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Probabilistic impacts of climate change on flood frequency using response surfaces II: Scotland

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Abstract

This paper uses a sensitivity framework approach to look at the probabilistic impacts of climate change on 20-year return period flood peaks, by applying a set of typical response surfaces alongside the probabilistic UK Climate Projections (UKCP09) for 10 river-basin regions over Scotland. The first paper of the pair used the same approach for 10 river-basin regions over England and Wales. This paper develops the methodology for Scotland, by first enabling better estimation of the response type of Scottish catchments. Then, as for England and Wales, the potential range of impacts is shown for different types of catchment in each river-basin region in Scotland, and regional average impact ranges are estimated. Results show clear differences in impacts between catchments of different types and between regions. The Argyll and West Highland regions show the highest impacts, while the North-East Scotland region shows the lowest impacts. The overall ranges are generally smaller for Scotland than England and Wales.

Keywords

Response surfaces; climate change; floods; adaptation

1. Introduction

This paper is the second of a pair using a sensitivity framework approach to look at the probabilistic impacts of climate change on 20-year return period flood peaks in Britain. Part 1 (Kay et al. 2013a) focussed on England and Wales (E&W), while this part focuses on Scotland. The studies use the latest, state-of-the-art probabilistic UK Climate Projections (UKCP09; Murphy et al. 2009), which provide sets of 10,000 changes in a number of climate variables, for areas across the UK, for a number of time-horizons and emissions scenarios. For winter daily mean temperatures in Scotland, the projections for the 2080s under the Medium emissions scenario suggest a median (50th percentile) increase of about 2°C, with a 10th–90th percentile range of approximately 1–3°C. Summer temperature increases are slightly higher than those for winter, and increases over western Scotland are generally greater than for eastern or northern Scotland. For annual total precipitation the projections for the 2080s under Medium emissions suggest a median change near zero (10th–90th percentile range -7–6%), but with an increase in winter precipitation (median 16%; range 3–33%) and general decrease in summer precipitation (median -14%; range -31–1%), with some regional variation. The sensitivity framework approach involves overlaying climate projections on response surfaces defined on a sensitivity domain. In this way, the impacts of large numbers of projections can be rapidly estimated. For very large ensembles, such as the UKCP09 probabilistic projections, the ease of application using response surfaces is a great advantage.

The sensitivity framework method applied here is described briefly below; a fuller description is provided in Part 1. The method involves a sensitivity domain of changes in precipitation (P) and temperature (T), with a single-harmonic function used to represent the monthly patterns of change, to reduce dimensionality (Prudhomme et al. 2010). This domain was used to model 154 catchments across Britain (England, Wales and Scotland), from which nine typical response types were identified for changes in 2-, 10-, 20- and 50-year return period flood peaks (Prudhomme et al. 2013a). These response types were named Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive (shorthand DpE, DpH, DpL, Neu, Mix, EnL, EnM, EnH, Sen). They were represented by 2-dimensional composite (average) response surfaces (Figure 1), which illustrate percentage changes in flood peaks given changes in P quantified by the P harmonic mean (X_{mean}, y-axis) and P harmonic amplitude (A, x-axis). The response surfaces for Damped types show flood peak changes generally smaller than corresponding maximum P changes, while the Neutral response surface has flood peak changes similar to those for P, and Enhanced response surfaces show flood peak changes often larger than for P. The surfaces for Mixed and Sensitive types are more dependent on the specifics of the P changes.

The response types were characterised by deriving decision trees, which divide a sample (set of catchments) into categories (response types) using a set of binary rules (based on catchment properties) (Prudhomme et al. 2013b). The resulting decision trees enable estimation of a catchment's response type from its physical and climatic properties. This method enables easy application of a large number of climate change projections, for any catchment with the required catchment properties, by overlaying projections on an appropriate response surface. For more robust application to a large set of catchments across E&W, taken from the National River Flow Archive (NRFA; www.ceh.ac.uk/data/nrfa/), some minor modifications were made to the decision trees (Part 1 Section 2.2).

For application in Scotland it was decided to derive new decision trees, based on a subset of catchments, rather than simply apply the trees initially developed using 154 catchments across Britain and then modified for use with 1120 NRFA catchments in E&W. Of the 154 catchments originally modelled on the sensitivity domain, 45 are in Scotland (Crooks et al. 2009). These catchments are, on average, steeper, wetter, of higher altitude but lower permeability, less affected by urban development but more affected by reservoirs and lakes, than those in E&W (Bayliss 1999). In particular, catchment properties based on soils/geology play a major role in the decision trees for E&W, but Scotland is more homogeneous in this respect (Boorman et al. 1995). A related factor is that Scotland contains few Enhanced or Sensitive catchments, but such types are much more numerous in south/east England so the original trees may overly focus on them. Also, the original trees were developed after merging several response types; this merging may not be so generally applicable for Scotland. In addition, the Damped-Extreme type was not characterised by the original trees, as there were only three such catchments in the modelled set, but these are all in Scotland so more consideration is given to them here.

This paper thus

a. Develops the response type estimation method of Prudhomme et al. (2013b), to allow robust application to a large set of catchments across Scotland.
b. Overlays the UKCP09 projections on the composite response surfaces of Prudhomme et al. (2013a), to estimate the impacts (percentage changes in flood peaks) for each response type in regions across Scotland.
c. Combines a and b above, to produce weighted regional impacts.

The derivation of new decision trees for Scotland is described in Section 2, and the impact assessment method is described in Section 3, with results in Section 4 and discussion and conclusions in Section 5. Although the results presented here focus on 20-year return period flood peaks (RP20), discussion is added for other return periods where appropriate; see Kay et al. (2011b) for full details.

2. Decision trees for Scotland

2.1 Catchments and catchment properties

From the original set of 154 catchments, the 45 catchments in Scotland are used to develop decision trees specific to Scotland, along with 12 catchments in northern England (to increase the sample size with similar catchments). Note that, of these 57 catchments, there are none with Enhanced-Low, Enhanced-High or Sensitive response types, and only two Enhanced-Medium and three Damped-Extreme (Supplementary Section 1.1).

As in Prudhomme et al. (2013b), catchment property data from the Flood Estimation Handbook (FEH; Bayliss 1999) and the NRFA (Marsh and Hannaford 2008) were used, along with the simulated response types of the 57 modelled catchments in Scotland and northern England, to characterise response types via decision trees. In addition, a new set of catchment properties was used, based on the seasonal occurrence of daily rainfall with the potential to generate a medium to high flood event. The threshold for this rainfall was taken as 20mm, with seasonal threshold-rainfall proportions calculated as the total rainfall on days when the threshold was exceeded in each season divided by the total of such rainfall over the complete time period. The standard four 3-month seasons were used, with rainfall for 1961–1990. Table 1 describes all the catchment properties used for decision tree development.

2.2 Decision tree development

A decision tree aims to divide the elements of the original sample (57 catchments) into sub-samples of the same category (response type), using properties of each element (catchment properties). However, full discrimination is rarely possible or desirable (due to over-fitting to the sample), so each path of a tree is associated with a probability for each response type. Decision trees thus enable the use of catchment properties to assign an estimate of the response type (generally that with the highest probability for the appropriate path) to a catchment. The R freeware package 'tree' was used to develop the decision trees, as for E&W (Prudhomme et al. 2013b).

The following points were considered when analysing decision trees:

- A comparatively small sample size for the range and combination of catchment properties over Scotland.
- Not all of the nine response types found for Britain occur in Scotland.
- The decision tree method will not split very small sets, so not all response types can be differentiated without manual input, even if there is a good discriminator.
- There may be several causes for the same response type.
- Only one modelled catchment has a high percentage of highly permeable bedrock.
- The impact of snowmelt on the runoff regime is much greater in Scotland than for Britain as a whole (Supplementary Section 1.2).

Initial tests showed that tree performance improved when the seasonal threshold-rainfall proportions were included. However, the tree structure and the properties used indicated paths for which it might be appropriate to reclassify the response types of some catchments (rather than the complete merging of Damped and Neutral types used in Prudhomme et al 2013b), so this option was investigated. The objective of reclassification is to avoid underestimating the change in flood peaks due to chance seasonal occurrence of baseline events. Catchments with Damped-Extreme and Enhanced response types were also investigated, to determine whether these should be retained or reclassified. These investigations (Supplementary Section 1.3) led to 19 catchments being reclassified to Neutral; 10 from Damped-Low, 8 from Damped-High, 1 from Damped-Extreme. It was decided that the other two Damped-Extreme catchments should retain their classification and be specifically included in the decision trees However, it was decided that Enhanced response types could not be specifically included in the decision trees as the two such catchments in the modelled set for Scotland (both Enhanced-Medium) appear to have different causative factors (Supplementary Section 1.3).

The reclassification of some Damped catchments gave improved performance in the resulting decision trees. Some manual adjustments were then made to the trees to enable characterisation of the Damped-Extreme response type, improve compatibility between decision trees for different return periods (2-, 10-, 20- and 50-years), and use catchment properties and threshold values likely to be robust for use with the larger sample of NRFA catchments in Scotland (as done in Part 1 for E&W).

2.3 Final decision tree for Scotland

The final decision tree for estimating the response type for RP20 changes (Figure 2) uses six catchment properties, all related to rainfall – seasonality (winR, sumR, autR/winR), intensity (RMED), catchment wetness (PROPWET) and water balance (MAL) (see Table 1 for definitions). Table 2 shows the probability of each response type for each path. Most paths are not associated with a highest probability of 1 but do have a highest probability greater than 0.5; the exception being path 1. A measure of confidence (High H, Medium M or Low L) is also given for each path, defined as in Prudhomme et al. (2013b). The relatively small sample size results in some uncertainty in designation of response type for some paths, especially Path 1. A contingency table (Supplementary Section 1.4) summarises performance of the RP20 decision tree by comparing the simulated and estimated (highest probability) response type for the 57 catchments. This shows that 49 catchments (86%) were correctly classified, with just four catchments with an over-estimated response type and four under-estimated. The two Enhanced-Medium catchments have an estimated type of Mixed, contributing to under-estimation. The other two under-estimated catchments are Mixed estimated as Damped-Low.

The decision tree (Figure 2) shows that:

- The Neutral response type is on the top-branch of the first split (wetter catchments).
- The Mixed response type (including Enhanced) is on the bottom-branch of the first split (drier catchments) and has high losses (MAL). This combination of properties, with a balance between input of rainfall and output through losses which is easily changed from a net loss to a net surplus (or vice versa), is what contributes to the increased chance of the percentage change in flood peak being greater than that of the change in rainfall.
- The Damped-Extreme response type has wetter soils (higher PROPWET), probably contributed to by a high proportion of summer threshold-rainfall (sumR) and a high ratio of autumn to winter threshold-rainfall (autR/winR).

The decision trees derived for changes in 2-, 10- and 50-year return period flood peaks (Kay et al. 2011b) confirm the above for RP20 changes. They also show that the catchment property used most prominently is PROPWET (proportion of time soils are wet): dry soils are likely to inhibit flood formation, while saturated soil conditions precede many large flood events (Marsh and Hannaford 2008). Also, the property used for the first split in the decision trees reflects a shift in emphasis according to flood severity; from importance of catchment wetness (PROPWET) for generation of comparatively common flood events (2-year return period), through overall availability of rainfall (standard average annual rainfall, SAAR) for medium frequency floods (10-year return period), to likelihood of threshold-rainfall occurring in the winter (winR) for more extreme floods (20- and 50-year return period).

3. Impact assessment method

3.1 Use of UKCP09 projections

As in Part 1, the UKCP09 river-basin region Sampled Data are applied. For each region, the data consist of 10,000 sets of changes in a number of climate variables. There are 10 river-basin regions covering Scotland: Orkney and Shetland, North Highland, West Highland, North-East Scotland, Argyll, Tay, Clyde, Forth, Solway, Tweed (Figure 4 top-left). The latter two regions cover small parts of England but are mainly in Scotland. Most of the results here are for the 2080s (2070-2099) time-horizon under Medium emissions (equivalent to A1B, IPCC 2000), but a comparison of impact ranges for alternative time-horizons and emissions is presented later.

To overlay the UKCP09 projections for a river-basin region onto a composite response surface, a single harmonic function (Part 1 Section 2.1) is fitted to each of the 10,000 sets of monthly P changes. Two harmonic parameters (mean and amplitude) determine the position of each projection on the sensitivity domain. Plots of P harmonic mean versus amplitude, for each river-basin region, show that the distribution of the projections on the domain differs between regions, in terms of the ranges, medians and correlations (Figure 3). In contrast to E&W (Part 1 Section 2.3), where only four of the 10 regions showed positive correlations between the P harmonic mean and amplitude, all 10 regions in Scotland have positive correlations (Pearson's r). Some of these correlations are high (>0.5), whilst some are low (<0.08); Orkney and Shetland (+0.69), West Highland (+0.56), Argyll (+0.50), Solway (+0.25), North Highland (+0.25), Forth (+0.23), Tweed (+0.18), Clyde (+0.08), North-East Scotland (+0.07), Tay (+0.07). The first six of these regions have correlations greater than the highest for E&W (North-West England, +0.21). These positive correlations between P harmonic parameters are important because response surfaces change fastest when the P harmonic mean increases with the P harmonic amplitude (i.e. from bottom-left to top-right of the sensitivity domain, Figure 1 top-row), so a region with a positive correlation would have a greater impact range than one with a negative correlation (given the same parameter ranges and medians). [See Supplementary Section 2 for a discussion of the appropriateness of the sensitivity domain simplifications for the UKCP09 projections for Scotland.]

3.2 Uncertainty

As explained in Part 1 Section 2.4, there are two main additional sources of uncertainty to consider when using composite response surfaces to estimate impacts (compared to performing a standard top-down impact assessment). The first, due to representation of a catchment response surface by a composite surface, can be quantified through use of corresponding standard deviation (sd) surfaces (Figure 1 bottom-row). The second, due to the assumptions and simplifications necessary for the development of the sensitivity framework approach, was assessed in Kay et al. (2013b) and shown to lead to some bias in the impacts extracted from response surfaces. The size of this bias varied with response type, in a way which was considered compatible with physical differences between response types. As for Part 1, the results presented by Kay et al. (2013b), and similar (unpublished) work for more catchments, were used to derive values for the correction of mean bias in the sets of impacts extracted from response surfaces, for the five response types characterised by the decision tree: Damped-Extreme 11%; Damped-High 12%; Damped-Low 7%; Neutral 3%; Mixed 11%.

4. Results

4.1 Response-type estimation for NRFA catchments

The decision tree (Figure 2) is used to estimate the response type for 349 NRFA catchments in the 10 river-basin regions over Scotland. These are summarised in Figure 4. Although Neutral is the predominant response type overall, it appears that some areas of Scotland have greater homogeneity of response types than other areas. While catchments with a Neutral response type dominate in more westerly or central regions of Scotland (due to the wetter climate there), catchments in more easterly regions can be of any type (due to the drier climate and greater variability of other catchment properties). Catchments with a Mixed response type are generally located nearer the east coast, particularly around the Firth of Forth.

4.2 Response-type impacts

As described in Section 3.1, the UKCP09 projections for each river-basin region (Figure 3) are overlaid on the composite response surfaces for each response type (Figure 1 top-row). An estimate of the impact of each projection is then taken from that of the nearest point of the sensitivity domain. The 10,000 projections per region thus become 10,000 impacts per response type per region, plotted as box-plots in Figure 5. As for E&W (Part 1 Figure 5), the plots for Scottish river-basin regions clearly show the differences between the response types. In contrast to the results for E&W, those for Scotland show a clear north/west to south/east split, with impact ranges being wider, with higher medians, in the former regions (e.g. Orkney and Shetland, West Highland and Argyll) and the ranges being narrower, with lower medians, in the latter regions (e.g. Tweed, Forth and Tay). These differences in impact ranges and medians are due to the higher P harmonic mean of the 10,000 projections, and the higher positive correlation between P harmonic mean and amplitude, for regions in the north and west compared to those in the south and east (Figure 3).

4.3 Weighted regional impacts

As for E&W (Part 1 Section 3.3), the numbers of NRFA catchments of each response type in each region in Scotland (Figure 4) are used to weight the response-type impact ranges (Section 4.2), to produce regional average impact ranges (right-most box-plots in Figure 5). These could be considered to represent a central-estimate of the average impact range for a catchment in the region, taking account of the range of the UKCP09 projections for the region and the range of response types in the region.

Figure 6 compares the regional average impact ranges for each region after the bias correction values have been added for each response type (Section 3.2). These give a more robust central-estimate of the impact range (allowing for bias due to the assumptions necessary to implement the sensitivity approach). The regional average impact ranges show that the river-basin regions with the highest impacts are Argyll and West Highland, with a median RP20 change of about 35%. These regions also have by far the largest 10^{th}-90^{th} percentile impact ranges (about 17%-63% and 15%-60% respectively). The region with the lowest impacts is North-East Scotland, with a median RP20 change of about 15%. This region also has the smallest 10^{th}-90^{th} percentile range (about 6%-28%). The Tweed region also has a relatively low median change (about 19%); North-East Scotland and Tweed are the only two regions to have a median change of less than 20%, although the Tay region has a median impact of only just over 20%. The other five regions have similar median impacts to each other, between about 24% and 29%, and similar impact ranges.

Also shown in Figure 6 are the alternative ranges when ±2sd is added to the central-estimate impact for each projection. This allows for the uncertainty from using composite response surfaces to represent what is actually a range of possible catchment responses classified as the same response type (Section 3.2). Some regions have a larger range of uncertainty from this source (e.g. Orkney and Shetland) than other regions (e.g. West Highland and Argyll). The variation in the size of the sd uncertainty is much less pronounced for Scotland than it is for E&W, since there are no Enhanced or Sensitive catchments identified in Scotland; these response types have greater sd ranges than other types (Figure 1 bottom-row).

As for E&W, the regional differences in the median impact and in the range of uncertainty are a result of both spatial differences in the UKCP09 projections (Figure 3) and a differing regional balance between the number of NRFA catchments of each type (Figure 4), given the differences between the composite response surfaces (and sd surfaces) of each type (Figure 1). For example, the Argyll and West Highland regions have the greatest range of P harmonic amplitudes, the highest median P harmonic amplitude and a high positive correlation between P harmonic mean and amplitude (Figure 3), thus have the highest median impact and the largest range of uncertainty from the 10,000 UKCP09 scenarios (Figure 6). However, they have the smallest range of uncertainty from the sd ranges, as they only contain Neutral catchments (Figure 4); Neutral and Damped-Low types have lower sd ranges than other types (Figure 1 bottom-row). The North-East Scotland region has the smallest range of P harmonic amplitudes, the lowest median P harmonic amplitude and a low positive correlation between P harmonic mean and amplitude (Figure 3), thus has the lowest median impact and the smallest range of uncertainty from the 10,000 UKCP09 scenarios (Figure 6). However, North-East Scotland does not have either the smallest or largest range of uncertainty from the sd ranges, as its catchments are a mixture of types with low sd and types with higher sd (Figure 4 and Figure 1 bottom-row). The Orkney and Shetland region has the largest range of uncertainty from the sd ranges but, as it only contains one NRFA catchment for which the type could be estimated, this result may not be robust.

4.4 Regional impacts for alternative UKCP09 projections

So far, only the projections for the 2080s under Medium emissions have been used. Here, as for E&W (Part 1 Section 3.4), comparisons are presented using Medium emissions for three time-horizons (2020s; 2050s; 2080s), and for three emissions scenarios (Low - B1; Medium - A1B; High - A1F1) for the 2080s time-horizon. The comparisons are again presented as maps (Figure 7) showing the range of impacts in each region, with the lower end represented by the 25th percentile selected from the central-estimate -2sd; the middle represented by the 50th percentile selected from the central-estimate; the upper end represented by the 75th percentile selected from the central-estimate +2sd. Many of the maps highlight the west to east split, with higher impacts in westerly regions than easterly ones. As for E&W, the first three rows of maps show the increase in impacts with time-horizon (from 2020s to 2080s under Medium emissions), and the last two rows show impacts under High emissions greater than for Low emissions. Again, the impacts under Low emissions for the 2080s (row 4) are very similar to those under Medium emissions for the 2050s (row 2).

Comparing the maps in Figure 7 with the maps for regions in E&W (Part 1 Figure 7), the overall range of impacts in Scotland is narrower than in E&W. That is, none of the Scottish regions have impacts less than -5% or greater than +75%, which are possible in more southerly regions of E&W. Also, for England, regions to the south and east generally have the greatest impacts, whereas for Scotland regions to the north and west generally have the greatest impacts; there is not a monotonic change in impacts across Britain.

5. Discussion and conclusions

Previous work developed a sensitivity framework approach to estimate the impacts of climate change on flood peaks in Britain (Prudhomme et al. 2010, 2013a,b), including decision trees to estimate the response type of un-modelled catchments in England and Wales (Kay et al. 2011a, Kay et al. 2013a). Due to relatively common differences between catchments in Scotland and those in the rest of Britain, particularly the greater homogeneity of physical catchment properties in Scotland compared to England, new decision trees have been developed here and used to estimate the response type of 349 NRFA catchments in regions across Scotland. The new decision trees enable better discrimination of Damped response types; Scotland has predominantly Damped and Neutral types and very few catchments with Enhanced types. The probabilistic UKCP09 projections for 10 river-basin regions across Scotland have been used to produce probabilistic response-type impact ranges for 20-year return period flood peaks, by over-laying the projections on the composite response surfaces of each type. This information has then been combined to estimate regional impact ranges for each region, by weighting the response-type impact ranges with the number of catchments of each type.

As for E&W, the results show that different regions have quite different impacts, in terms of medians and uncertainty ranges: north and west Scotland have greater median impacts, and wider impact ranges, than areas of Scotland to the south and east. These regional differences are again due to both spatial differences in the distribution of UKCP09 projections on the sensitivity domain and a differing regional balance between the numbers of NRFA catchments of each response type. However, these regional differences in the impacts of climate change on flood peaks do not provide the full picture, as flood risk is a combination of both the probability of occurrence and the consequences of a flood. Although the probability of larger increases in flood peaks is greater in the north-west, the consequences of flooding may be greater in the south-east due to the population distribution in Scotland, and so the change in flood risk may actually be larger in the south-east. The regional results presented here have been used to support adaptation for climate change in Scotland, through the development of flood maps incorporating appropriate regional climate change allowances (Wang et al. 2013).

The numbers of NRFA catchments of each type may not be truly representative of the distribution of the response types within each region. Decision trees developed here enable estimation of the response type of any catchment in Scotland with the required catchment properties, but (as for E&W) one of the properties required is not available for ungauged catchments (Mean Annual Loss - MAL). Future work will hopefully allow replacement of MAL with alternatives that can be estimated for any catchment in Britain, which would be particularly useful for the Scottish regions with very few NRFA catchments (Orkney and Shetland and West Highland; Figure 4). Also, the decision trees developed for Scotland made use of a new set of catchment properties, based on seasonal rainfall above a threshold, which were not available during development of the original trees used for E&W (Prudhomme et al. 2013b). It would be interesting to revisit that work to see if inclusion of these rainfall properties improves those trees. However, for Scotland as for E&W, the potential limitations of the methodology for certain types of catchment should be borne in mind, particularly for catchments with a high attenuation of flows due to reservoirs and lakes as such catchments are more common in Scotland.

The decision trees developed for Scotland, unlike those used for E&W, do not allow identification of Enhanced or Sensitive catchments, as there are only two Enhanced catchments in the subset used for Scotland and these appear to have different causative factors. Such catchments are likely to be estimated as having a Mixed response type by the trees, resulting in a potential under-estimation of their impacts. Further modelling is required to determine catchment properties to distinguish Enhanced response types in Scotland. In contrast, the decision trees developed for Scotland, unlike those used for E&W, do allow identification of Damped-Extreme catchments. The composite response surface for the Damped-Extreme response type has a much lower impact of change than even that for Damped-High (Figure 1 top-row). This difference is characterised predominantly by the lack of baseline rainfall events exceeding 20mm in winter, and the occurrence of such events in both summer and autumn, in Damped-Extreme catchments. However, the response surfaces are based on the use of the delta change downscaling (Prudhomme et al. 2013a), and a premise of this method is that seasonal extremes change in a similar way to seasonal means. The extent to which this may or may not be appropriate for Damped-Extreme catchments is unclear (and the reliability of changes in extreme precipitation projected by climate models is generally lower than that for mean changes, Kjellstrom et al. 2010). Therefore, it may be advisable to consider a more precautionary response type (e.g. Damped-High) for catchments where the best-estimate of the response type is Damped-Extreme; there are only 9 such catchments out of the 349 NRFA catchments in the 10 river-basin regions over Scotland (Figure 4).

As for E&W, the impact for larger catchments may be greater than suggested by the results presented here, as the uncertainty bias correction values applied (Section 3.2) may need to be increased for larger catchments (Kay et al. 2013b). However, only 8 of the 349 NRFA catchments in the 10 river-basin regions over Scotland have a catchment area greater than 2,000km^2.

The typical response surfaces used here are those averaged over the eight temperature (and corresponding potential evaporation) scenarios of the sensitivity domain; any differences in response surfaces between temperature scenarios are accounted for within the standard deviation surfaces, along with variation between catchments of the same response type. While most catchments show relatively little difference between their modelled response surfaces for different temperature scenarios, a small number of high-altitude catchments show more obvious differences which appear to be related to the effect of temperature changes on snow (Supplementary Section 1.3). The decision trees derived here do not include properties, like altitude, that might distinguish such catchments, so their estimated response type is likely to be Neutral (i.e. such catchments are generally also wetter, Figure 2). This may over-estimate the impacts for minimal winter temperature increases, as the Neutral response type is more likely to apply to higher temperature increases. One such catchment is the Dee at Mar Lodge, for which Kay and Crooks (2013) show minimal changes in daily mean peak flows but much more significant changes in 30-day mean peak flows, using a transient climate change run for 1950-2099. If a sensitivity-type approach is applied to investigate potential changes in longer duration flows, or flows in more continental climates, then the effects of changes in snowfall, accumulation and melt, and thus the influence of catchment properties like altitude related to them, are likely to be more important than here (e.g. Köplin et al. 2012, Weiß and Alcamo 2011, Wetterhall et al. 2011).

A number of reasons why the results using UKCP09 Sampled Data and response surfaces may under-estimate the full range of impacts were discussed in Part 1. This includes use of the Sampled Data change factors applied to fixed observed baseline time-series, rather than using time-series directly (e.g. from a weather generator), and hydrological model uncertainty. Although the UKCP09 projections were designed to cover a wide range of uncertainty (from climate modelling and natural variability), any new projections may be quite different, as knowledge and understanding of the climate system improves. The sensitivity framework method applied here provides a quick way of assessing new projections for the scale of any differences.

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Tables

Table 1 Catchment properties used in decision tree development for Scotland.

Property name	Units	Source	Description
EAST	m	FEH	Easting of catchment outlet (GB national grid reference)
NORTH	m	FEH	Northing of catchment outlet (GB national grid reference)
AREA	km^2	FEH	Catchment drainage area
ALTBAR	m	FEH	Mean catchment altitude
ASPBAR	°	FEH	Mean aspect of catchment slopes
ASPVAR	-	FEH	Index describing the degree of alignment of drainage paths
BFIHOST	-	FEH	Base flow index derived using HOST*
DPLBAR		FEH	Mean drainage path length
DPSBAR	m/km	FEH	Mean drainage path slope
FARL	-	FEH	Index of flood attenuation due to reservoirs and lakes
LDP	km	FEH	Longest drainage path length
PROPWET	-	FEH	Proportion of time soils are wet
RMED	mm	FEH	Median annual maximum daily rainfall
SAAR	mm	FEH	Standard average annual rainfall, 1961-90
SMDBAR	mm	FEH	Mean soil moisture deficit defined by MORECS**, 1961-90
SPRHOST	%	FEH	Standard percentage runoff derived using HOST*
$URBEXT_{1990}$	-	FEH	Index of urban/suburban extent
FPEXT	-	FEH	Proportion of the catchment estimated to be inundated by a 100-year flood
FPLOC	-	FEH	Index of location of floodplains relative to the catchment outlet, for a 100-year flood
FPDBAR	cm	FEH	Index of volume of water stored on floodplains for a 100-year flood (standardised by catchment area)
MARU	mm	NRFA	Mean Annual Runoff; depth of water over the catchment equivalent to the mean annual flow
MAL	mm	NRFA	Mean Annual Loss; difference between mean annual rainfall and mean annual runoff for a catchment
BHP	%	NRFA	Percentage of the catchment underlain by rock formations of high permeability
BMP	%	NRFA	Percentage of the catchment underlain by rock formations of moderate permeability
BVLP	%	NRFA	Percentage of the catchment underlain by rock formations of low permeability
ALTMIN	m	NRFA	Minimum catchment altitude (i.e. gauging station altitude)
ALTMED	m	NRFA	Median catchment altitude
ALTMAX	m	NRFA	Maximum catchment altitude
ALTDIFF	m	NRFA	ALTMAX – ALTMIN
sprR	-	Rainfall data	Proportion of rainfall (1961-90) where the daily rainfall total is above 20mm, for spring (March-May)
sumR	-	As sprR	As sprR but for summer (June-August)
autR	-	As sprR	As sprR but for autumn (September-November)
winR	-	As sprR	As sprR but for winter (December-February)
autR/winR	-	As sprR	Ratio of the above proportions of autumn and winter rainfall

*HOST: Hydrology Of Soil Types classification (Boorman *et al.* 1995)
**MORECS: Met Office Rainfall and Evaporation Calculation System (Thompson *et al.* 1982)

Table 2 Probability of each response type for each path of the decision tree for RP20 changes (Figure 2), with the best-estimate of the response type of each path (highest probability) and its associated confidence level (H – High, M – Medium, L – Low). Note the three equal probabilities (DpH, DpL and Mix) for Path number 1; DpL has been chosen to represent the best-estimate for this path.

Path #	Flood response type of path	Confidene level	Probability of response type						Size of leaf (number of elements from sample)
			DpE	DpH	DpL	Neu	Mix	EnM	
1	DpL	L	0	**0.33**	**0.33**	0	**0.33**	0	6
2	Mix	H	0	0.11	0	0	**0.67**	0.22	9
3	DpH	H	0	**1**	0	0	0	0	5
4	DpL	H	0	0	**1**	0	0	0	4
5	DpE	M	**1**	0	0	0	0	0	2
6	Neu	H	0	0.1	0.03	**0.87**	0	0	31
Original category size			2	11	7	27	8	2	57

Figures

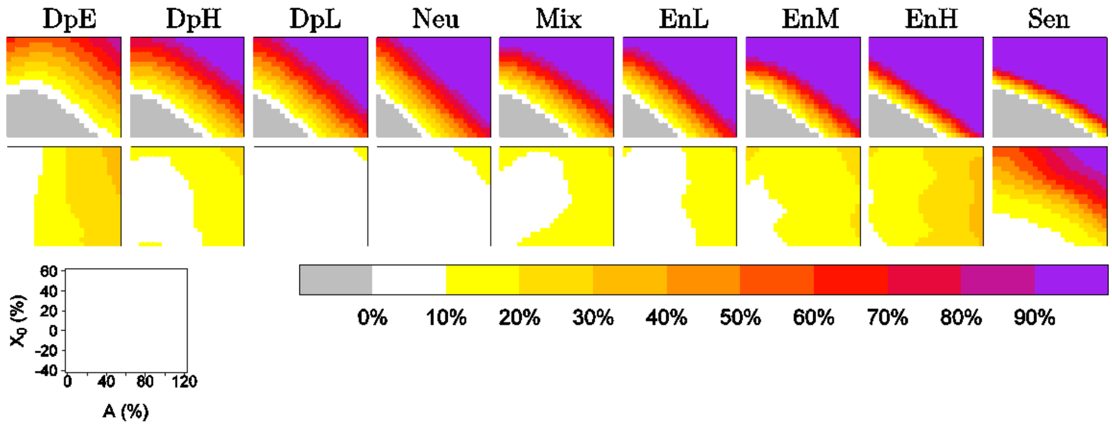


Figure 1 Composite response surfaces (top-row) and standard deviation surfaces (bottom-row) on the P sensitivity domain, for each response type, for percentage changes in 20-year return period flood peaks (see colour key, bottom-right). The P sensitivity domain axes are shown in the bottom-left diagram.

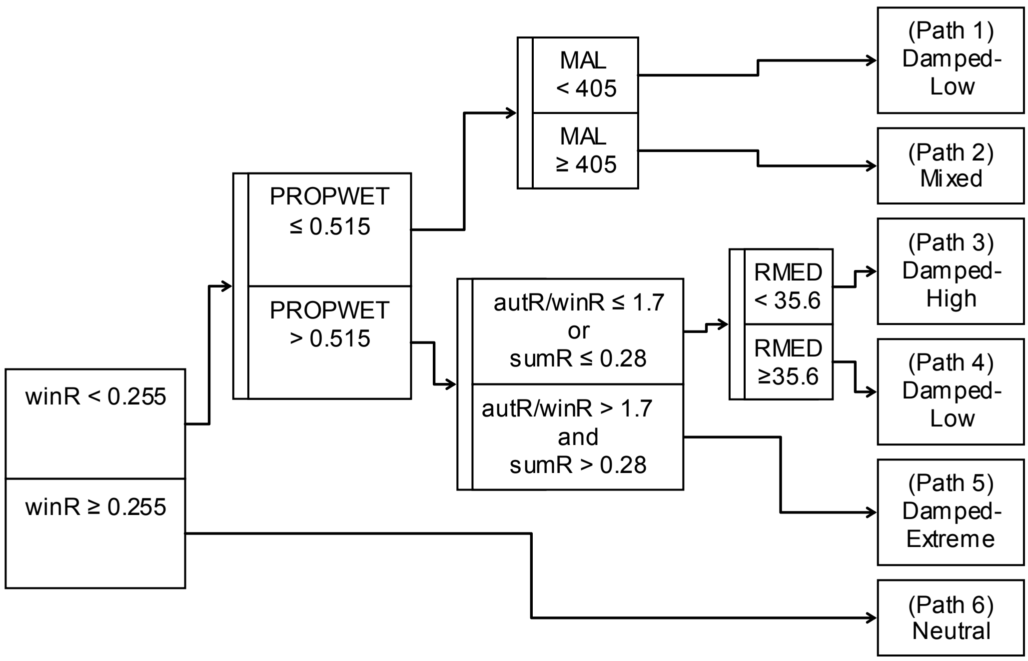


Figure 2 Final decision tree for Scotland, for response type estimation for RP20 changes. The final column gives the path number and the best-estimate of the response type for each path. See Table 1 for catchment property definitions.

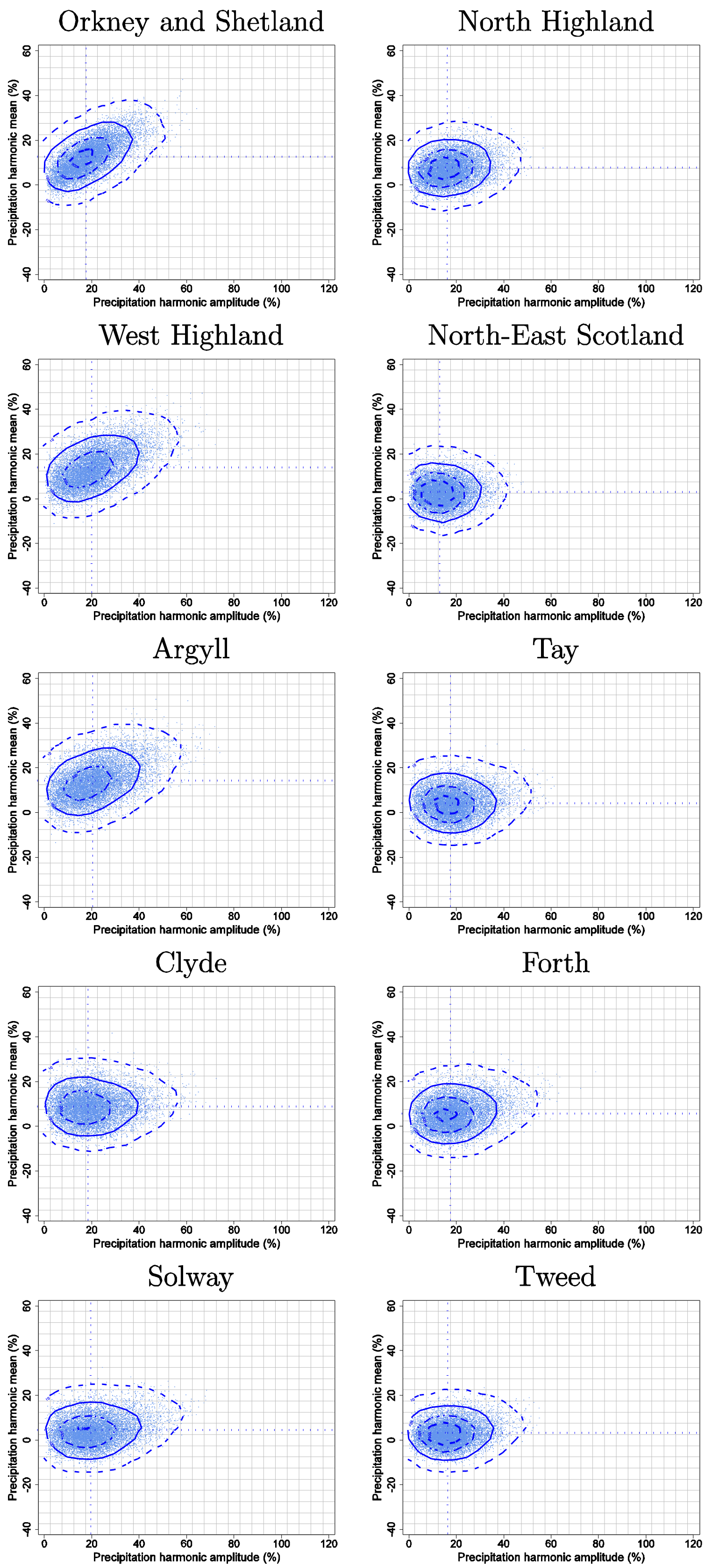
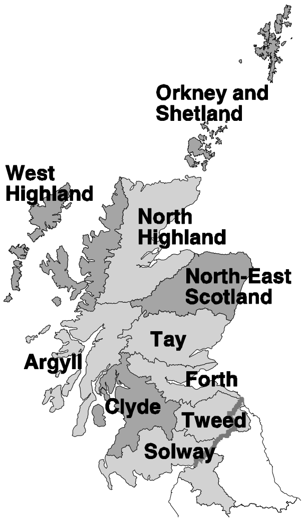


Figure 3 P harmonic mean versus amplitude on the sensitivity domain grid, for the 10,000 UKCP09 projections (2080s Medium) for each river-basin region in Scotland (dots). Contours delineate densities of 10, 100, 300 and (possibly) 500 projections per 5%x5% sensitivity domain square. Dotted horizontal and vertical lines indicate the median harmonic mean and amplitude respectively.



River-basin region	Response type: Damped-Extreme	Damped-High	Damped-Low	Neutral	Mixed	Total
Orkney and Shetland	0	1	0	0	0	1
North Highland	1	5	5	27	4	42
West Highland	0	0	0	6	0	6
North-East Scotland	4	4	18	17	3	46
Argyll	0	0	0	14	0	14
Tay	0	0	6	41	7	54
Clyde	4	5	16	34	0	59
Forth	0	4	7	20	22	53
Solway	0	3	2	37	1	43
Tweed	0	3	6	14	8	31
Total	9	25	60	210	45	349

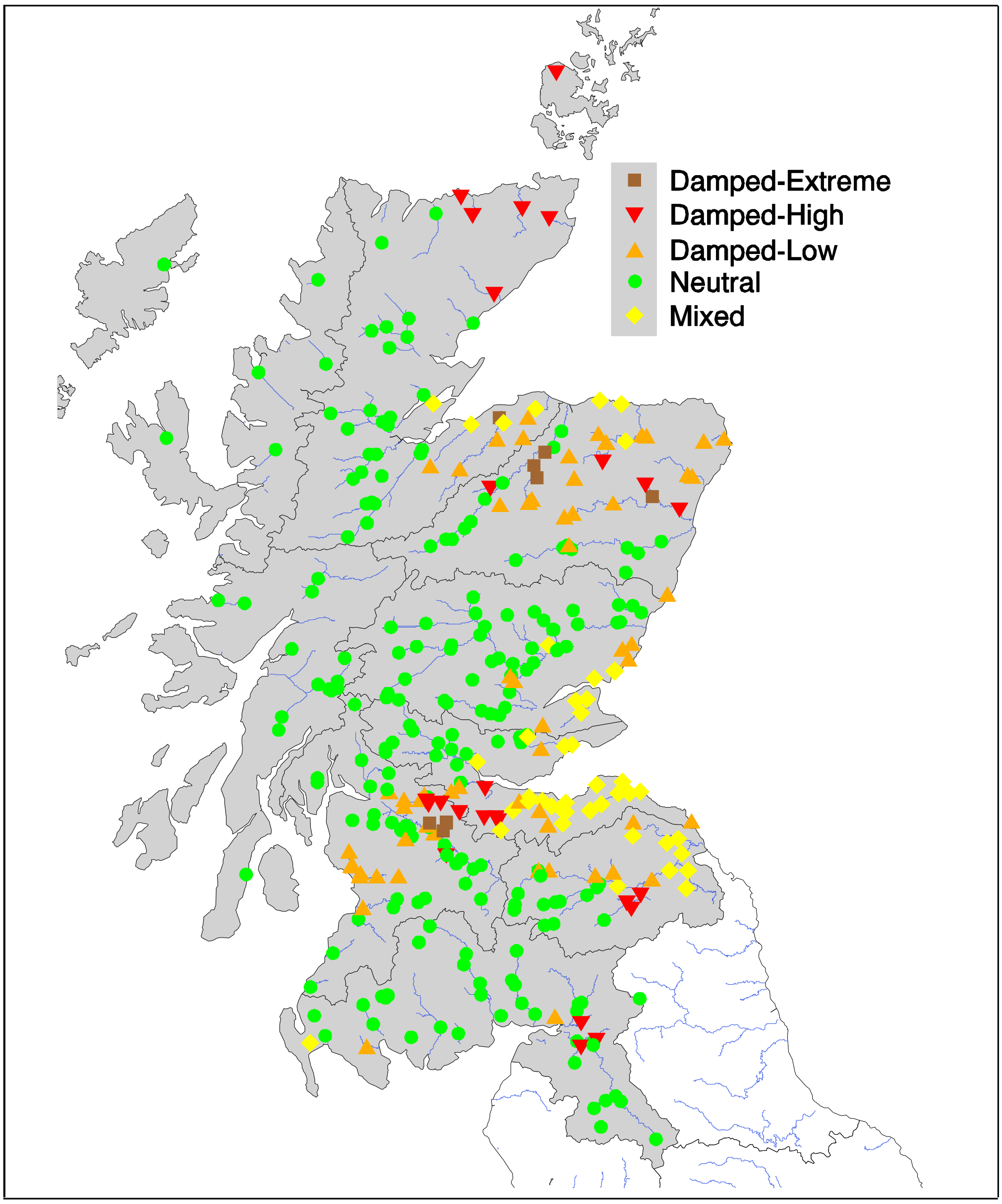


Figure 4 Summary of the estimated response type for each NRFA catchment in 10 river-basin regions over Scotland. Region names are in the top-left map, with the Scotland/England border (thick grey line).

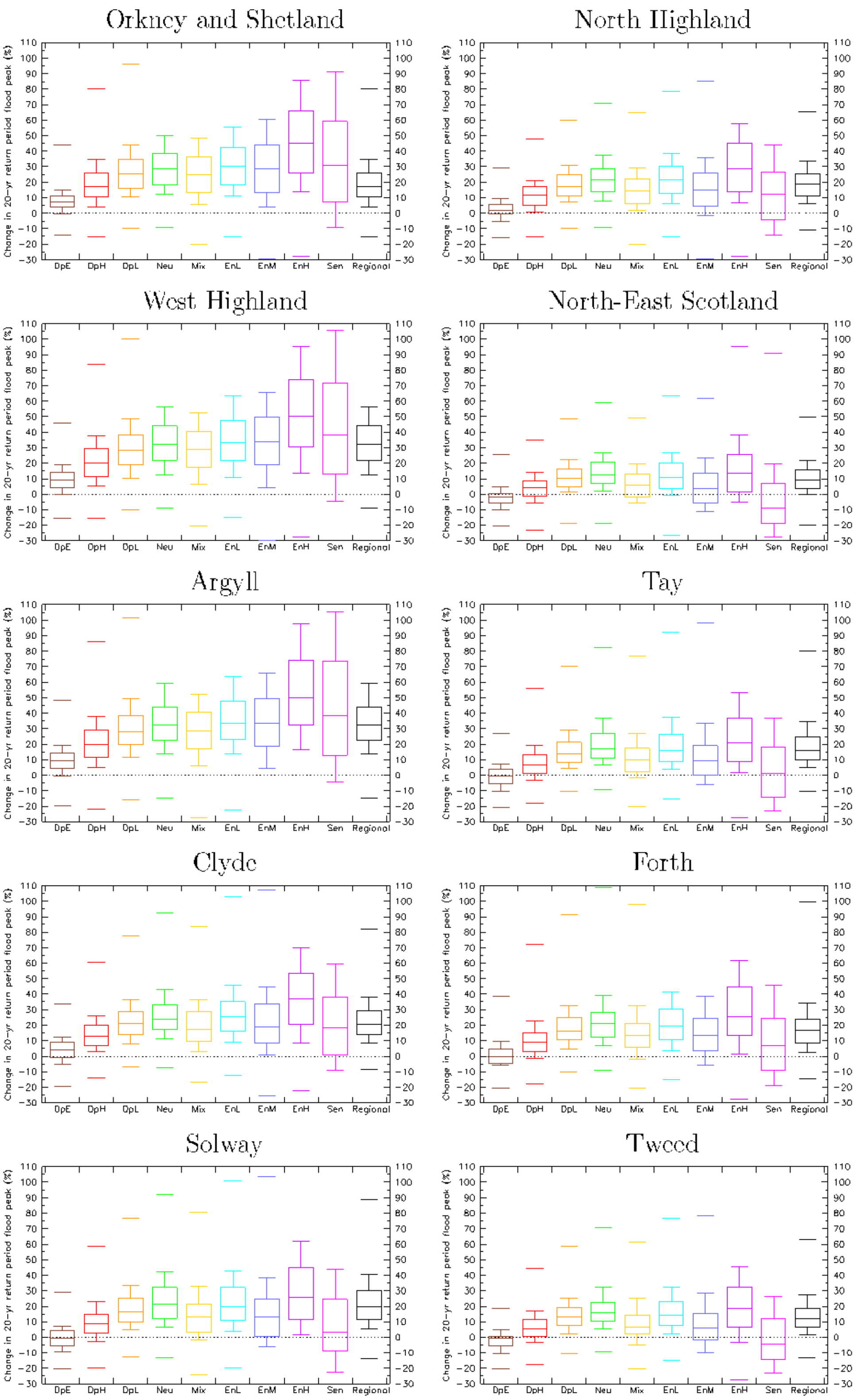


Figure 5 Box-and-whisker plots showing the impact ranges for each response type (DpE - brown, DpH - red, DpL - orange, Neu - green, Mix - gold, EnL - cyan, EnM - blue, EnH - purple, Sen - magenta) in each river-basin region in Scotland (2080s Medium). Also shown are regional average impact ranges (right-most box-plot for each region). Boxes indicate the 25th–50th–75th percentile range; whiskers the 10th–90th percentile range; additional markers are minima and maxima (if within the plotted range -30%–110%).

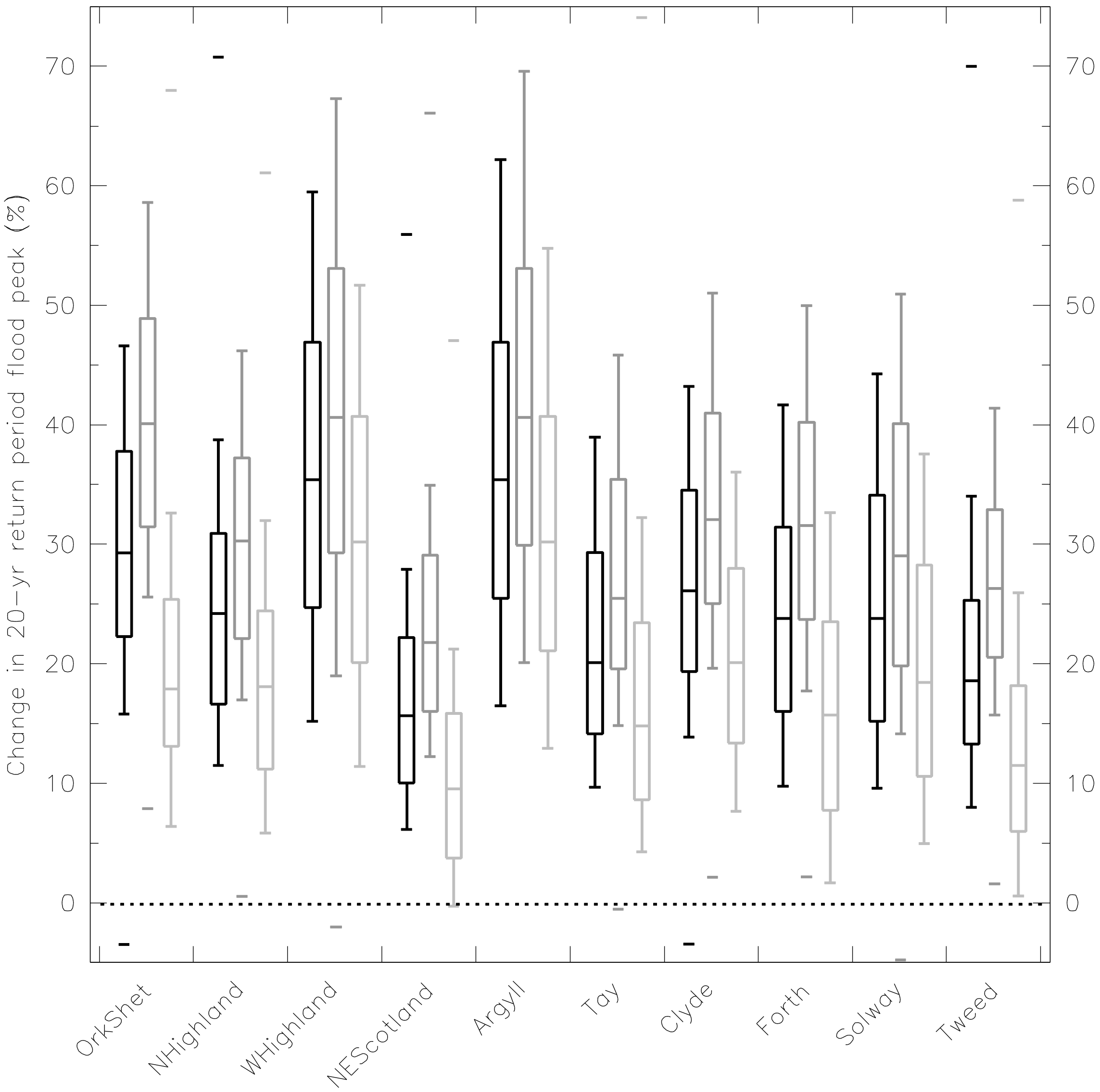


Figure 6 Box-and-whisker plots comparing the central-estimate of the regional average impact ranges (black), including bias correction values (Section 3.2), for each river-basin region in Scotland (2080s Medium). Additional boxes for each region show alternative ranges when adding ±2sd (mid-grey and light grey respectively). Box-and-whisker percentiles as Figure 5.

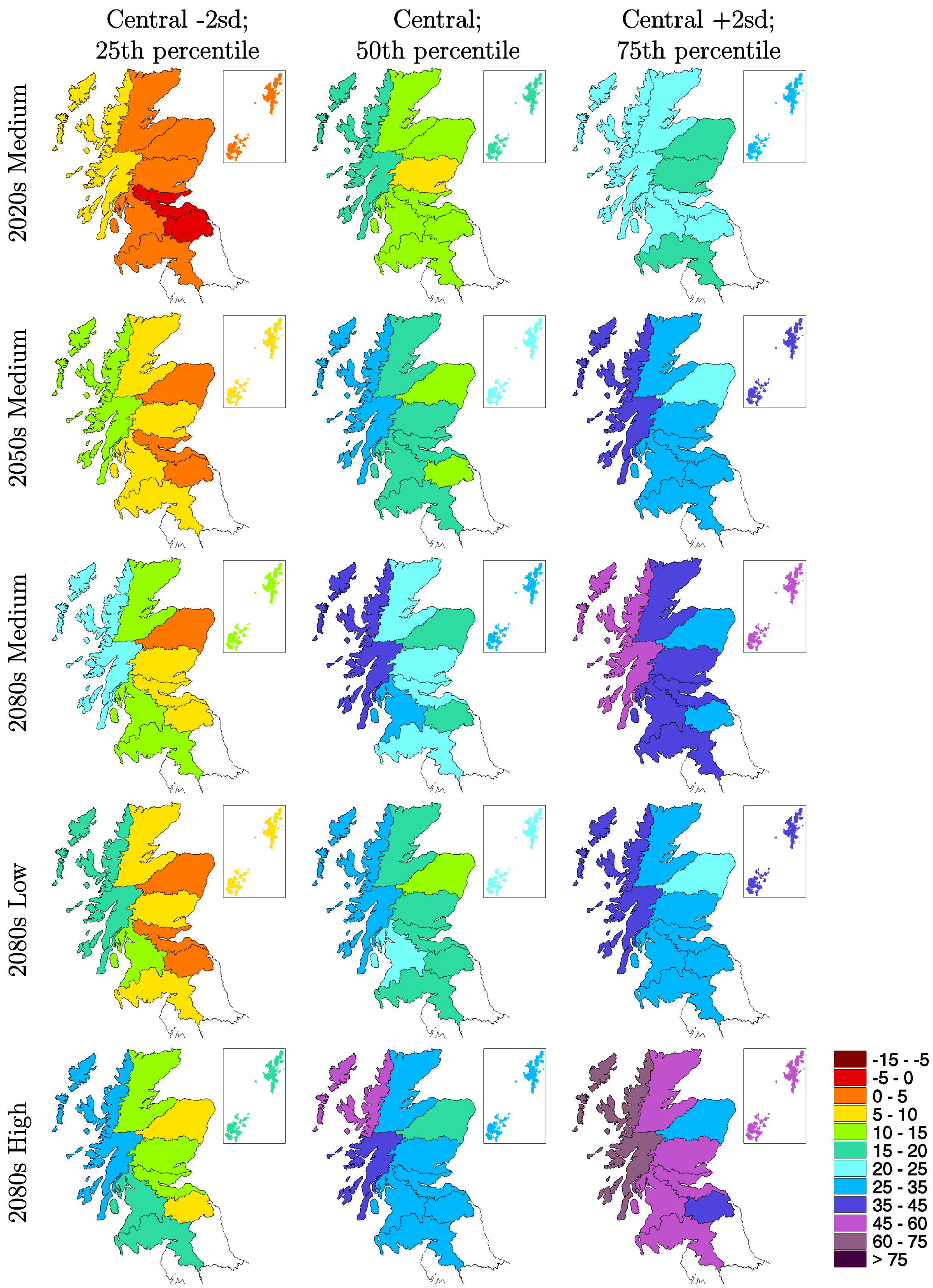


Figure 7 Variation in regional impacts (percentage changes in 20-year return period flood peaks) for Scotland for several time-horizons and emissions scenarios.

Probabilistic impacts of climate change on flood frequency using response surfaces II: Scotland

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Supplementary Material

1. Decision tree development

1.1 Catchments and catchment properties

Figure 1 shows the boundaries of the 45 catchments in Scotland and 12 catchments in northern England used for decision tree development for Scotland. Table 1 summarises the simulated response types of these catchments, for RP20 changes (Prudhomme et al. 2013a Figure 4).

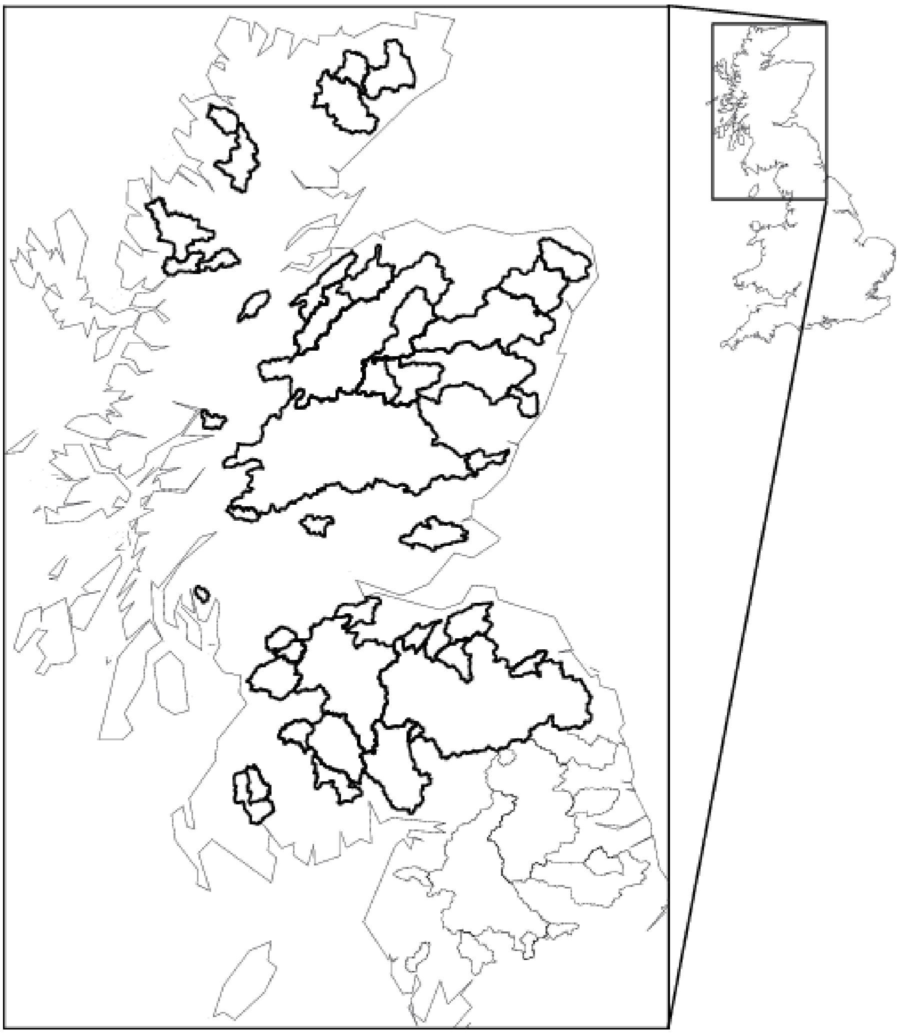

Figure 1 Boundaries of the 45 catchments in Scotland (thick black), and additional 12 catchments in northern England (thin black), used in the development of decision trees for Scotland.

Table 1 Summary of the simulated response types of the 57 modelled catchments in Scotland and northern England, for RP20.

Response type	Number of catchments
Damped-Extreme	3
Damped-High	16
Damped-Low	16
Neutral	12
Mixed	8
Enhanced-Low	0
Enhanced-Medium	2
Enhanced-High	0
Sensitive	0

1.2 Snow

An issue which is more influential in Scotland than in much of England and Wales is snow, and the effect it has on flood peaks. The relationship between snowfall, melt and floods is complex as snowmelt may increase the flood peak when rapid snowmelt is combined with rainfall, but may decrease a peak where melt from heavy snowfall occurs more gradually. Timing of temperature rise with rainfall occurrence, combined with differences in timing from different altitudes, may be critical in determining runoff rates from combined snowmelt/rainfall events and may not be well simulated when modelling at a daily time-step. For mountainous catchments the impact of snow is generally to give a Damped response type, from gradual melt, but see below on discussion of Damped-Extreme catchments. For catchments with a range of altitudes, snowmelt/rainfall floods are likely to be part of the current flood history but not a dominant characteristic. Therefore such events are not sufficient to affect the catchment response type. See Kay and Crooks (2013) for a general discussion of the potential impacts of climate change on snowfall, accumulation, melt and subsequent river flows.

1.3 Catchment reclassification

During development of the original decision trees (Prudhomme et al. 2013b, Reynard et al. 2009), catchments with Damped-High or Damped-Low response types were merged to Neutral at higher return periods. This merging was undertaken partly to allow for the seasonality of baseline events combined with the fixed month of maximum precipitation change (January) used in the sensitivity framework (Prudhomme et al. 2010). The majority of these merged catchments are located in Scotland, so consideration was given to whether it is appropriate that there is no Damped response type for RP20 changes in Scotland. A Damped response type may be caused by the delaying impact of snowmelt, as well as the main flood events in the baseline not occurring in winter. With the latter situation, a decision is required as to whether this is likely to be by chance (natural variability) or because flood-producing rainfall mainly in seasons other than winter is a local climatic feature. Where the Damped response could have occurred by chance the catchments were reclassified (see below); where the Damped response is likely to be a real feature of local climate, the classification was retained.

The structure of the initial trees, and the properties used, provided an indication of paths for which it might be appropriate to reclassify the Damped response types of some catchments to Neutral for higher return periods. Consideration of the catchments affected showed that all have an autumn/winter threshold-rainfall ratio (autR/winR; main text Table 1) below 1.32. The distribution of this catchment property for all 57 catchments shows a bi-modal distribution, with the trough between the peaks having a ratio between 1.3 and 1.4. The shape of the distribution may be indicative of non-random differences in the seasonal pattern of intense rainfall. An autumn/winter threshold-rainfall ratio of 1.35 was therefore used as the criterion for reclassifying the response types; catchments with a Damped response type and a ratio below 1.35 were reclassified as Neutral at 20- and 50-year return periods. Thus 10 catchments were reclassified from Damped-Low, 8 from Damped-High, and 1 from Damped-Extreme. The objective of reclassification is to avoid underestimating the change in flood peaks due to what may be chance seasonal occurrence of events in the baseline.

The decision tree of Prudhomme et al. (2013b) could not characterise the three original Damped-Extreme catchments alongside the full range of response types in Britain. Given that these catchments are in Scotland, the validity of their extremely damped response to changed rainfall and temperature inputs was further investigated. This showed that one of the three (the Dee at Mar Lodge) has response surfaces of different types according to whether or not snowmelt is modelled, and under different temperature scenarios, whereas the response surfaces of the other two (the Findhorn at Forres and the Avon at Delnashaugh) are always Damped-Extreme. This difference in behaviour is likely to be due partly to altitude and partly to seasonality of high rainfall. The Dee at Mar Lodge has the highest mean altitude of all 57 modelled catchments in Scotland and northern England, and runoff from the whole catchment is affected by accumulation of snow during the winter (Kay and Crooks 2013). The lower mean and minimum altitude for the Findhorn and Avon catchments suggest that the impact of snowmelt in these catchments is less. Similarly, the seasonal threshold-rainfall proportions show a difference between the Dee and the other two catchments, with the latter having a higher proportion of summer threshold-rainfall and higher ratio of autumn to winter threshold-rainfall. The higher incidence of threshold-rainfall during the summer and autumn, compared with the winter, leads to the Damped-Extreme response for the Findhorn and Avon. Thus there are different causes behind the Damped-Extreme responses for the three catchments. In fact, the Dee at Mar Lodge is reclassified to Neutral, as it has an autumn/winter threshold-rainfall ratio below 1.35 (see previous paragraph). This reclassification from Damped to Neutral is also compatible with change from a winter runoff pattern characterised by gradual release of snowmelt to a rainfall-dominated regime. The Damped-Extreme response type was retained for the Findhorn and the Avon, and included in the development of the decision trees.

Enhanced response types could not be included in the decision trees, as there are only two such catchments in the modelled set for Scotland (both Enhanced-Medium; Table 1). These two catchments appear to have different causative factors behind the Enhanced response, as one has high proportion of high permeability bedrock (BHP) while the other is much less permeable, though both have high Mean Annual Loss (MAL) compared to standard average annual rainfall (SAAR). However, the impact of bedrock permeability on the flow regime for the catchment with high permeability may be reduced by the presence of extensive drift cover, as the baseflow index is only 0.35. As the catchments are at different ends of the permeability range it is not possible to set threshold values, and using those from the original trees may not be appropriate as the relationship between permeability and response type in Scotland may be different to that in England. Thus it was considered inadvisable to attempt to characterise the Enhanced response types in Scotland. Further modelling is required to determine which catchment properties are of importance for distinguishing Enhanced response types from other types in Scotland.

1.4 Decision tree performance

The performance of the decision tree for RP20, for the 57 catchments, is presented in a contingency table (Table 2) comparing the simulated and estimated (highest probability) response type. The aim is to maximise the number of correctly classified catchments (on the diagonal), while minimising the number of catchments where the response type is either over-estimated (below the diagonal) or under-estimated (above the diagonal). With misclassification, preference is given to over-estimating rather than under-estimating the response type. Table 2 shows that 49 catchments (86%) were correctly classified by the tree, with just four catchments where the response type is over-estimated and four where it is under-estimated. Thus the performance is relatively good given that the number of catchments available for deriving the trees for Scotland is quite small relative to the range of causes of floods and combinations of catchment properties and climatological factors. However, the small sample size does result in some uncertainty in designation of response type for some paths, especially Path 1 (main paper Table 2). Table 2 shows that the two catchments with a simulated response type of Enhanced-Medium have an estimated response type of Mixed, so contribute to the under-estimation. The other two catchments contributing to under-estimation are two Mixed catchments estimated as Damped-Low.

Table 2 Contingency table summarising decision tree performance. Bold numbers, on the diagonal, show the number of catchments correctly classified (49); numbers below the diagonal indicate 'over-estimation' (4 catchments); numbers above the diagonal indicate 'under-estimation' (4 catchments).

		Simulated response type					
		DpE	DpH	DpL	Neu	Mix	EnM
Estimated response type	DpE	**2**	0	0	0	0	0
	DpH	0	**5**	0	0	0	0
	DpL	0	2	**6**	0	2	0
	Neu	0	0	1	**30**	0	0
	Mix	0	1	0	0	**6**	2
	EnM	0	0	0	0	0	**0**

2. Use of UKCP09 projections

A comparison of the ranges of monthly changes from the 10,000 projections for each region in Scotland, before and after fitting the harmonic functions, suggests that the harmonic function provides a reasonable approximation to the full monthly data sets (Figure 2).

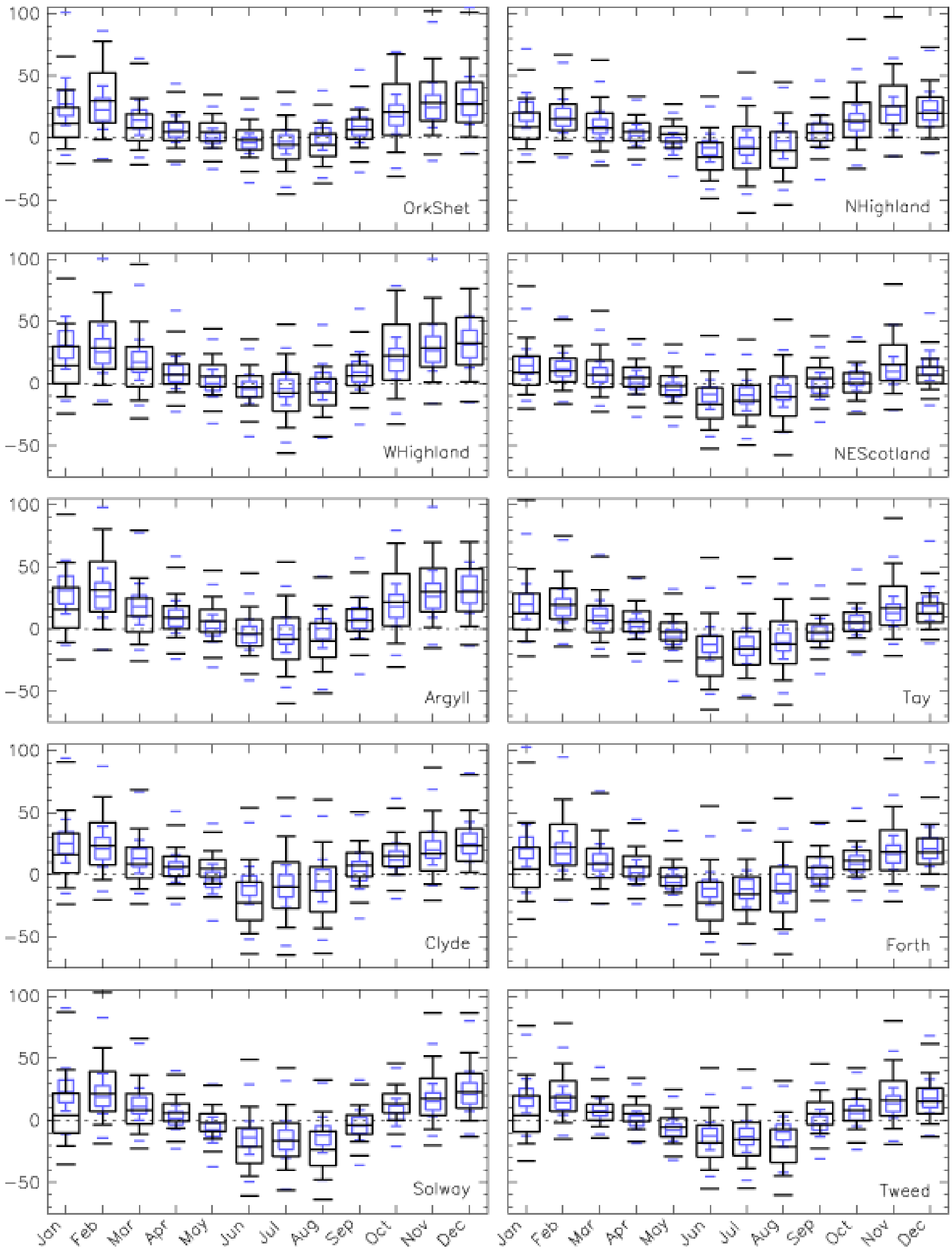

Figure 2 Box-and-whisker plots showing the range of the 10,000 monthly P percentage changes (2080s Medium) for each river-basin region in Scotland, using the UKCP09 Sampled Data as provided (wider boxes; black) and after fitting harmonic functions (narrower boxes; blue). Boxes indicate the 25th–50th–75th percentile range; whiskers indicate the 10th–90th percentile range; additional markers indicate minima and maxima (if within the plotted range -75%–105%).

Histograms of P harmonic phase for each river-basin region show that the assumption of a January phase is reasonable (Figure 3). January is the dominant month for all regions except Orkney and Shetland and North Highland, where it is (marginally) the second most frequent after December. For the eight regions where January is the dominant month, the next most frequent month is December. January seems to be more dominant as the phase month for the more southerly regions of Scotland than it is for the more northerly ones. The alternative response surfaces presented by Kay et al. (2013b) suggest that, in general, if the phase is set in December then the response is likely to be similar or slightly greater than for a January phase. Consequently, the use of January-phase response surfaces may slightly under-estimate the impact, particularly for the more northerly river-basin regions in Scotland, due to the number of scenarios where the phase is really December. However, it is not thought that this affect will be large and the characterisation of response types using decision trees took some account of the variation of response surfaces with harmonic phase (see main text Section 2.2).

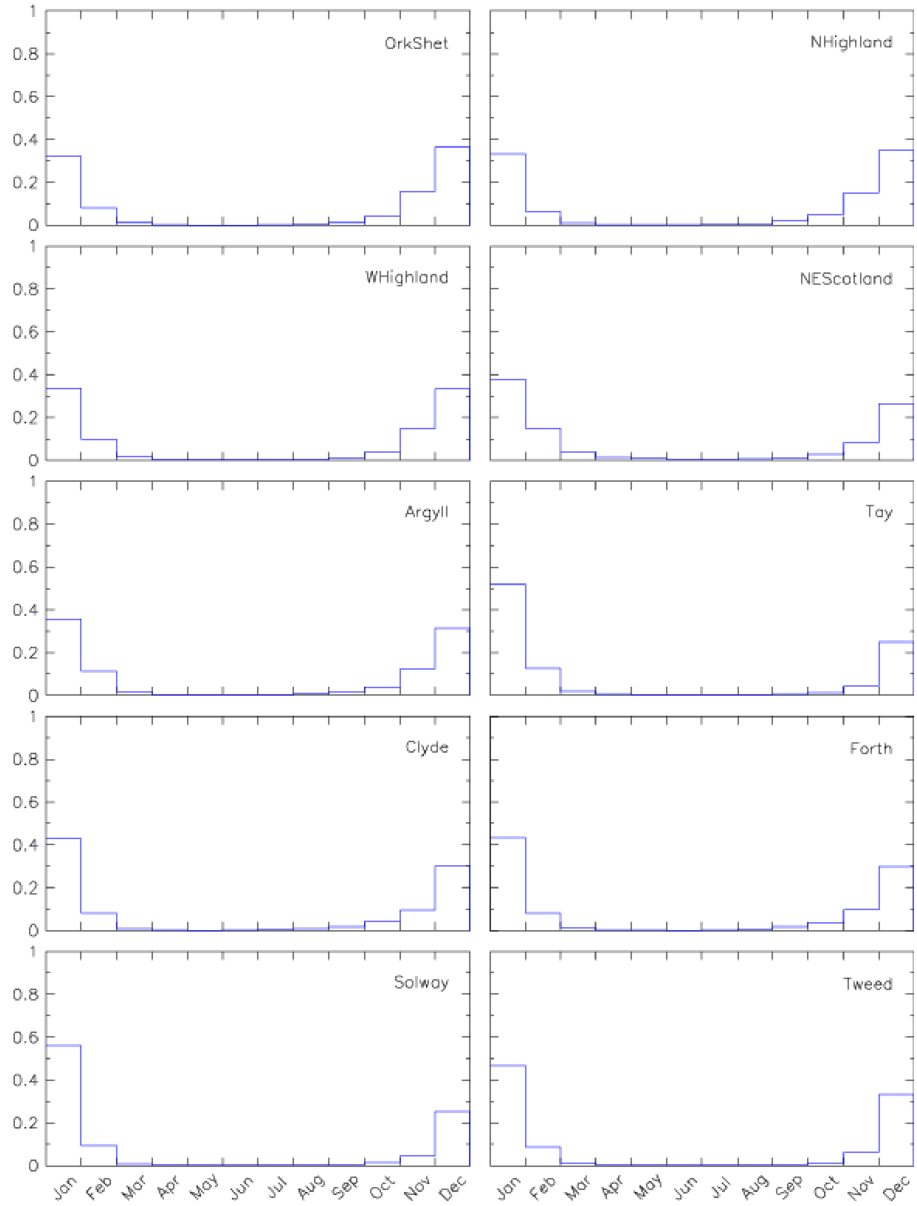

Figure 3 Histograms of P harmonic phase, for the 10,000 UKCP09 projections (2080s Medium) for each river-basin region in Scotland.