-High) shows a below-average level of uncertainty at the 2-year return periods, but an above-average level at higher return periods (cf. PDM catchment 02001 in Table 3.1).

Table 3.1 The maximum difference (%) between the means from alternative options and the mean values extracted from the flood response patterns (*gcm_rpat* for GCM-based results and *rcm_rpat* for RCM-based results in Figure 3.2), for each of the PDM example catchments at each of the four return periods.

PDM catchment	Return period [years]			
(response type)	2	10	20	50
07002 (Damped-E)	10	11	11	11
02001 (Damped-H)	8	11	12	16
14001 (Damped-L)	8	6	6	8
47007 (Neutral)	3	3	3	4
34003 (Mixed)	16	13	11	10
54008 (Enhanced-L)	7	6	7	8
21023 (Enhanced-M)	12	12	14	18
43005 (Enhanced-H)	14	12	9	6
38003 (Sensitive)	21	20	19	18
Mean	11	10	10	11

Table 3.2 The difference (%) between the means from the use of the RCM time-series (*rcm_tseries* in Figure 3.5) and the mean values extracted from the response patterns (*rcm_rpat* in Figure 3.5), for each of the CLASSIC example catchments at each of the four return periods.

CLASSIC catchment	Return period [years]			
(response type)	2	10	20	50
27009 (Damped-H)	4	13	18	26
39001 (Damped-L)	5	9	12	17
76007 (Neutral)	4	5	7	10
33026 (Mixed)	9	15	21	30
Mean	6	11	15	21

Of the four CLASSIC catchments, 33026 (Mixed) shows the highest level of uncertainty across all four return periods. This is comparable to the results for PDM catchment 34003 (Mixed) if only the four PDM catchments with the same flood response type as the four CLASSIC catchments are considered (that is catchments 02001, 14001, 47007 and 34003). Then, catchment 34003 would give the highest level of uncertainty at the 2- and 10-year return periods (Table 3.1), and although at the higher return periods catchment 02001 (Damped-High) gives a slightly higher level of uncertainty, the results for CLASSIC catchment 27009 (Damped-High) are also high, and actually quite close to those for 33026 (Mixed) at the 20- and 50-year return periods (Table 3.2).

It can also be seen from Table 3.2 and Table 3.1 that each of the CLASSIC catchments has a higher level of uncertainty (above the 2-year return period) than the PDM catchment with the same flood response type (and a lower level of uncertainty at the 2-year return period). The mean values follow the same pattern. This probably reflects the larger catchment area of the CLASSIC catchments, as discussed in Section 3.3.

4. Discussion

A number of assumptions and simplifications were necessary to develop project FD2020's 'scenario neutral' approach to regionalisation of climate change impacts on flood flows. These constraints facilitated the production of 'flood response patterns' representing the vulnerability of a given flood indicator for a catchment to a particular set of changes in precipitation, temperature and PE. In order to assess the potential level of uncertainty from a number of these assumptions and simplifications, various alternative delta-change methods, as well as direct use of time-series data from an RCM ensemble, have been applied to a small subset of catchments.

The results from these alternatives methods, under given GCM/RCM scenarios, have been compared to values extracted from the flood response patterns for those scenarios. This comparison shows that different catchments can have different causes of uncertainty (that is, the differences in comparison to the flood response pattern results occur at different stages in the uncertainty analysis). Perhaps more importantly, some catchments have an overall higher potential level of uncertainty than other catchments. Furthermore, some catchments have a similar level of uncertainty across all four of the return periods investigated, whereas others have a level of uncertainty which increases/decreases with return period.

Assuming these differences also apply to other catchments of the same flood response type as the example catchments, it is possible to say something about the potential level of uncertainty for different types of catchment. For instance, a catchment classified as 'Neutral' will have quite a low level of uncertainty (as will catchments classified as 'Damped-Low' or 'Enhanced-Low'), while a catchment classified as 'Damped-High' or 'Mixed' is likely to have a higher level of uncertainty, and a catchment classified as 'Sensitive' is likely to have the highest level of uncertainty.

These results are compatible with the underlying climatological and hydrological differences between the flood response types (Prudhomme *et al.* 2009b). The characteristics selected in the decision trees (determining which flood response type a catchment is likely to belong to) demonstrate how change in the water balance is the dominant factor determining change of flood potential. For 'Neutral' catchments, where the flood response patterns show a near-linear response to changes in rainfall, the water balance throughout the year is not unduly affected by changes in rainfall and PE. Thus uncertainty to flood change for this type of catchment is small. In contrast, for 'Sensitive' catchments the flood response patterns have a very narrow band where the change in flood peak can be anywhere between 0 and 90%, and so seasonal changes to rainfall and PE can easily alter the balance between these two factors and consequent flood potential. Precisely how and when changes occur causes differences in impact on the water balance, resulting in a comparatively high level of uncertainty. Catchment classified as 'Mixed', 'Enhanced-Medium' and 'Enhanced-High' are also susceptible to seasonal changes in the water balance, so they too have fairly high levels of uncertainty. Uncertainty for catchments classified as 'Damped-High' is probably less affected by potential changes to the water balance than by the causes and month of occurrence of extreme events, for example changes in temperature or rainfall which affect the incidence of snowmelt floods or summer storms.

Despite the small number of catchments investigated here, the fact that the results are physically reasonable, and the similarity of the results for comparable PDM and CLASSIC example catchments, gives confidence in the extension of the results to catchment type. The next step is to develop guidance on what level of uncertainty to allow, according to flood response type and return period. The potential effect of catchment area on the level of uncertainty will also have to be borne-in-mind.

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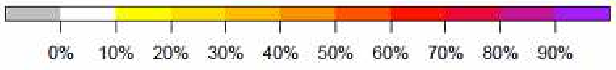
Appendix A: Standard flood response patterns for the example catchments

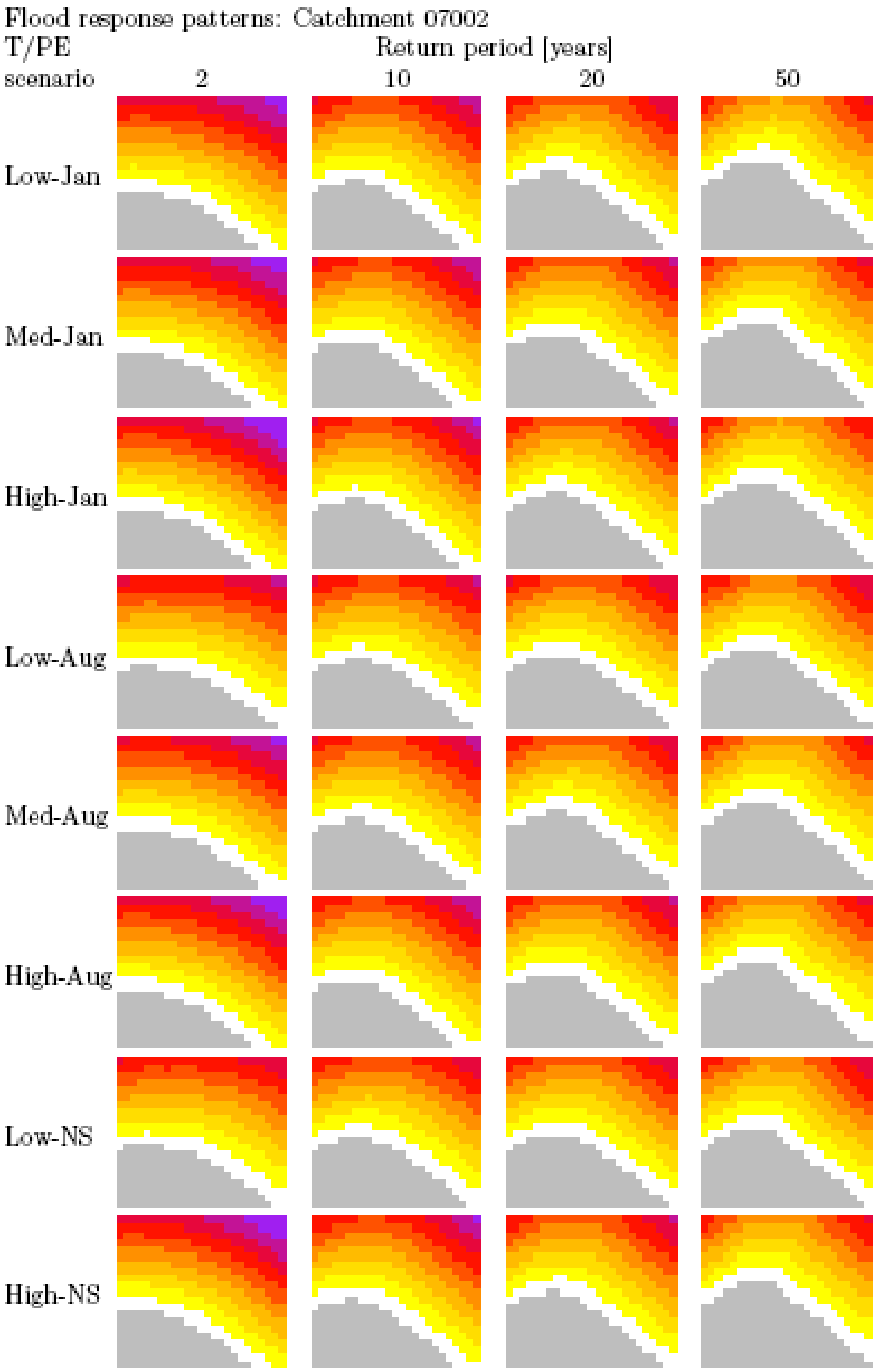
This appendix contains, for each of the nine PDM and four CLASSIC example catchments (listed below), and for each of the eight T/PE scenarios, the standard (i.e. January peak precipitation change) flood response patterns showing the percentage change in the flood peak for each of the four return periods (2-, 10-, 20- and 50-years).

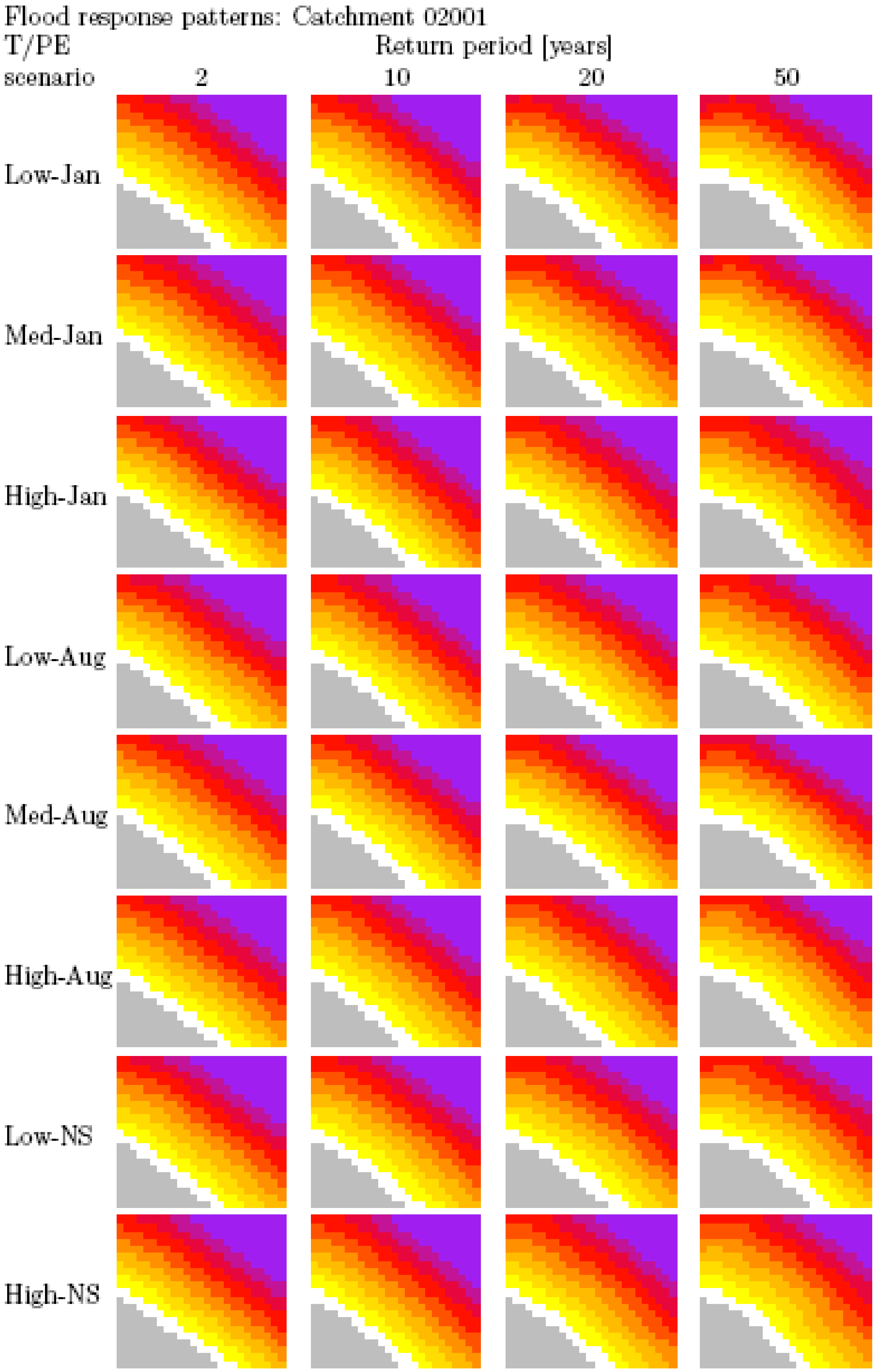
PDM example catchments:
07002 (Damped-Extreme)
02001 (Damped-High)
14001 (Damped-Low; Mixed at 20-year return period)
47007 (Neutral)
34003 (Mixed)
54008 (Enhanced-Low)
21023 (Enhanced-Medium)
43005 (Enhanced-High)
38003 (Sensitive)

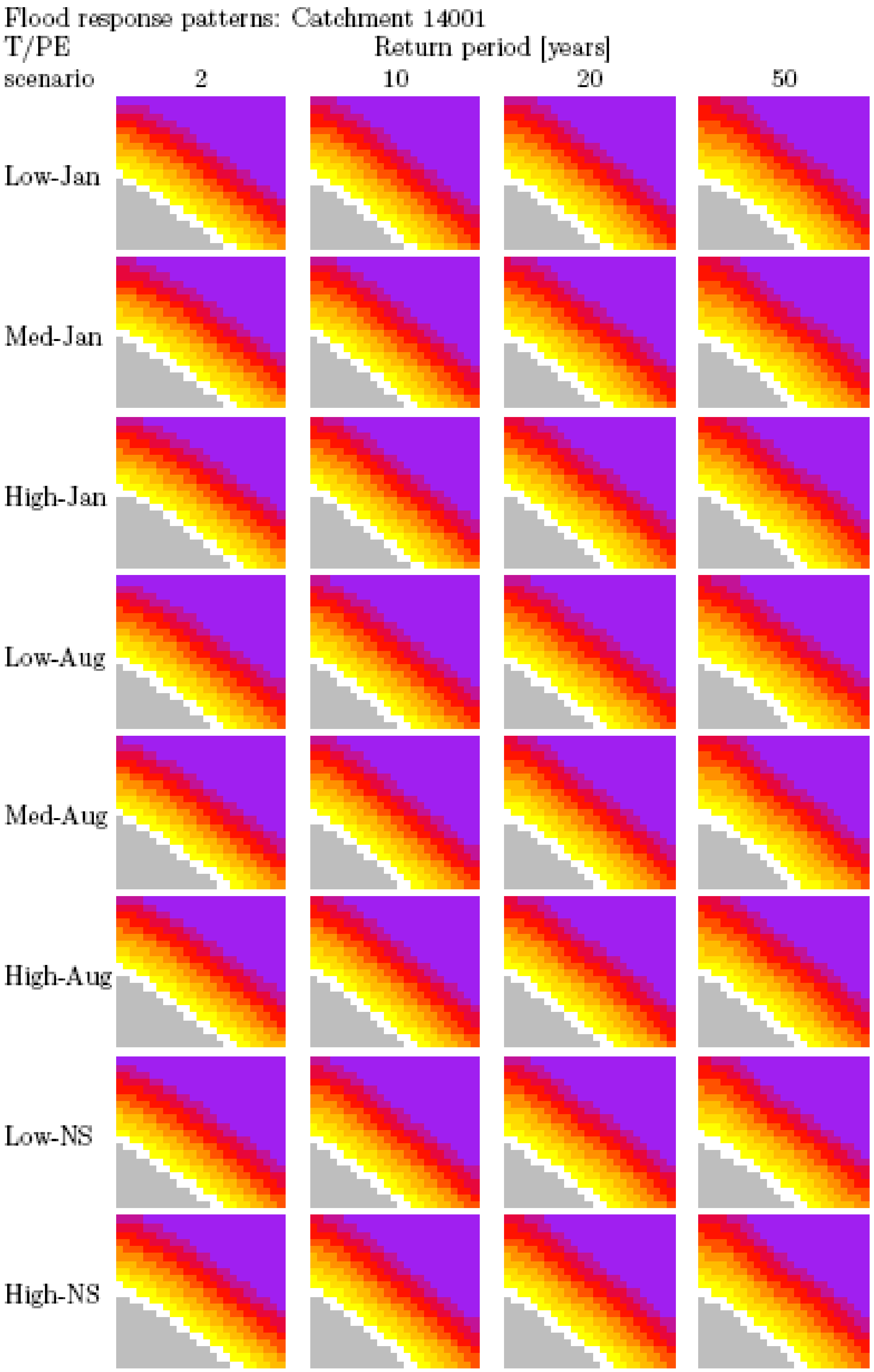
CLASSIC example catchments:
27009 (Damped-High; Damped-Low at 2-year return period)
39001 (Damped-Low; Mixed at 20- and 50-year return period)
47007 (Neutral)
34003 (Mixed)

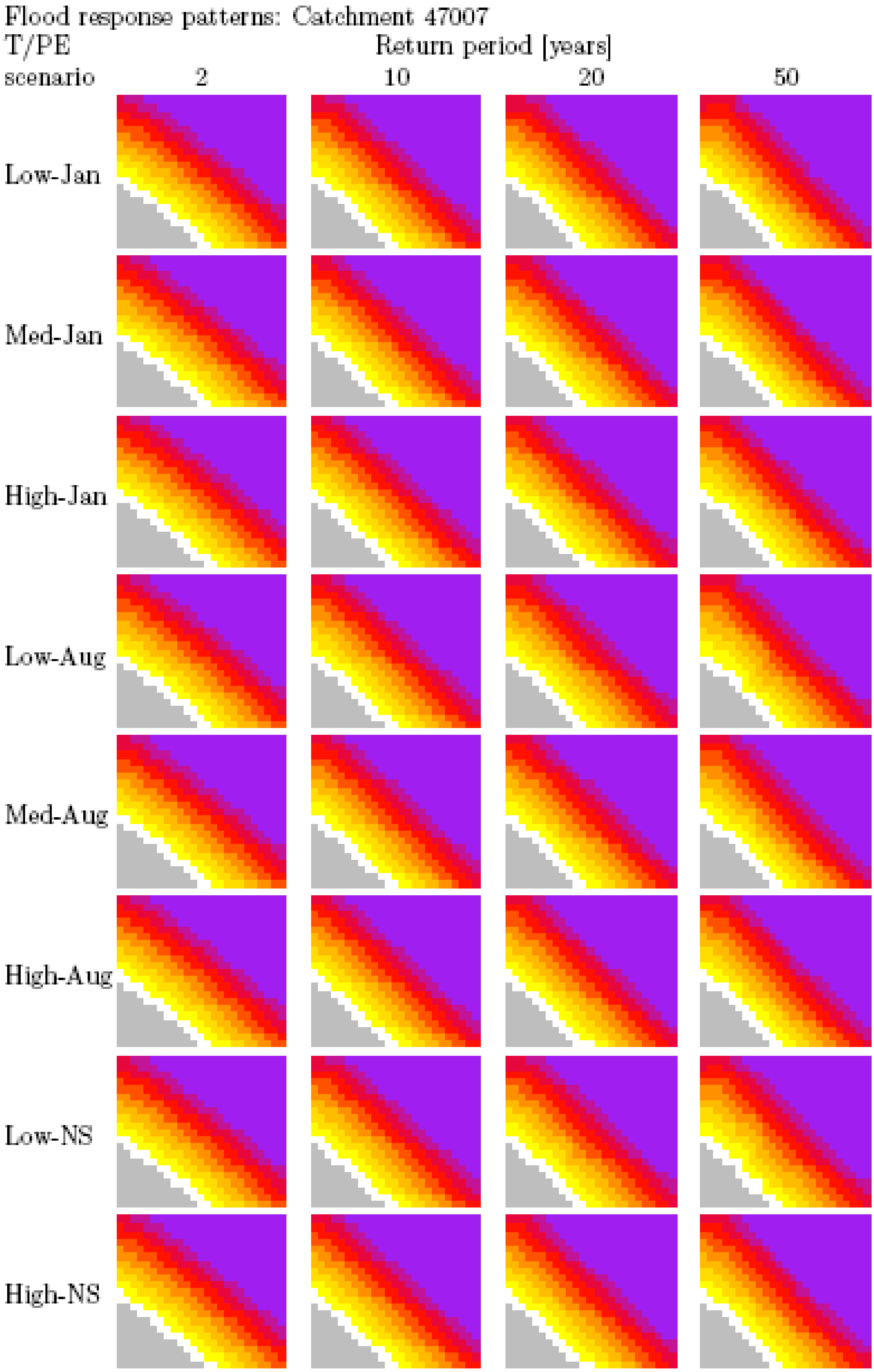
Key for flood response patterns:

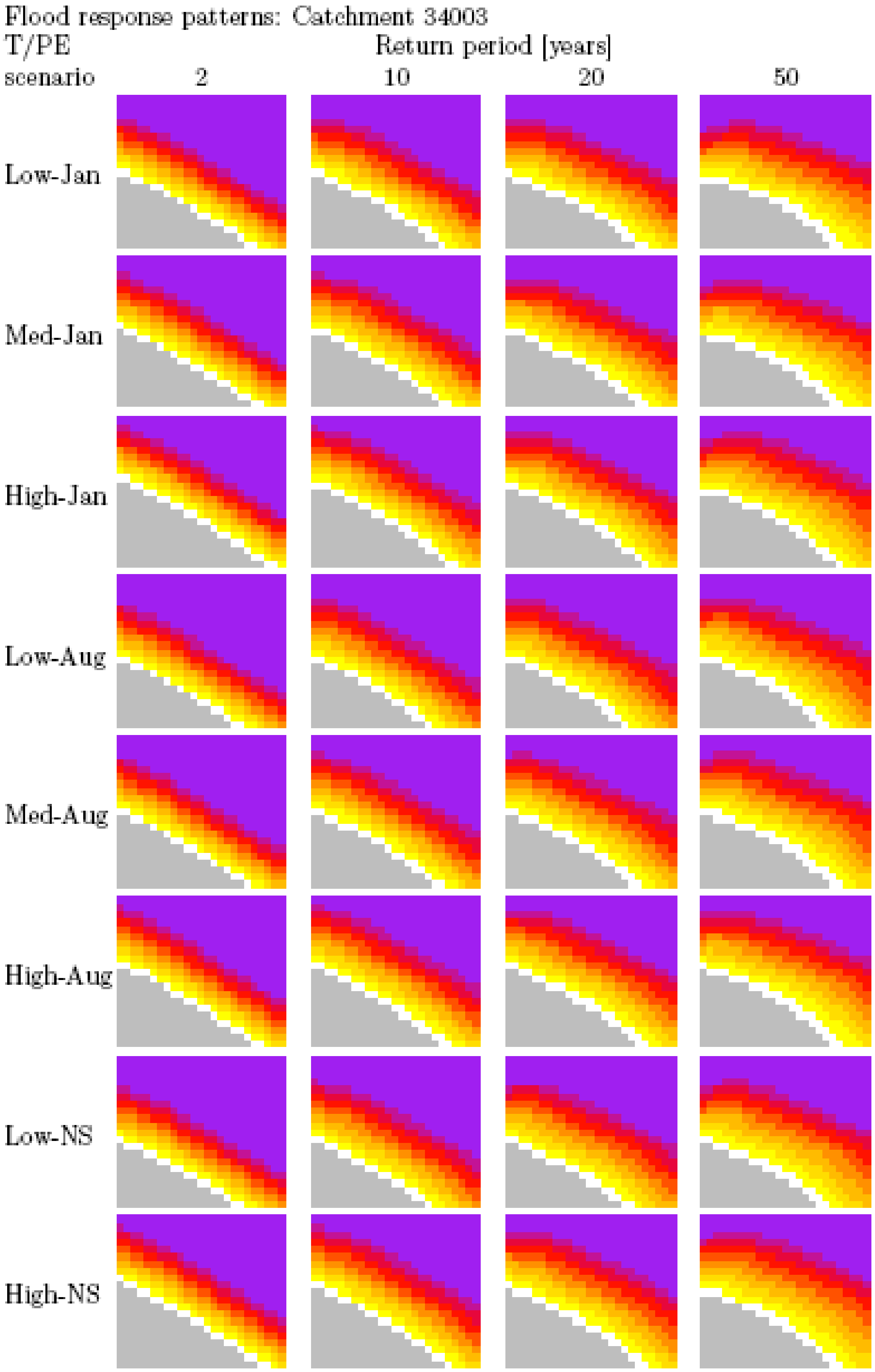


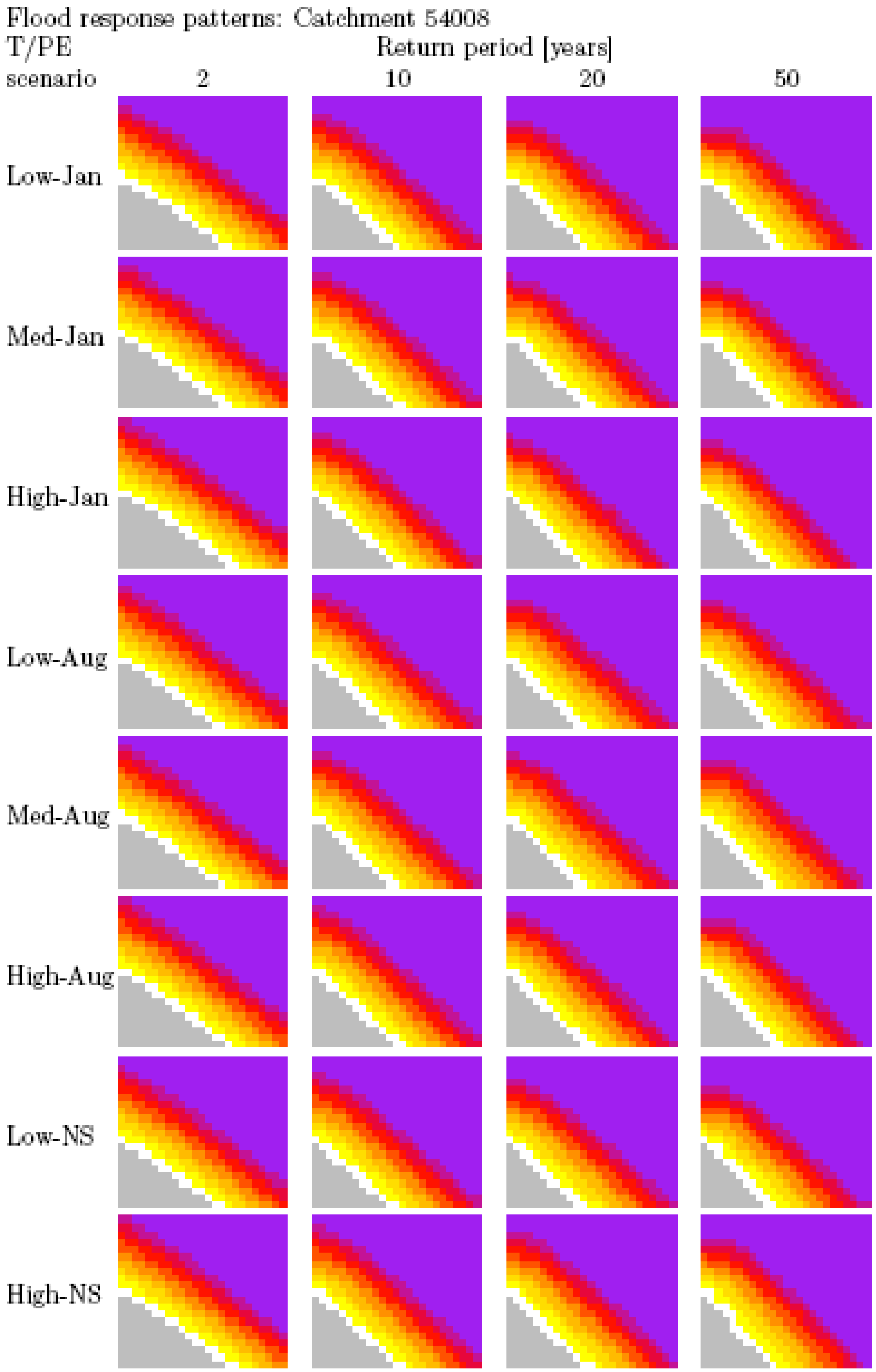

Flood response patterns: Catchment 07002
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS

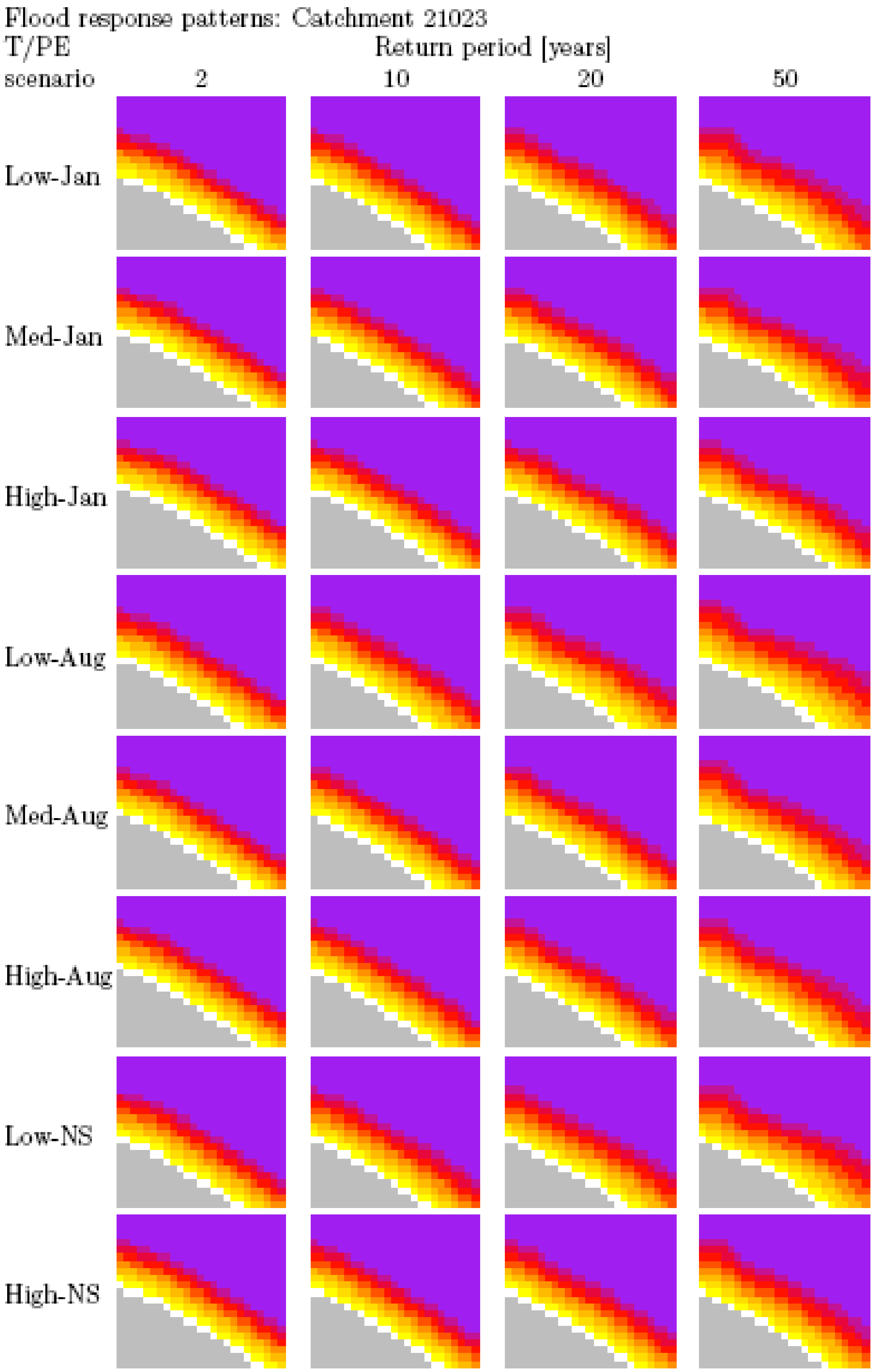

Flood response patterns: Catchment 02001
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Flood response patterns: Catchment 14001
T/PE scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Flood response patterns: Catchment 47007
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Flood response patterns: Catchment 34003
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Flood response patterns: Catchment 54008
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Flood response patterns: Catchment 21023
T/PE
scenario
Return period [years]
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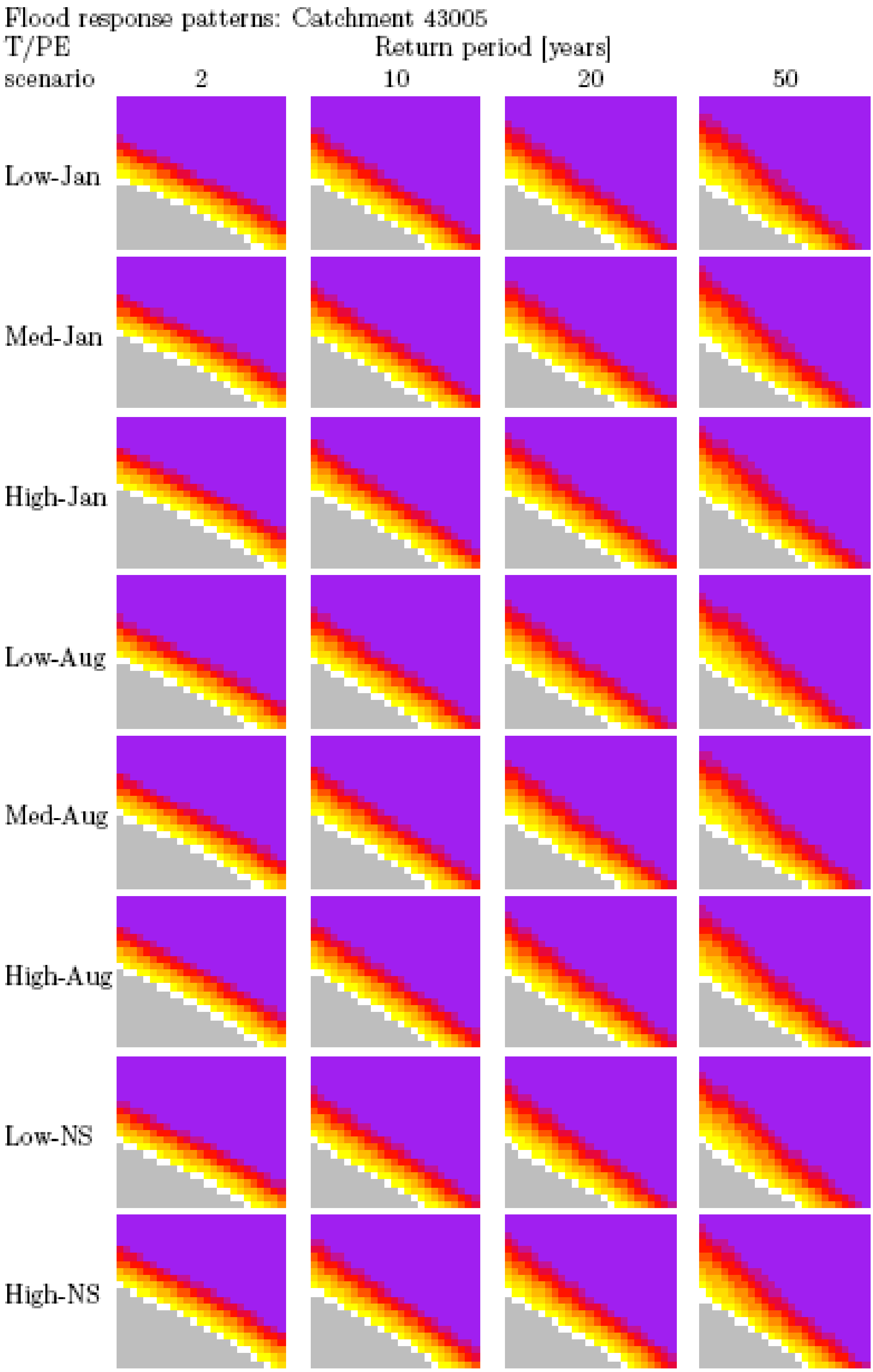
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS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T/PE
scenario
Return period [years]
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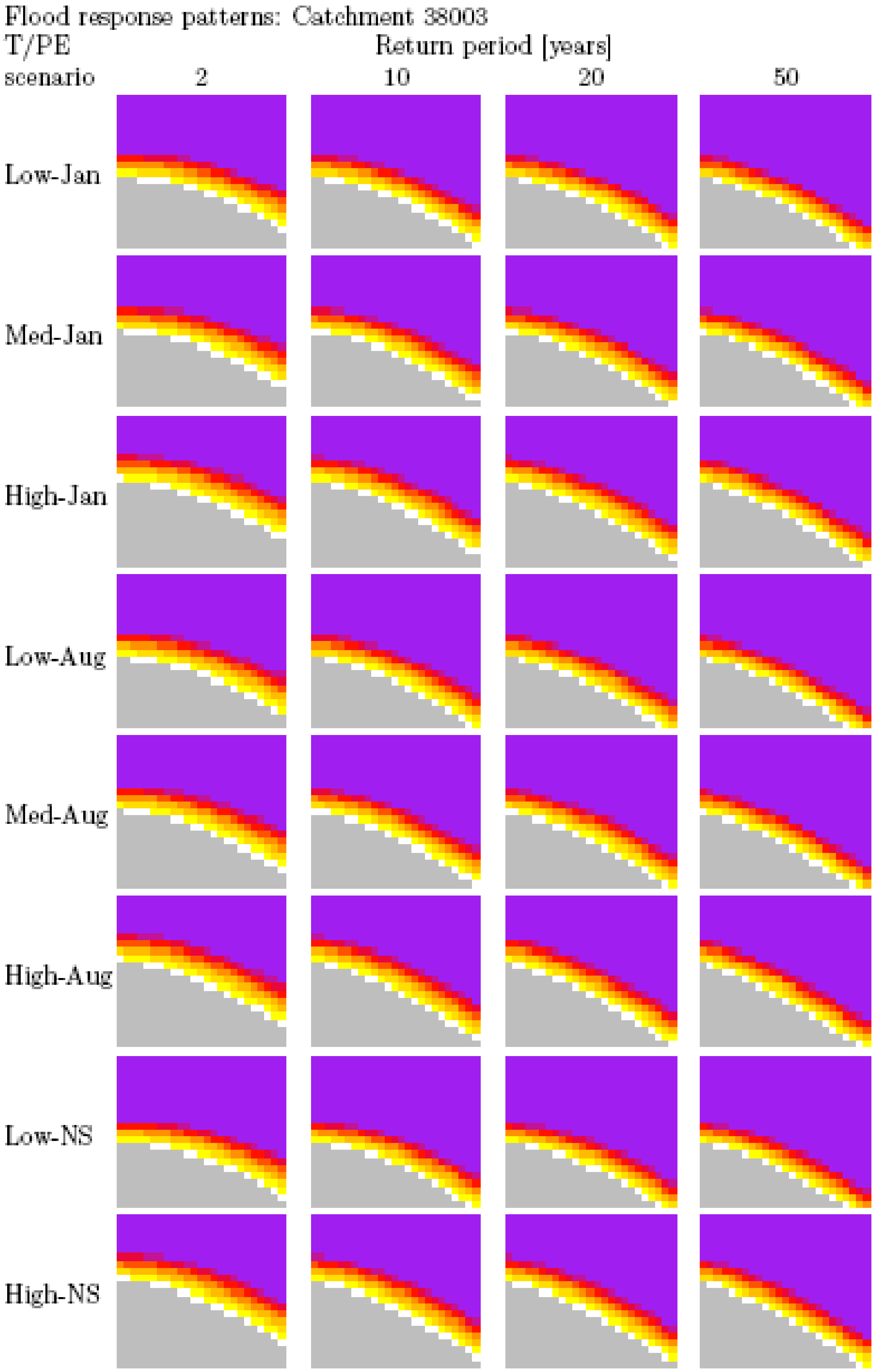
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS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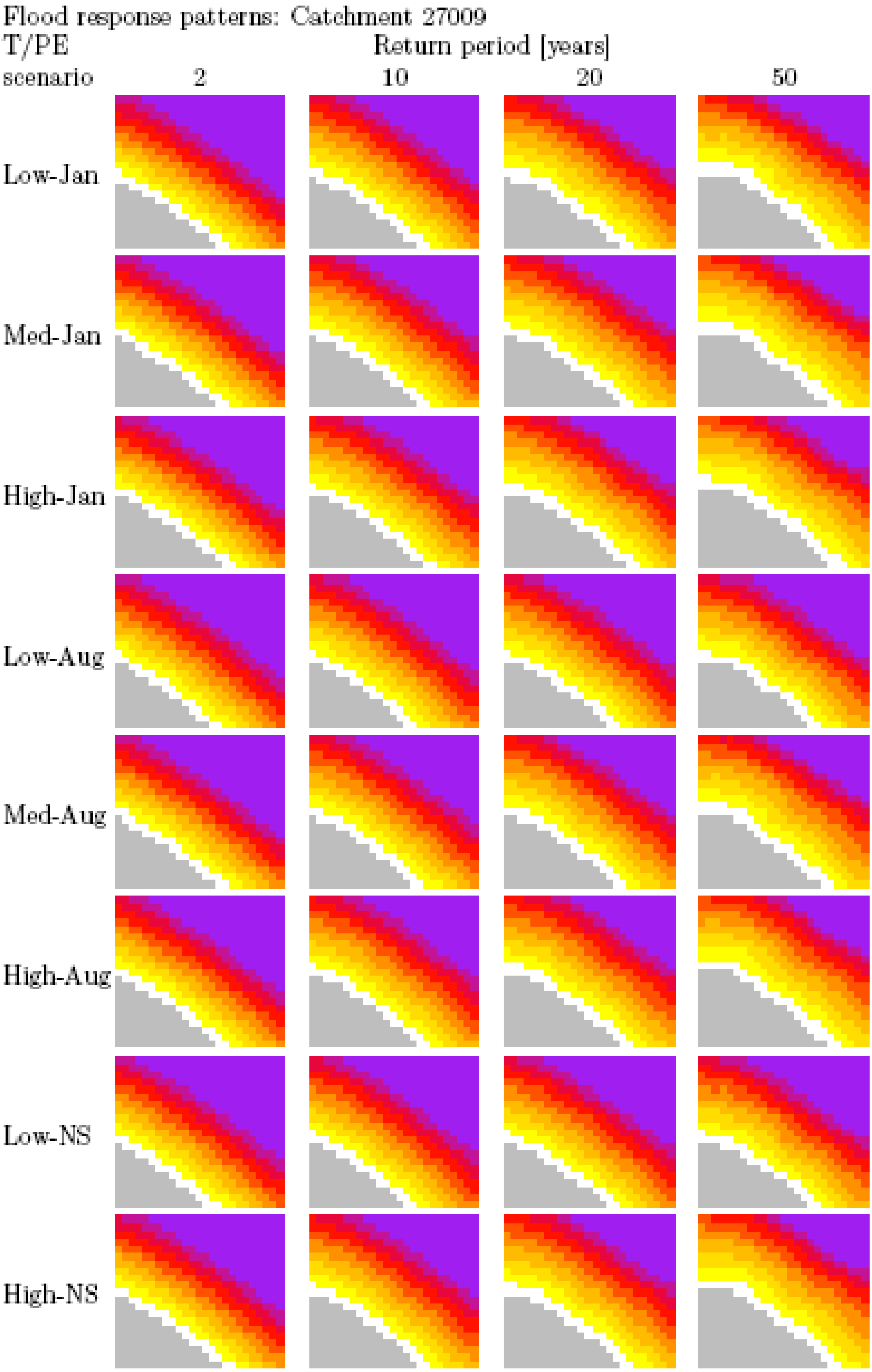
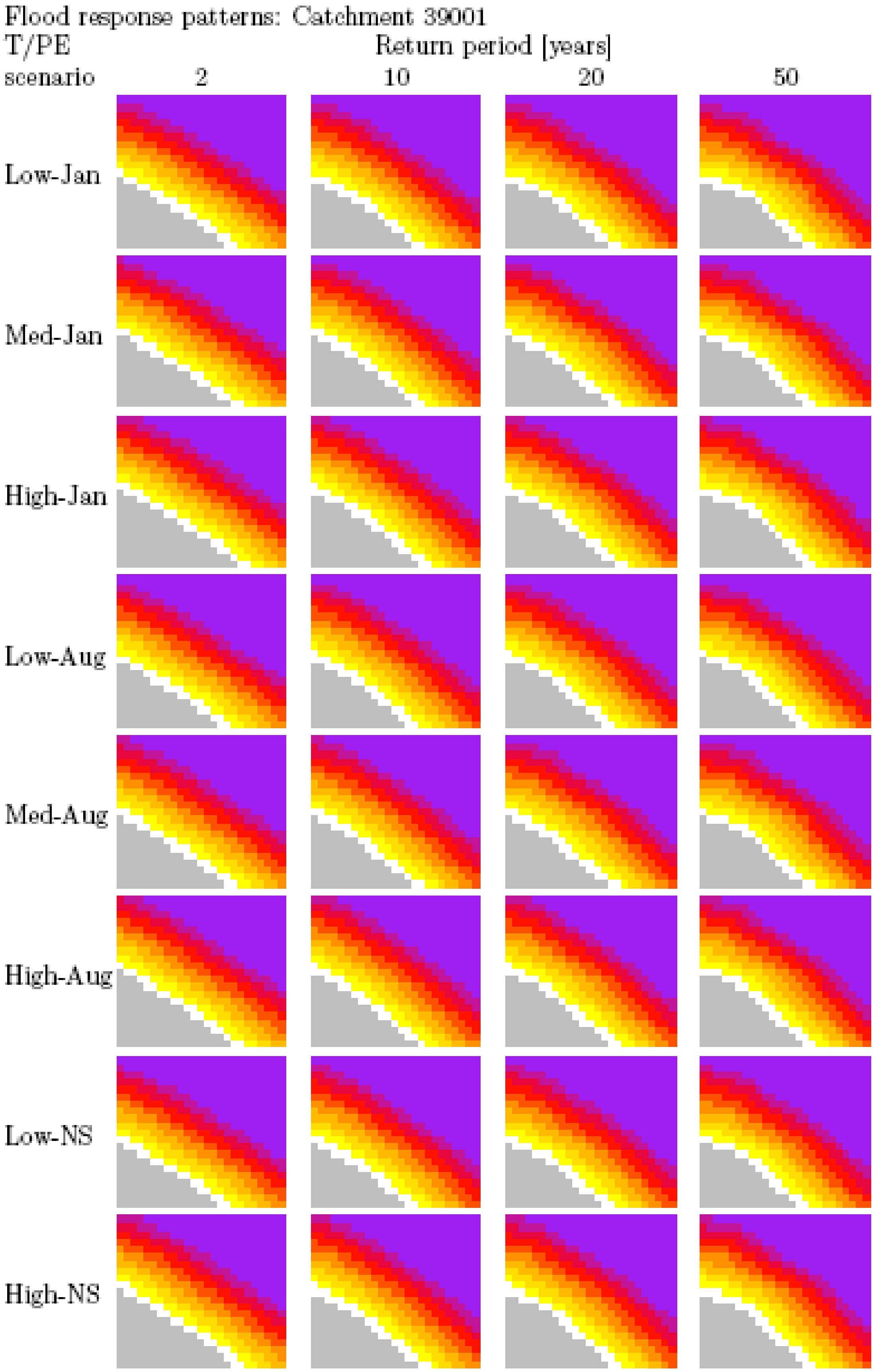
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Flood response patterns: Catchment 27009
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS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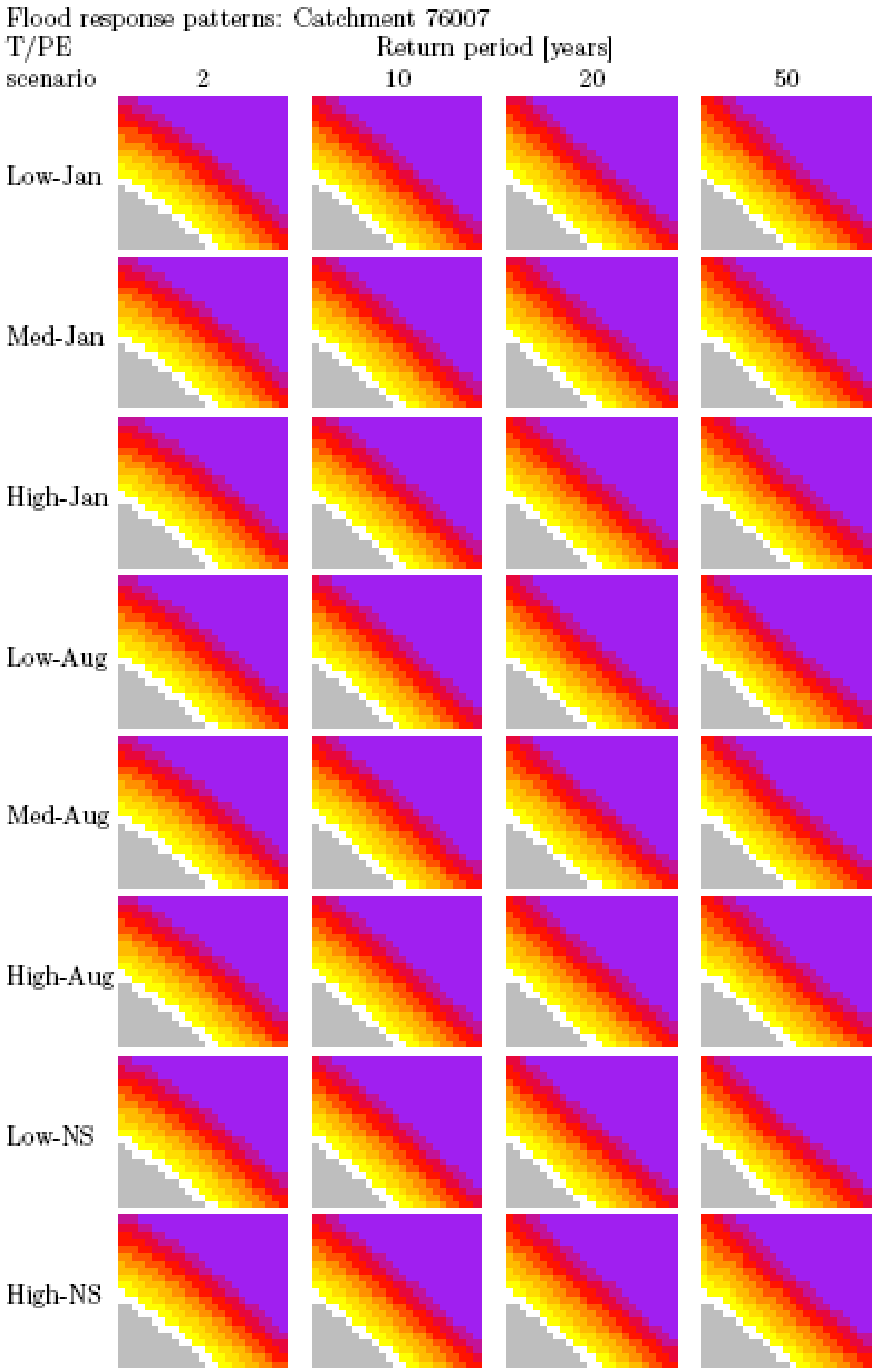
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS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T/PE
scenario
Return period [years]
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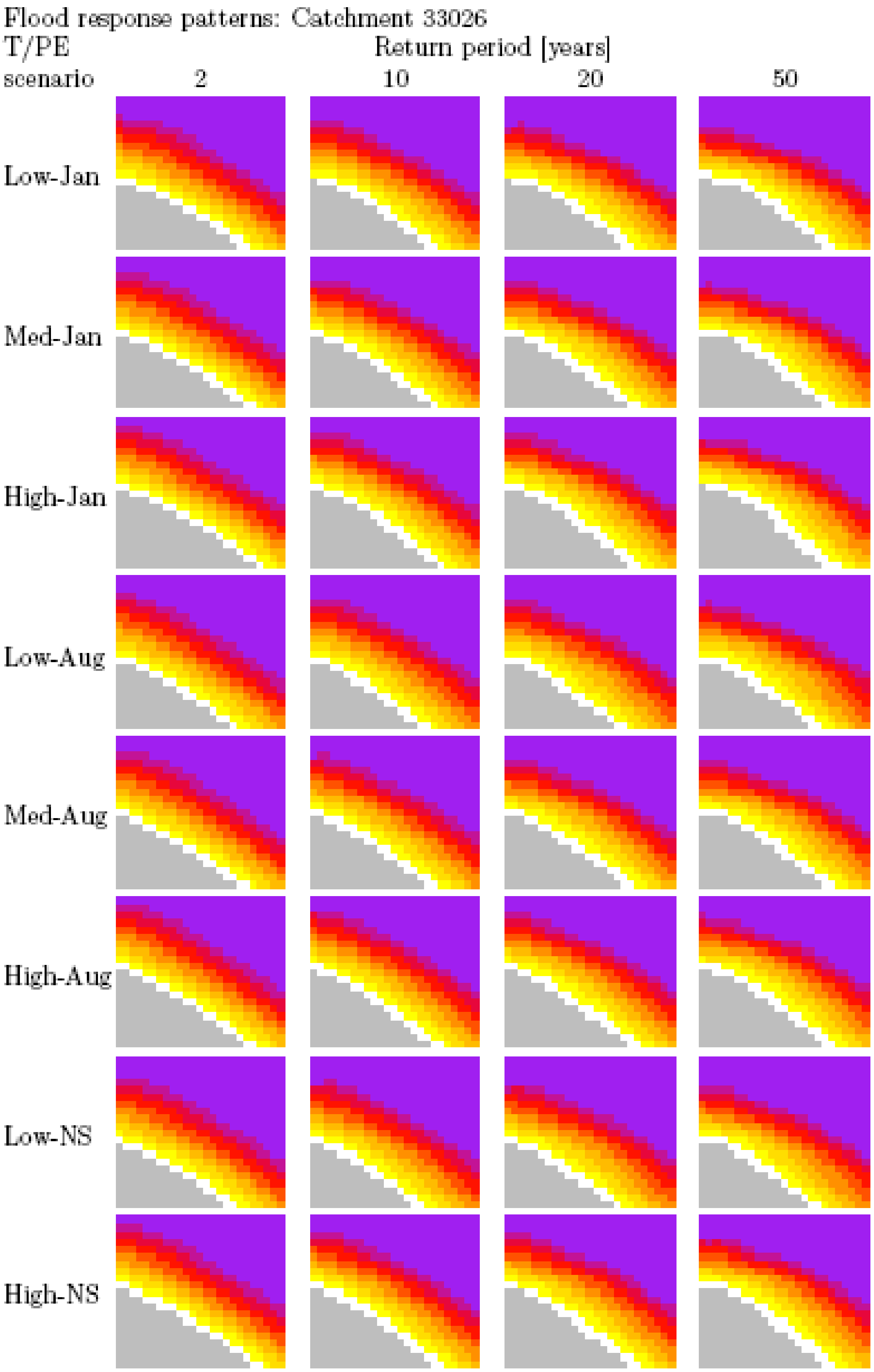
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS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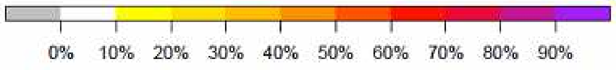
T/PE
scenario
Return period [years]
2
10
20
50
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS

Appendix B: Flood response patterns for alternative months of peak precipitation change

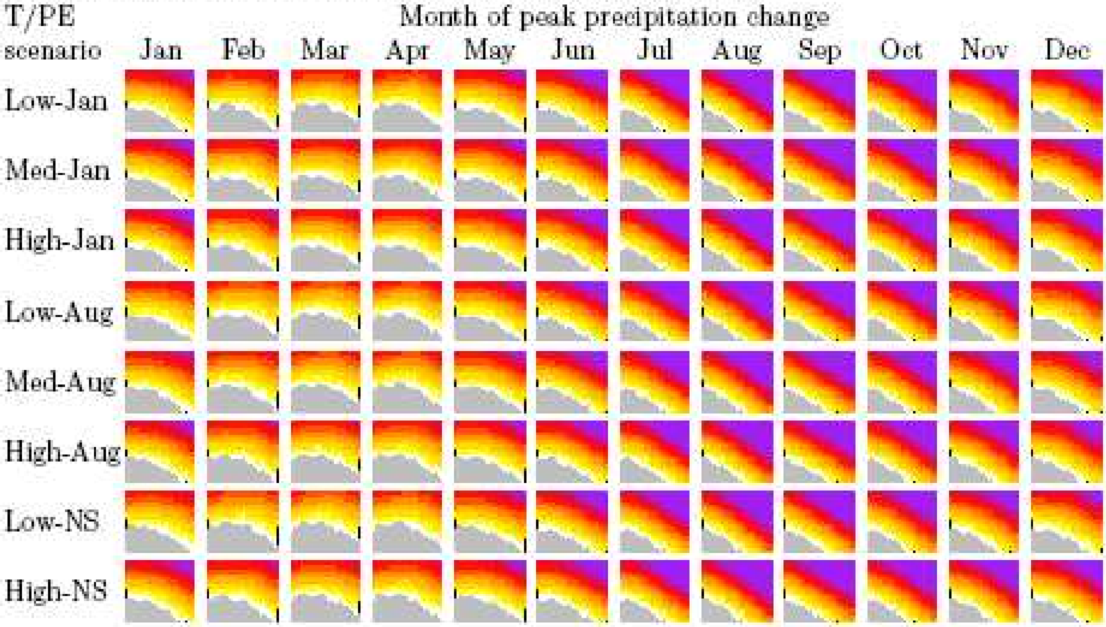
This appendix contains, for each of the nine PDM example catchments (listed below), for each of the eight T/PE scenarios, the flood response patterns produced when the month of peak precipitation change is taken to be in each month from January through to December in turn, showing the percentage change in the flood peak for each of the four return periods (2-, 10-, 20- and 50-years).

PDM example catchments:
07002 (Damped-Extreme)
02001 (Damped-High)
14001 (Damped-Low)
47007 (Neutral)
34003 (Mixed)
54008 (Enhanced-Low)
21023 (Enhanced-Medium)
43005 (Enhanced-High)
38003 (Sensitive)

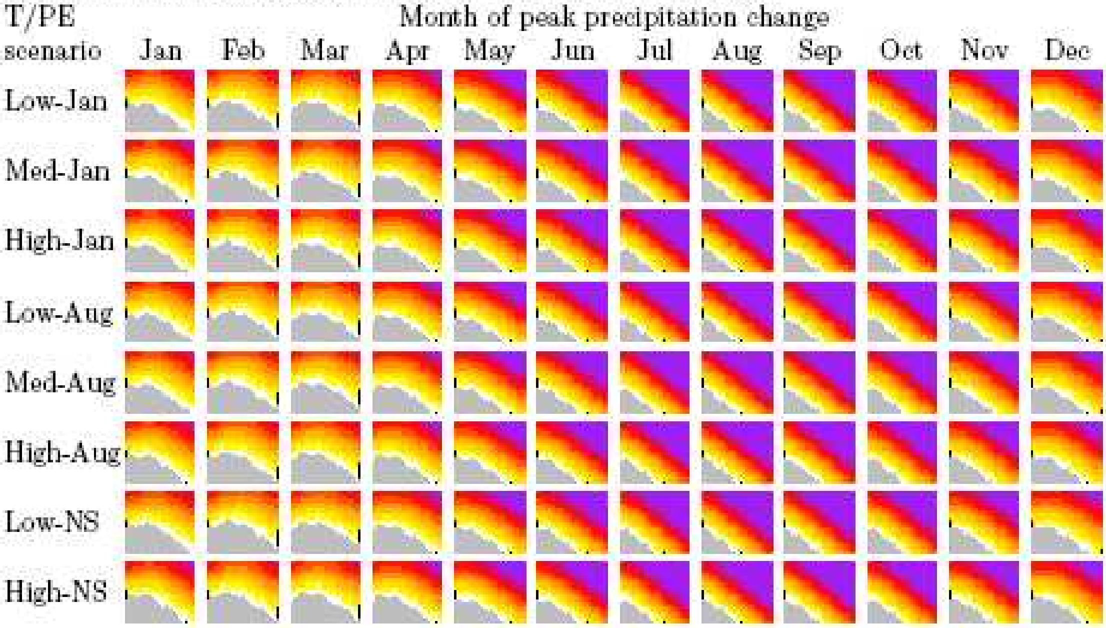
Key for flood response patterns:

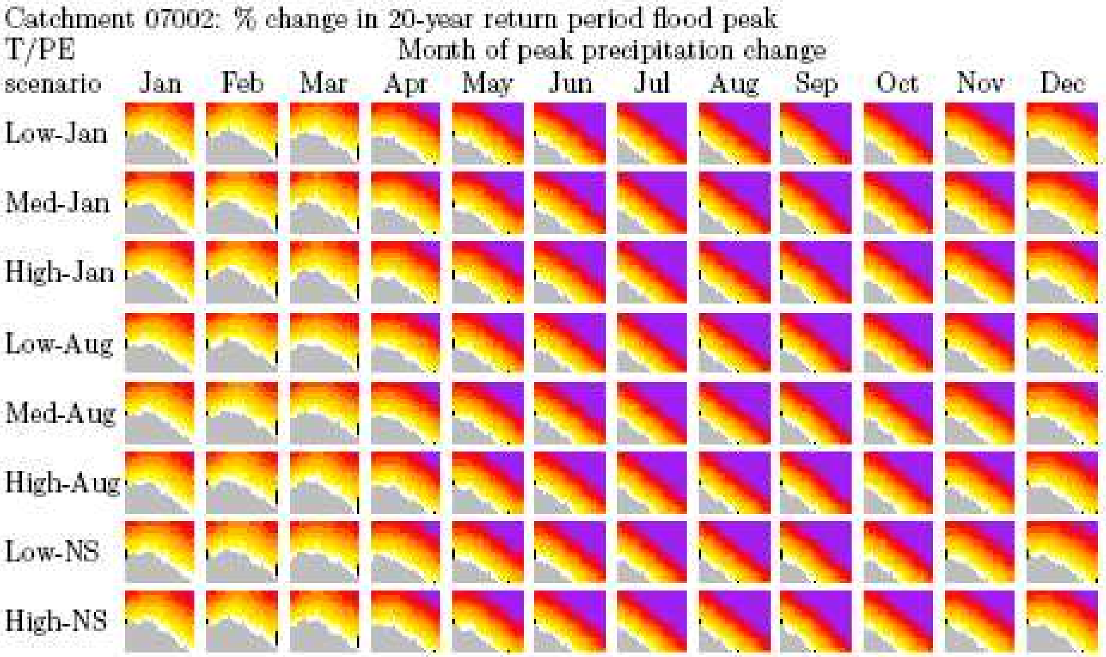


Catchment 07002: % change in 2-year return period flood peak

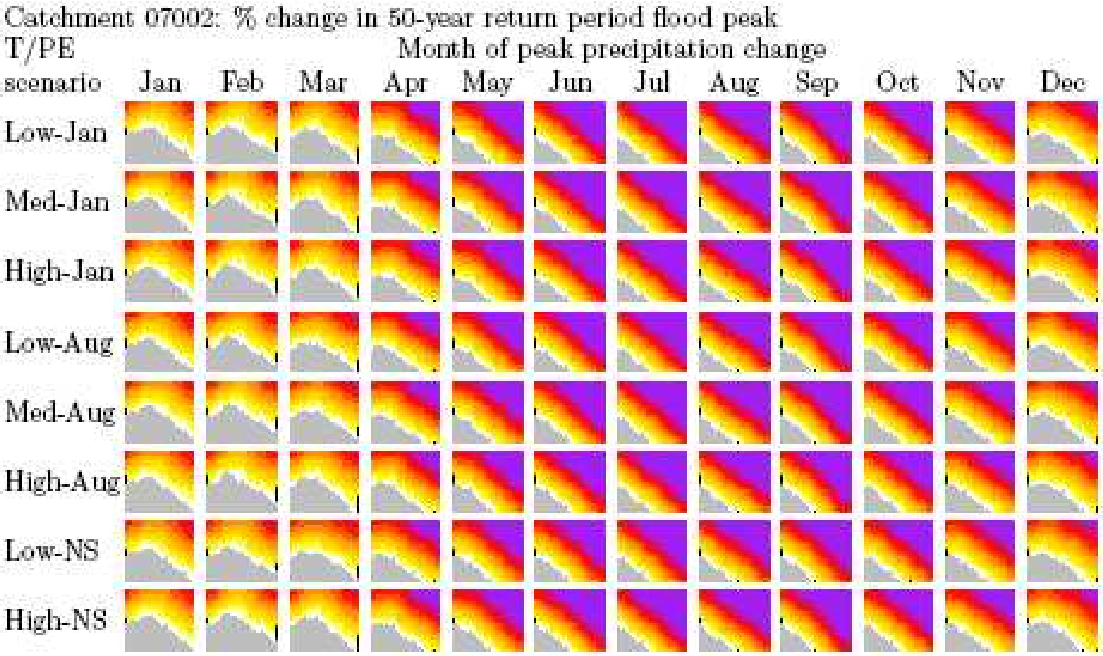


Catchment 07002: % change in 10-year return period flood peak

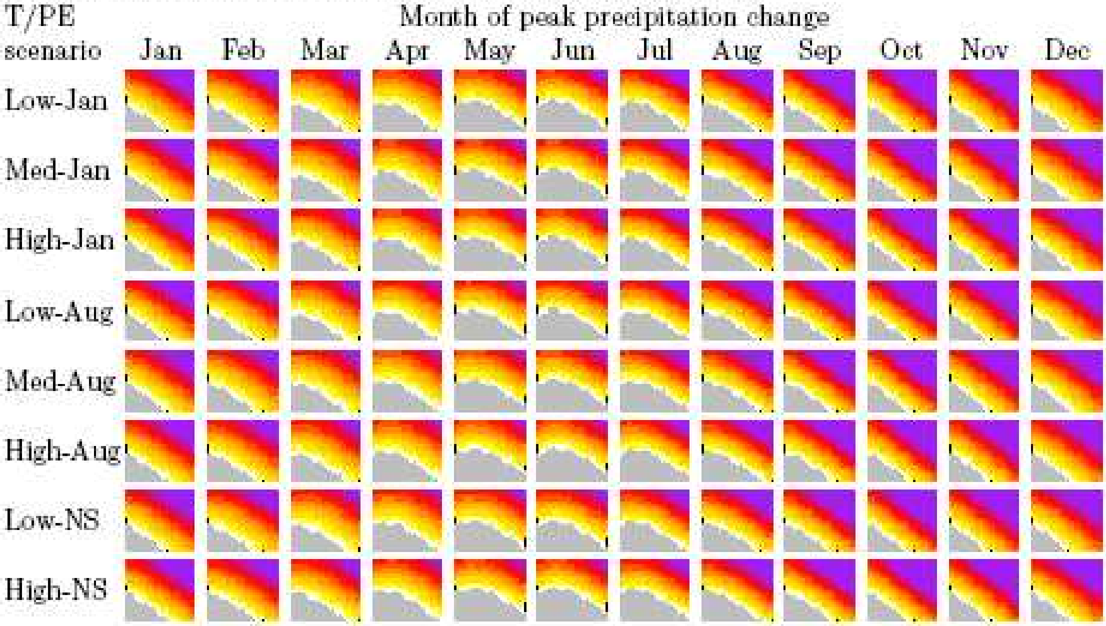




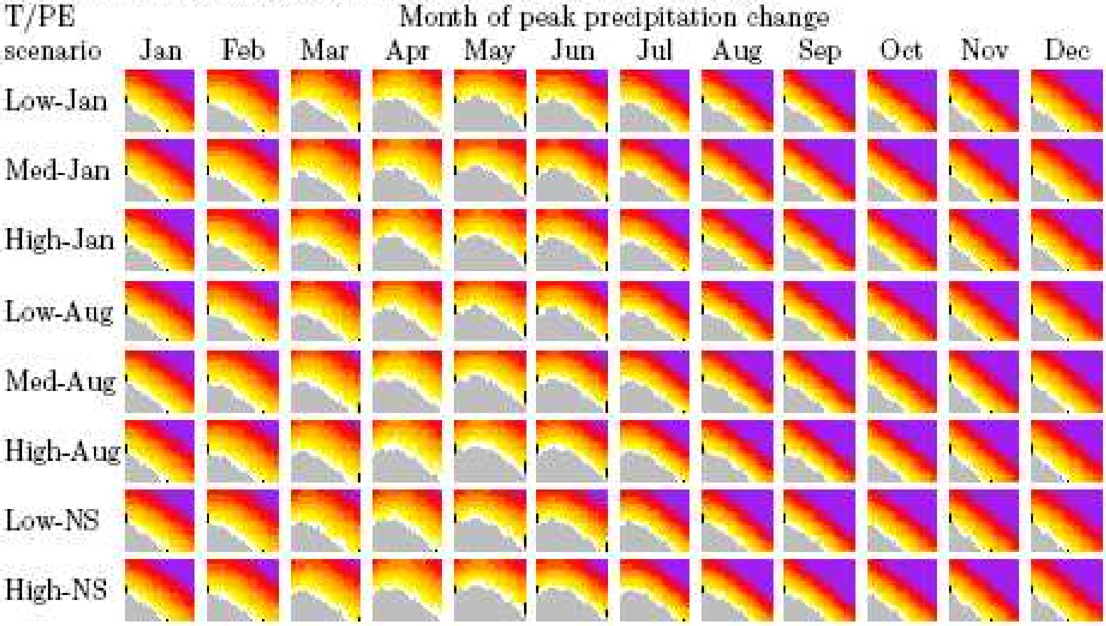
Catchment 07002: % change in 20-year return period flood peak



Catchment 07002: % change in 50-year return period flood peak

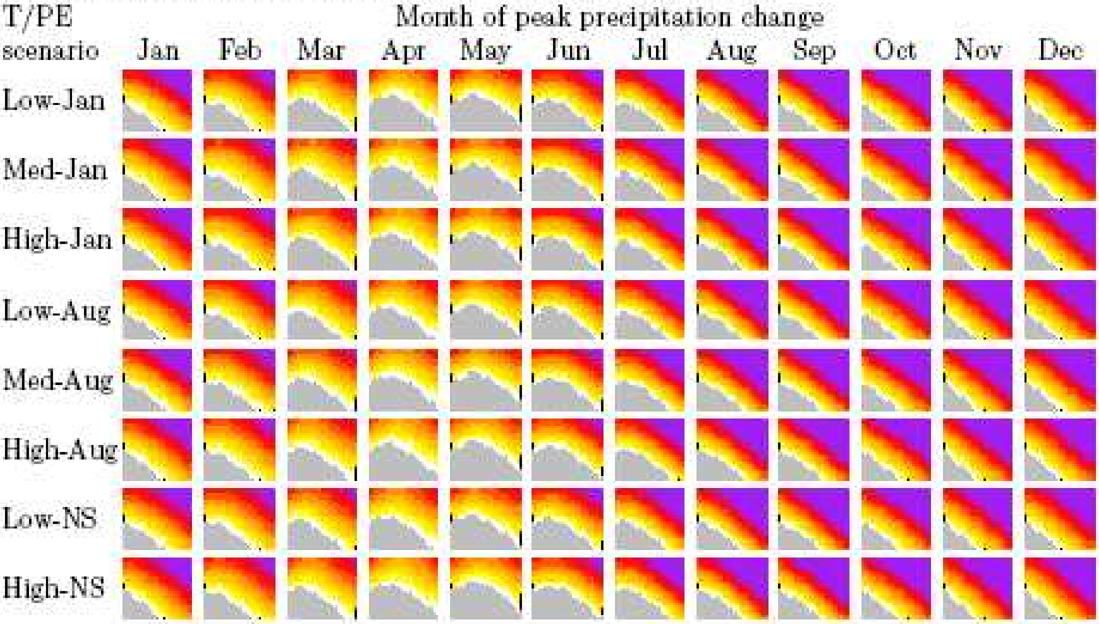


Catchment 02001: % change in 2-year return period flood peak

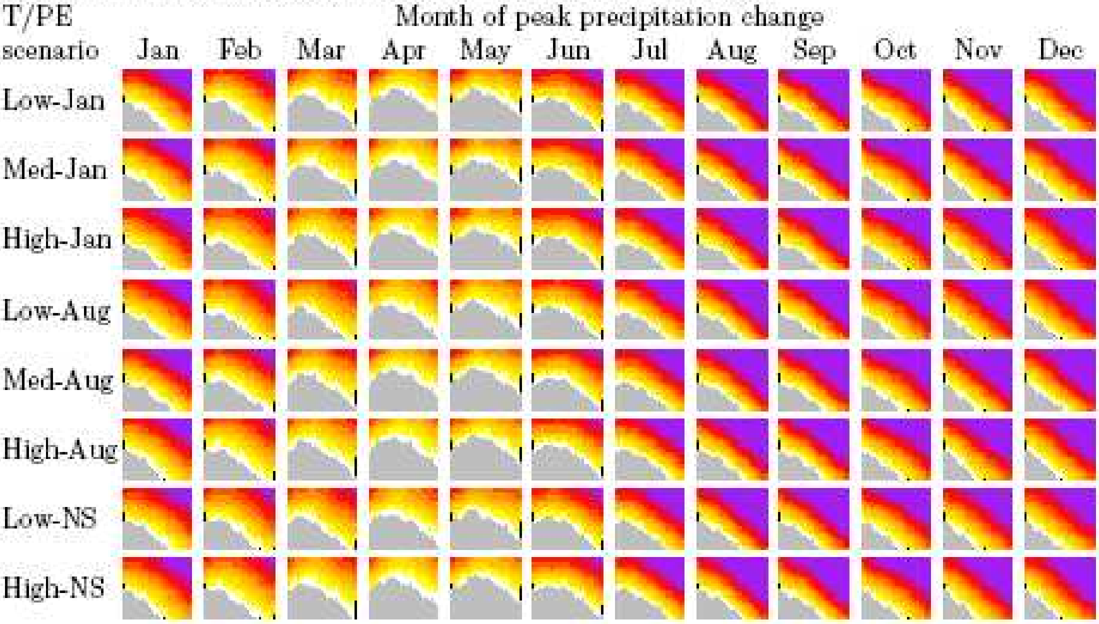


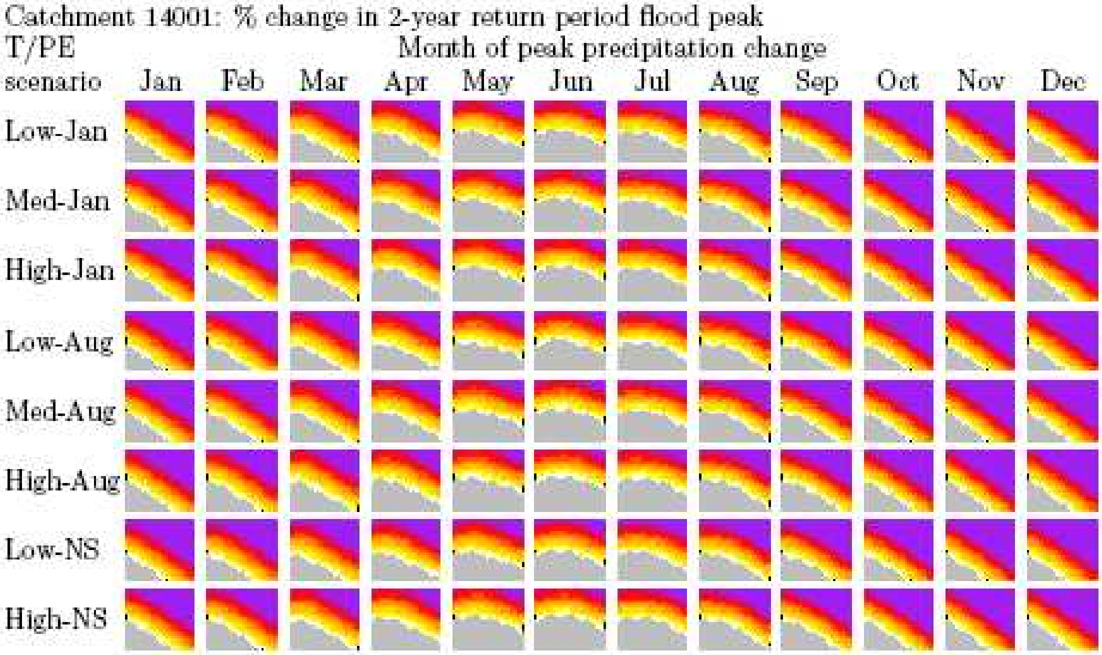
Catchment 02001: % change in 10-year return period flood peak

Catchment 02001: % change in 20-year return period flood peak



Catchment 02001: % change in 50-year return period flood peak




Catchment 14001: % change in 2-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
Feb
Mar
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Nov
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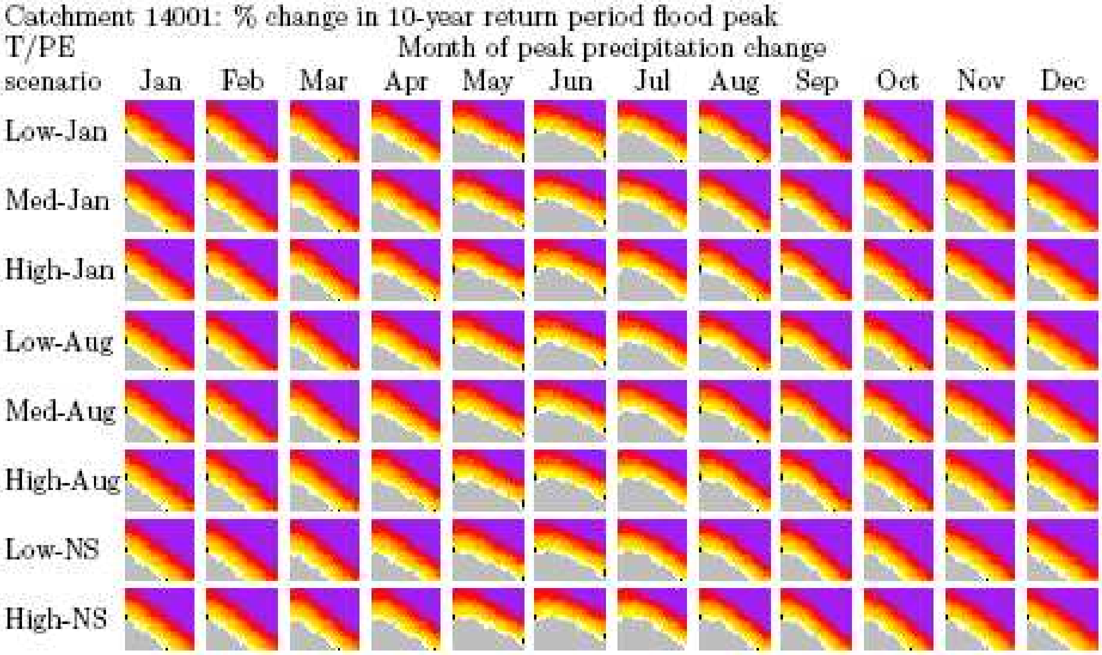
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Catchment 14001: % change in 10-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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Nov
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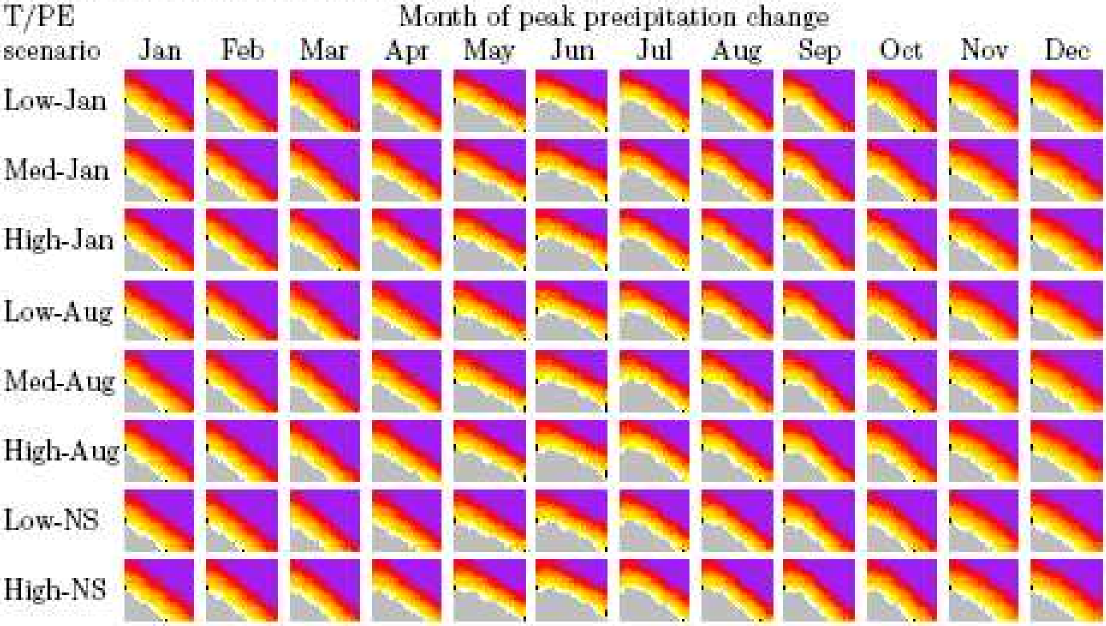
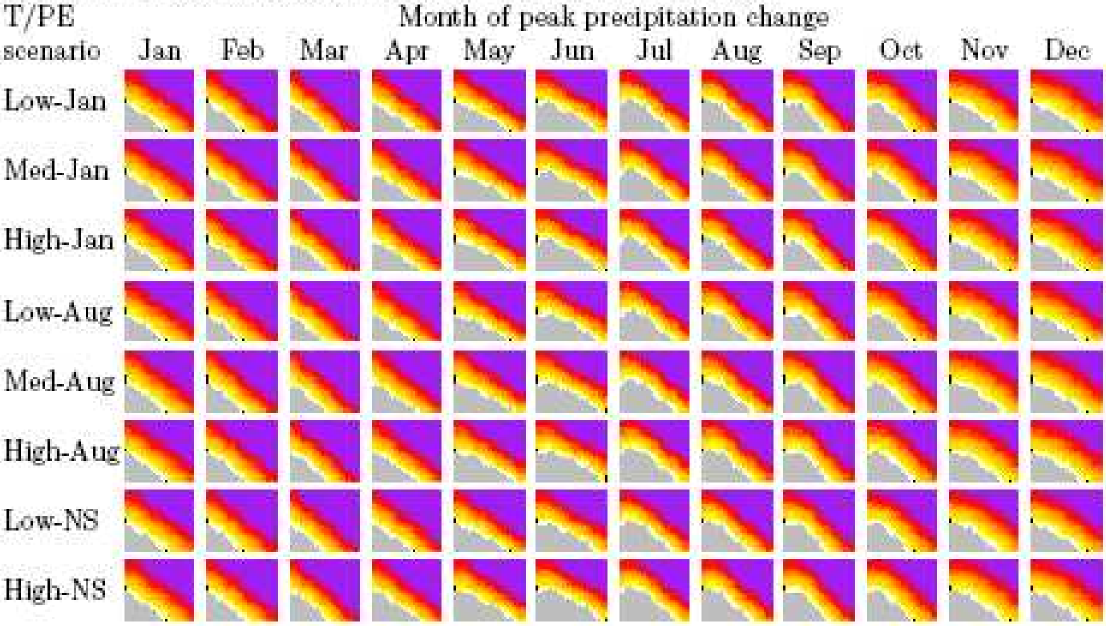
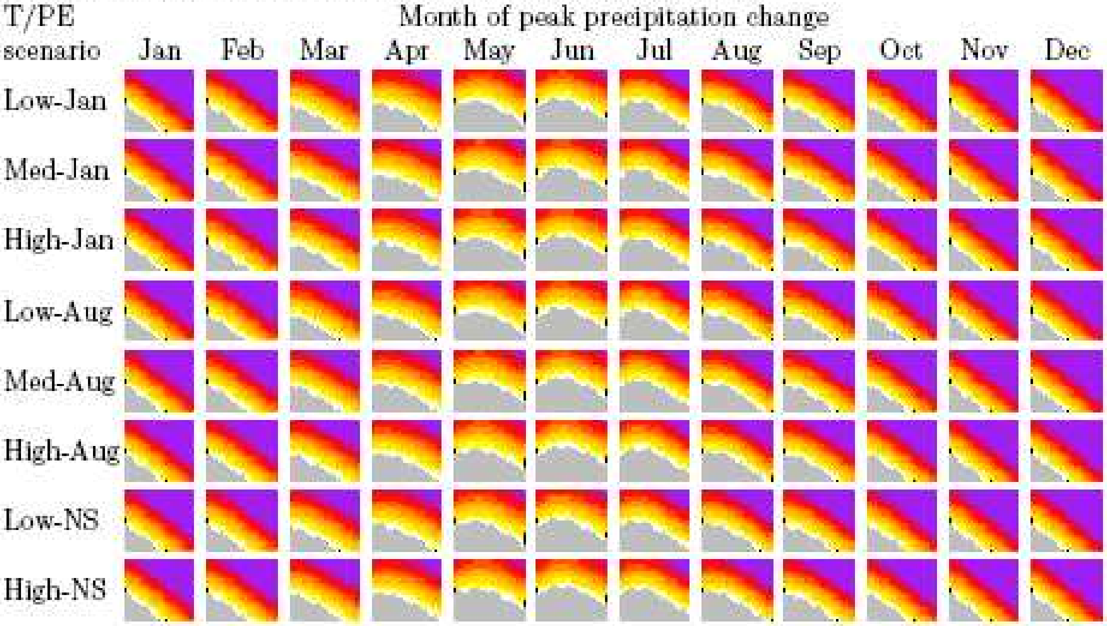
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS

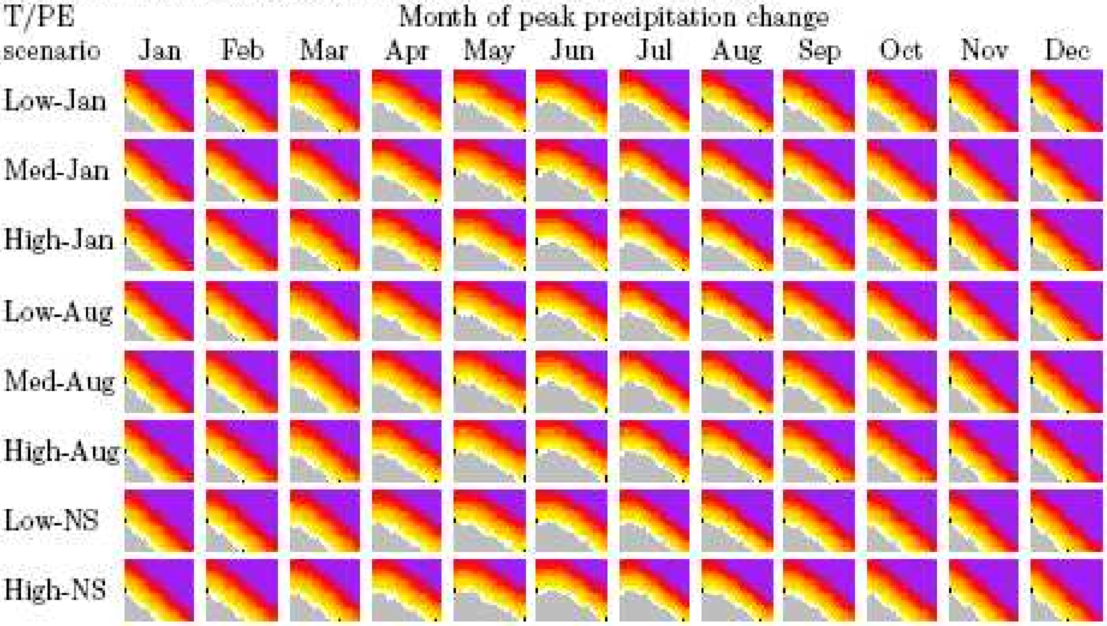


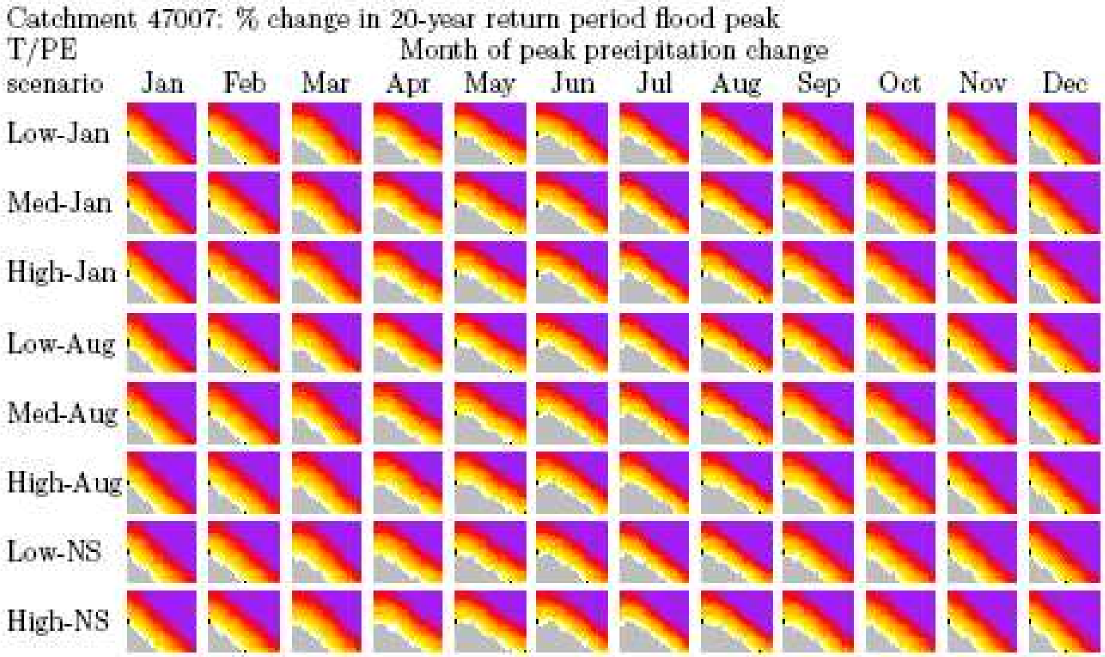
Catchment 14001: % change in 20-year return period flood peak



Catchment 14001: % change in 50-year return period flood peak


Catchment 47007: % change in 2-year return period flood peak


Catchment 47007: % change in 10-year return period flood peak


Catchment 47007: % change in 20-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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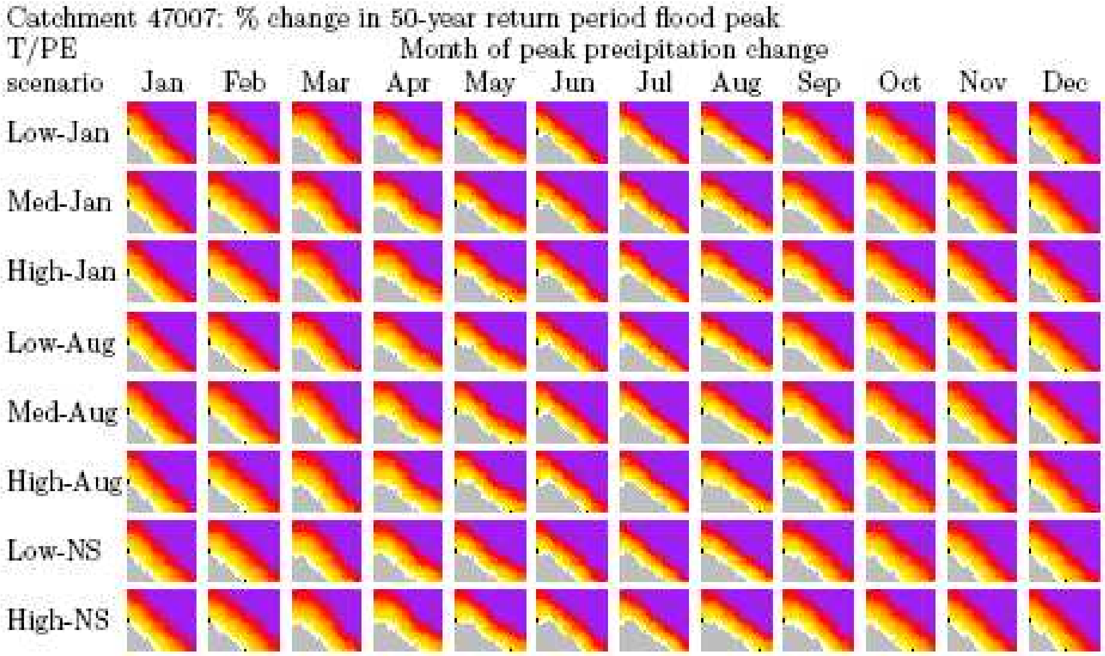
Oct
Nov
Dec
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Catchment 47007: % change in 50-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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Low-Jan
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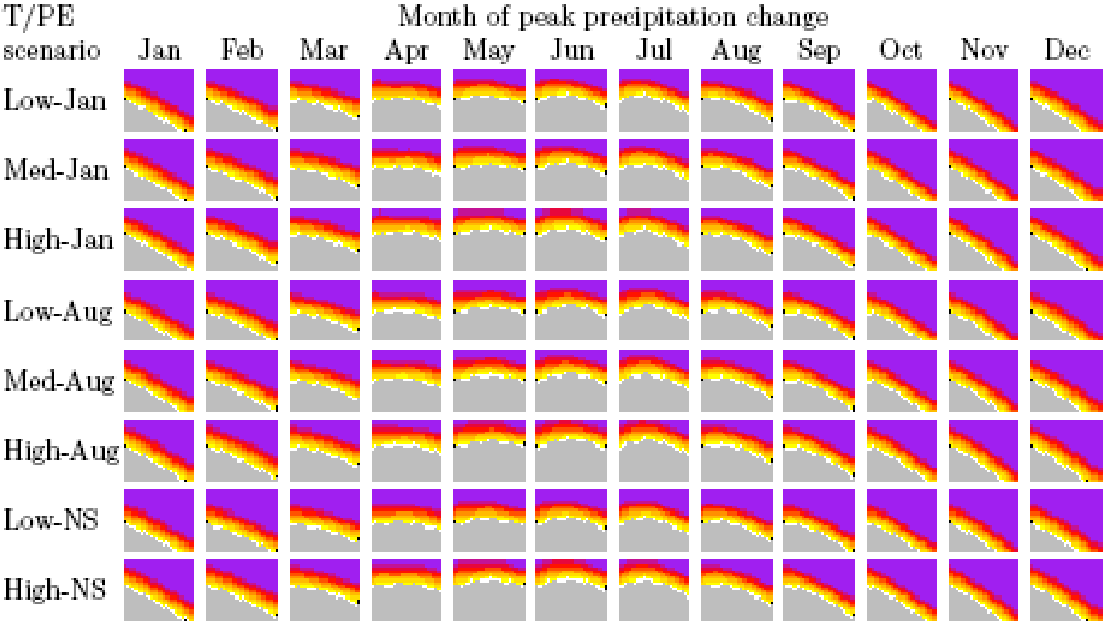
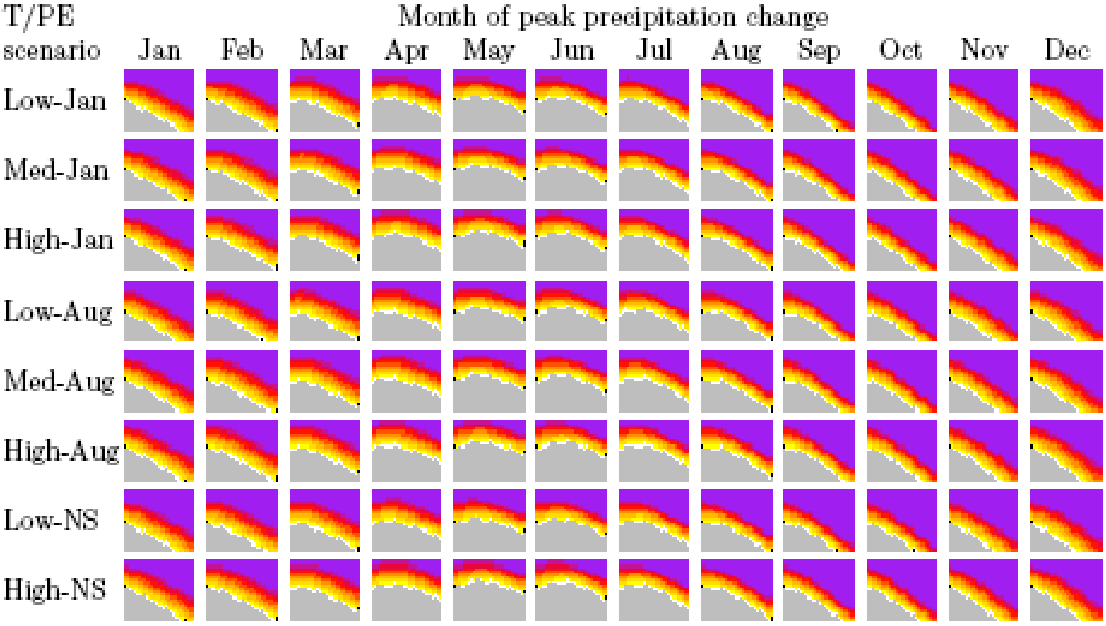
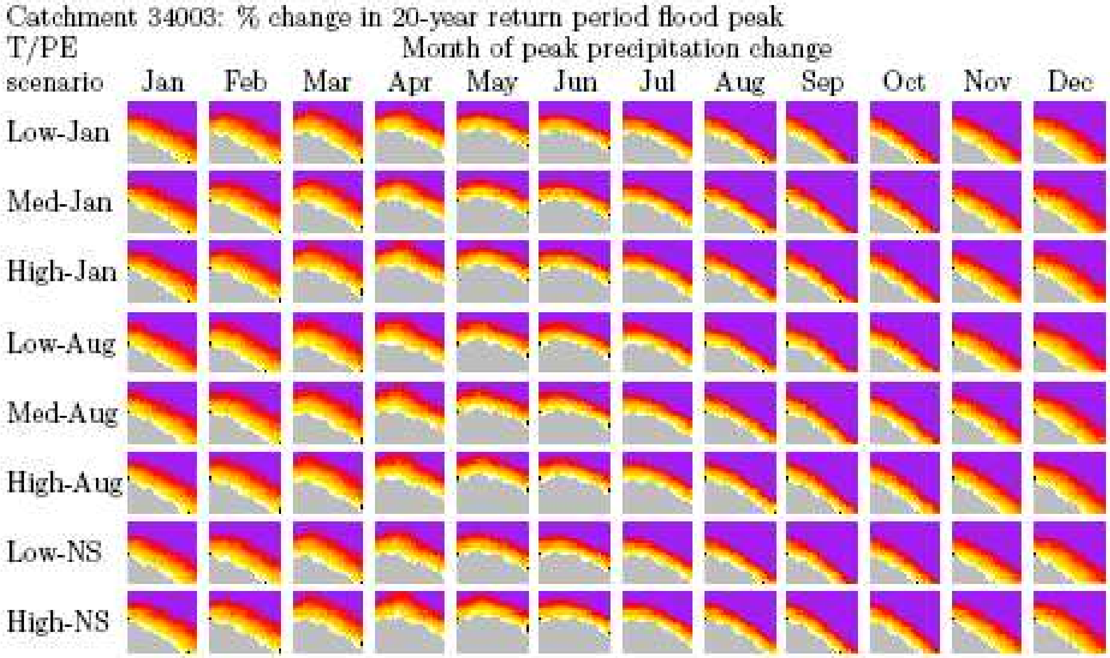
Med-Aug
High-Aug
Low-NS
High-NS

Catchment 34003: % change in 2-year return period flood peak



Catchment 34003: % change in 10-year return period flood peak




Catchment 34003: % change in 20-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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Low-Jan
Med-Jan
High-Jan
Low-Aug
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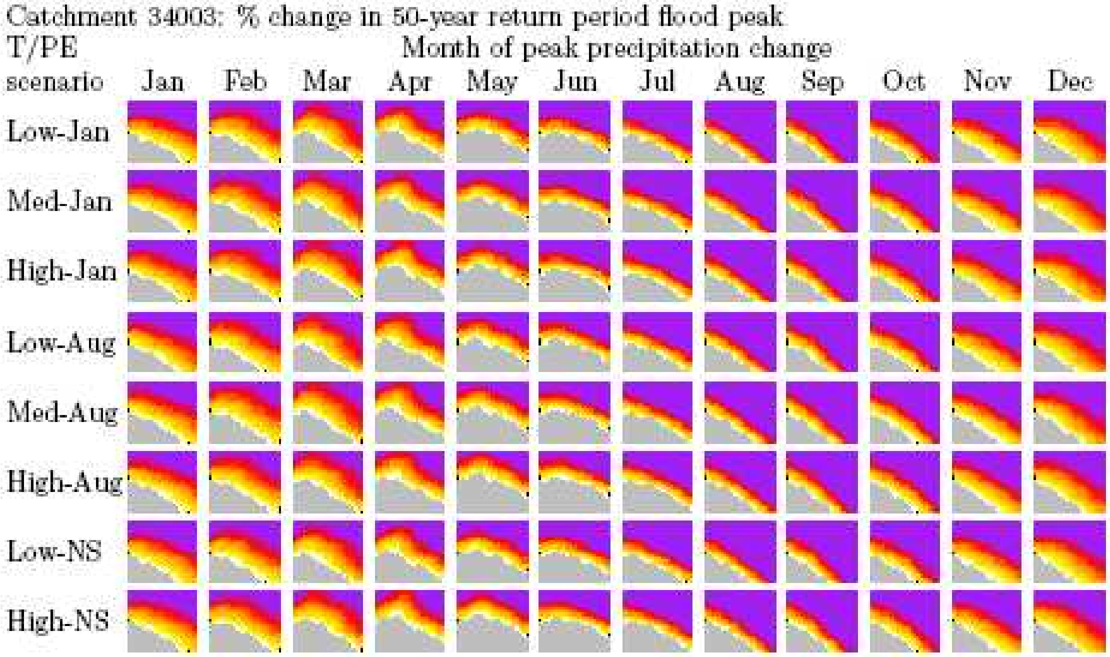
High-Aug
Low-NS
High-NS


Catchment 34003: % change in 50-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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Low-NS
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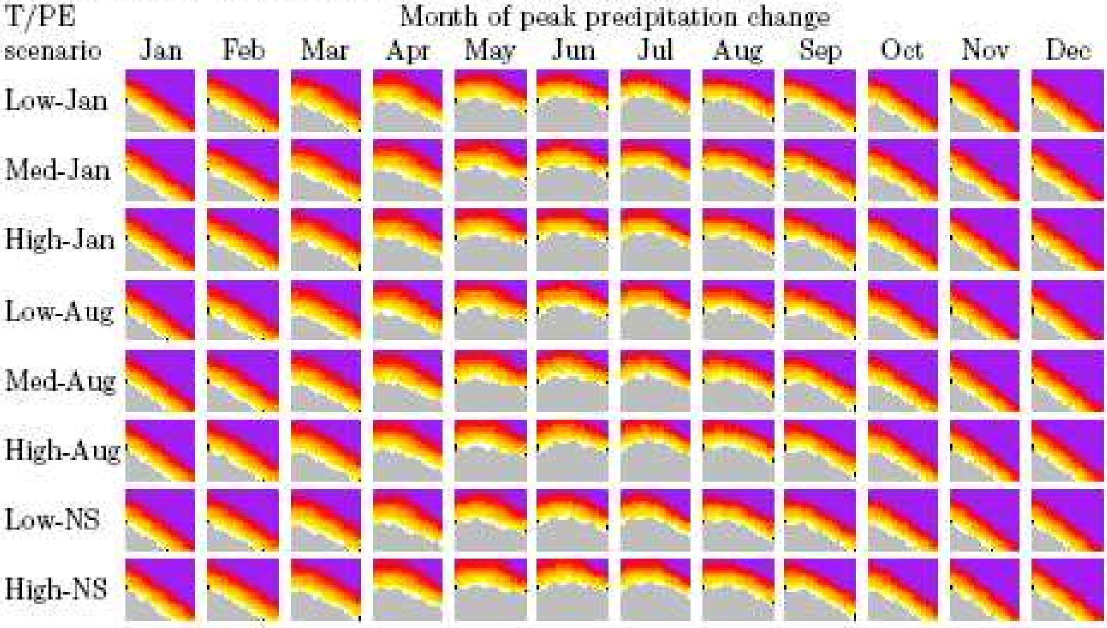
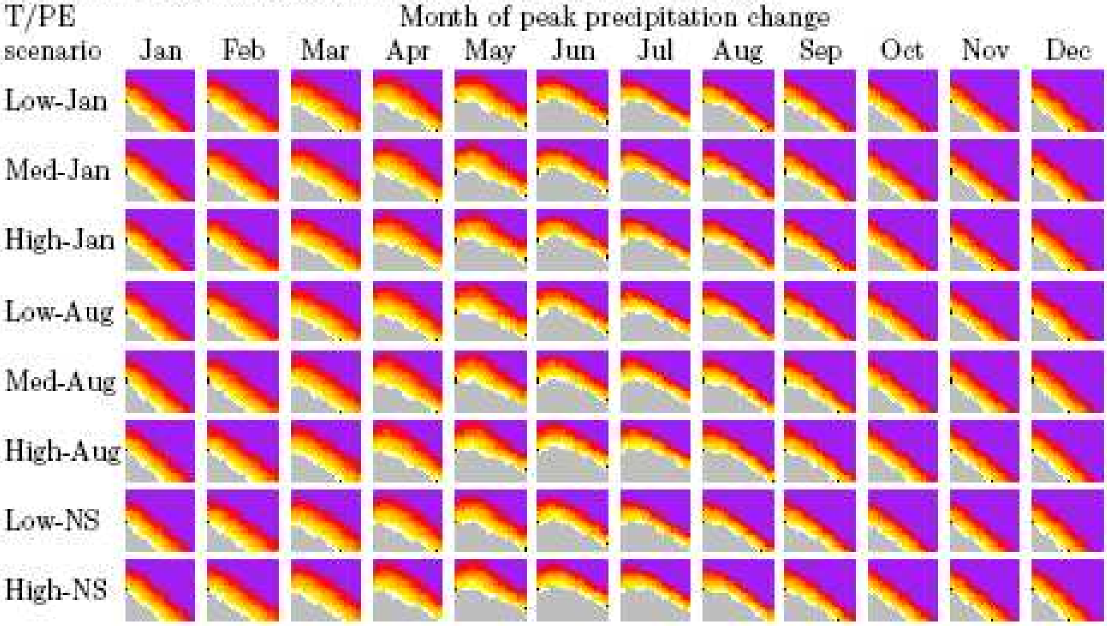
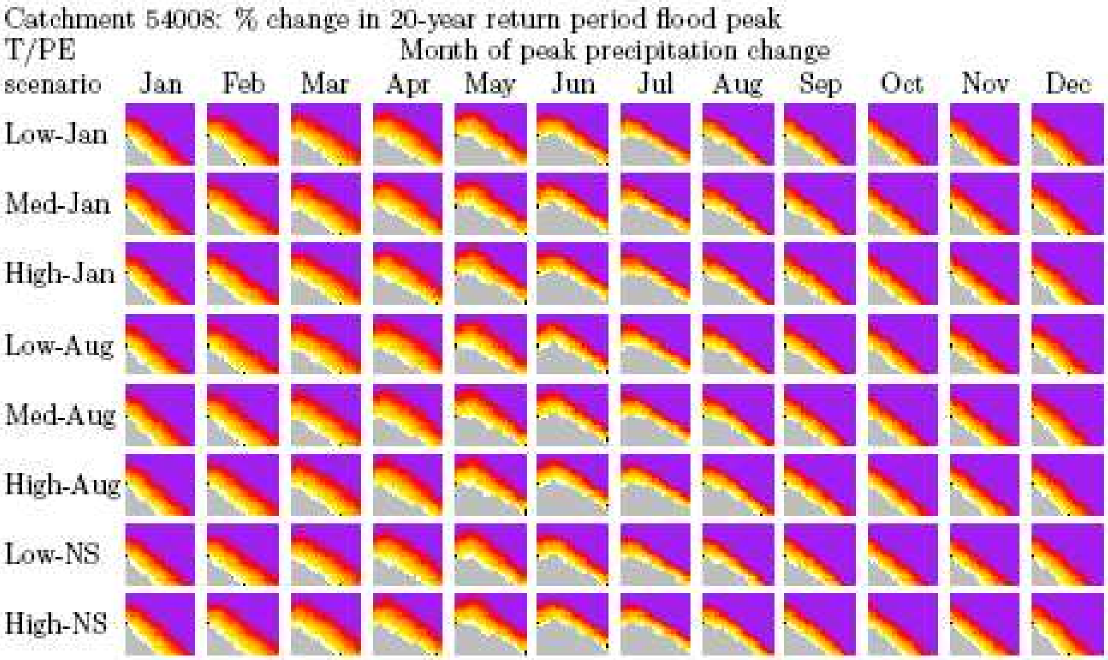
Catchment 54008: % change in 2-year return period flood peak



Catchment 54008: % change in 10-year return period flood peak




Catchment 54008: % change in 20-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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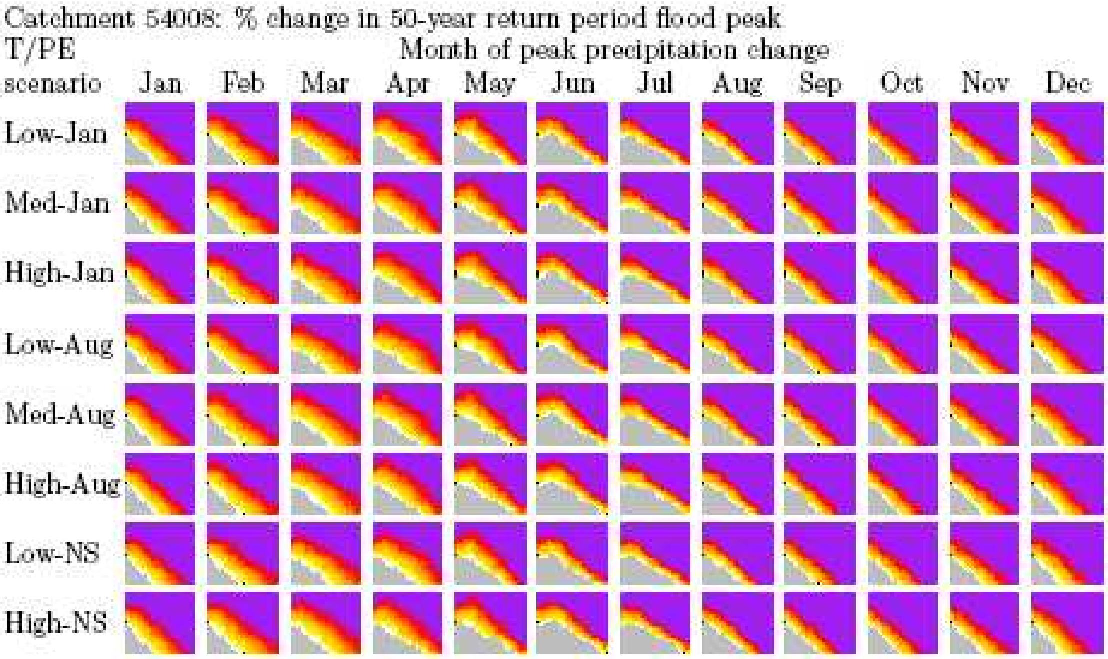
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Catchment 54008: % change in 50-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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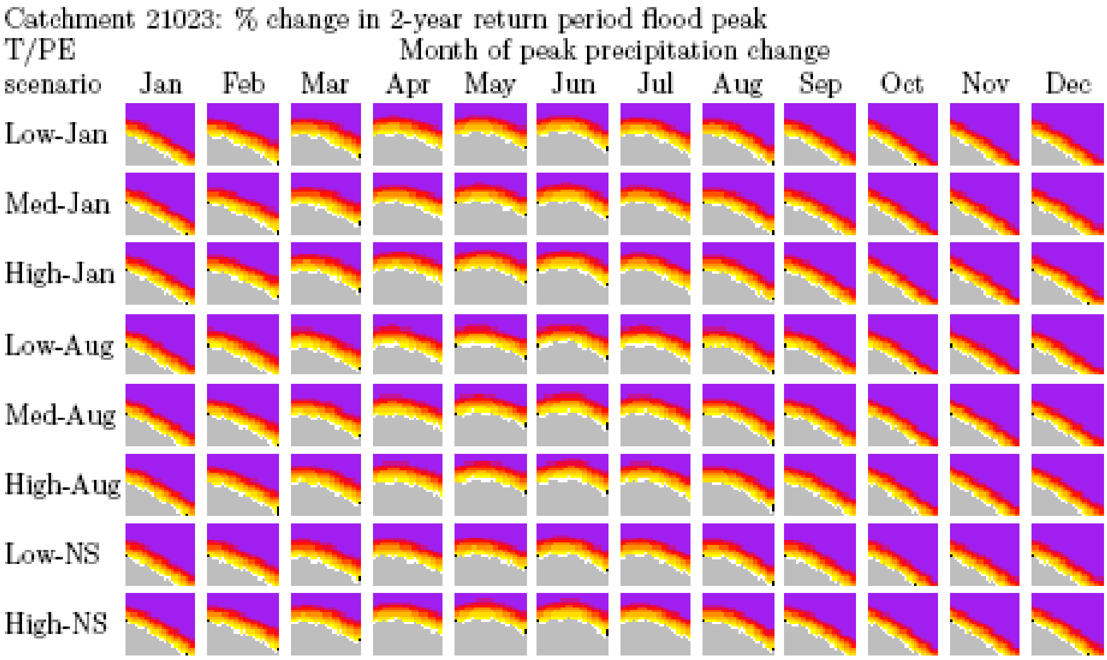
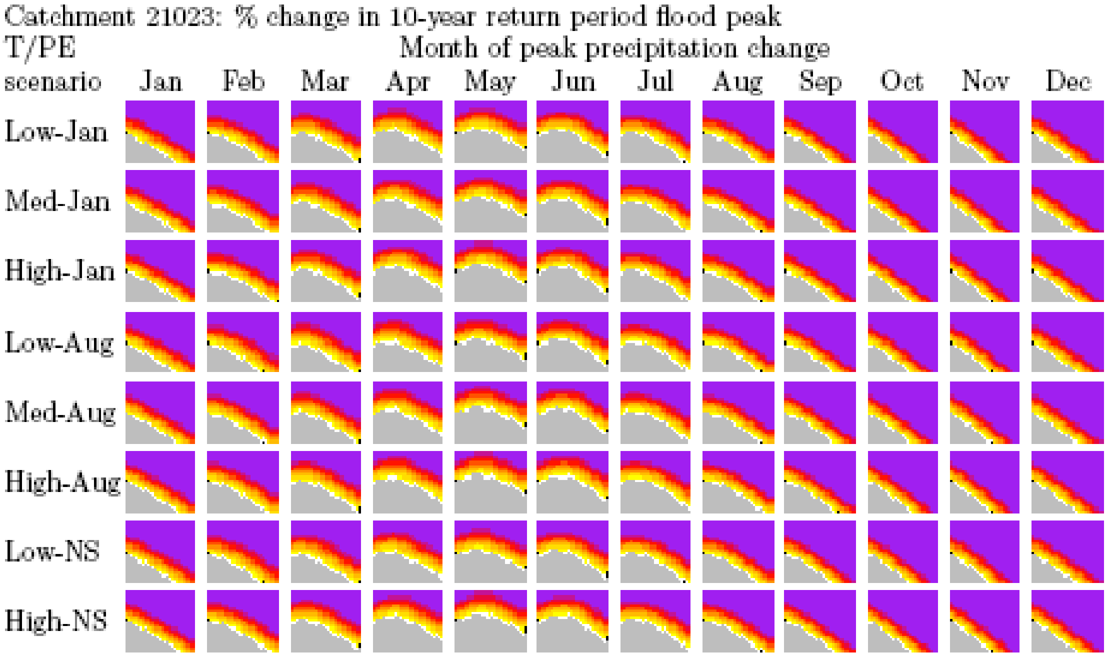
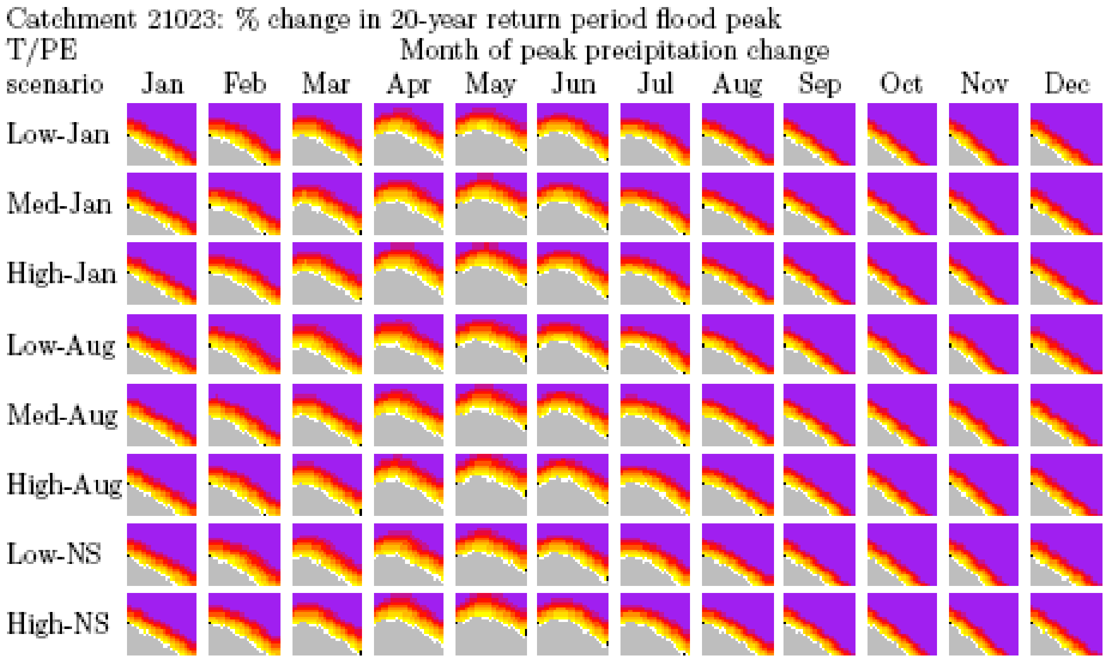
Oct
Nov
Dec
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Catchment 21023: % change in 2-year return period flood peak


Catchment 21023: % change in 10-year return period flood peak


Catchment 21023: % change in 20-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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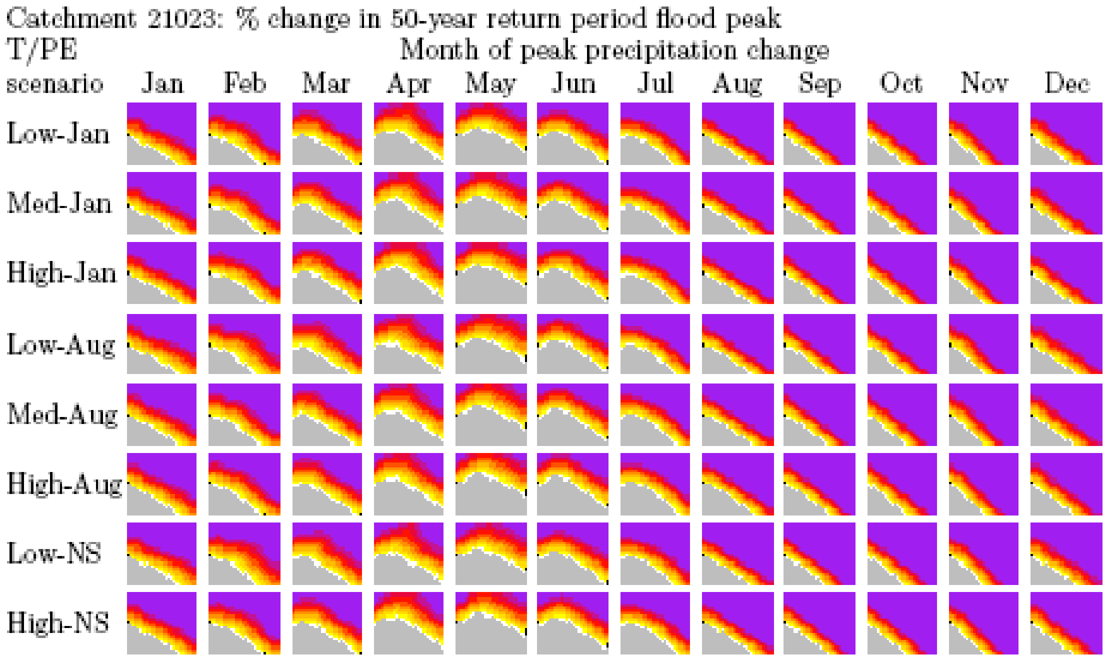
Oct
Nov
Dec
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS


Catchment 21023: % change in 50-year return period flood peak
T/PE scenario
Month of peak precipitation change
Jan
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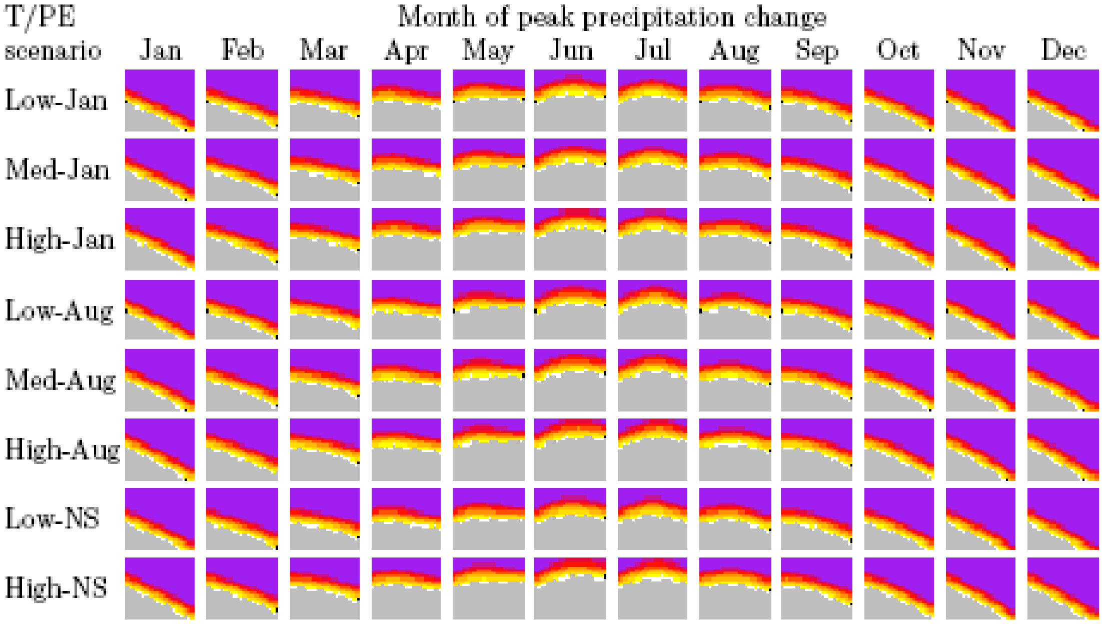
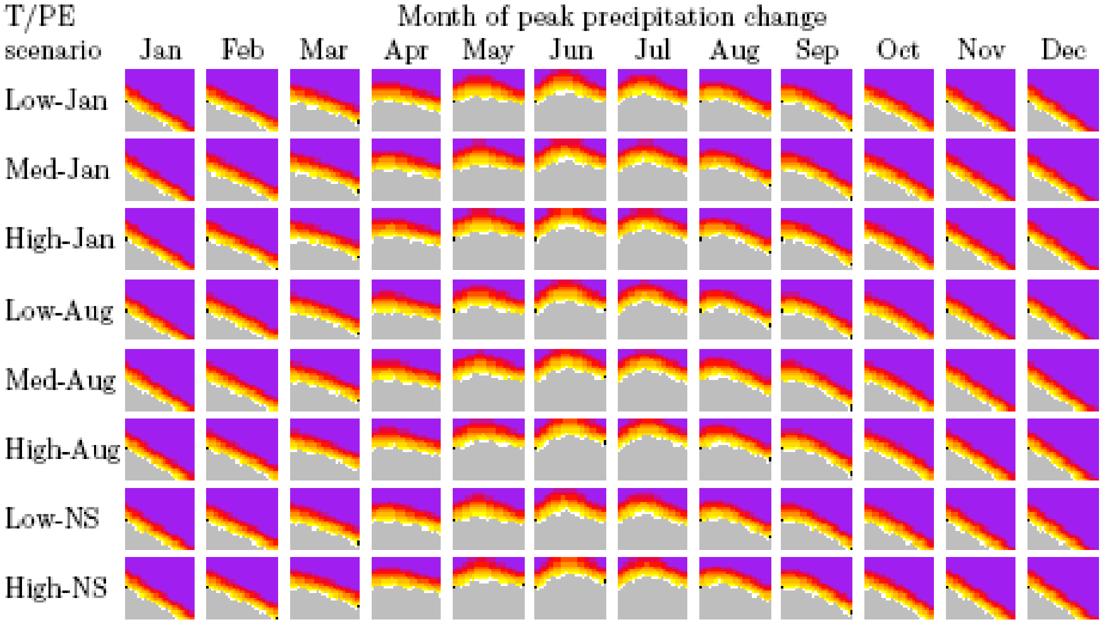
Low-Jan
Med-Jan
High-Jan
Low-Aug
Med-Aug
High-Aug
Low-NS
High-NS

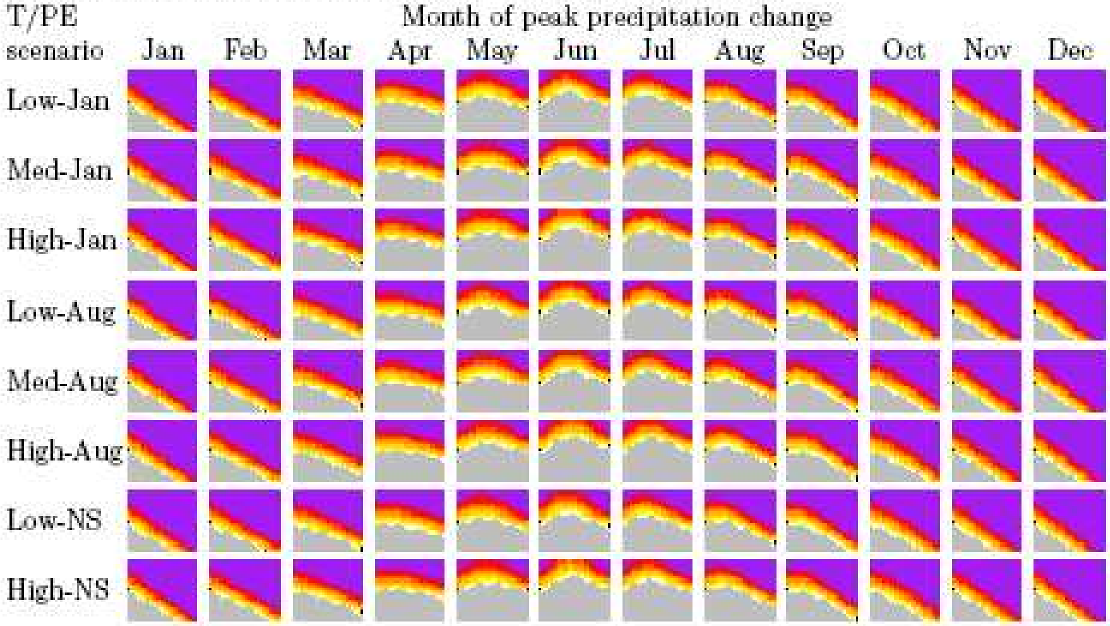
Catchment 43005: % change in 2-year return period flood peak



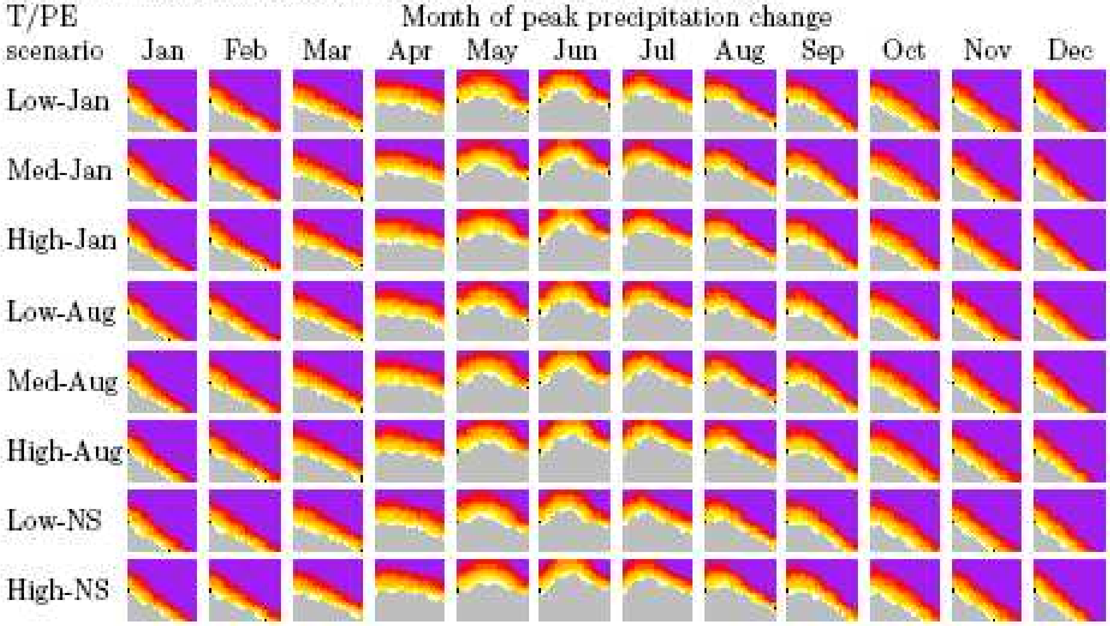
Catchment 43005: % change in 10-year return period flood peak



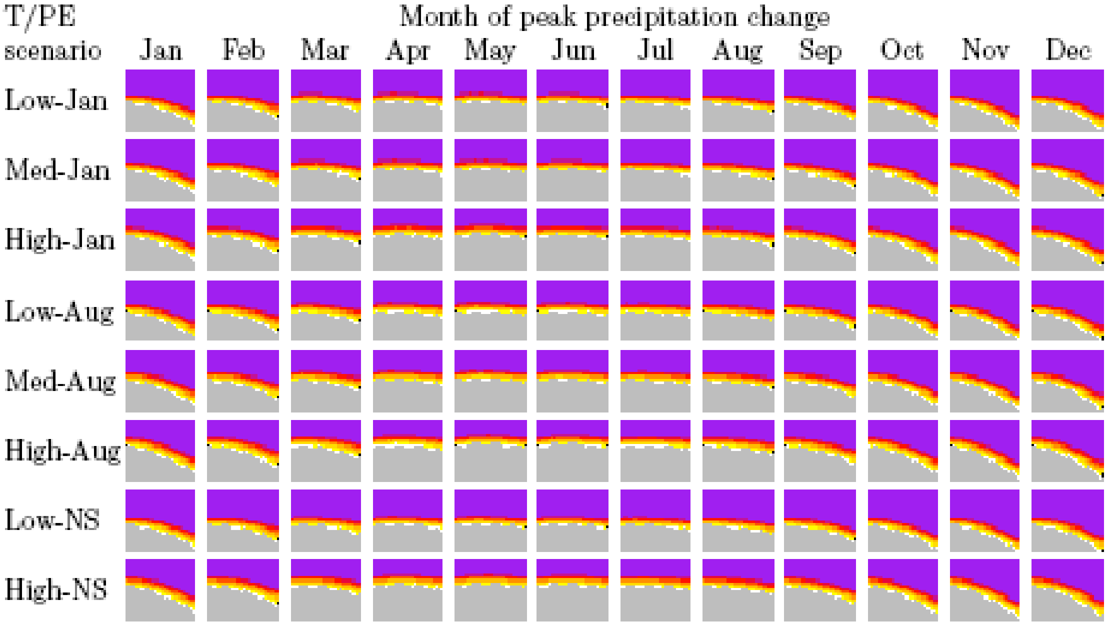
Catchment 43005: % change in 20-year return period flood peak



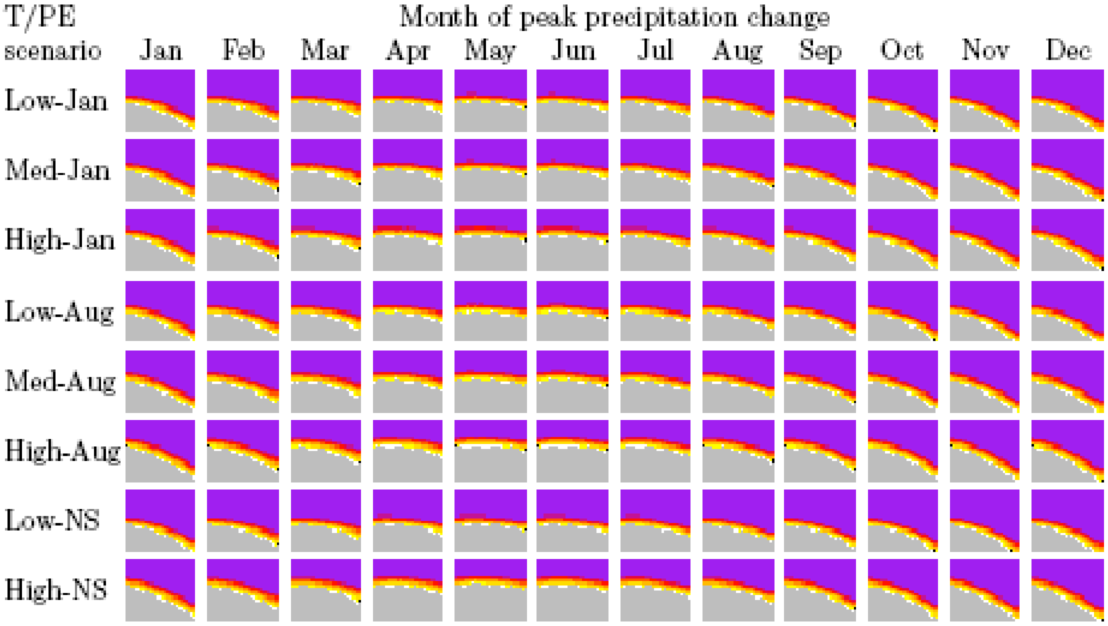
Catchment 43005: % change in 50-year return period flood peak

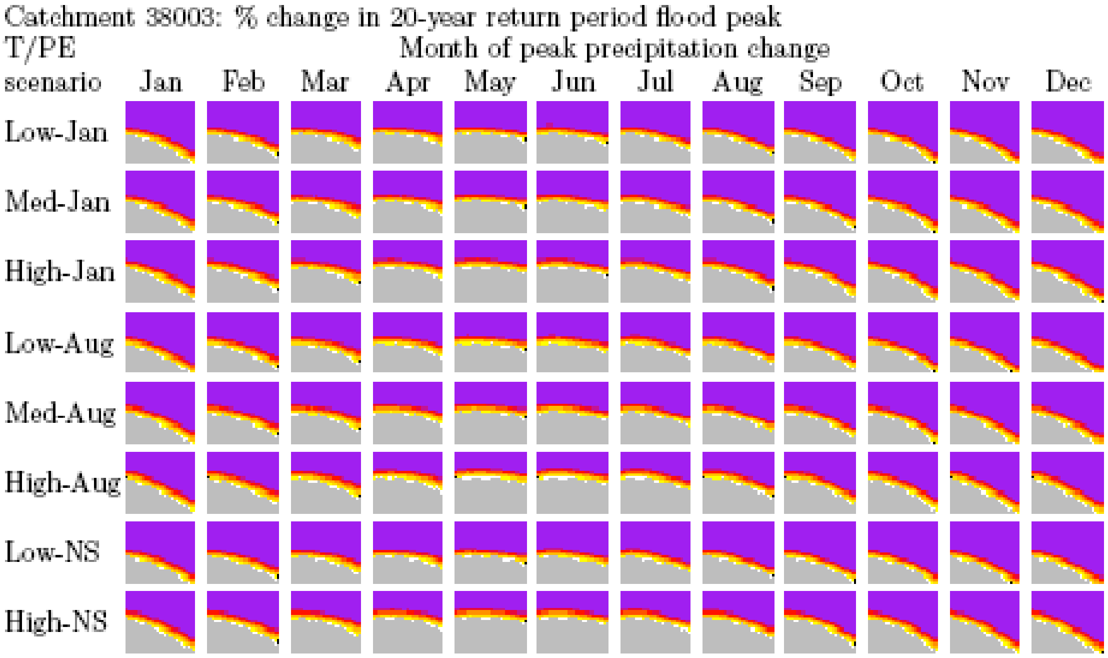


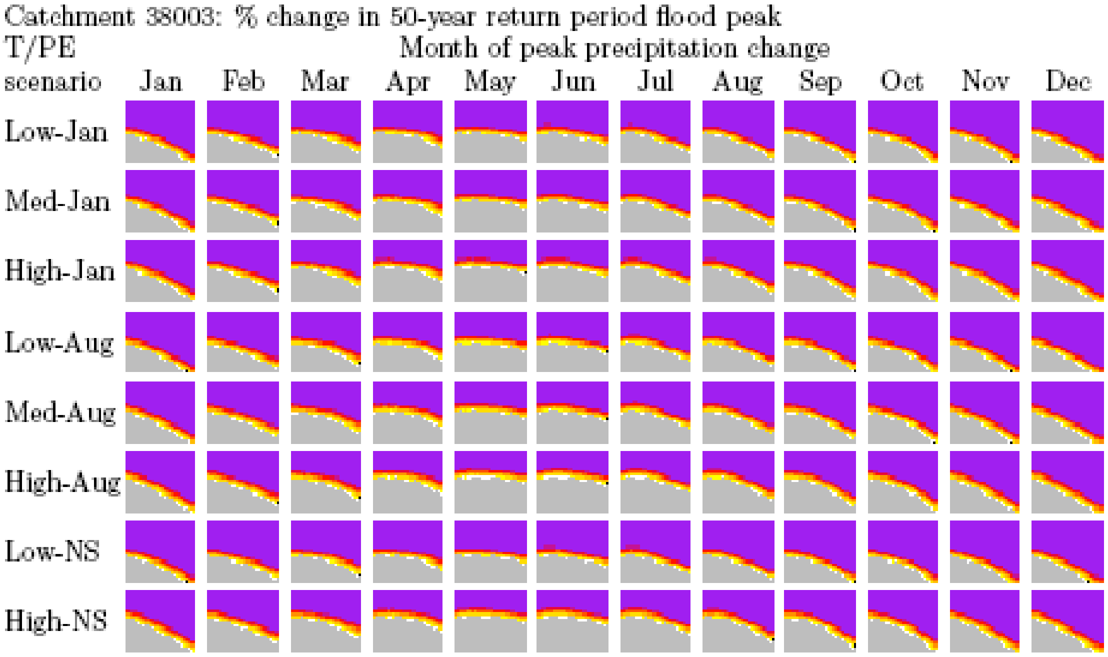
Catchment 38003: % change in 2-year return period flood peak



Catchment 38003: % change in 10-year return period flood peak




Catchment 38003: % change in 20-year return period flood peak


Catchment 38003: % change in 50-year return period flood peak

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