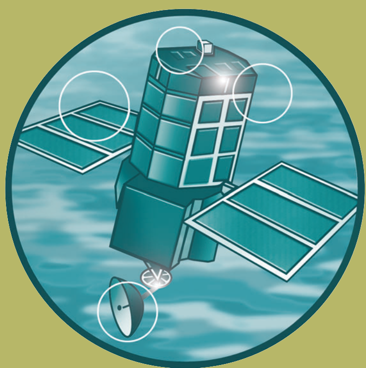
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Regionalised Impacts of Climate Change on Flood Flows:

Identification of Flood Response Types for Britain

R&D Milestone Report FD2020/MR3



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Regionalised impacts of climate change on flood flows: Identification of flood response types for Britain

Milestone report 3 – Project FD2020

Produced: July 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.

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Executive summary

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

A **scenario-neutral** approach based on a broad sensitivity analysis to determine catchment response to changes in climate as chosen for FD2020. The method separates the climate change that a catchment may be exposed to **(the hazard)** from the catchment response (change in peak flows) to changes in the climate **(the vulnerability)**. By combining current understanding of climate change likelihood (the 'hazard') with the vulnerability of a given catchment, it is possible to evaluate the **risk** of flood flow changes.

The vulnerability of a catchment is characterised in two steps: first, the response of a set of catchments to a range of climatic changes is modelled, then analysed for similarity, and second the main responses are characterised according to catchment properties. This is achieved by defining a sensitivity framework of changes to the mean and seasonality of precipitation and temperature and modelling the response of each catchment within this fixed framework.

This milestone report describes the first step of the vulnerability assessment. The changes in flood peaks for 154 catchments across Britain are modelled in a comprehensive '*scenario-neutral'* sensitivity study based on 4,200 patterns of changes in rainfall, temperature and potential evaporation (PE). These changes were defined using a single harmonic function peaking in January for rainfall, and either in January or in August for temperature, with the range in mean annual change and seasonal change guided from latest IPCC-AR4 and PRUDENCE scenarios for the UK. The sensitivity analysis is composed of 525 rainfall patterns of change, combined with eight temperature and PE patterns of change.

The harmonic functions lead to 'smoothed' monthly climate change factors, producing daily climate input series using the change factor method. These time series were input to the hydrological model to generate river flow time series. These 'changed' river flow time series were compared with those simulated from the observed climate series. Changes in the magnitude of flood peaks of 2, 10, 20 and 50-year return period were selected as the indicators of flood change. Because the sensitivity study scans systematically through a domain of possible changes in rainfall, temperature and PE, the results obtained are '*scenario-neutral'*. The percentage changes in the flood indicators are representative of the response of the catchment to a variety of different climates, and hence are not directly linked to specific climate change scenarios.

For each catchment, these changes are organised according to the mean annual and seasonal change of rainfall for all eight temperature and PE scenarios: they form eight flood response patterns per flood indicator, i.e. the response of a catchment to a range of climatic changes.

The analysis of all the individual flood response patterns identified nine flood response types for all flood indicators that can be described by five main families of behaviour: Neutral catchments, for which the changes in flood peak magnitude are of similar magnitude to the maximum change in monthly rainfall; damping catchments, which are relatively resilient to small changes in rainfall (3 subgroups); enhancing catchments, which are relatively vulnerable to small increases in rainfall (3 sub-groups); mixed catchments, which are both vulnerable and resilient to changes in rainfall, depending on the magnitude and seasonal pattern of the rainfall changes; and sensitive catchments, which are very vulnerable to most increases in rainfall.

These nine flood response types fully describe the range of responses in the flood regime to climate change in Britain. They characterise the vulnerability of a catchment's flood regime to changes in climate.

Contents

1. Introduction

1.1 Background

This milestone report for the project FD2020 'Regionalised impacts of climate change on flood flows' describes the results of a comprehensive sensitivity study on the impact of climate change on four flood indicators for 154 catchments over Britain (there are 155 sets of results, with one catchment having results from both hydrological models used in the project).

With a traditional climate change impact study where each catchment is run with its corresponding climate change projections, it would be difficult to separate out the differences due to catchment properties from those imposed by the spatial variation in the climate signal, as GCM projections have a seasonal and spatial variation. Thus it would be difficult to truly regionalise the impact of climate change on flood flows. In addition, traditional impact studies only provide impacts for specific climate scenario projections (e.g. from 'GCMa' or HadCM3 etc…). With the science of climate modelling constantly evolving, and the regular emergence of new sets of scenarios (e.g. the new UKCP09 for the UK), results of traditional impact studies become out-of-date very quickly and must be updated with each new set of scenarios.

The FD2020 project is based on the analysis, for each catchment, of the percentage change in the magnitude of the 1:2, 1:10, 1:20 and 1:50 flood peaks for a range of possible climate scenarios. This methodology is *scenario-neutral*, in other words, it does not rely on a particular climate model projection, but considers the impact of a range of possible rainfall and warming scenarios. For the UK, this range is described by 525 rainfall scenarios combined with eight warming scenarios (including PE scenarios, total of 4,200 scenarios, see Section 2), as described in the Milestone report 2 (Prudhomme and Reynard, 2009).

1.2 Vulnerability, hazard and risk

The framework developed results in three components inherent to climate change impact assessment:

- The vulnerability. This is the description of how a flood indicator changes under a change in climate. The sensitivity framework tested 4,200 possible different climates, summarised in a set of eight flood response patterns. Each set is specific to a catchment.
- The hazard. This is what is projected to happen to the climate in the future, according to latest understanding and modelling. Here we have summarised the hazard in a simple 3-parameter function (the 1-phase harmonic). This is specific to the climate projections (generally provided for a given location). The uncertainty introduced by this harmonic assumption is analysed in Kay *et al.* (2009).
- The risk. This is the combination of the vulnerability and the hazard. Two catchments with a similar vulnerability to change might have very

different risk if the projected changes in precipitation are very different, for example because they are located in different parts of the country.

1.3 Identification of the vulnerability

This report presents the first part of the regionalisation procedure, which aims to identify the vulnerability of the flood regime of a catchment to climatic changes, and identify key flood response patterns found in Britain from a pool of 154 catchments. The second part of the regionalisation, which aims to characterise the vulnerability using catchment properties, is described in a separate report. The hazard and the risk found for the 154 catchments is described in a Final technical Report.

2. Sensitivity framework – an overview

For this project to achieve its objectives of understanding the dynamics of the relationships between catchment properties, climatic changes and changes in flood flows, it is essential that the considered climate change scenarios capture the range of potential climatic changes expected to occur in Britain, including the large Global Climate Model (GCM) uncertainty. This will allow the conclusions of the modelling exercise and regionalisation study to be as robust as possible, and provide a sound science-base for subsequent policy guidance to the flood management community.

FD2020 has developed a radically new way of investigating the response of catchments to rainfall and temperature changes through a sensitivity framework. This section summarises the methodology described in full detail in the companion report (Prudhomme and Reynard, 2009).

Instead of defining monthly change factors, as is traditionally done, the seasonal patterns of change in climatic variables are described by a single harmonic function. This facilitates the application of a sensitivity analysis of the response of catchments to multiple changes in the climate, thus accounting for a major source of uncertainty in GCM outputs, but also captures the seasonal variability in the changes. This sensitivity domain provides a framework to create many climate scenarios used to simulate the flood regime under changed climate conditions.

To keep the computing load manageable, the ‘change factor’ method was chosen to implement the climate scenarios: the observed catchment precipitation, temperature (T) and potential evaporation (PE) time series are modified according to monthly change (Fowler *et al.* 2007; Prudhomme *et al.* 2002). This technique relies on key assumptions listed in Prudhomme and Reynard (2009). The uncertainty introduced by this simple downscaling technique is tested and compared to other sources of uncertainties in a separate report (Kay *et al.* 2009).

The analysis of projections for Britain at the 2080 time horizon showed that for precipitation, a single-peak harmonic function fits well monthly change factors and generally peaks in winter for all emission scenarios, while the range in mean annual change is large. For temperature, there is no distinct season of maximum change, with both winter and summer equally projected. No significant correlation was found between change in precipitation and temperature patterns (Prudhomme and Reynard, 2009). This resulted in defining two sensitivity frameworks, one for precipitation and one for temperature (Table 2.1). Because the effect of the warming pattern on the flood regime is smaller than that of change in the rainfall pattern, the number of temperature scenarios (and corresponding PE scenarios) was restricted to eight. However, both precipitation and T/PE sensitivity frameworks describe a range of possible scenarios larger than suggested by current climate model projections. This means that the results of the project will remain able to characterise impacts from new projections showing greater changes than current projections.

Table 2.1 Sensitivity framework for precipitation and temperature changes

	Phase	Mean annual change	Seasonality	Scenarios
Precipitation	January	-40% to 60%	0 to +120%	All combinations by increments of 5% Total: 525 scenarios
Temperature	January and August	1.5° 2.5° 4.5°	1.2° 1.8° 1.6°	Low Jan and Low Aug Medium Jan and Medium Aug High Jan and High Aug
	None	0.5°; 4.5°	0°	Non-Seasonal (NS) Low/High Total: 8 scenarios

2.1 Sensitivity domain and application

For each catchment, the eight warming scenarios (temperature and corresponding PE changes) are each run in combination with the 525 precipitation scenarios to create an **8-member ensemble** (one member per warming scenario). Results for each ensemble member are displayed in a 2-dimensional space:

- Y-axis: Mean annual change; the bottom half of the graph represents an overall decrease in the mean annual precipitation (dryer climate); the top half of the graph represents an overall increase in the mean annual precipitation (wetter climate).
- X-axis: Maximum seasonal change; the left part of the graph represents scenarios where changes in the winter and in the summer are not very different (little change in the seasonal pattern of precipitation); the right part of the graph represents scenarios where changes in winter are much larger than changes in the summer (increased seasonality with wetter winters and dryer summers). This can be interpreted as intensification of the seasonal cycle.

Each diagram contains 525 squares, each corresponding to a different precipitation scenario (or inter-annual change pattern). A schematic of the space (with its corresponding precipitation scenarios) is given in Figure 2.1.

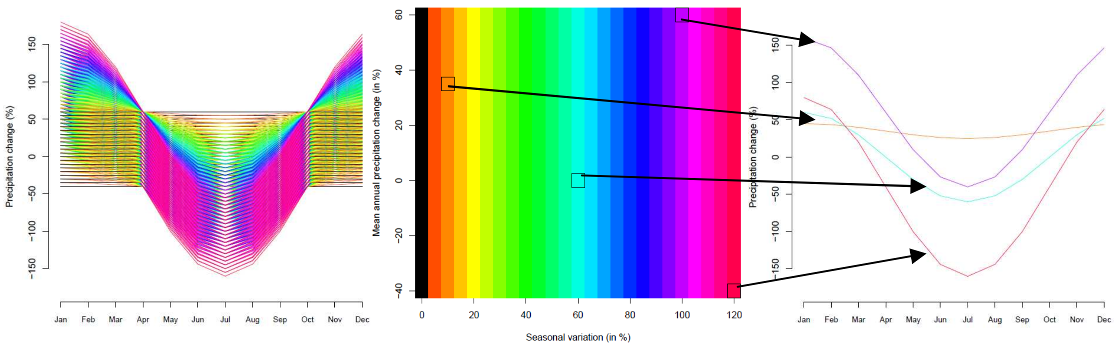

Figure 2.1 Construction of the sensitivity domain and corresponding inter-annual change scenarios

In the top left (grey) of the sensitivity domain (Figure 2.2) rainfall increases throughout the year, including in the summer. In the bottom right (black), rainfall reduction reaches 100% for some summer months (i.e. rainfall is nil in those months).

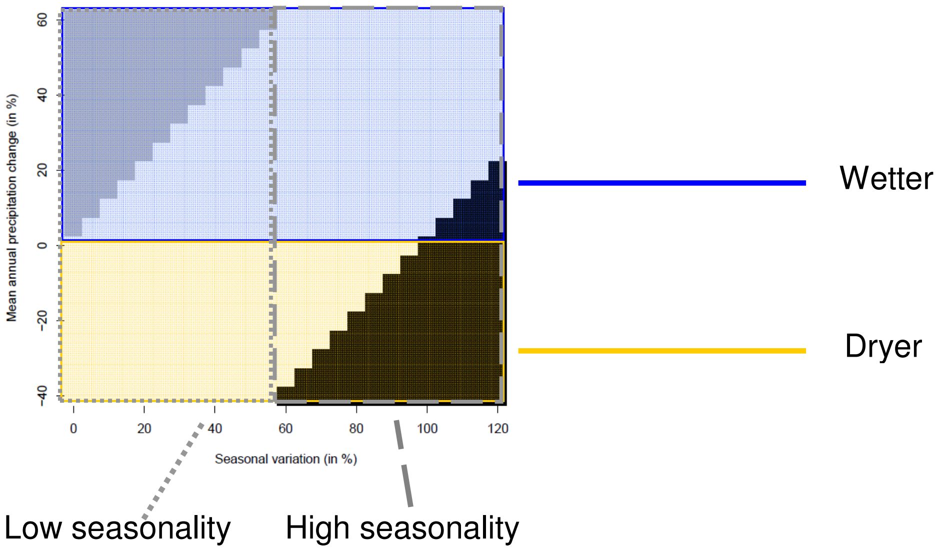

Figure 2.2 Scenario characteristics of the sensitivity domain

2.2 Construction of future time series

The factor of change method is used to create a future climate time series for each climate scenario: 525 precipitation time series, and eight temperature and eight PE time series. Using the observed catchment climate (precipitation, temperature or PE) time series as reference, a future synthetic series is created by adding/subtracting, for each day/hour of the month, an amount in proportion to the reference value for that day/hour and the factor of change given by the harmonic function for that month. For temperature series, the changes are expressed in degrees C, so an absolute value is added/subtracted rather than a proportion.

For example, for a precipitation scenario of mean annual change of +20% with no extra seasonality (very extreme left of the sensitivity domain): 20% is added to all data throughout the year. For a scenario of mean annual change of 20% with an extra 40% seasonality, the change in January will be: 20% (mean annual change) + 40% (seasonality, peak in January) = +60%; in July: 20% (mean annual change) – 40% (seasonality, trough in July) = -20%.

Because catchments have different reference time series, they also have different future synthetic time series, but they all follow the same scenario of change (the harmonic functions).

2.3 Analysis of changes and flood response patterns

The calibrated hydrological model for each catchment (Crooks *et al.* 2009) is run with each synthetic future time series to produce future river flow series. These modelled scenario flow series are compared with the modelled baseline series to determine statistics of change. It is assumed for all modelling that the only change in rainfall-runoff response is from the changes in precipitation, temperature and PE. All catchment properties and model parameters are taken as stationary.

The largest independent daily peak flows simulated are sampled to produce a flood sub-series of Peak-Over-Threshold POT (Bayliss and Jones, 1993). Here, an average of 2 peaks per year was chosen to provide the POT series. A Generalised Pareto Distribution was fitted to each POT2 series to produce a flood frequency curve (Figure 2.3). A flood frequency curve relates flood magnitude to flood frequency, which can be expressed in terms of expected interval between years with a maximum peak exceeding the flood magnitude (Robson and Reed, 1999). This time interval is generally referred to as Return Period and here labelled RP. No uncertainty due to sampling error and choice of distribution was added to the estimates of the flood magnitude.

Four flood indicators are selected for the analysis: changes in the magnitude of the 2-year, 10-year, 20-year and 50-year return period flood peak (the 1:2, 1:10, 1:20 and 1:50 flood peak, labelled RP2, RP10, RP20 and RP50). This corresponds to the difference between the black curve (baseline value) and the blue dashed curve (scenario value), expressed as a percentage of the baseline value, for a given return period as in Figure 2.3.

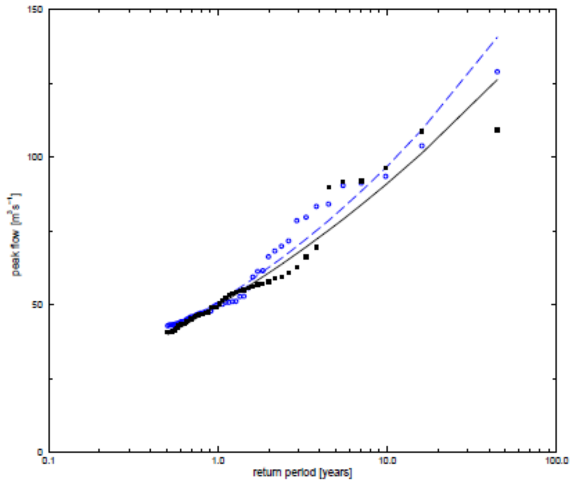

Figure 2.3 Schematic of flood frequency curves derived from baseline modelled flows (solid black) and scenario-led climate (dashed blue)

For a given catchment, each ensemble member is composed of a set of 525 percentage changes per flood indicator (i.e. flood response) which will form the basis of the regionalisation analysis. For illustration, each member is represented graphically using the sensitivity diagram framework introduced in Section 2.1 and Figure 2.1, with changes colour-coded according to their magnitudes (Figure 2.4). These diagrams are called 'flood response patterns', as they represent the response of a catchment to a set of climatic changes. Each ensemble member represents a different warming scenario (i.e. temperature and PE future time series), and there is one flood response pattern per indicator. This means that for each catchment, there is a set of 32 (8 * 4) flood response patterns and underpinning flood changes.

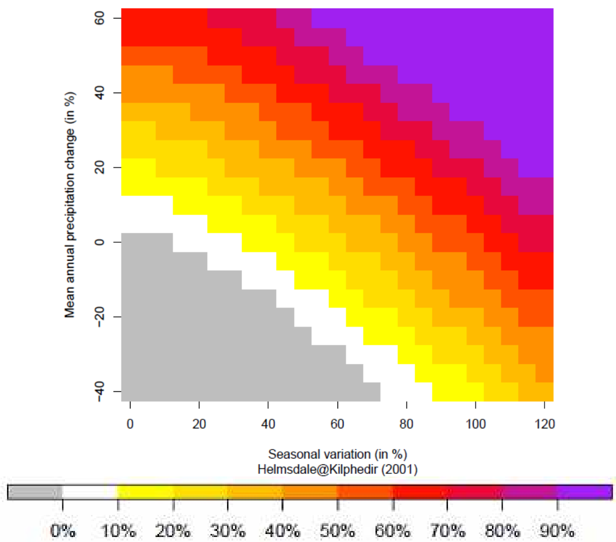

Figure 2.4 Flood response for percentage changes in 20-year flood peak for the Helmsdale @ Kilphedir with the Medium Aug temperature and PE scenario (maximum rainfall change in January)

Another way to express flood changes is to calculate the ratio between the percentage change in flood peak and the maximum percentage change in precipitation (i.e. the January precipitation change) of the corresponding scenario:

$$Ratio\ of\ change = \frac{Indicator\ Change\ (\%)}{January\ Precipitation\ Change\ (\%)}$$

The ratio is a useful way to highlight the non-linearity in the rainfall-runoff processes and the differences in transforming the rainfall change signal into flood changes found in Britain. When the ratio is smaller than 1 (yellow shades in Figure 2.5), this means that the change in flood peak is proportionally smaller than the maximum input change in precipitation: the signal in changes precipitation-to-flood is damped (e.g due to the catchment properties, to the time of the year when the maximum peak has been observed, or to the changes in temperature and PE). When the ratio is greater than 1 (red shades in Figure 2.5), this means that the signal in changes precipitation-to-flood is enhanced. A ratio near 1 would indicate a quasi-linear relationship between the maximum change in rainfall and the change in flood peak. Thus the ratio response patterns highlight which scenarios (or seasonal changes in rainfall monthly totals) lead to damping/enhancement of changes in the flood generation mechanisms.

An illustration of the ratio of changes is given in Figure 2.5, for the same case as in Figure 2.4: although different, it holds exactly the same information (set of percentage changes in flood magnitude). For simplicity, it is called the '*ratio response*'.

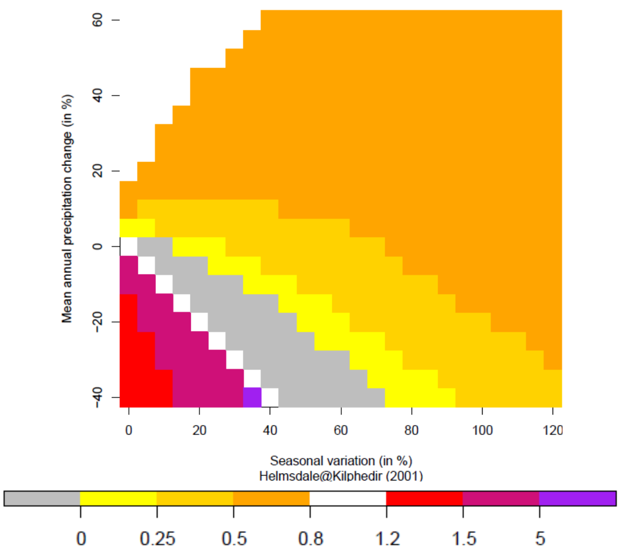

Figure 2.5 Ratio response for changes in 20-year flood peak for the Helmsdale @ Kilphedir with the Medium Aug temperature and PE scenario (maximum rainfall change in January)

3. Regionalisation analysis

The regionalisation of the impact of climate change on flood flows is divided into two parts:

1. Identification of key flood response patterns, which fully describe the range of responses in the flood regime to climate change in Britain. These flood response patterns are scenario-neutral (this report);
2. Characterisation of the key flood response patterns using catchment properties. From a set of catchment properties, it is possible to associate a key flood response pattern to any catchment in Britain, without undertaking the full sensitivity analysis of the 4,200 scenarios (separate report, Prudhomme *et al.* 2009).

3.1 Nationwide picture

The flood and ratio response patterns associated with changes in the 20-year flood peak for all 154 catchments are plotted to the catchment approximate locations (Figure 3.1 and Figure 3.2). This provides a visual display of the variation in the flood response patterns found in Britain (for a maximum change in rainfall in January).

There is great similarity amongst all simulated flood responses (Figure 3.1): flood magnitude decreases with mean annual rainfall when the seasonal variation is small (bottom left corner of flood response pattern); flood magnitude gradually increases when both mean annual rainfall and seasonal variation increase; increases in flood magnitude can be very large for large mean annual rainfall and/or large seasonal variability increases (purple shows increases of more than 90%). However, some geographical features emerge: large increases dominate the responses (i.e. a lot of purple) in the south-east while increases in flood magnitude are gradual (coloured bands large and dominant) in the west and the north.

The ratio responses highlight the variations in the rainfall-runoff processes (Figure 3.2). Despite some coarse geographical groupings, the location of the catchments is not the only factor influencing the response to change in the climate in Britain: those catchments with very large increase (dominated by purple in the flood response patterns, and by red and magenta in the ratio response patterns) are also found in the north; the catchments with a very gradual increase (large coloured bands in flood response patterns, and yellow-dominated in the ratio response patterns) are found in most regions.

These maps capture well that:

1) The response to climate change is not uniform across the considered catchments, and key flood response patterns can be identified.
2) The regionalisation of the key flood response patterns purely by geographical location would not be appropriate to distinguish the true variation in the response of catchments to changes in the climate.

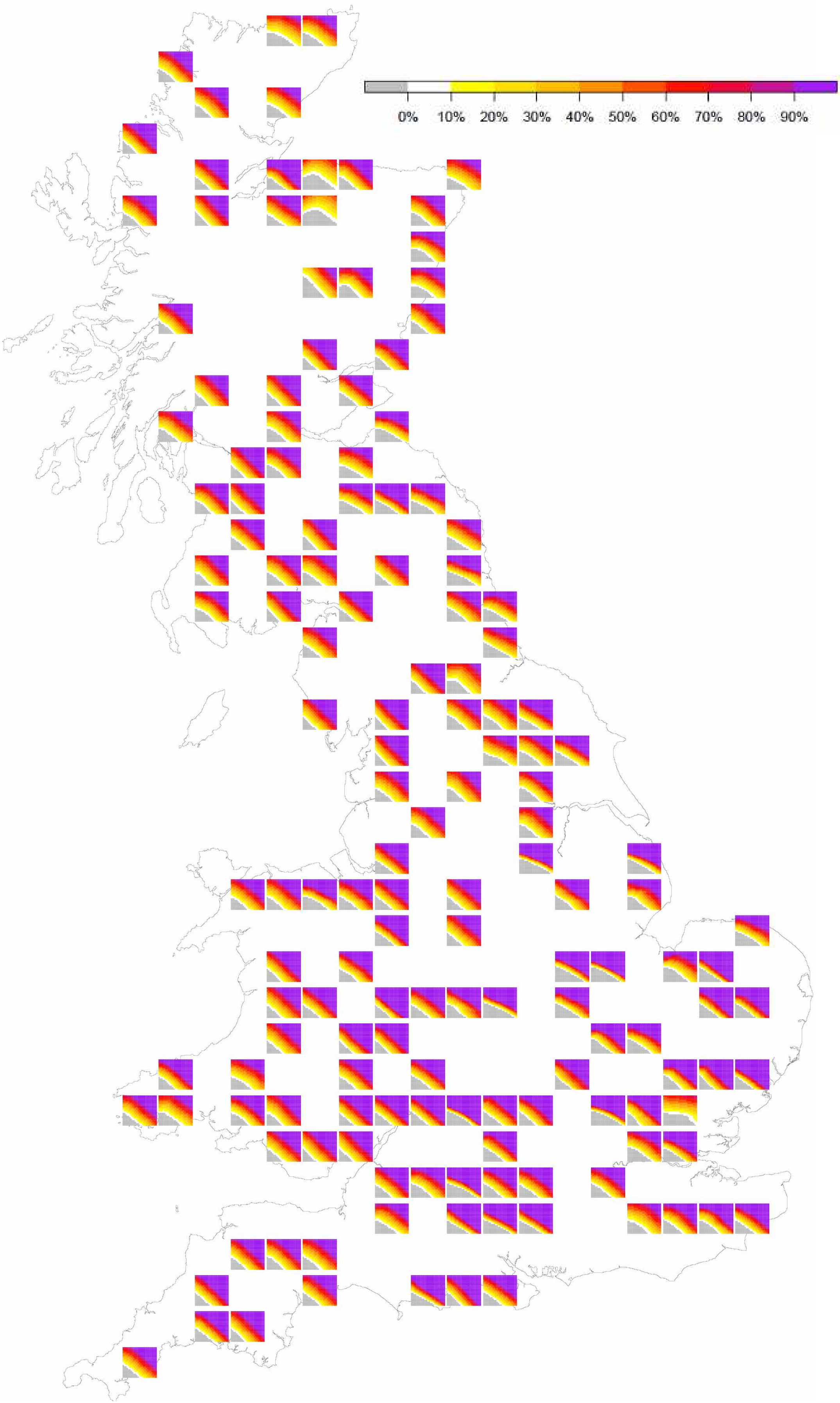

Figure 3.1 Flood responses for RP20 with Medium Aug temperature and PE scenario for the 154 catchments (maximum rainfall change in January)

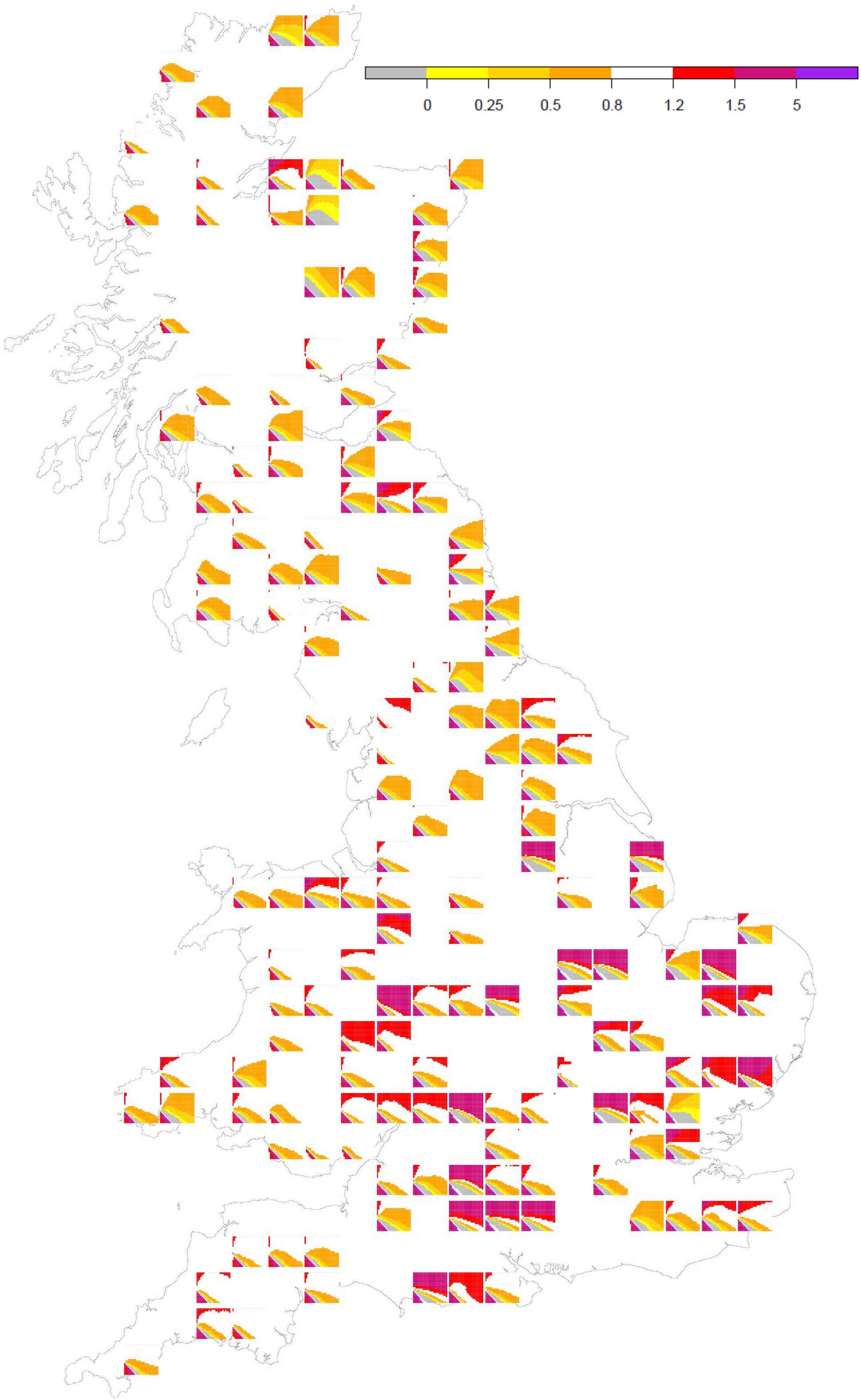

Figure 3.2 Ratio responses for RP20 with Medium Aug temperature and PE scenario for the 154 catchments (maximum rainfall change in January)

3.2 Impact of warming

For a given catchment, the analysis of all the flood and ration responses showed that the spread between the ensemble members (i.e. different warming scenarios for the same 525 rainfall scenarios and the same catchment) is much smaller than the spread between different ensembles (i.e. representing the response of different catchments). This confirms that, when analysing change in the flood regime, the variation due to a change in the temperature pattern is not as important as that due to a change in rainfall. The influence of changes in temperature and PE are further discussed in 3.6.

For each flood indicator, the identification of the key flood response patterns across Britain was thus done by considering together the eight members as representative of a catchment response. Because the largest changes in flood peaks were obtained from the most extreme rainfall scenarios (high mean annual change combined with a high seasonal change), and because such extreme scenarios are not projected to occur in Britain with current climate models, it was decided that the key flood response patterns should be determined from the responses obtained from 'average' scenarios (i.e. low seasonal variation) rather than from the extreme scenarios. To that effect, the grouping procedure was implemented on a sub-domain of the responses corresponding to a maximum in seasonality change of 80%. However, the full extent of the responses is always displayed in the resulting key flood response patterns.

The identification of the key flood response patterns was done independently for each flood indicator. However, an effort was made in the interpretation of the results so that similar patterns belong to the same overall type across the different indicators.

The terminology *'flood response pattern'* is used to characterise the pattern of percentage changes in flood peak for a catchment (or an average for a group of catchments) to changes in climate for a given flood indicator. The terminology *'flood response type'* is the name of a key response pattern, which has consistent characteristics across all the considered flood indicators.

3.3 Grouping methodology

The methodology used to identify the key flood response patterns in Britain is an agglomerative clustering technique, also described as a hierarchical technique. The algorithm used is the **agnes** function from the statistical software R (part of the package cluster, http://www.stats.bris.ac.uk/R/), and was applied to the sets of flood changes underpinning the flood response pattern graphs. Three catchments showed very different flood response for all flood indicators but could not be discriminated by the grouping algorithm for all return periods, and were thus set aside as a group to start with. For the remaining 151 catchments, the following methodology was used.

At first, each flood response pattern (i.e. the set of changes in flood peak for the 8-member ensemble scenarios for one catchment and one flood indicator) is a small cluster by itself. Clusters (or groups) are merged until only one large group remains, which contains all the flood response patterns. At each stage, the two 'nearest' groups are combined to form one larger group. The distance between two groups is calculated as the average dissimilarity measure between the flood response patterns in one group and the flood response patterns in the other group. Here the dissimilarity measure is the sum-of-squares of differences (also called Euclidian distance). Following Mardia *et al.* (1979), eight key flood response patterns were identified from the 151 catchments for each flood indicator, organised in eight flood response types. The pruning technique can be used to obtain a specified number of groups, based on the dissimilarity measure and the number of group requested. To avoid too many small groups being identified, a 2-stage process was used, where first four groups were produced, and the two largest further divided. Finally, some manual adjustment was made to the groupings at RP20 and RP50 to ensure consistency of groups across all four flood indicators.

Each flood response type is characterised by four summary diagrams for each flood indicator:

- <u>The key flood response patterns</u>, obtained by computing the arithmetic mean of each 525 element of the flood response pattern for all ensemble members (i.e. all T/PE series) and all catchments assigned to that flood response type. These sets of flood changes and associated diagrams give the percentage changes in flood peak
- <u>The key ratio response patterns</u>, obtained by computing the arithmetic mean of each 525 element of the ratio response pattern for all ensemble members and all catchments assigned to that flood response type. These sets of values and associated diagrams show whether the climate signal is damped, neutral or enhanced
- <u>The standard deviation of the flood response patterns</u>, obtained by computing the standard deviation of each 525 element of the flood response pattern for all ensemble members and all catchments assigned to that flood response type. These diagrams are a measure of the spread in the flood response patterns within that flood response type
- <u>The coefficient of variation in the flood response patterns</u>, obtained by computing the ratio of the standard deviation over the arithmetic mean of each 525 element of the flood response pattern for all ensemble members and all catchments assigned to that flood response type. It can be understood as a measure of the signal-to-noise ratio, and is dimensionless: a small coefficient of variation shows that the variability amongst the flood response patterns is lower than the information contained in the key flood response pattern

For each warming scenario (or ensemble member), individual key flood response patterns can also be generated (see Section 3.6).

3.4 Flood response types

The nine flood response types identified from the grouping procedure were analysed and organised according to the changes they characterise (Table 3.1). Each is discussed in detail in this section.

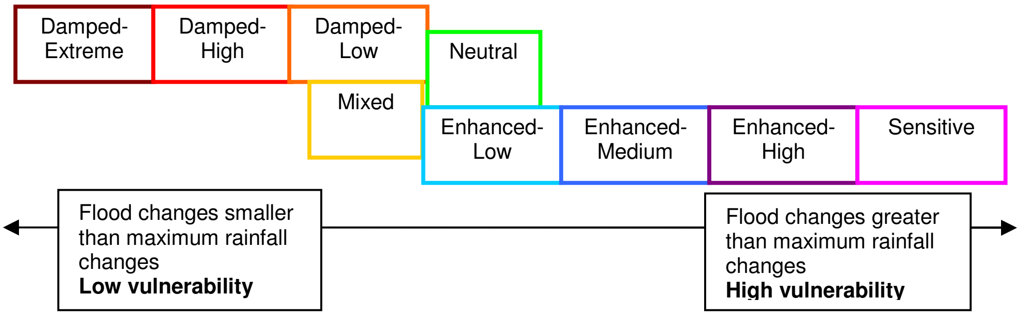

Figure 3.3 Schematic of the five families of flood response types of Britain

Overall their characteristics represent five main families (Figure 3.3):

- Neutral catchments. The percentage changes in flood peak are of similar magnitude to the maximum percentage change in rainfall.
- Damping catchments. The percentage changes in flood peak are of similar magnitude or generally lower than the maximum percentage increase in rainfall. These catchments are relatively resilient to small increases in rainfall (low vulnerability).
- Enhancing catchments. The percentage changes in flood peak are of similar magnitude or generally greater than the maximum percentage increase in rainfall. These catchments are relatively vulnerable to small increases in rainfall (high vulnerability).
- Sensitive catchments. The percentage changes in flood peak are very dependent on the precise characteristics of change – a small increase in rainfall may lead to a much greater increase in flood peak. These catchments are very sensitive to small changes in rainfall (very high vulnerability).
- Mixed catchments. The percentage changes in flood peak are mixed (damped/neutral/enhanced) depending on the magnitude and seasonal pattern of rainfall changes. These catchments are particularly vulnerable to increases in summer rainfall.

While only a quarter of catchments fall in the same flood response type across all four indicators, 90% are entirely in the neutral/damped/mixed or enhanced/sensitive families. Discussion on the hydrological and climatological factors behind the key flood response patterns is given in Section 3.5.

Table 3.1 Summary description of changes in flood peaks for flood response types in Britain from 154 catchments

Response type	Signal description	Increase in mean annual rainfall with increase in summer rainfall	Increase in mean annual rainfall with decrease in summer rainfall	Decrease in mean annual rainfall with increase in winter rainfall	Decrease in mean annual rainfall with decrease in all months
Neutral	Neutral	Similar	Similar	Similar or lower	Decrease
Damped L	Slightly damped	Similar or higher	Similar or lower	Lower or much lower	Decrease
Damped H	Very damped	Similar	Similar or lower	Much lower or decrease	Decrease
Damped E	Extremely damped	Lower	Much lower	Much lower or decrease	Decrease
Enhanced L	Slightly enhanced	Higher	Similar or higher	Similar or lower	Decrease
Enhanced M	Enhanced	Much higher	Similar or higher	Lower or much lower	Decrease
Enhanced H	Very enhanced	Much higher	Similar to much higher	Lower to decrease	Decrease
Sensitive	Sensitive	Much higher	Much lower to much higher	Much lower or decrease	Decrease
Mixed	Mixed	Higher or much higher	Similar or lower	Much lower or decrease	Decrease

Similar – percentage increase in flood peak of similar magnitude to maximum monthly percentage increase in precipitation (ratio of 0.8 to 1.2)
Lower – percentage increase in flood peak lower than maximum monthly percentage increase in precipitation (0.5 to 0.8)
Much lower – percentage increase in flood peak much lower than maximum monthly percentage increase in precipitation (0 to 0.5)
Higher – percentage increase in flood peak higher than maximum monthly percentage increase in precipitation (1.2 to 1.5)
Much higher – percentage increase in flood peak much higher than maximum monthly percentage change in precipitation (more than 1.5)
Decrease – percentage decrease in flood peak

Summer – change in at least one month from May to September
Winter – change in at least one month from November to March
Change in rainfall derived from harmonic function with peak in January and trough in July

Neutral flood response type

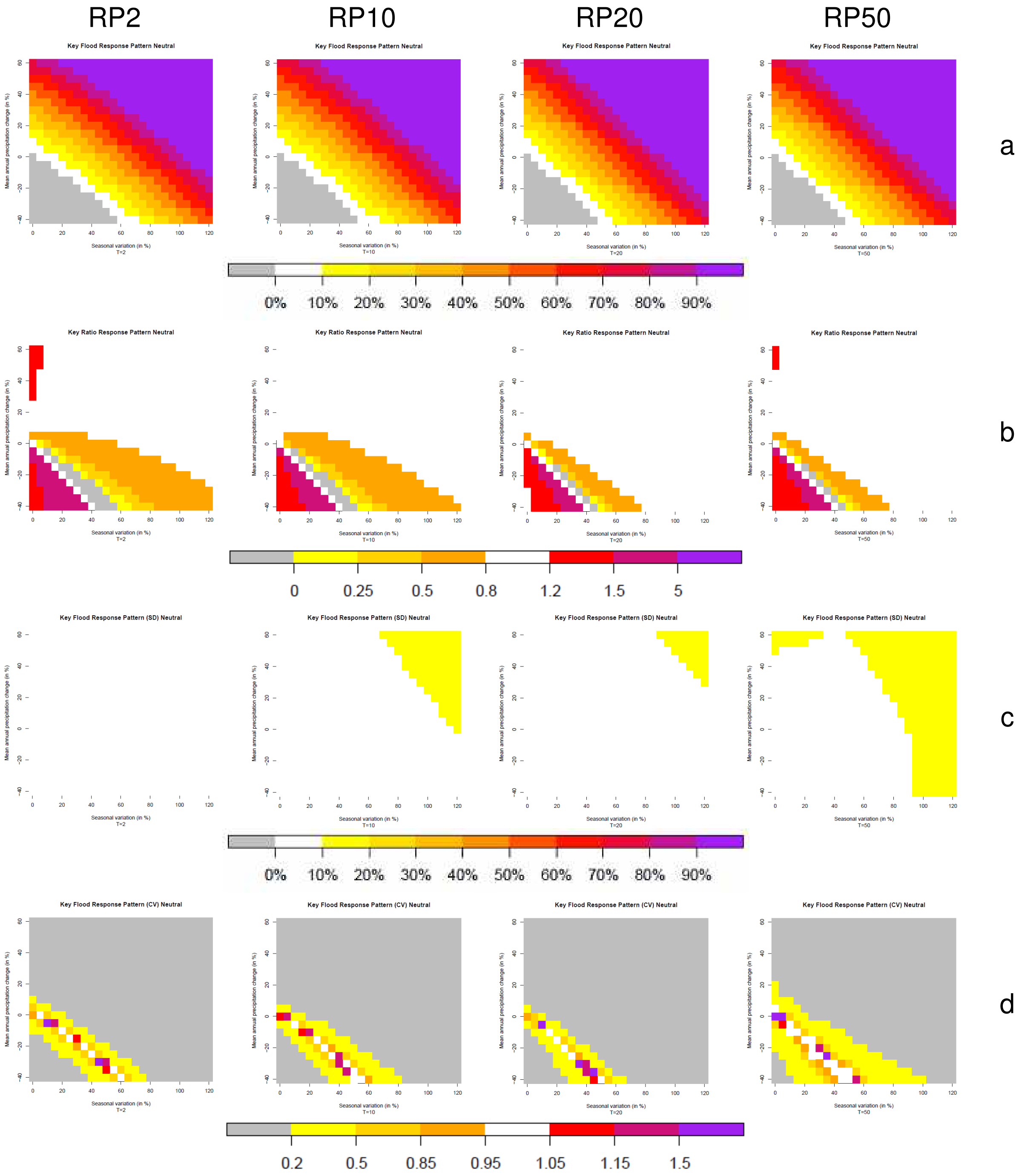

Figure 3.4 Neutral flood response type (averaged over all ensemble members and catchments) for RP2 (far left), RP10 (middle left), RP20 (middle right) and RP50 (far right): (a) flood response patterns; (b) ratio response patterns; (c) standard deviation in flood response; (d) coefficient of variation in flood response

The **Neutral** flood response type characterises catchments with changes in peak flood magnitude of similar magnitude to the maximum changes in mean monthly rainfall: the bands of changes in flood peak are parallel to the diagonal with the same maximum rainfall increase (mean annual rainfall change + seasonal variation change) in the flood response patterns (Figure 3.4a). The ratio between flood peak and maximum rainfall change is generally around 1 (white in Figure 3.4b). The catchments do not significantly modify the signal of rainfall changes when generating flood peaks. Note that for small return periods, changes in flood peak are a little smaller than change in maximum mean monthly rainfall. Even for a decrease in the mean annual rainfall (bottom half of the graphs), there is still a simulated increase in flood peak when the additional seasonal change is large enough (right half of the graphs).

Generally, the signal from rainfall change to flood peak change is unchanged: the catchments are neutral to rainfall increases.

The variability (as measured by the standard deviation) in the response pattern of flood change is less than 10% for RP2, and up to 20% for the other return periods, with variability between 10% and 20% associated with most of the high seasonality scenarios for RP50 (Figure 3.4c). Compared to the average change (Figure 3.4a), this variation is very small, as reflected by the coefficients of variation (Figure 3.4d). The CVs are greater than 0.5 (orange and purple shades) for a very small band of scenarios surrounding the ‘no rainfall increase’ scenario diagonal from [0 mean annual change, 0 seasonal change] to [-40% mean annual decrease, 40% seasonal increase].

For a few scenarios, the variation in the response is greater than the average (SD > mean, or CV>1, purple shades in Figure 3.4d). For these rainfall scenarios, an increase (from white in Figure 3.4a) or a decrease (grey in Figure 3.4a) in the flood peak is generated, depending on the catchment or the warming scenario. This means that for a small set of rainfall scenarios, flood magnitude could increase or decrease, but it is not possible to generalise further the expected responses.

Damped Low (L) flood response type

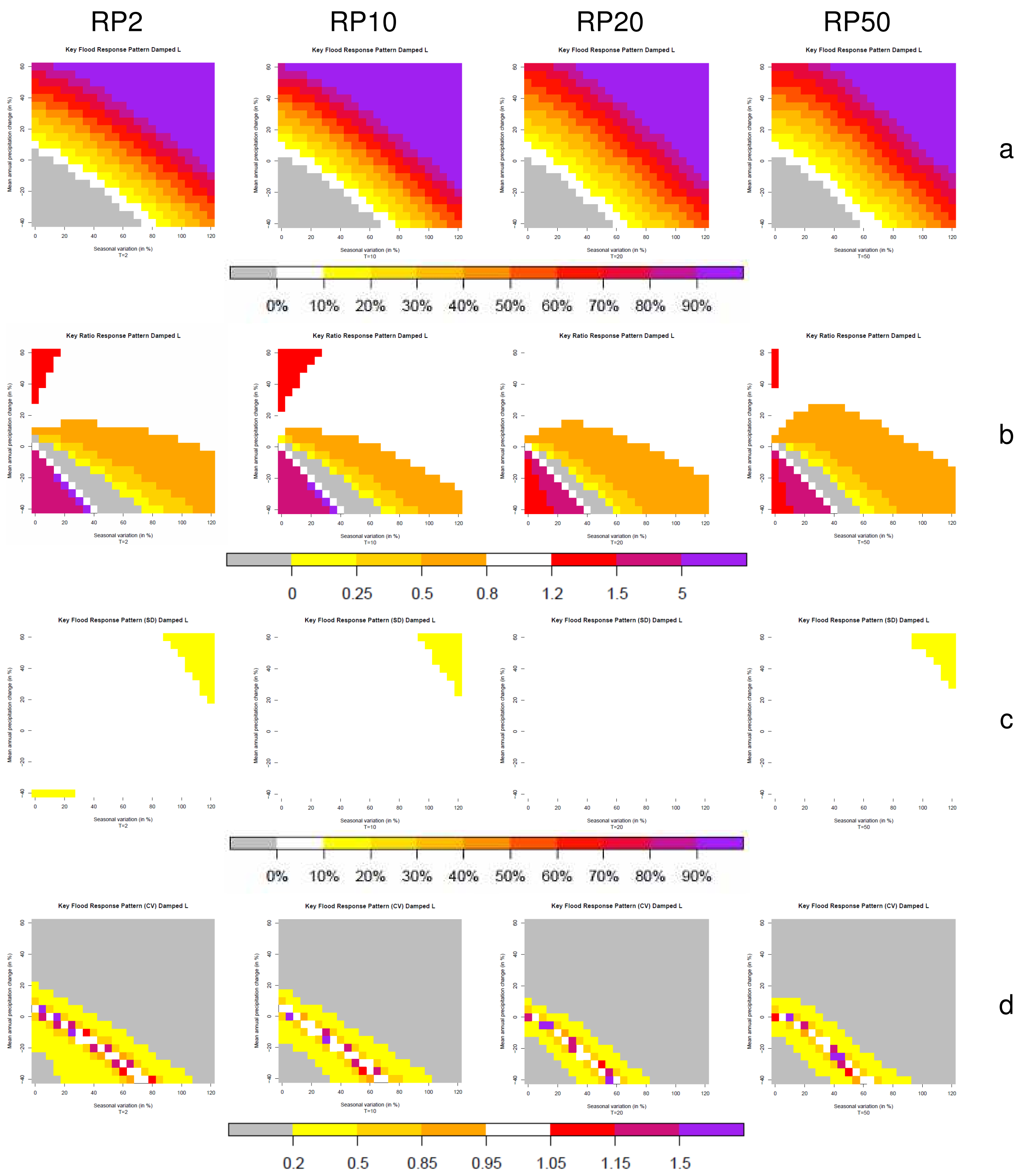

Figure 3.5 Damped L flood response type. Caption as in Figure 3.4

The **Damped L** flood response type has two main features:

1) flood peak increases slightly higher or of similar magnitude to the maximum mean monthly rainfall increase when rainfall increases all year round
2) with increase in seasonality, small mean annual rainfall increases are associated with proportionally smaller changes in flood peak magnitudes

(yellow shades in Figure 3.5b indicate flood increases less than 80% of the changes in maximum mean monthly rainfall).

Generally, the signal from rainfall change to flood peak change is of similar magnitude or damped: the catchments are resilient to a small increase in rainfall.

The variation in the flood response patterns obtained for the different warming scenarios and catchments is very small compared to the changes in flood peak (up to 20% compared to maximum flood change over 90%, Figure 3.5c), and are very little influenced by the severity of the floods considered (patterns similar for changes in flood peak magnitude for return periods of 2, 10, 20 and 50 years). The coefficient of variation in the flood response pattern is smaller than 0.2 for the majority of tested scenarios of change (grey in Figure 3.5d). The number of scenarios generating a higher variability in the response is similar to the **Neutral** type.

Damped High (H) flood response type

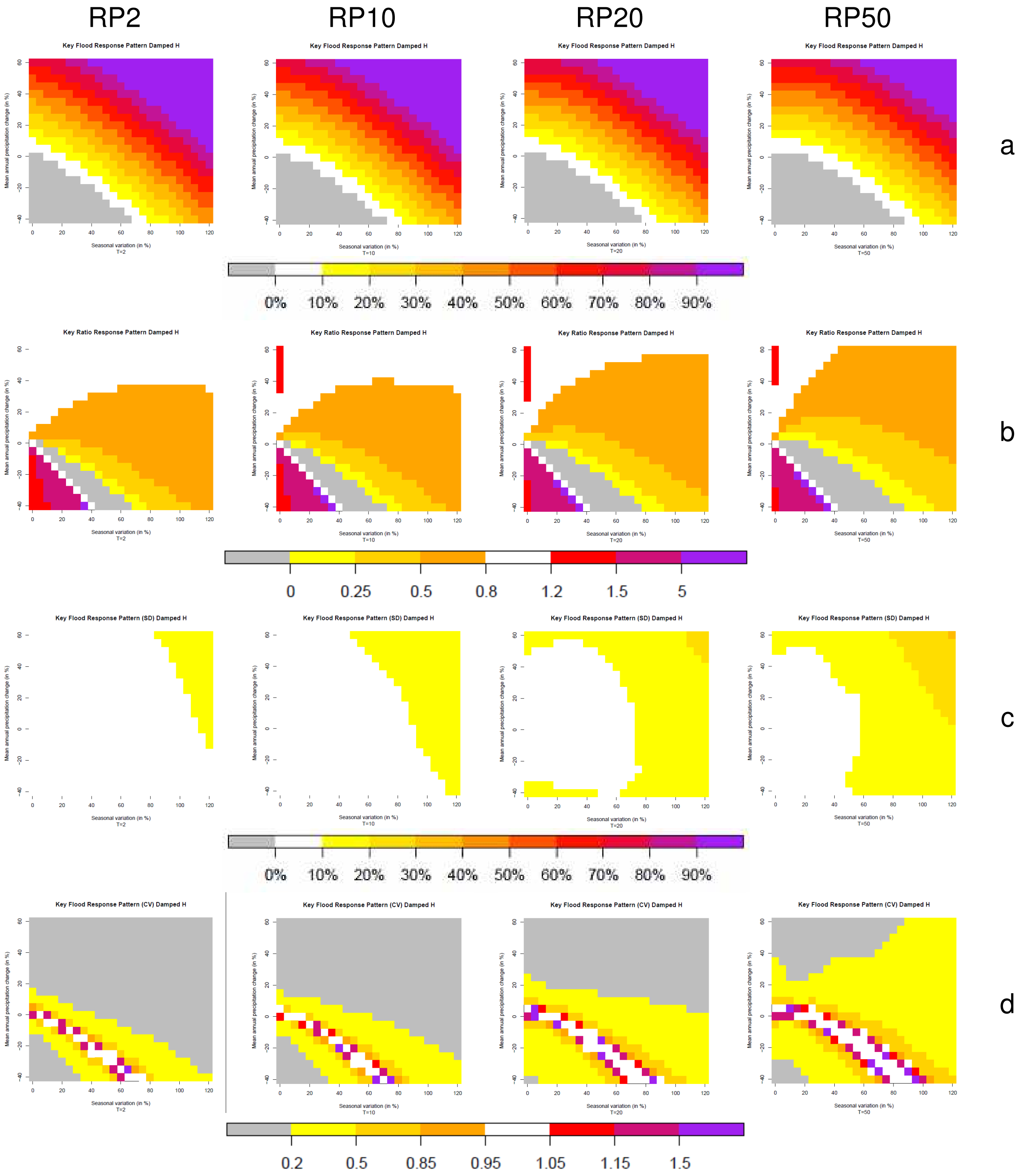

Figure 3.6 Damped H flood response type. Caption as in Figure 3.4

The **Damped H** flood response type has four main features:

1) changes in peak flood are small compared to maximum changes in precipitation
2) peak flood increases gradually with the rainfall changes (Figure 3.6a)

3) for a decrease of mean annual rainfall of 40% (very bottom of the graphs) seasonal change must be at least 60% for flood peaks of RP2 to RP20 to increase (80% for RP50) (Figure 3.6a)
4) for smaller changes in seasonal variation, flood peaks decrease at all return periods.

The ratio between the change in flood peak indicator and the January rainfall change (maximum mean monthly rainfall change) is generally lower than 1 (yellow shades in Figure 3.6b): this is an indication of a damping of the signal of climatic change.

Generally, the signal from rainfall changes to flood peak change is damped for the majority of scenarios: the catchments are very resilient to increases in January rainfall.

For all flood indicators, there is a very small spread in the flood response patterns of the catchments associated with **Damped H**, lower than 20% for RP2, and up to 40% for RP50, where average flood magnitude changes are greater than 90% (Figure 3.6c).

The coefficients of variation of **Damped H** are generally very small, and lower than 0.5 (upper value of yellow in Figure 3.6d), showing a generally homogeneous group.

Damped Extreme (E) flood response type

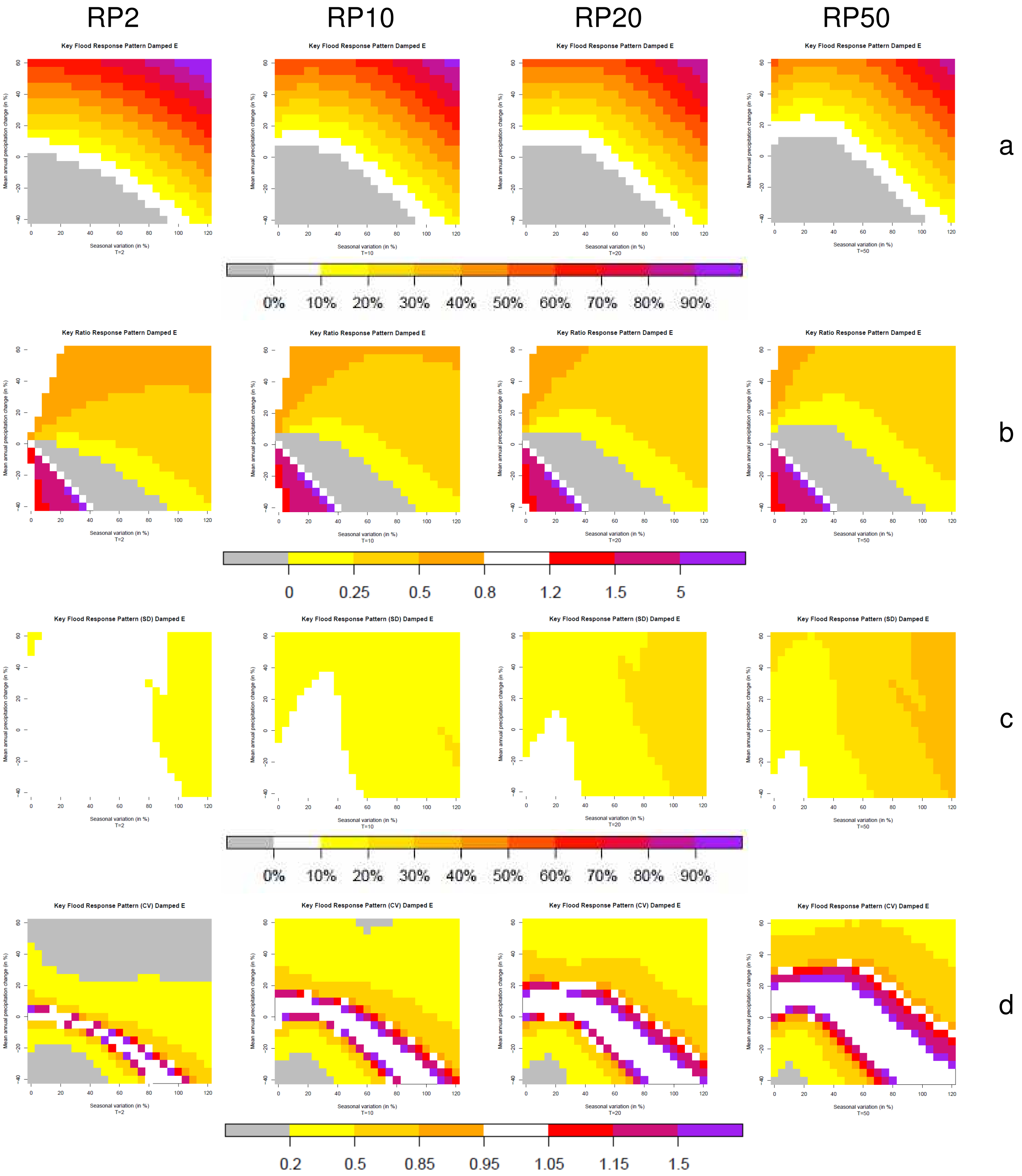

Figure 3.7 Damped E flood response type. Caption as in Figure 3.4

The **Damped E** flood response type is seen in three catchments where changes in flood peaks are the lowest (Figure 3.7a) of all analysed responses, and always smaller than the maximum changes in mean monthly rainfall (yellow shades in Figure 3.7b).

The variation in the response (Figure 3.7c) and in coefficient of variations are the largest of all the damped types identified (Figure 3.7d).

Generally, the signal from rainfall change to flood peak change is very damped: the catchments are extremely resilient to increases in January rainfall.

These three catchments are all affected by snow melt, but not all snow-dominated catchments have such extreme response. The effect of temperature changes on snowmelt and changes in flood frequency are discussed further in the report on regionalisation of flood response types.

Enhanced Low (L) flood response type

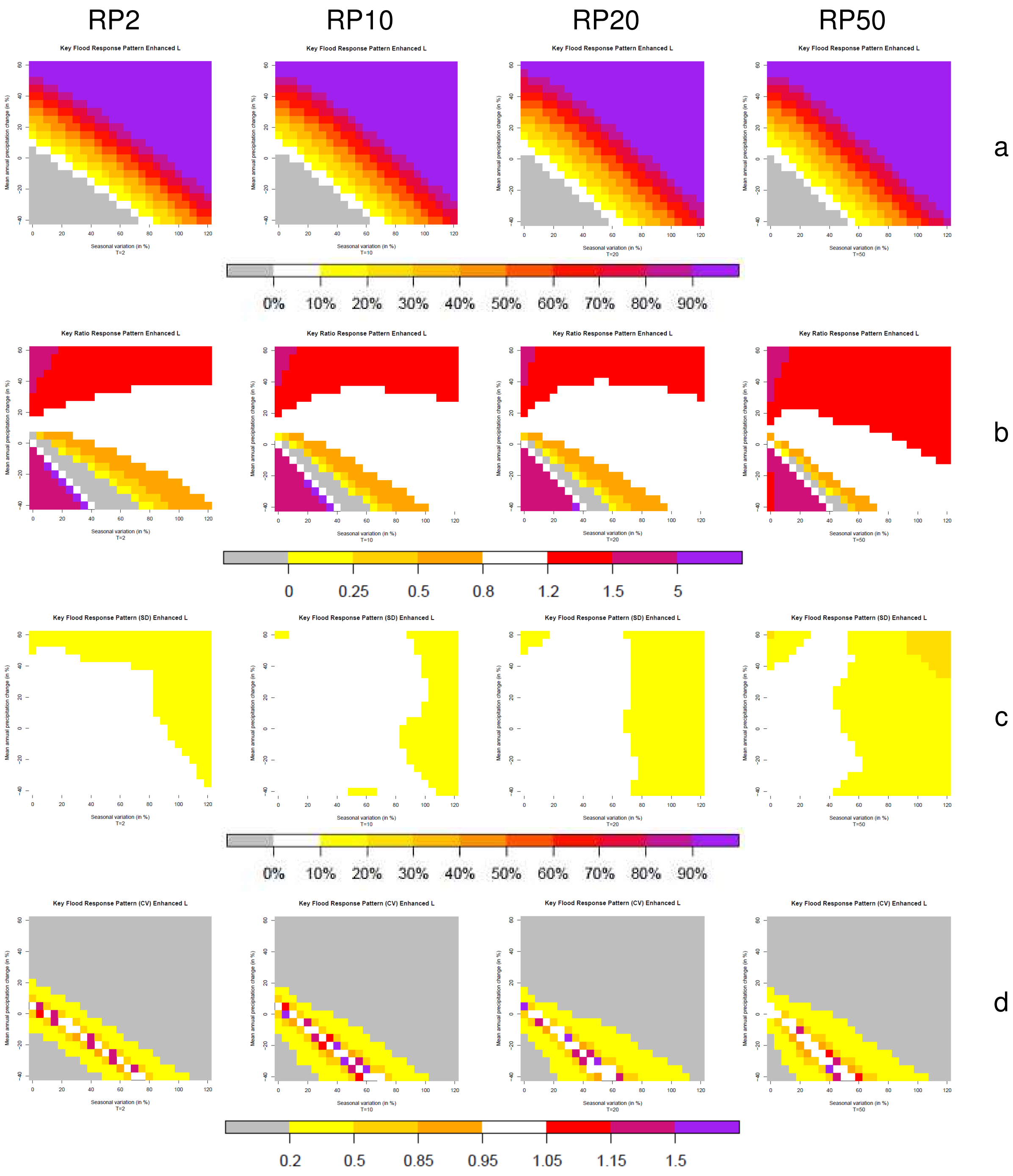

Figure 3.8 Enhanced L flood response type. Caption as in Figure 3.4

The Enhanced L flood response type has three features:

1) For mean annual rainfall increase of 25% (RP50) or 30-45% (RP2 to RP20), increases in flood peak are larger than the mean monthly maximum rainfall increases (ratio greater than 1.2, red shades in Figure 3.8b): this is an enhancement of the rainfall change.

2) For smaller mean annual changes, the flood peak increase is more or less proportional to the increase in rainfall, as seen with the size and spacing of the coloured bands in Figure 3.8a
3) Only very few scenarios generate a ratio smaller than 0.8 (i.e. representing a damping of the rainfall change signal).

Generally, the signal from rainfall changes to flood peak change is of similar magnitude or a little enhanced: the catchments are slightly vulnerable to increases in rainfall.

The variation in the response remains low (less than 30% for the most extreme scenarios, Figure 3.8c) and the coefficients of variation generally less than 0.2 (i.e. the spread of the flood response patterns within the group is less than 20% of the magnitude of the average flood response pattern, grey in Figure 3.8c).

Enhanced Medium (M) flood response type

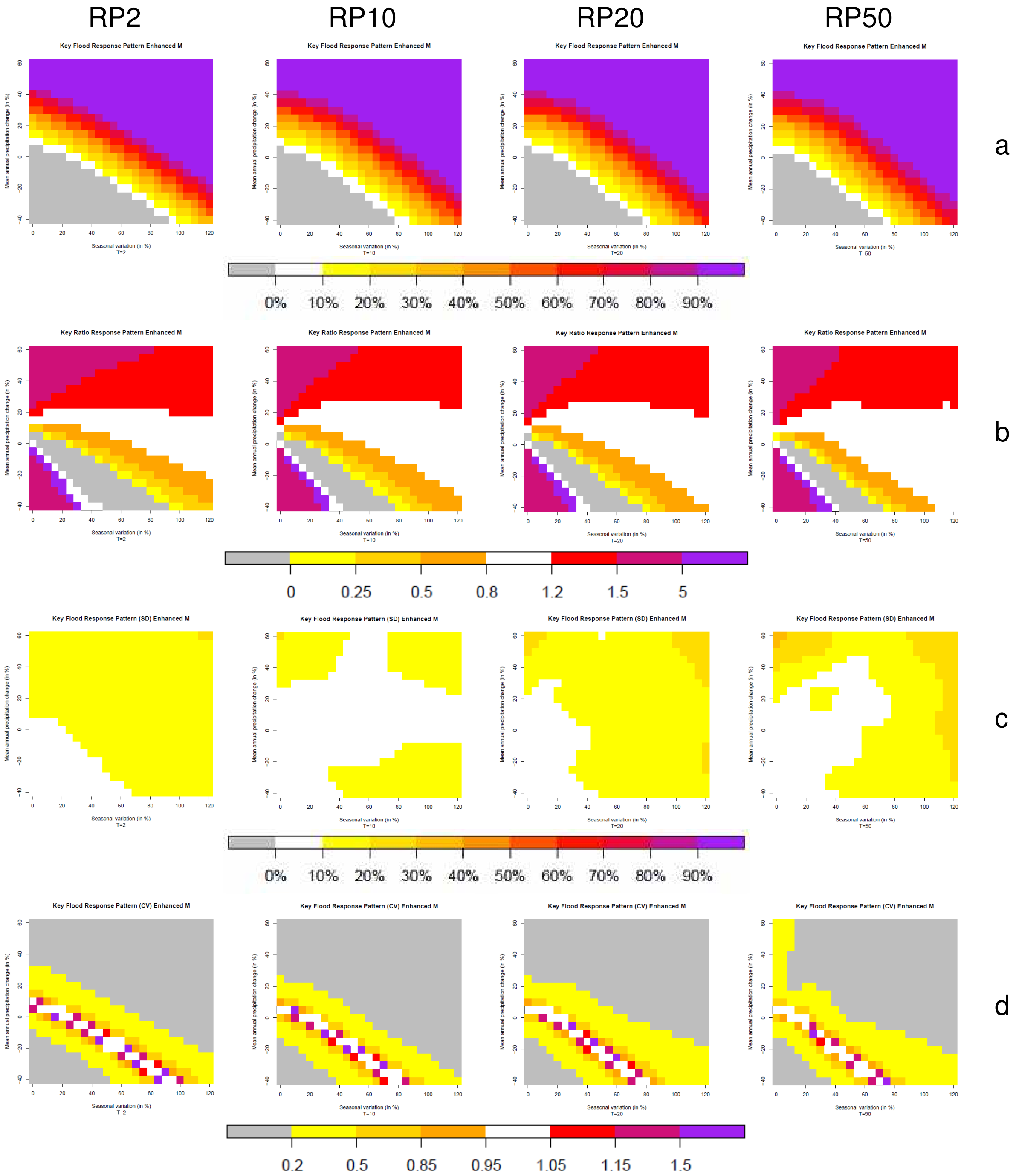

Figure 3.9 Enhanced M flood response type. Caption as in Figure 3.4

The **Enhanced M** flood response type shows a systematic increase in flood peak magnitude greater than the change in maximum mean monthly rainfall from an increase in mean annual rainfall of more than 20%: the coloured bands are not as wide as the changes they represent, (Figure 3.9a) and the ratio pattern is greater than 1.5 (red and magenta shades in Figure 3.9b). Changes in flood peak greater than 90% are generated for a mean annual rainfall change in excess of 40% (if there is additional seasonal pattern of change). These characteristics are shared across all the four considered return periods (Figure 3.9a).

Across the range of tested rainfall scenarios, only a small percentage generates an increase in peak floods lower than the maximum change in mean annual rainfall, even at a low return period (Figure 3.9b). The increase in peak flood is greater than 50%, compared with change in rainfall, for scenarios with an all-year round rainfall increase (i.e. also with an increase in summer rainfall; magenta in top left corner of Figure 3.9b).

Generally, the signal from rainfall changes to flood peak change is enhanced: the catchments are vulnerable to increases in rainfall.

The variability in the flood response pattern across the warming scenarios and catchments does not show any structure linked to the rainfall changes and remains lower than 30% (Figure 3.9c) and very small compared to the magnitude of the average responses to changes (Figure 3.9d).

Enhanced High (H) flood response type

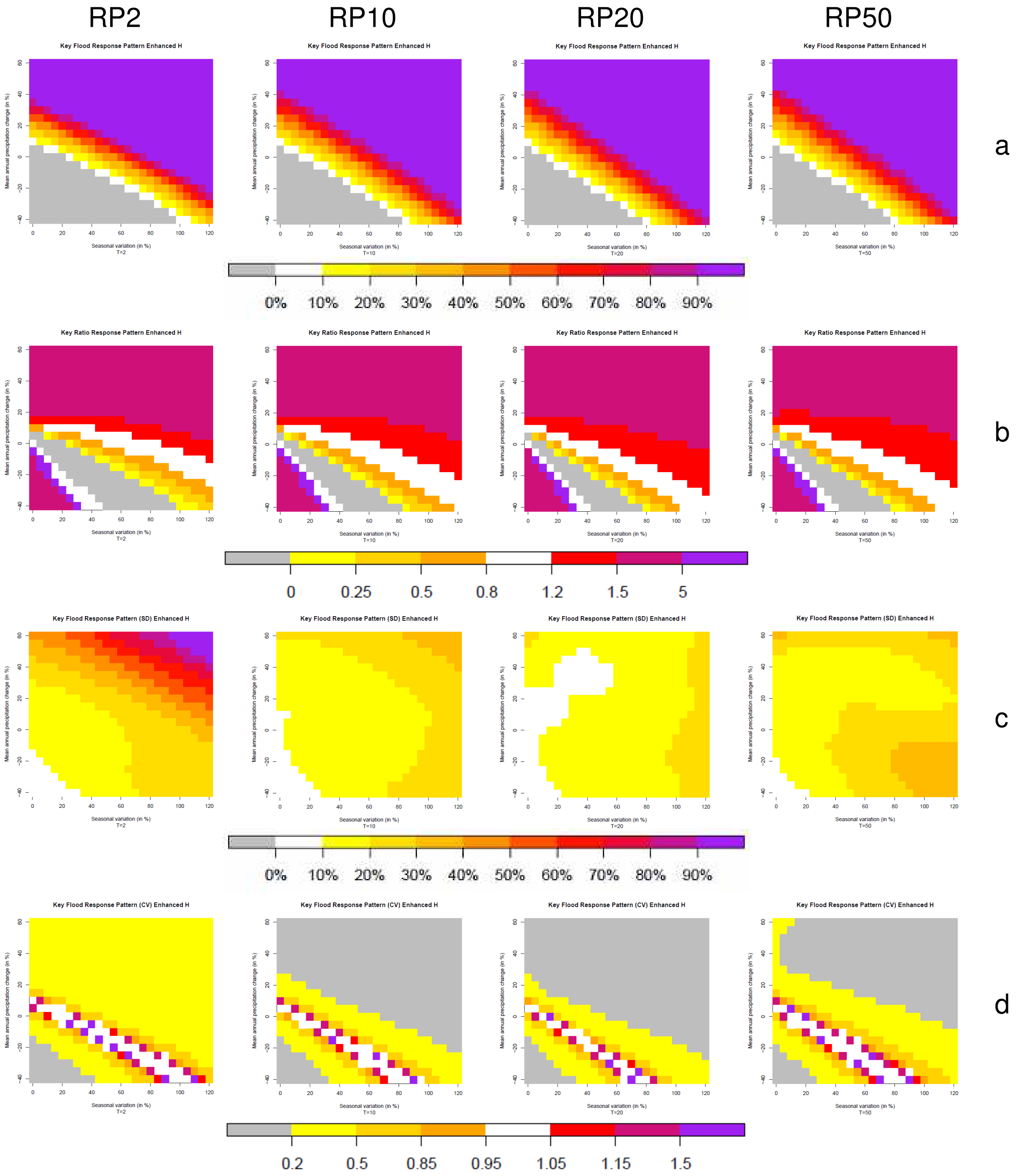

Figure 3.10 Enhanced H flood response type. Caption as in Figure 3.4

The Enhanced H flood response type shows a large number of scenarios generating increases in flood peak magnitude greater than 90% (purple in Figure 3.10a). Note that the scenarios generating a decrease in flood peaks (grey in Figure 3.10a) is not significantly smaller compared to **Enhanced M**. This means that it is the number of scenarios generating changes between 0% and 90% that is reduced: a small increase in rainfall generates proportionally a much greater increase in flood peak.

Generally, the signal from rainfall change to flood peak change is very enhanced: the catchments are very vulnerable to increases in rainfall, either due to a shift in the mean annual rainfall, or due to significantly wetter winters (large seasonal change).

The enhancement of the signal to change is well illustrated by the ratio between January rainfall and change in flood peak magnitude (Figure 3.10b): for a mean annual increase of more than 20%, regardless of the seasonal change, the corresponding peak increase is at least 50% greater (ratio > 1.5, magenta in Figure 3.10b), which applies throughout the return periods. Note also a strong decrease in the flood peak when winter rainfall decreases (bottom left corner). This amplification of the signal reflects a strong non-linearity in the rainfall-runoff response.

The variability in the flood response pattern for catchments in the group under different warming scenarios is larger for change of RP2 (far left graph Figure 3.10c), but remains small compared to the average response (Figure 3.10d) and very small for flood peaks of RP10, RP20 and RP50.

Sensitive flood response type

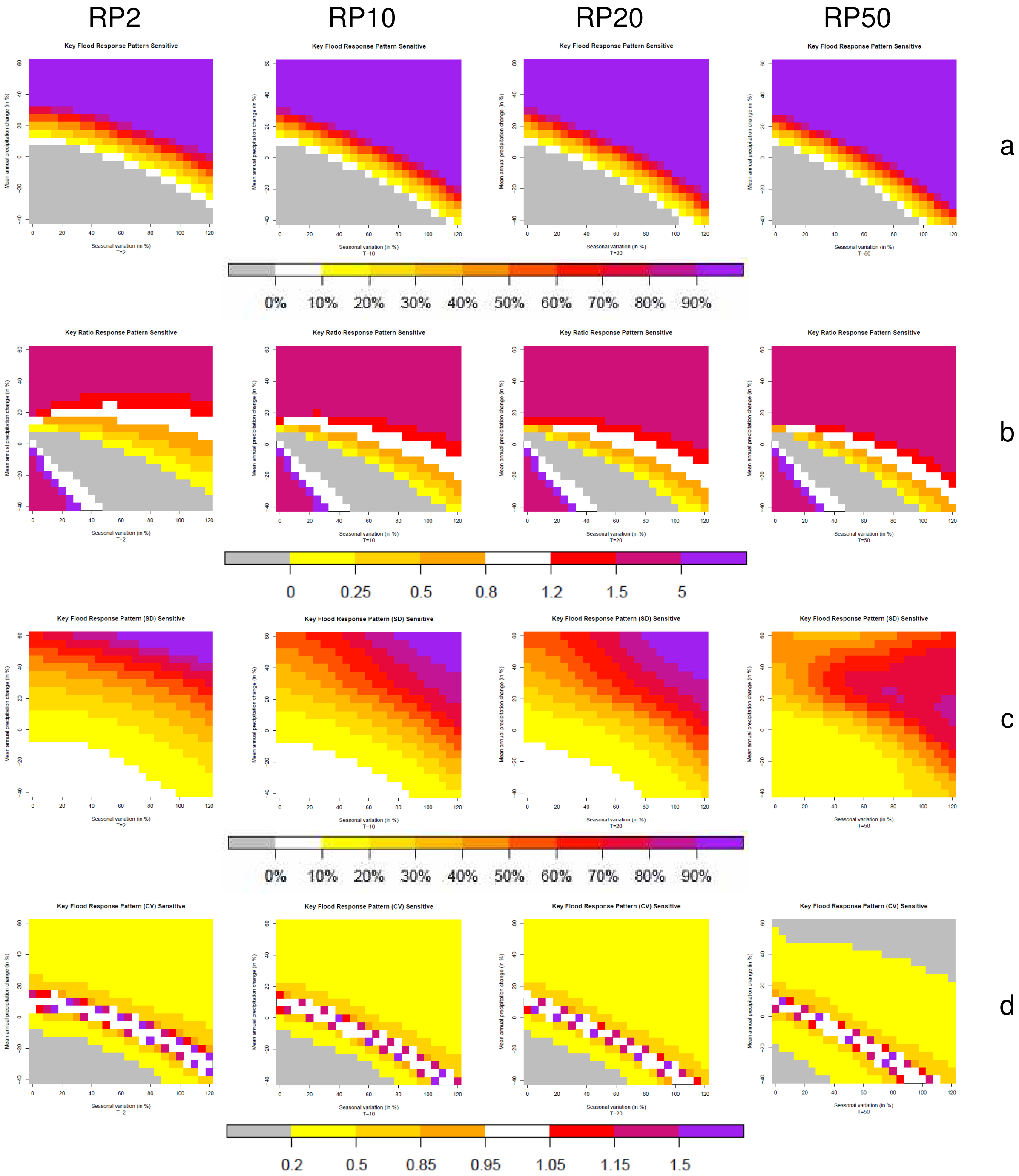

Figure 3.11 Sensitive flood response type. Caption as in Figure 3.4

The **Sensitive** flood response type characterises catchments where a small increase in rainfall can lead to a much larger increase in flood peak, as represented by the very narrow bands of change of Figure 3.11a. There are virtually no rainfall scenarios generating a neutral response near the 1-1 change (linearity of the signal, shown in white in Figure 3.11b). Virtually all increases in flood peak are at least 50% greater proportionally than the associated increase in January rainfall (magenta in Figure 3.11b).

Generally, the signal from rainfall change to flood peak change is very dependent on the precise characteristics of the change: the catchments are extremely sensitive to small changes in the water balance. This is the most extreme key flood response pattern identified in the Britain.

The high magnitude of changes in the flood response pattern is associated with high variability in the changes (Figure 3.11c): the higher the change in flood peak, the higher the spread in the results, except for RP50 where there is no real structure in the variability pattern (far right graph of Figure 3.11c). However, the variability in the flood response patterns remains very small compared with the average changes, as measured by the coefficient of variation (Figure 3.11d).

The group leading to the characterisation of the **Sensitive** flood response pattern includes a small number of catchments with very extreme responses, but which are not shared amongst enough catchments to justify a new flood response pattern. This generates a high variability in the flood response patterns.

Mixed flood response type

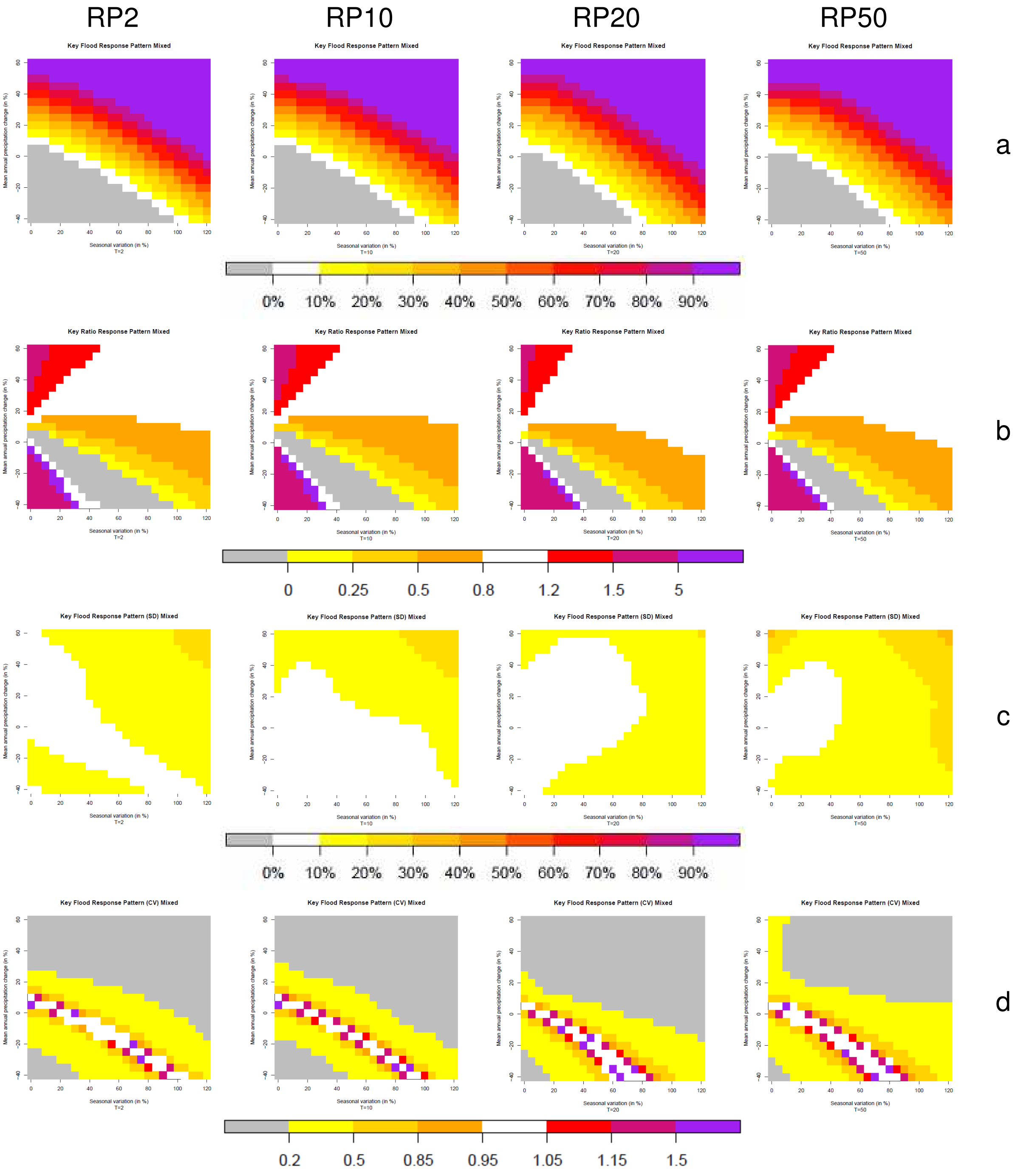

Figure 3.12 Mixed flood response type. Caption as in Figure 3.4

The **Mixed** flood response type represents two distinct responses:

1) when rainfall increases all year round, including in the summer (top left corner), the increase in flood peak is proportionally greater than the increase in maximum rainfall (red and magenta shades represent flood changes at least 20% greater than the maximum change in mean monthly rainfall, Figure 3.12b)

2) up to an overall increase of 20% in mean annual rainfall and for scenarios where rainfall decreases in the summer (May-September) but increases during the rest of the year, the changes in peak flood are proportionally smaller than the maximum rainfall change (yellow shades in Figure 3.12b). Above 20% the increase in peak flood becomes of similar magnitude to the increase in maximum mean monthly rainfall

Note that the number of scenarios leading to changes between 0% and 90% (i.e. width and size of the coloured bands, excluding purple in Figure 3.12a) is slightly smaller than the **Neutral** flood response types.

Generally, the signal from rainfall changes to flood peak change is mixed: the catchments are resilient/neutral/vulnerable depending on the seasonal pattern and the magnitude of rainfall changes.

The variability in the flood response pattern is greater than for **Neutral** (Figure 3.12c), but remains smaller compared to the average changes (as represented by the coefficient of variation of the changes, Figure 3.12d).

3.5 Hydrology of flood response types

Nine flood response types have been identified to represent change in flood frequency under climate change. These have been grouped into five families of change – Neutral, Damping, Enhancing, Mixed and Sensitive. The differentiating factors between these flood response types can be understood in terms of climatology, seasonality, catchment hydrology and natural variability. As it is the impact of changing the climate which is being investigated, it follows that the balance between climatological parameters is of major importance to future changes in rainfall-runoff response.

a) Water balance
The seasonality of the hydrological water balance between incoming precipitation (P) and outgoing losses, mainly through evapotranspiration (PE) and water usage, provides the background which determines whether a 'precipitation event' is sufficient to generate a flood. In the winter (Dec – Feb) inputs generally greatly exceed losses and therefore the balance is not unduly affected by changing P and PE. On average, the flood potential is not changed. However, in the remainder of the year the water balance may be considerably altered by changes in P and PE with consequent effects on the flood potential.

b) Catchment memory
The rate of response between rainfall and runoff is determined by catchment properties such as permeability, soil type and slope. These properties determine the lag between rainfall and river flow or the 'memory' of the catchment. With a short memory catchment changes in the water balance impact over only a limited time, such as hours or days. Whereas for a long memory catchment changes to the water balance may be evident over months, or even years.

c) Natural variability
The future climate series have been created using the factor of change method applied to observed precipitation, temperature and PE. The sequencing and time of year of extreme rainfall events in the observed data series, inherent with natural variability of the climate, may have an effect on the resultant change in frequency of the associated flood events. This aspect is considered further in the companion reports on the regionalisation of the flood response types (Prudhomme *et al.*, 2009) and uncertainty analysis (Kay *et al.*, 2009).

d) Frequency of floods
Four flood indicators have been selected for analysing the impacts of climate change: changes in the magnitude of the 2-year, 10-year, 20-year and 50-year return period daily peak flows. Floods, typical of different return periods, may tend to occur at different times of the year and have different causative factors (e.g. cyclonic/convective rainfall or snowmelt). Therefore, when the impact of the three factors described above combine, it is to be expected that changes to current flood frequency may not be of the same magnitude, or direction, across all return periods. For example, an

increase in mean annual rainfall of 5% with 10% seasonality could result in a decrease in the 2-year return period peak but an increase in the 20-year event.

The specific characteristics of the four factors described above for each of the flood response types form the subject of the report on regionalisation of flood response types (Prudhomme *et al.*, 2009).

To determine if there is any relationship between the flood response type and the characteristics of the sampled flood peak data series, the mean and coefficient of variation (cv) of the observed and modelled POT2 series for each catchment (see Crooks *et al*. 2009) were analysed according to the flood response type. The results are shown in Figure 3.13 for two flood indicators, RP10 (left) and RP50 (right). As discussed in Crooks *et al* (2009), the time period for the flood peak data series is governed by the length of the observed flow series and is therefore not the same for all catchments. Also, differences between observed and modelled values of the mean flood discharge and coefficient of variation may be attributable to a number of data measurement factors.

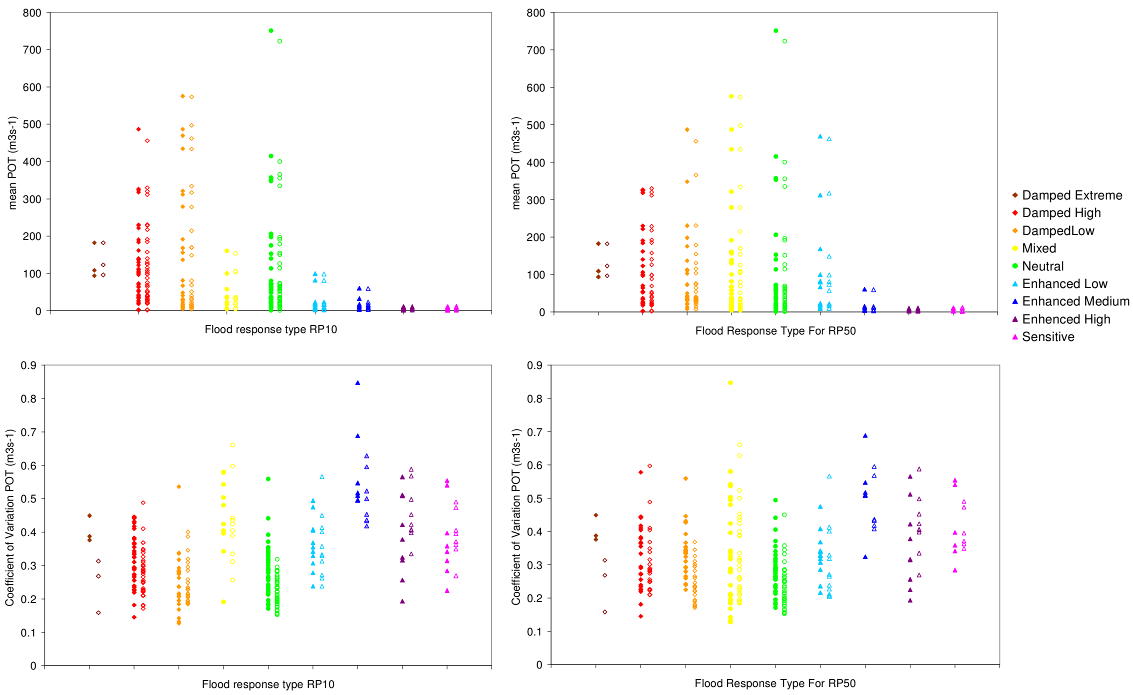

Figure 3.13 Mean (top) and coefficient of variation (bottom) of observed POT2 series according to the flood response types for RP10 (left) and RP50 (right). Filled symbols are for observed POT series, open symbols for modelled POT series

Generally, catchments of enhancing types are associated entirely with low mean flood discharge (maximum of 100 m^3s^{-1} for enhanced medium, high and sensitive), while there is no distinct characteristic for the damping catchments (Figure 3.13 top). There is a shift in the flood response type of catchments with the largest mean POT2 from damping type for RP10 towards a more enhancing type (mixed, neutral and enhanced low) for RP50. When looking at the dispersion of POT2 series, there is no marked difference between the nine flood response types (Figure 3.13 bottom). Note that apart from the three damped extreme catchments (brown, left hand side) where the modelling underestimates the observed dispersion in POT2 series, there is no systematic bias in the reproduction of the daily flood peak variability for particular flood response types and families. Therefore, the flood response type for a catchment is not related to flood history.

3.6 Variability in the key flood response patterns

3.6.1 Effect of temperature/potential evaporation scenario

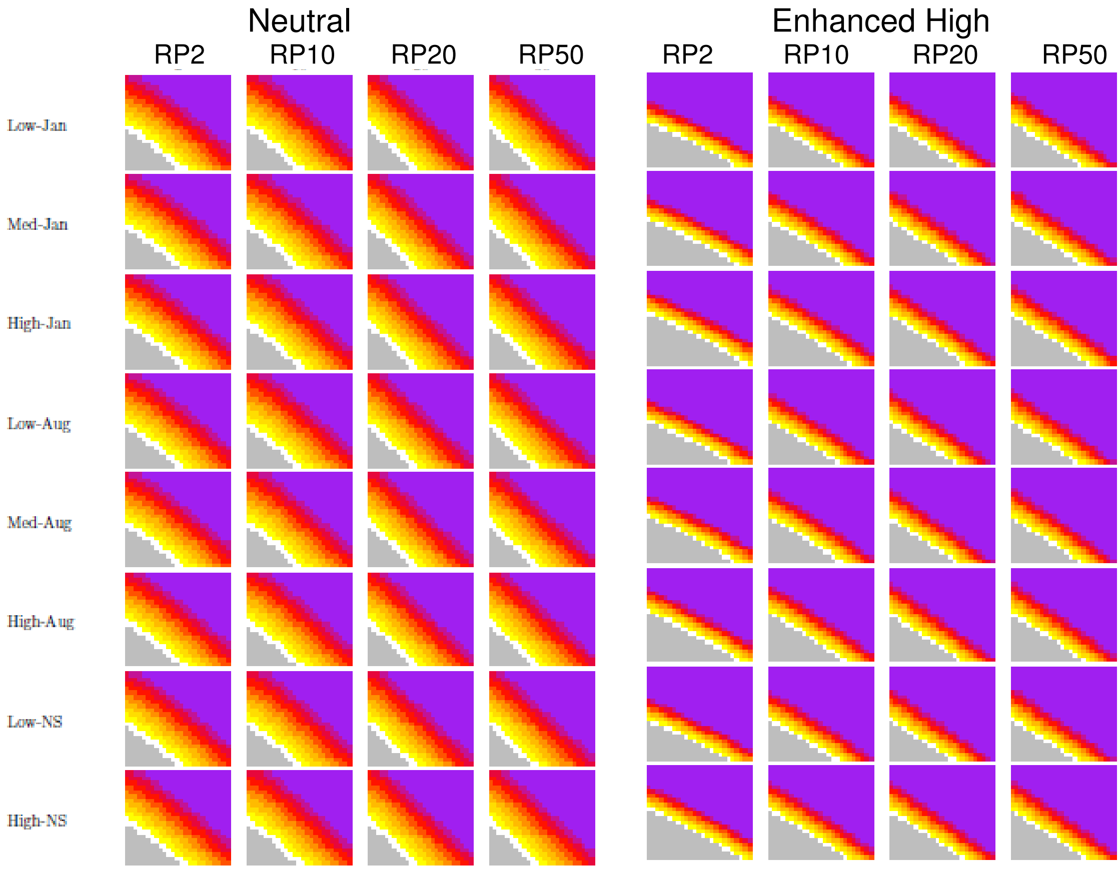

Figure 3.14 Flood response patterns for the eight T/PE ensemble members for Neutral (left) and Enhanced H (right) for the four flood indicators

Although the eight temperature/ potential evaporation (T/PE) ensemble members have been combined in each key flood response pattern, the differences in PE between them do have a small impact on the seasonal water balance. The degree to which the water balance is impacted depends on the relative values of precipitation and PE. Thus for the **Neutral** flood response type (Figure 3.14 left), there is little difference with phase and value of the temperature increase while for the **Enhanced High** flood response type (Figure

3.14 right), there is a noticeable difference with both phase and temperature change (e.g. size and shape of the grey, or purple, areas which represent the scenarios leading to a reduction, or increase of more than 90%, in the flood peak magnitude). The **Damped Extreme** pattern also shows a variation with change in temperature (not shown).

3.6.2 Group inter- and intra-variability

The flood response types identified for Britain synthesise in nine groups the range of changes in flood peak due to changes in the climate found for 154 catchments. It is however important to check that the groups used to define the flood response types (i.e. the composite flood response patterns made by the arithmetic mean of all flood response patterns from all catchments of the types and all T/PE scenarios) are homogeneous, i.e. that the spread in the type is not too large. One summary measure of this spread already discussed is the standard deviation of all the flood response patterns (see Section 3.4). Another way to assess the inter-group similarity (and variation) is the Taylor diagram (Taylor, 2000).

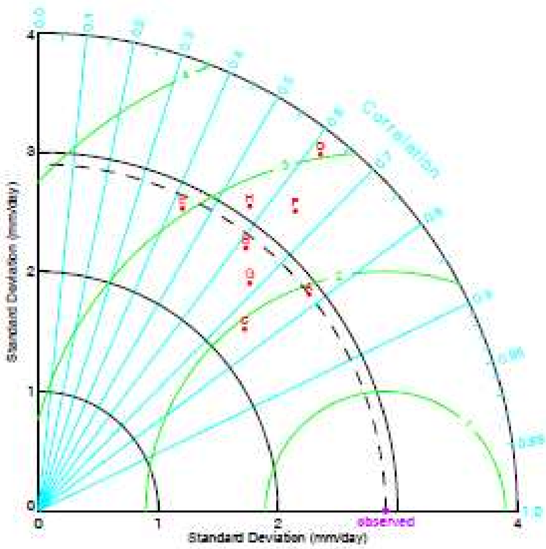

Figure 3.15 Sample Taylor diagram displaying a statistical comparison with observations of eight model estimates of the global pattern of annual mean precipitation (from Taylor, 2005)

In a Taylor diagram, the similarity between two patterns is quantified in terms of their correlation, their centred root-mean-square difference (dissimilarity) and the amplitude of their variation (represented by their standard deviation: is the pattern very uniform or not). Figure 3.15 shows an example for eight different series (here modelled precipitation), each series represented by a letter, compared with observation. The diagram is formed by a quarter circle, and points are located according to three criteria. For example for Model A:

- The standard deviation (i.e. how smooth the pattern is) defines Model A's distance from the centre of the circle (A's radius)
- The correlation of Model A's pattern with the observed pattern defines the angle between the x-axis and A's radius

- The centred root-mean-square distance defines the distance between Model A and the position of the observed pattern on the x-axis. Examples of similar distances are shown in green

The closer the points are to the observation/reference, the more similar their pattern is to the observed/reference pattern. The more distant the points are from the observation/reference, the less similar their pattern is to the observed/reference pattern. In the example of Figure 3.15, Model A is the closest to the observed pattern: largest correlation with Model C but same standard deviation as the observed pattern. At the opposite, Model E has the smallest correlation with the observed pattern despite a similar standard deviation: it is the model the least representative of the observations. Grey circles are drawn in the background of the Taylor diagrams to help the reader evaluate how similar/different a pattern is from the reference.

An alternative plot shows the standard deviation (y-axis) of each catchment flood response pattern against the correlation of each catchment flood response pattern with the composite flood response pattern representative for the nine flood response types (x-axis) (e.g. Figure 3.16, top right).

For both diagrams, the coloured dots represent the catchment flood response patterns and the reference dot has the plotting position of (1,1). There is one graph for each of the nine key flood response pattern taken in turn as reference. For both graphics, standard deviations are scaled according to the SD of the reference composite pattern: normalised SD is lower than 1 when the catchment flood response pattern is less variable than the reference composite pattern; and greater than 1 when the catchment flood response pattern is more variable that the reference composite pattern. For both graphics, single colour symbols (i.e. representative of all catchments belonging to the same flood response type) should be as close as possible to their composite pattern (e.g. for green dots, close to the reference point of the ‘Neutral’ graph). The spread of symbols with the same colour represents the internal variability of that group. The distance and spread of symbols of other colours away from the composite pattern represent the variability between the groups. It should be larger than the variability within groups (i.e. the symbols of different colours are generally further away from the reference composite pattern than the symbols of same colour).

Taylor diagrams were drawn for the nine groups for RP2 (Figure 3.16) and RP20 for the Medium Aug T/PE scenario (Figure 3.17). Each diagram contains 155 points and compares the catchments flood response pattern with the key flood response pattern for that group. The patterns of each catchment are represented by a symbol/colour representative of the flood response type associated with that catchment. The reference point is given by the key flood response pattern of the considered flood indicator for a given group: e.g. for Neutral and RP20, the reference pattern is Figure 3.14 left Medium Aug RP20.

Generally, the catchments associated with a key flood response pattern have flood response patterns similar to that key flood response pattern (points of same colour/symbol are close to the reference of the same colour/symbol). This is expected by construction as the key flood response pattern is computed as the arithmetic mean of all flood response patterns of associated catchments. However, the spread around the reference is small compared with the spread of all flood response patterns: *the internal group variability is much smaller than the external group variability*. This is an indication that the groups are homogeneous and each key flood response pattern is significantly different from another.

Damped flood response types (left hand side of Figure 3.16 and Figure 3.17, down triangles) are representative of the catchments with the least variability (down triangles towards the inner limit of the circle). As they dampen the climate change signal to flood, the variation in the changes in flood magnitude is small. At the opposite, **Enhanced** flood response types (right hand side of Figure 3.16 and Figure 3.17, up triangles) are characterised by larger internal variance in their pattern (up triangles towards the outer limit of the circle): changes in flood magnitude are large. The variability of **Mixed** and **Neutral** flood response types (yellow stars and green circles, respectively) is between that of **Damped** and **Enhanced** flood response types. As already discussed, the **Sensitive** flood response types (bottom right Figure 3.16 and Figure 3.17) show the largest internal pattern variability (the points have the largest standardized standard deviation), and the largest intra-group variability (the points are not all very close to the reference pattern).

The variability in the catchment flood responses is larger for low return periods (Figure 3.16) than for higher return periods (e.g. RP20 Figure 3.17), in particular for the **Enhanced High** and **Sensitive** flood responses (large up triangles). This means that it is not necessary to discriminate as many flood response types for high return periods as it is for low return periods, and few key flood response patterns are representative of the majority of the catchment responses.

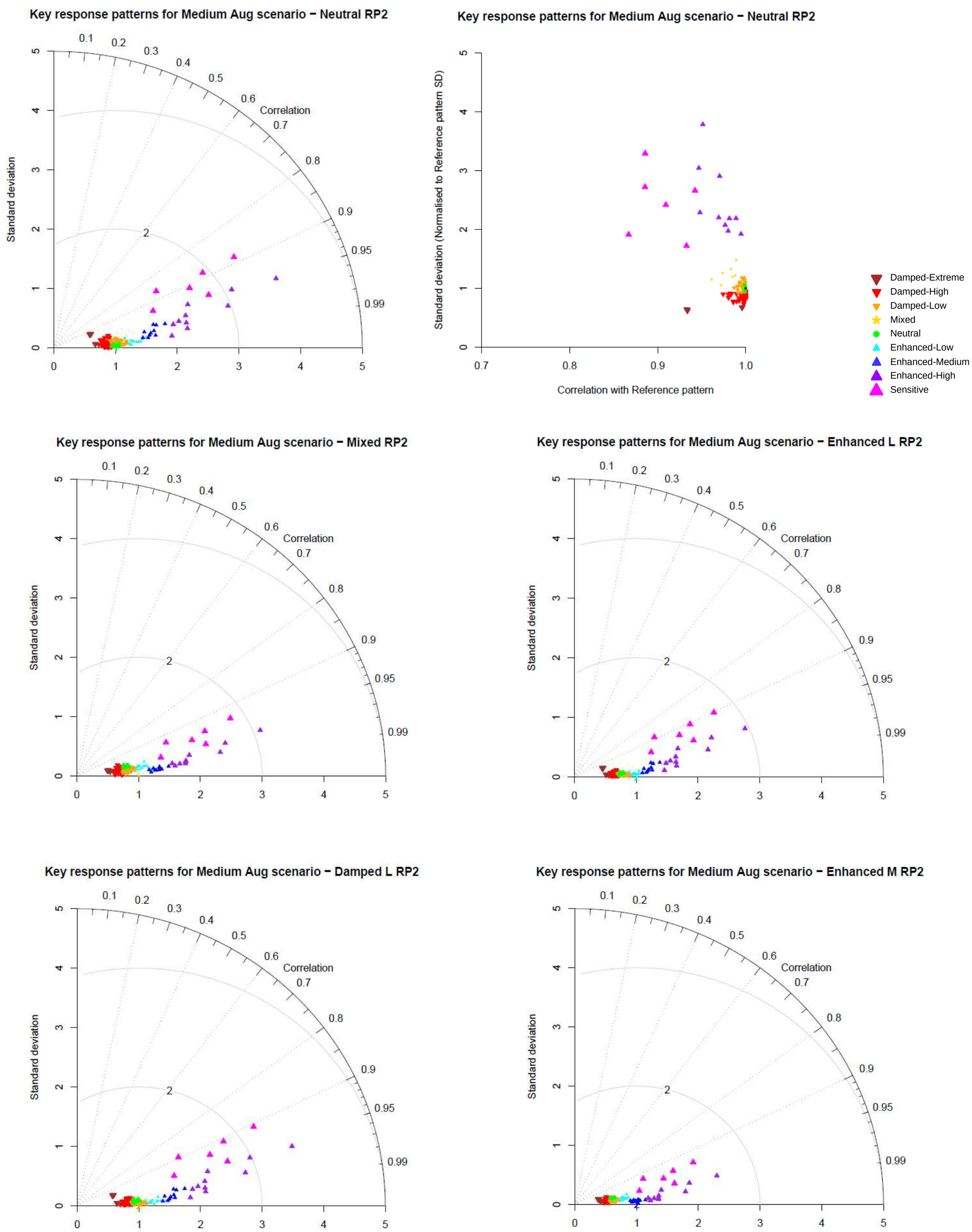

Figure 3.16 Taylor diagrams for all flood response patterns compared with each of the nine key flood response patterns for RP2 Medium Aug T/PE scenario. The reference key flood response pattern is given in the graph title. The top right diagram is an alternative plot for the neutral pattern

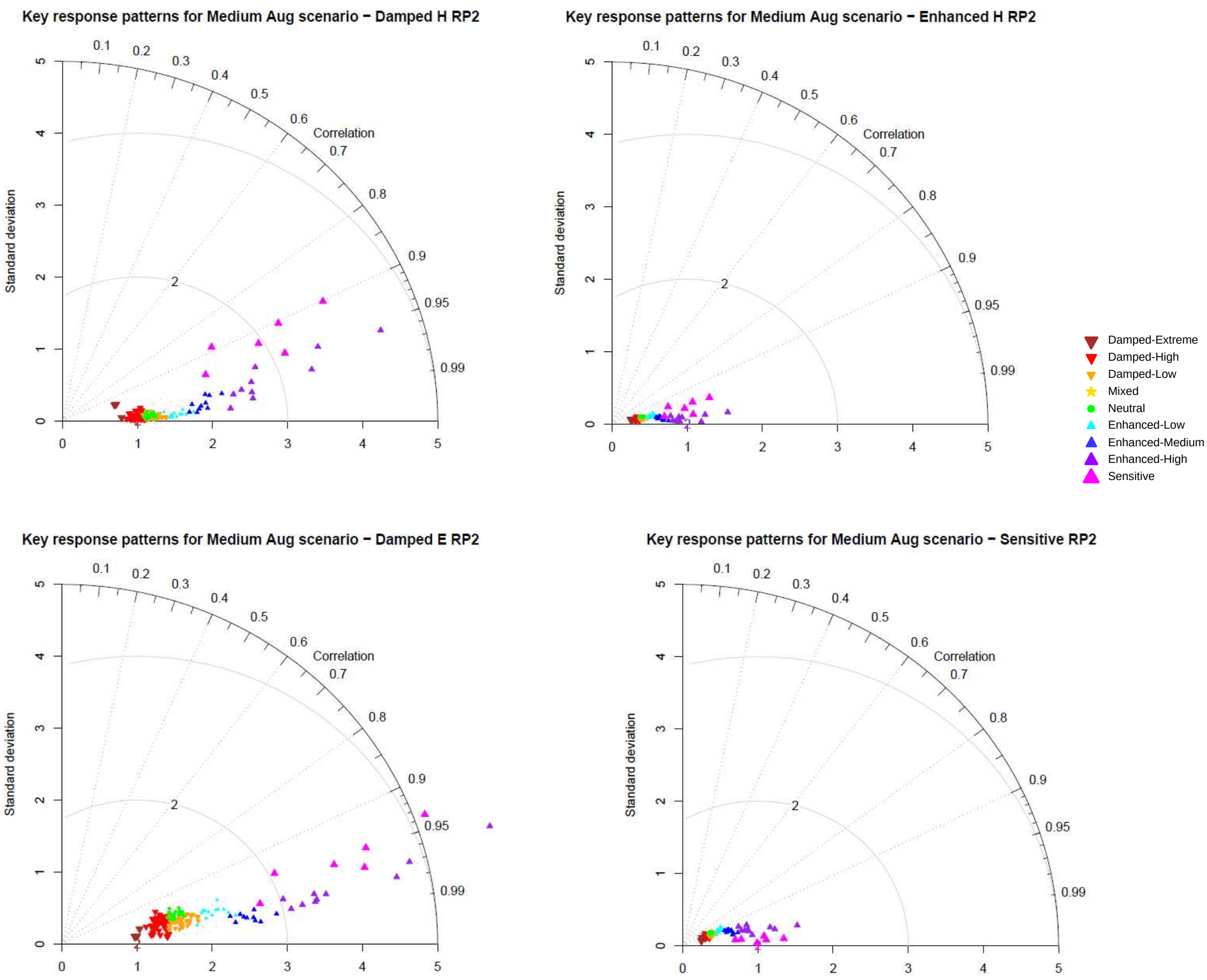

Figure 3.16 (continued)

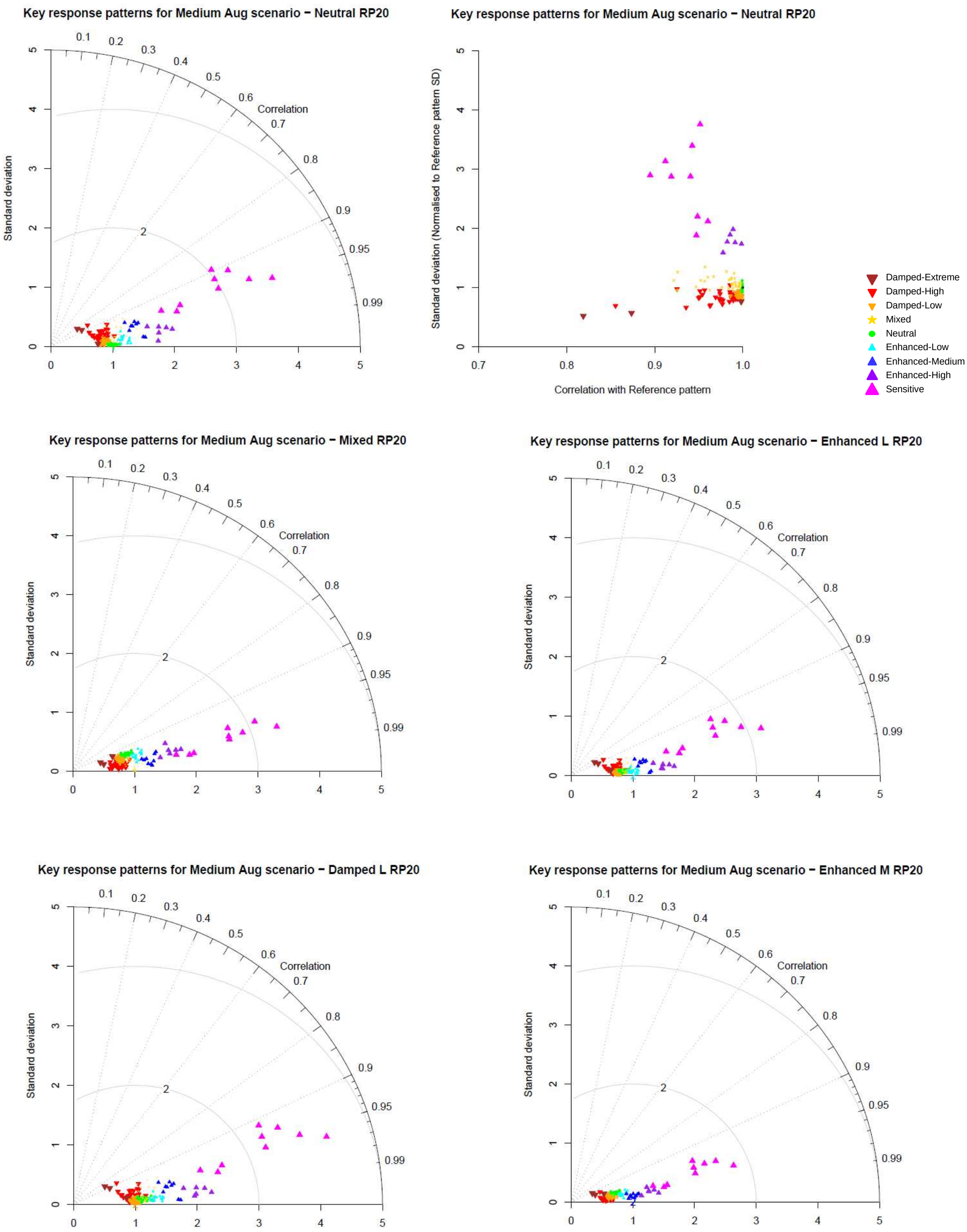

Figure 3.17 Taylor diagram of all flood response patterns compared with the nine key flood response patterns for RP20 Medium Aug T/PE scenario

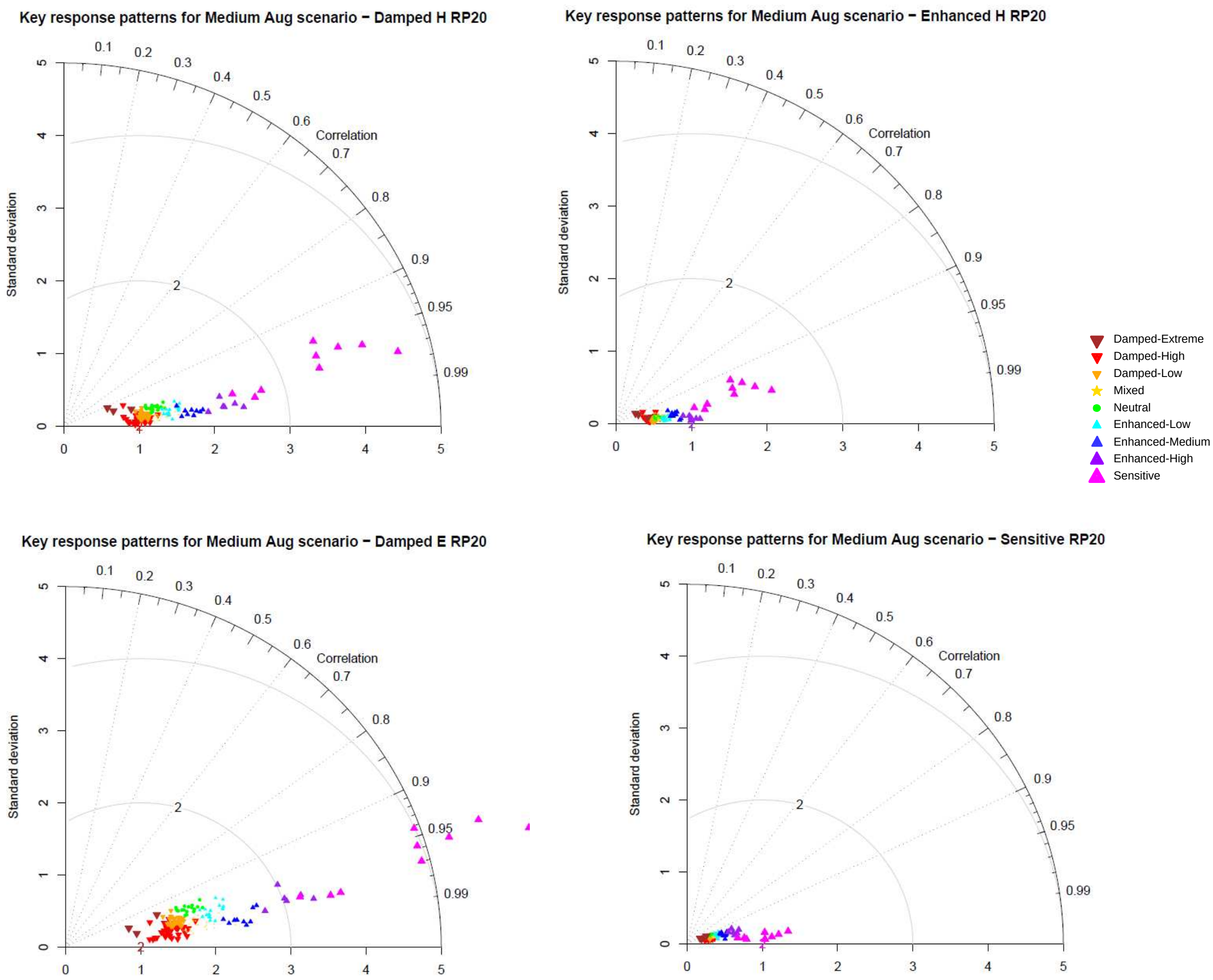

Figure 3.17 (continued)

3.6.3 Geographical location of flood response types

There is no particular geographical pattern in the location of the flood response types across Britain (Figure 3.18), but some important features emerge:

- Different flood response types can be associated with the same catchments for different flood indicators: the symbols in the maps show different geographical patterns
- There is no geographical region associated with only one flood response type: a characterisation of the flood response type cannot be done on a purely geographical basis
- **Damped** patterns (down triangles) are generally found in the west and in the north for low return period, but move eastward for RP20 and RP50
- The **Neutral** pattern (circles) is found in the west
- The **Mixed** pattern (stars) is found in most parts of Britain for RP2, while it is found mostly in south and East of England at RP50
- **Enhanced** patterns are generally found in the southern part of the country (and principally in England), but a few catchments in Wales and Scotland are also found at higher return period

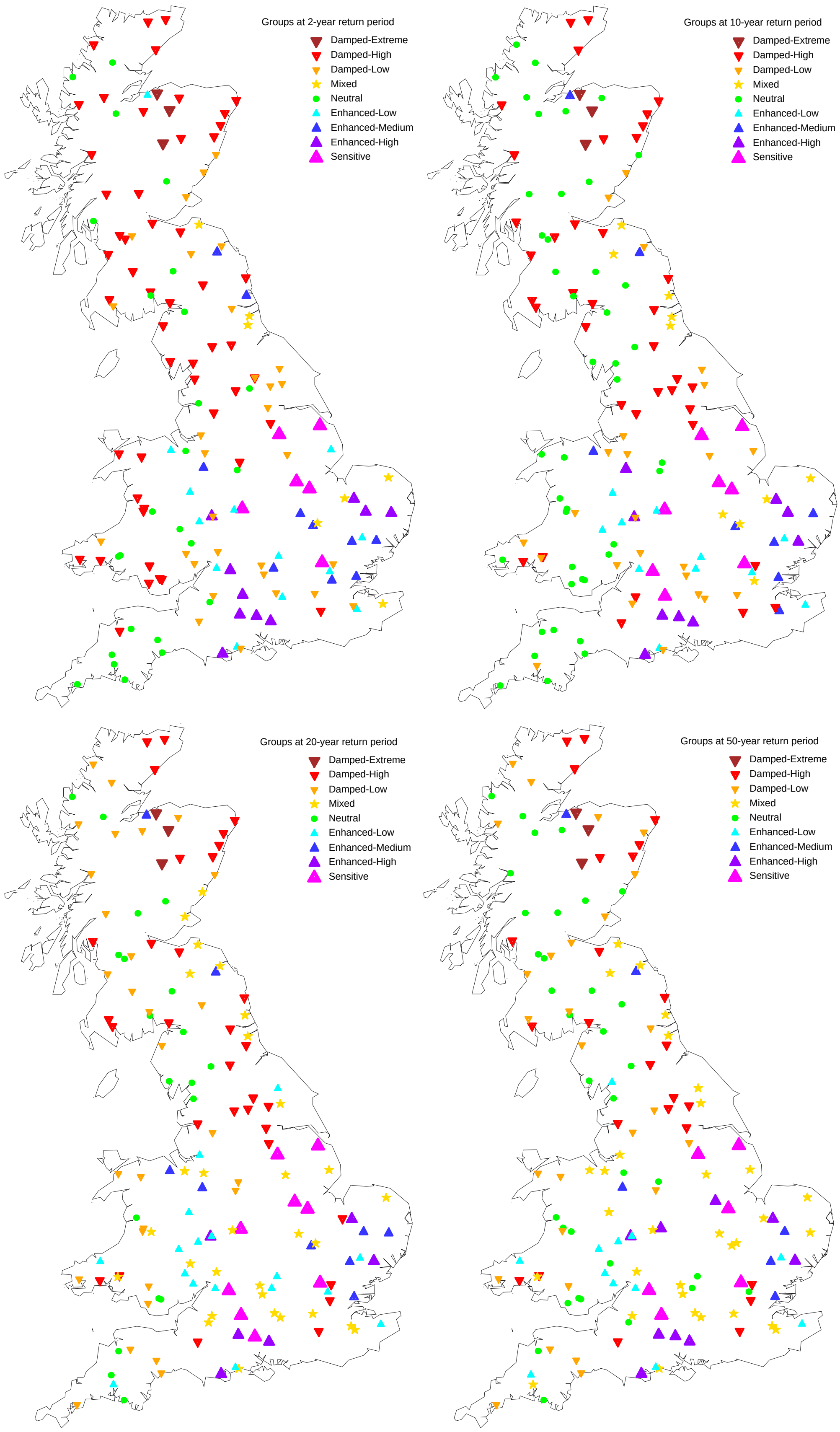

Figure 3.18 Flood response types associated with the 154 catchments for RP2, RP10, RP20 and RP50 (maximum rainfall change in January)

4. Conclusion

This project report describes the changes in flood peaks obtained for 154 catchments across Britain for 4,200 climate and temperature/potential evapotranspiration scenarios. From these results, nine flood response types were identified, which fully describe the range of responses in the flood regime to climate change in Britain for four indicators of change in flood frequency. These flood response types are scenario-neutral.

The next step in the project is the characterisation of the flood response types from catchment properties. This part of the regionalisation will enable any catchment in Britain to be associated with a flood response type and its response pattern of changes for a given flood indicator from a set of catchment properties, without undertaking the full sensitivity analysis of 4,200 scenarios. This is reported in a separate Milestone report (Prudhomme *et al.* 2009).

5. References

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