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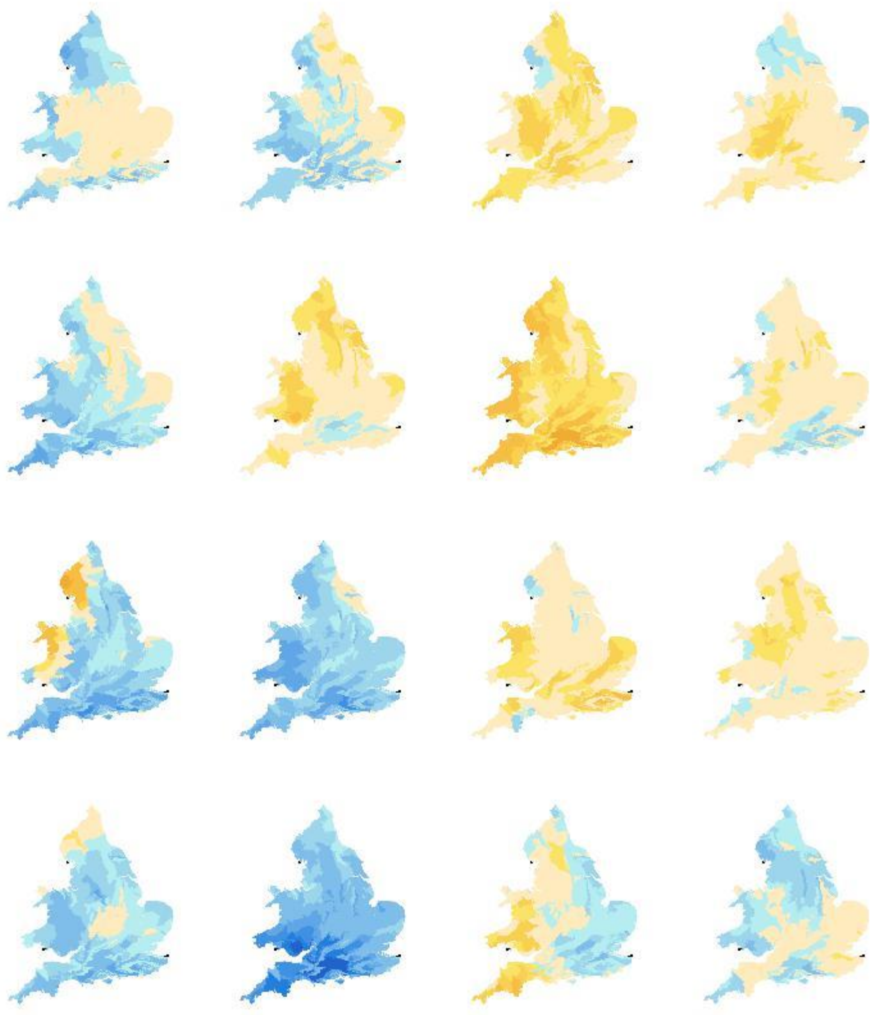
Summary of results for national scale recharge modelling under conditions of predicted climate change

Groundwater Directorate

Commissioned Report OR/17/026



BRITISH GEOLOGICAL SURVEY

GROUNDWATER Directorate PROGRAMME

COMMISSIONED REPORT OR/17/026

Summary of results for national scale recharge modelling under conditions of predicted climate change

M M Mansour, A G Hughes

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National Grid Reference

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Monthly changes to forecast recharge (2020s).

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Summary

This report describes the application of the BGS distributed recharge model ZOODRM to produce recharge values (potential recharge) for Great Britain (England, Scotland and Wales). This model has been run with the rainfall and potential evaporation for the Future Flows Climate datasets (11 ensembles of the HadCM3 Regional Climate Model or RCM). The following results have been produced:

- For groundwater bodies in England and Wales:
  - The mean, standard deviation and the following percentiles: 10, 25, 50, 75, 90 (absolute values of annual recharge produced by ranking annual recharge values) have been produced for annual recharge totals for the following periods: simulated historic (1950-2009), 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
  - The 25^{th} percentile and 75^{th} percentile for the simulated historic recharge for each month have been calculated. The estimated daily recharge values were aggregated to monthly values first and the analysis was undertaken using these monthly values. Further, a proportion of recharge values above and below these values for the future climate has been calculated.
  - Mean monthly recharge values were calculated for each month for the simulated historic period. The change in recharge value for each month in absolute terms compared to monthly value calculated for the historic simulation was calculated for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
  - Monthly change factors (percentage difference between monthly average recharge for future climate and historic simulation) for each groundwater body for each of the 11 ensembles were produced. These have been summarised in maps of England and Wales, which illustrate for each month the minimum, maximum and median monthly change factor from all the ensembles for each groundwater body.
- River Basin Management Districts (RBMD) in England and Wales:
  - The mean monthly recharge value was calculated for each month for the RBMD. The change in recharge value in absolute terms was calculated for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
  - The total recharge volume for the RBMD for the time periods 1961-90, 1971-00 and for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099) was calculated.
  - Empirical cumulative distribution functions (ECDF) have been produced for seasonal (spring, summer, autumn and winter) as well as monthly averages for historic simulation (both 1961-1990 and 1971-2000) as well as for the 2020s, 2050s and 2080s.

Generally the recharge season is shorter in the future. For the historical simulation (1950-2009) the recharge season is between five to seven months each year (September to April). It appears that this is reduced to three to four months for the future climate predictions. This is seen in both the changes in 25% / 75% recharge values and the monthly differences. There appears to be agreement between ensemble outputs. This could make aquifers more vulnerable to droughts if rainfall fails in one or two months rather than a prolonged dry winter as can occur now.

When recharge volumes were produced for the RBMDs then the volumes tend to increase from the historical simulation to the 2020s/2050s, but more significantly in the 2080s. For example in the Thames RBMD the average recharge volume increases from 67 x 10^6 Ml/d in the 2020s/2050s to just over 73 x 10^6 Ml/d in the 2080s. However, the range of possible outcomes also increases and so one possible future outcome is that recharge volumes could reduce.

The recharge season appears to be forecast to become shorter, but with greater amount of recharge “squeezed” into fewer months. This is acceptable for ensuring that recharge for groundwater water

resources is maintained from a water balance perspective, but could result in greater "lumpiness" of the recharge signal. This increased "lumpiness" could result in flashier groundwater level response and potentially greater drought vulnerability. Groundwater drought could, therefore, occur if rainfall "fails" for one month, i.e. recharge totals are reliant on fewer months of rainfall.

Finally, the results show that the balance between climate variability and climate change shifts towards the end of the future period (2010-2099) with a stronger climate signal being observed in changes to the recharge values in the 2080s than either of the 2020s or 2050s.

Given the amount of data produced, a more detailed examination of the results for groundwater bodies would enable more value to be gained from the work. Alongside this, understanding how water balances for the RBMD varies in the future would be beneficial. Three issues should be examined: 1) Disaggregation of recharge volumes for the River Basin Management Districts to examine how recharge to individual aquifers may change; 2) Shortening of recharge season and vulnerability to drought; and 3) Variability of results from the ensembles and likely worse cases.

Finally, whilst the initial analysis has focussed on how recharge will change for water resources, no consideration of groundwater flooding has been included and this should be examined.

1 Introduction

1.1 GROUNDWATER IN THE CONTEXT OF CLIMATE CHANGE

The UK Government 25 year Environment Plan has an ambition to improve air and water quality and protect our many threatened plants, trees and wildlife species. The environment plan sets out goals for improving the environment within a generation and leaving it in a better state than we found it. It details how the government will work with communities and businesses to do this. The Government's 25 Year Plan recognizes the role of groundwater as an important source of natural capital.

Groundwater is a vital source of water for public water supply, agriculture and industrial operations and is also a natural asset that supports a wide range environmental benefits.

Within the 25 year Plan there are two key environmental benefits and pressures that groundwater is intrinsically linked.

Clean and plentiful water: We will achieve clean and plentiful water by improving at least three quarters of our waters to be close to their natural state as soon as is practicable. This includes reducing the damaging abstraction of water from rivers and groundwater, ensuring that by 2021 the proportion of water bodies with enough water to support environmental standards increases from 72% to 77% for groundwater bodies

Mitigating and adapting to climate change: We will take all possible action to mitigate climate change, while adapting to reduce its impact. This will include making sure that all policies, programmes and investment decisions take into account the possible extent of climate change this century

The Environment Agency (EA), which is responsible for the management of groundwater, must ensure that goals and targets for short term and long term plans includes improving groundwater sustainability while adapting to the impact of climate change.

The Environment Agency has a requirement under the Water Framework Directive (WFD) to assess the quantitative status of groundwater bodies. This has been undertaken for recharge based on current conditions. Climate change is likely to affect rainfall, temperature, land cover and growing season and could significantly change recharge. If climate change significantly reduces recharge then this could degrade the quantative status of groundwater bodies. An assessment, therefore, is required to determine how recharge will change in the future.

1.2 STRUCTURE OF REPORT

This report describes the work undertaken for the Environment Agency under contract entitled "Ground water resources and climate change" (Project number: SC160018). It presents the main results of running the recharge model ZOODRM for Great Britain (England, Scotland and Wales) under conditions of climate change. The Future Flows Climate dataset (Prudhomme et al., 2012), produced by the Future Flow and Groundwater Level (FFGWL) project, which consists of rainfall and potential evaporation produced from 11 ensembles has been run through the model. Preliminary analysis of the results produced has been undertaken.

The report consists of three main sections: description of the methodology for producing the results including the model used to create them, presentation of the narrative, and the results to support it. A brief summary section with recommendations for further work is provided at the end of the document.

Due to the significant amount of results produced by this work the majority of the results are contained in Appendices, which include descriptive text.

2 Methodology

2.1 INTRODUCTION

The following section describes the recharge model (the code itself and its application to the British mainland) and its use with climate change scenarios. For this project climate change scenarios using the 11 member ensembles from the HadCM3 RCM created by FFGWL project (Prudhomme et al., 2012) (rainfall and potential evaporation) have been run through the recharge model. The basis of climate change scenarios used are outlined below. To allow the impact of climate change on recharge to be assessed the modelled daily potential recharge values (mm/d) have been processed in a number of different ways for both groundwater bodies and for river basin management districts. Monthly recharge has been calculated along with seasonal (winter, spring, summer and autumn) totals for different time slices: 2020s, 2050s and 2080s. The methodologies to produce these results is then described in detail.

2.2 MODEL CODE AND ITS APPLICATION

2.2.1 Model code

ZOODRM (Mansour and Hughes, 2004) is an Object Oriented model developed by BGS as part of the ZOOM suite of models. It is a distributed recharge model that simulates runoff and recharge processes and provides the output in a gridded form for use with groundwater flow models or on a catchment basis for water balance purposes. It has been applied in both in the UK (e.g. Mansour et al., 2011), to the GB landmass (Mansour et al., 2018) and overseas (e.g. Hughes et al., 2008).

2.2.2 Model Instance - Application to the GB mainland

The GB-wide recharge model was built using BGS' code ZOODRM (Mansour and Hughes, 2004; Hughes et al., 2008). Recharge is calculated on a grid with 2 km square cells over the area described by the following National Grid Reference: Bottom Left (40000, -10000) Top right (680000, 1010000). The model has been run from 1st January 1962 to 31st December 2010 and calibrated against the runoff component of river gauged flow. It calculates recharge on a daily basis and aggregates the recharge to a monthly basis (Mansour et al., 2018).

The calculation method used is the modified FAO (Hulme et al., 2001) as proposed by Griffiths et al. (2006). It uses the distribution of soil parameters and crop parameters obtained from the HOST soil data map ,which includes 33 classes of soil types (Boorman et al., 1995), and the land cover map, Land Cover Map 2000 (Fuller et al., 2002), which includes 9 land use classes. The values of these parameters are obtained from the literature, e.g. Hulme et al. (2001). The full set of data used for the model are presented in Table 1.

Table 1. Data used for the GB-wide recharge model

Data	Source	Reference
Rainfall	CEH CERF / GEAR	Keller et al., 2005 CEH-GEAR Data set
Potential Evaporation (PE)	MORECS PE	Hough and Jones, 1997
Landuse	LCM2000	Fuller et al., 2002
DEM	CEH DTM	Morris and Flavin, 1990
River network	CEH	Moore et al., 1994
Geology	BGS Digmap	
Soil map	HOST	Boorman et al., 1995
Crop distribution	LCM2000	NERC, 2000

The model calculates potential recharge, which is the amount of water calculated to leave the bottom of the soil zone. It does not, therefore, take into account any modification of recharge resulting from the unsaturated zone and interaction with other, minor aquifers which may lie above the water table.

2.2.3 Climate Change datasets – Future Flows Climate

Funded by DEFRA and produced in 2009, UKCP09 provides projections of climate change in the UK (Prudhomme et al., 2012; Murphy et al, 2007; Jenkins et al., 2009; Murphy et al, 2009). The probabilistic climate projections provided by UKCP09 are not fully spatially coherent. To overcome this problem, 11 physically plausible simulations were generated under the medium emissions scenario also known as the A1B SRES emission scenario (IPCC, 2000). Based on the 11 variants of the Hadley Centre Regional Climate Model HadRM3-PPE, which underpins the UKCP09 scenarios, the Centre of Ecology and Hydrology (CEH) applied a bias-correction and downscaling procedure to produce 11 scenarios of Future Flow Climate data. The 11 ensembles consist of an unperturbed example (afgcx) and ten perturbed simulations (Murphy et al., 2009). These data are 1km gridded climate time variant projections of rainfall (Prudhomme et al., 2012) and potential evaporation (Prudhumme and Williamson, 2013) and allow comparison of results across a range of scales and geographical regions. The data were produced as daily grids from 1st January 1950 to 30th November 2099. The 11 ensembles are named as follows:

1. afgcx
2. afixa
3. afixc
4. afixh
5. afixi
6. afixj
7. afixk
8. afixl
9. afixm
10. afixo
11. afixq

The recharge model has been run with rainfall and potential evaporation for all 11 ensembles and the results processed as discussed in the following section.

The output from the 11 ensembles run through the recharge model can be seen as complimentary to Future Flow Hydrology (Prudhomme et al., 2013) which produced an ensemble of daily river flows and monthly groundwater levels for Great Britain. The CERF model produced gridded outputs but didn't explicitly examine recharge values and how they might vary under conditions of climate change. The monthly groundwater levels were produced from point models (24 overall). The recharge modelling presented here seeks to provide output at a range of scales from gridded 2 km data, groundwater bodies (310) and for the River Basin Management Districts (11).

2.3 PROCESSING MODEL OUTPUT

2.3.1 Groundwater bodies

The following processing was undertaken to produce summary statistics for the groundwater bodies for England and Wales. There are 310 groundwater bodies and they are used for reporting requirements for the EU Water Framework Directive (WFD). Figure 1 shows their distribution.

The results for each ensemble have been analysed for each groundwater body as a whole and presented as colourised spatial plots for each groundwater body.

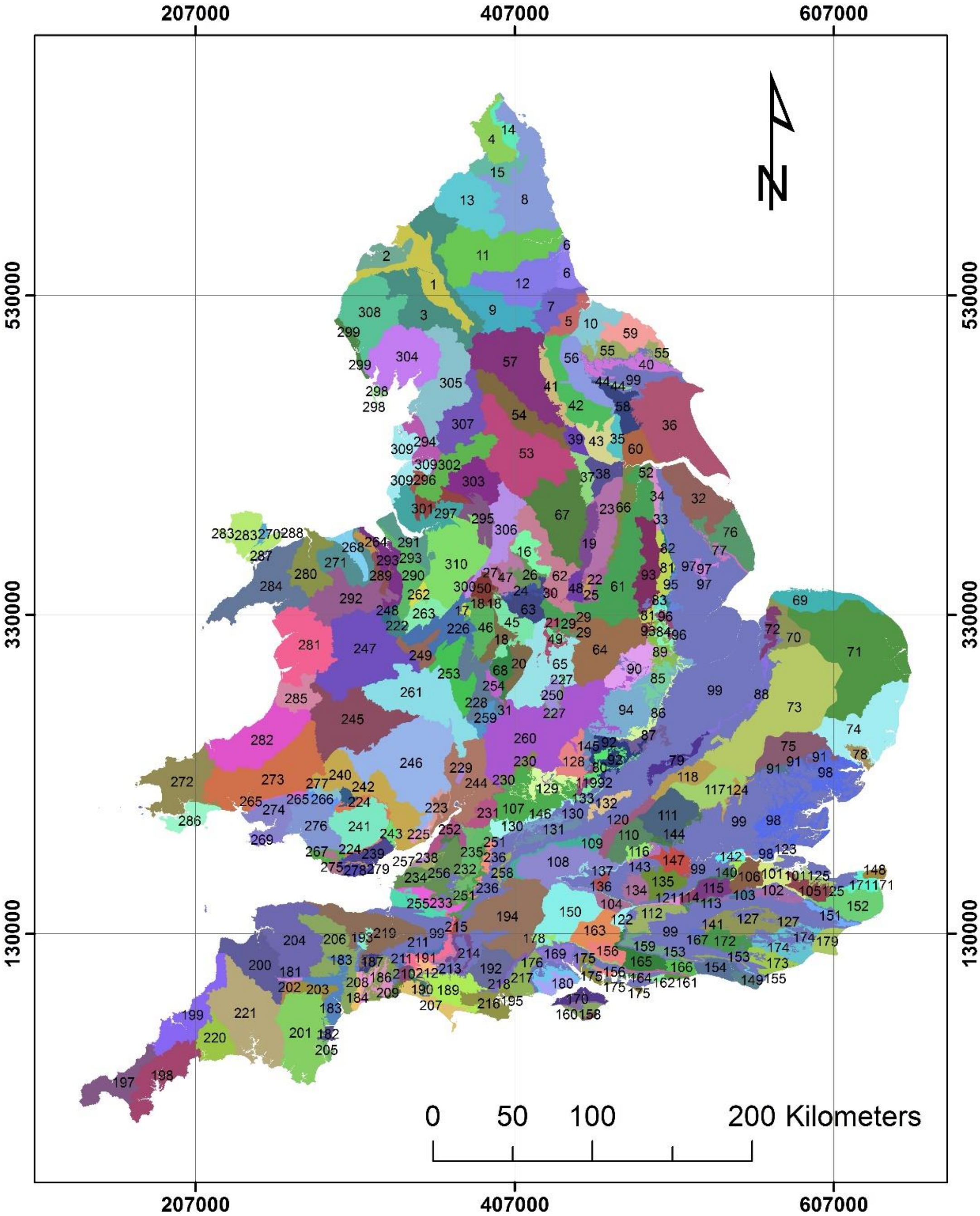


Figure 1. Distribution of groundwater bodies (Contains public sector information licensed under the Open Government Licence v3.0)

2.3.1.1 Average and percentiles

The mean, standard deviation and the following percentiles: 10, 25, 50, 75, 90 of annual recharge values for each groundwater body have been produced for the following periods: simulated historic (1950-2010), 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099) (see Appendix 1). The percentiles have been calculated from the ranking of the annual recharge value, so the annual recharge for the 10% value is that which has 90% of the values greater than this value. The use of annual recharge in this section is aligned with the calculation of average recharge used by the EA for each groundwater body for WFD reporting purposes.

Generally speaking the values for mean, SD and the percentiles increase in areas of higher recharge, i.e. western England (Cumbria and Cornwall) and Wales and are lower to the east of England. This follows the spatial distribution of rainfall and evaporation over England and Wales, with the highest rainfall / lowest evaporation in the west and lowest rainfall / highest evaporation in the east.

2.3.1.2 Exceedance of 75% and occurrence under 25%

The 25th percentile and 75th percentile of the total monthly recharge over the simulated historic period (1961-2009) for each month has been calculated (see Appendix 2). Daily recharge values produced by the historic simulation are aggregated to total monthly recharge values. A list of monthly recharge values was derived for each month, ranked from the greatest to the lowest and the 25th and 75th percentiles were calculated. The number of occurrences where future total monthly recharge values, simulated in the period between 2010 and 2099, exceed the 75th percentile and the number of values occurring below the 25th percentile were then calculated for each month. These calculations are presented in Appendix 2 where recharge values are in mm/month.

2.3.1.3 Monthly changes

The mean monthly recharge values were calculated for each month for the simulated historic period (see Appendix 3). The change between future and historical recharge value in absolute terms was calculated for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).

2.3.1.4 Change factors summary

Using the standard change factor methodology as used by the Environment Agency for water resource assessment, summary plots were produced of average monthly recharge (Minimum, maximum and median) across all 11 ensembles (see Appendix 4). The change factors (percentage difference between future and historical average monthly recharge for each month) were calculated for each month for all 11 ensembles and for all the groundwater bodies. This was undertaken for the 2050s and 2080s and summarised in plots showing greatest negative change factor, greatest positive change factor, median change factor from all 11 ensembles for each groundwater body for each month. This method, whilst not the only method for undertaking this, produces an appreciation of the range of results from the 11 ensembles.

The detailed methodology is as follows:

- Produce mean monthly recharge for each ensemble for each groundwater body (310 in all) for 1961-1990 within the historic simulation period and for the 2050s (2040-69) and 2080s (2070-2099)
- Calculate mean monthly recharge values for each ensemble for each groundwater body (310 in all) for the simulated future periods: the 50s (2040-2069) and the 80s (2070-2099)
- Calculate future 50s and 80s change factors using the mean monthly recharge for each month for all 11 ensembles for each groundwater body (each month will have 11 ensembles for each groundwater body)
- Calculate the greatest negative change factor, greatest positive change factor and median value for each groundwater body for each month for the 2050s and 2080s
- Produce the following sets of plots:

    i. Baseline (1961-90): minimum average monthly recharge, maximum average monthly recharge and median average monthly recharge from all 11 ensembles for each groundwater body for each month (3 x 12 plots)

    ii. 2050s (2040-2069): greatest negative change factor, greatest positive change factor, median change factor from all 11 ensembles for each groundwater body for each month (3 x 12 plots)

    iii. 2080s (2070-2099): greatest negative change factor, greatest positive change factor, median change factor from all 11 ensembles for each groundwater body for each month (3 x 12 plots)

2.3.2 River Basin Management Districts

To understand the impact of Climate Change on potential recharge on the main catchments used for River Basin Management District (RBMD) planning the model results were summarised over the extents of these catchments (See Appendix 5). There are 11 RBMD in England and Wales numbered from 2 to 12 as illustrated by Figure 2.

The results for the RBMDs were averaged for each RBMD as a region and also for each ensemble.

Total volumes of recharge are calculated for each RBMD for 1961-90, 1971-2000 and for the 2020s, 2050s and 2080s.

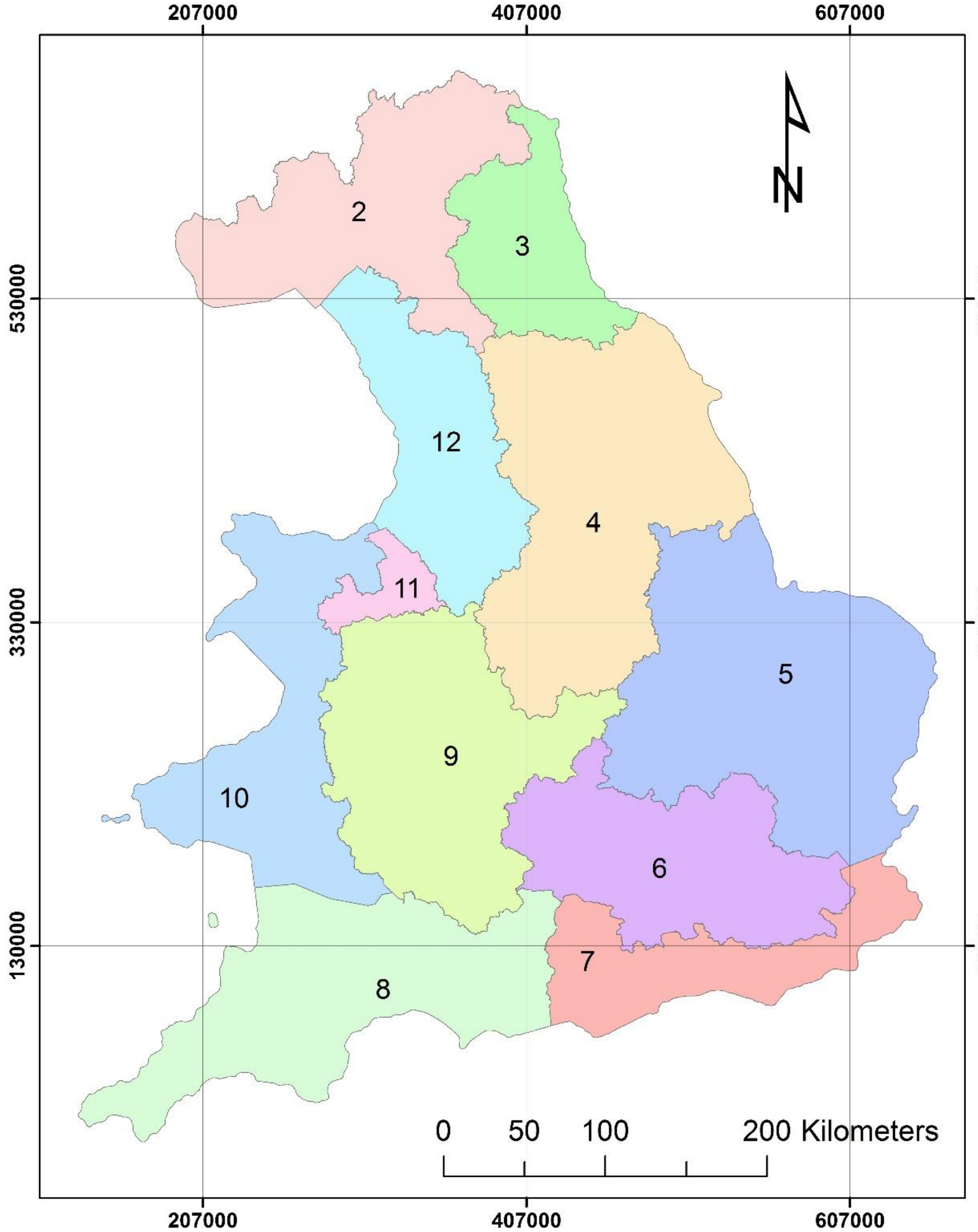


Figure 2. Distribution of river basin management districts (Contains public sector information licensed under the Open Government Licence v3.0)

2.3.2.1 Monthly changes

The mean monthly recharge value was calculated for each month. The change in recharge value in absolute terms was calculated for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).

These results are presented as annual time series plots for each month (see Appendix 5).

2.3.2.2 Empirical cumulative distribution functions (ECDFs)

ECDFs are produced by ranking the data from the smallest to the largest value. By putting the data in ascending order and then for every assigned value x, the number of data points less than or equal to x is determined. This number is divided by the sample size to calculate a probability of the occurrence of x. Each value is then plotted against the cumulative probability from the smallest to the largest to obtain the ECDF curve. Using this approach allows the median (50%tile) of each distribution to be compared so that change can be assessed. Further the slope of the line can be used to indicate whether the nature of the distribution changes . For example two ECDF plots, one with an increased median value but both with similar slopes means that the distributions are identical, but that the values are generally greater for the ECDF with the higher median value. Increasing slope means that the distribution is more “spikey” with a smaller standard deviation.

ECDFs have been produced by totalling the recharge produced for each RBMD both seasonally (winter, spring, summer and autumn) and monthly for two historic simulation periods (1961-90 and 1971-2000) and for the 2050s and 2080s.

3 Summary of key results and narrative

3.1 INTRODUCTION

Given the sheer volume of outputs produced (see Appendices) and to ensure that the report is as readable as possible, the main story has been summarised into a single narrative using a selected sub-set of model results. Whilst care has to be taken to avoid bias in selecting the results, using a reduced set of figures makes the story accessible to as wide an audience as possible.

The following results are selected:

- One set of seasonal (spring, summer, autumn and winter) recharge changes (as seasonal average value in mm/d) for each groundwater body for all of the 11 ensemble member for the 2020s, 2050s and 2080s (See Figures 3 to 5). These are based on the long-term average values for each period.
- One set of monthly averaged recharge changes (as a percentage) for each groundwater body for the median for all 11 ensemble member for the 2050s and 2080s (See Figures 6 and 7). These are based on the long-term average values for each period.
- Plots of changes in recharge (long-term monthly average as mm/d) for three (North-west, Humber and Thames) River Basin Management Districts for each ensemble member along with histograms of minimum, maximum and average of recharge totals (long-term average recharge values in 10^6 x Ml/day) for all the 11 ensembles (See Figures 8 to 13)
- Plots of empirical cumulative distribution function (ECDF) for seasonal and monthly long-term average total recharge for all the RBMD (No. 2-12). ECDF is a way of producing cumulative distribution function curves by modelling the distribution of measured data. Recharge totals are produced for seasonal summaries (Figure 16): winter (DJF), spring (MAM), summer (JJA) and autumn (SON) as well as for monthly values (Figure 17) for all of the RBMDs covering England and Wales (Nos 2 -12).

3.2 CHANGE IN SEASONAL (WINTER, SPRING, SUMMER AND AUTUMN) RECHARGE FOR EACH ENSEMBLE

To correspond with the previous work for the Future Flows and Groundwater Level project (see for example: Prudhomme et al., 2012), seasonal averages expressed as mm/d for all groundwater bodies for England and Wales for all 11 ensembles were produced. This enables the results for all 11 ensembles to be presented in a digestible form and compared against each other. Figures 3 to 5 shows the results summarised by meteorological season (winter – December, January and February (DJF); spring – March, April and May (MAM); summer – June, July and August (JJA); autumn – September, October and November (SON)). The change in fraction of recharge for the 2020s, 2050s and 2080s are presented and discussed below.

2020s: (Figure 3) In general there is increasing winter recharge with a subsequent reduction in recharge for spring and summer. For the latter this is less important as there is limited potential recharge occurring between June and August. Importantly there is a mixed signal in spring with some ensembles showing a decrease in recharge and others an increase.

2050s: (Figure 4) There is an increasingly polarised picture compared to the 2020s with winter, for a vast majority of groundwater bodies, showing an increase for each ensemble. Recharge in summer shows a consistent reduction, although not as significant as for the 2020s described above. In spring four out of the 11 ensembles demonstrate increasing recharge which is repeated for autumn.

2080s: (Figure 5) The pattern is similar to the 2050s but with increases in the number of ensembles in autumn which show an increase in recharge (six in total). However, the spatial pattern of the results in spring is mixed, with equal numbers of ensembles showing increases and decreases.

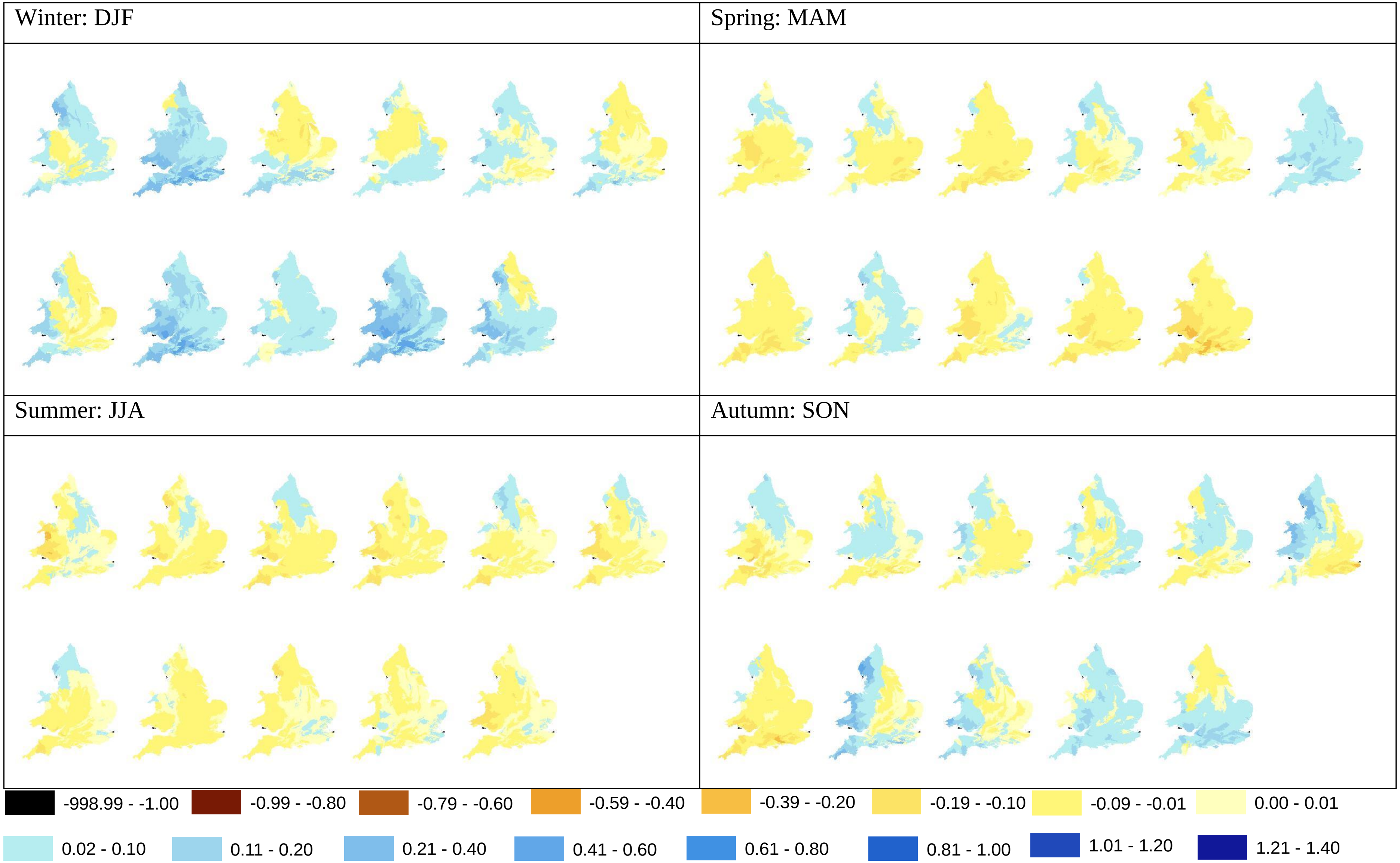


Figure 3. Seasonal changes in recharge values as seasonal average (mm/d) for groundwater bodies for each ensemble member (2020s)

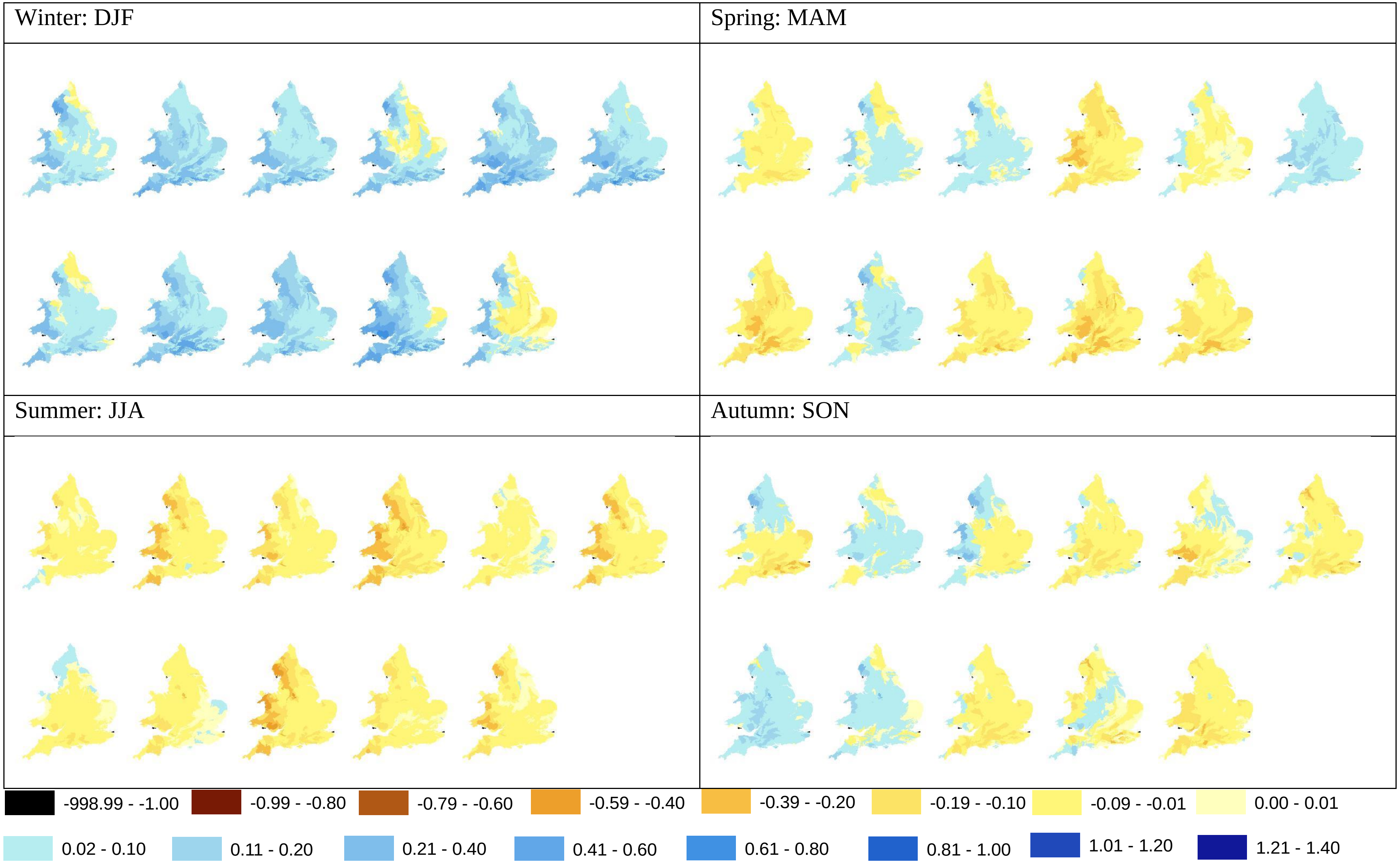


Figure 4. Seasonal changes in recharge values as seasonal average (mm/d) for groundwater bodies for each ensemble member (2050s)

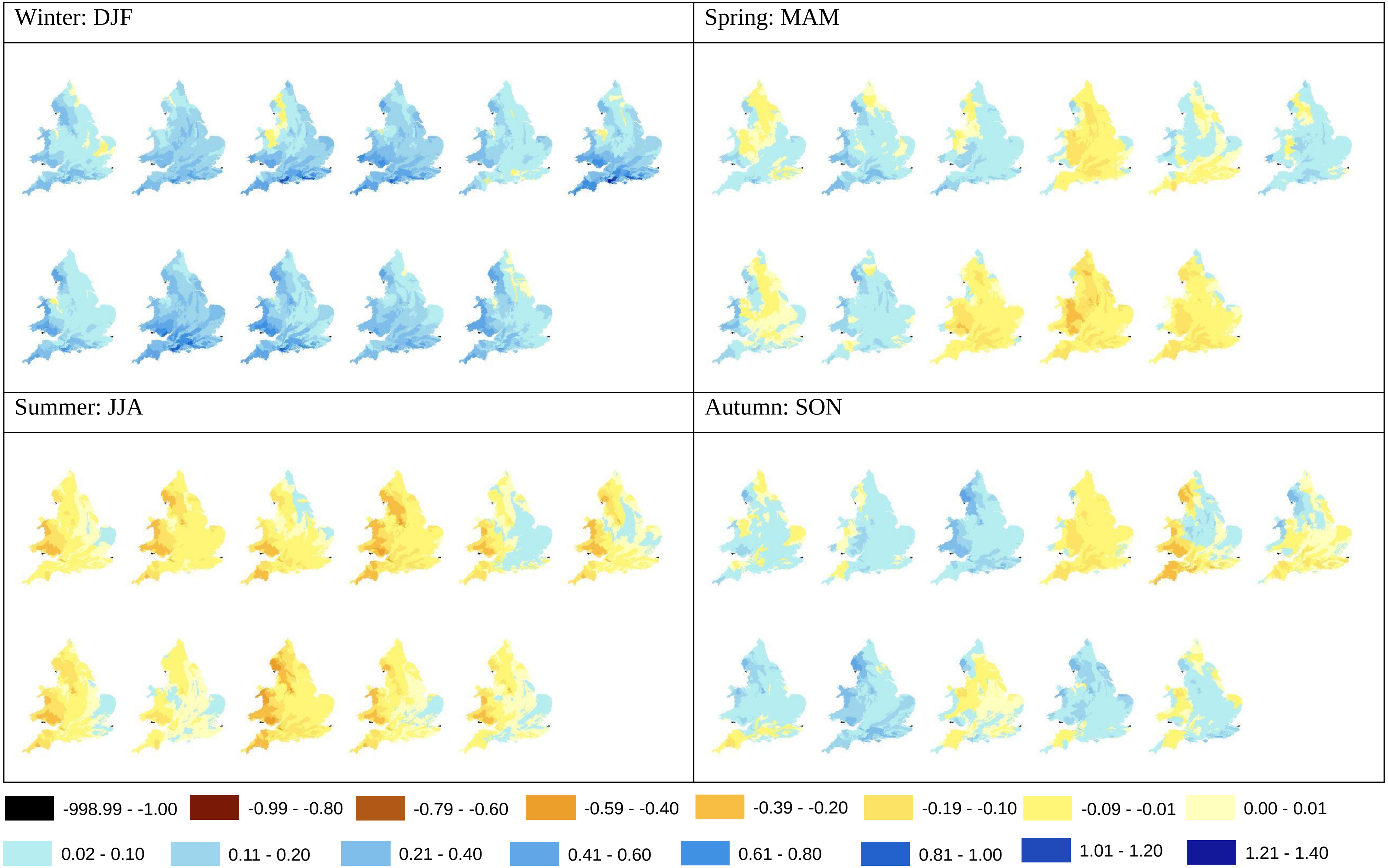


Figure 5. Seasonal changes in recharge values as seasonal average (mm/d) for groundwater bodies for each ensemble member (2080s)

3.3 MONTHLY MEDIAN PERCENTAGE CHANGE FOR ALL 11 ENSEMBLES

To investigate the details of which months exhibit the greatest change in monthly average recharge (mm/d) for groundwater bodies, the median of the change of all the 11 ensembles was produced for the 2050s (Figure 6) and 2080s (Figure 7). Note that the 2020s were not included as they are thought to be overly influenced by the climatic variability rather than climate change. The changes are summarised in Table 2 below and demonstrate that for both the 2050s and 2080s recharge increases during winter and for November and decreases during summer. The pattern is much more mixed for both autumn and spring with both seasons exhibiting spatial variability.

Table 2. Summary of seasonal changes for median of the change for each ensemble

Season	**2050s**	**2080s**
Winter	Widespread increases for all winter months confirm the pattern observed in seasonal summaries	Consolidates patterns observed for 2050s
Spring	March – spatially variable with central and southern England showing increases, rest decreases. April and May show widespread decreases	Much more mixed picture (spatially varying increases and decreases)
Summer	Very significant and widespread reductions for all summer months	Less pronounced change in June and July than 2020s and more spatially variable. August more consistent with 2020s except for parts of east Anglia which show increases
Autumn	September and October also exhibit significant decreases Increase is only seen for November.	September mainly decreased but some areas increase. November again has a significant increase

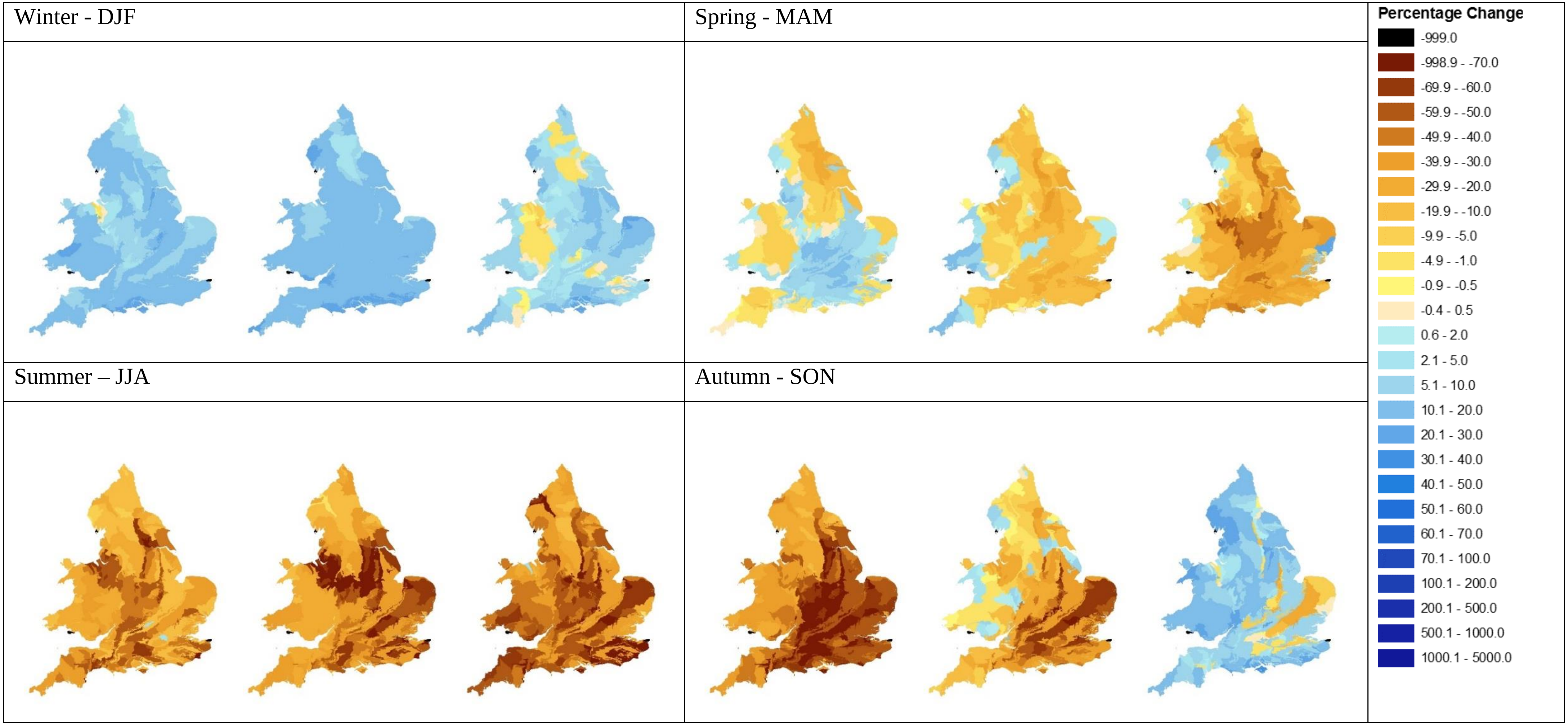


Figure 6. The Median percentage change in monthly recharge of the ensemble members shown for each month (2050s)

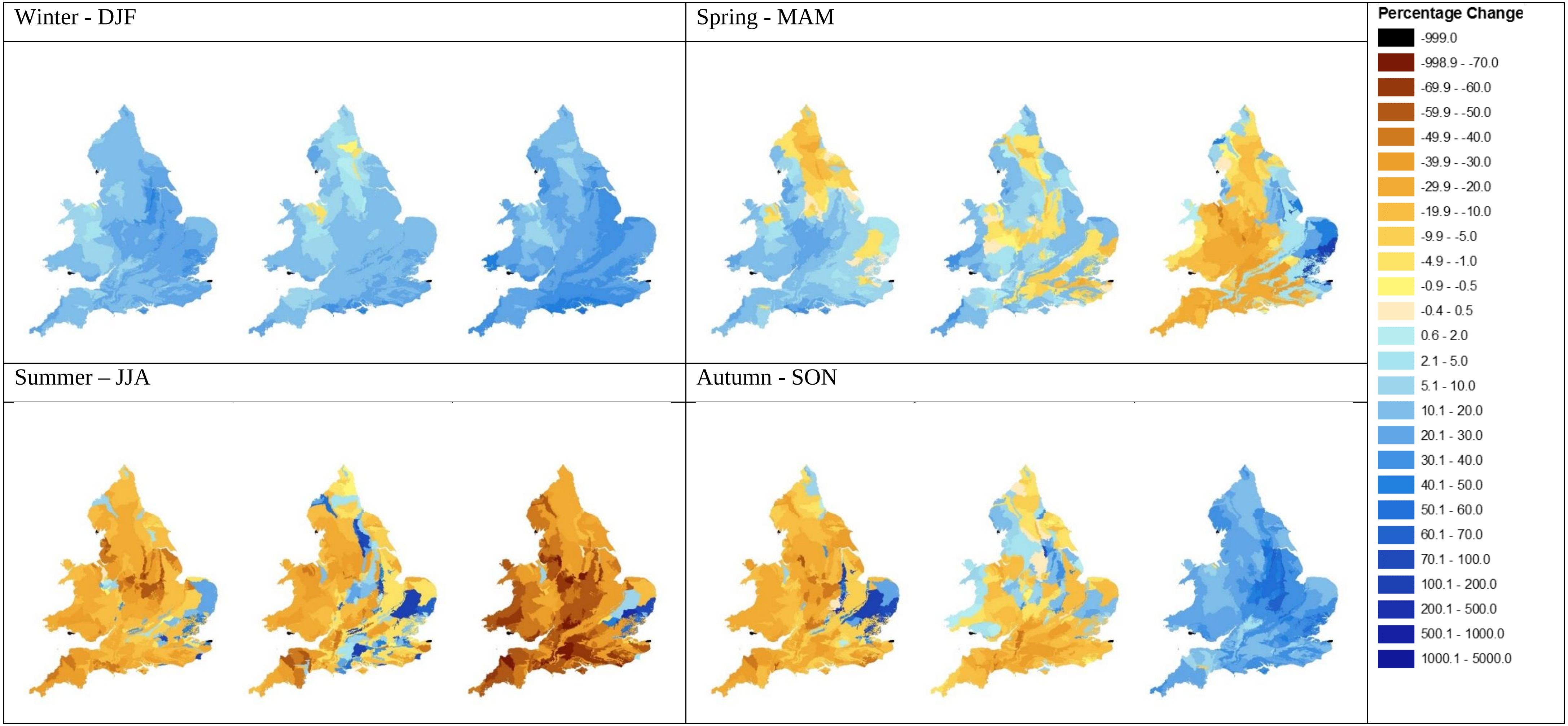


Figure 7. Median values for percentage change in monthly recharge of all 11 ensemble members (2080s)

3.4 TOTAL RECHARGE FOR RIVER BASIN MANAGEMENT DISTRICTS

Recharge summaries for the North-west (RBMD no. 12), Humber (RBMD no. 4) and Thames (RBMD no. 6) were used to illustrate the general trends for the impact of climate change on potential recharge in different parts of England and Wales (Figures 8 to 13 and Tables 3 to 5). The plots are of monthly average recharge (as mm/d) for the historical simulation and changes in monthly average recharge (as mm/d) for the 2020s, 2050s and the 2080s. Histograms were provided of minimum, maximum and average recharge totals expressed as Ml (equivalent of annual average recharge).

The general view is that climate signal (however that manifests itself for each RBMD) predominates as the time slices go forward in time (i.e. 2020s to 2050s to 2080s).

- North-west: broad agreement across ensembles showing a decrease in recharge over summer / early autumn which becomes more prevalent from the 2020s to the 2050s and on to the 2080s. This is followed by an increase in winter recharge and a more mixed picture in spring. Overall, the total recharge volume (Table 3 and Figure 9) increases over the 2020s, 2050s and 2080s.
- Humber: generally more subdued response than the North-west and Thames. The ensembles show variable recharge over late winter and early spring recharge, followed by relatively small change predicted for late spring and early summer recharge. Consistent decreases in recharge are confined to August and to a lesser extent September, whilst consistent increases occur in late autumn/early winter. The variability is similar in all three time slices. There is an increase in the average recharge volume totals compared to the Historical Simulation with results from the 2050s showing greater totals than the 2020s and 2080s (Table 4 and Figure 11).
- Thames: Generally increasing within the recharge season, i.e. late autumn and winter. The greatest increase is observed in January and February. Average totals of recharge increase compared to Historic Simulation, but with a corresponding increase in range (minimum value to maximum) – see Table 5 and Figure 13.

Note that all ensembles are equally likely and that whilst the average increases from the 2020s to the 2050s and onto the 2080s there is an equal likelihood that recharge volumes could decrease.

In summary the results for the Humber RBMD shows that the response in the east of the country is more damped. The North-west RBMD sees a reduction in late summer / early autumn which could be interpreted as resulting from changes to the western predominance of weather systems. The recharge response in the Thames RBMD is similar to North-west RBMD with increases in recharge in the current recharge season. However, the response in the Thames RBMD in January and February is more pronounced than North-west RBMD possibly due to higher recharge signals in the west of the catchment and lower in the east of the catchment.

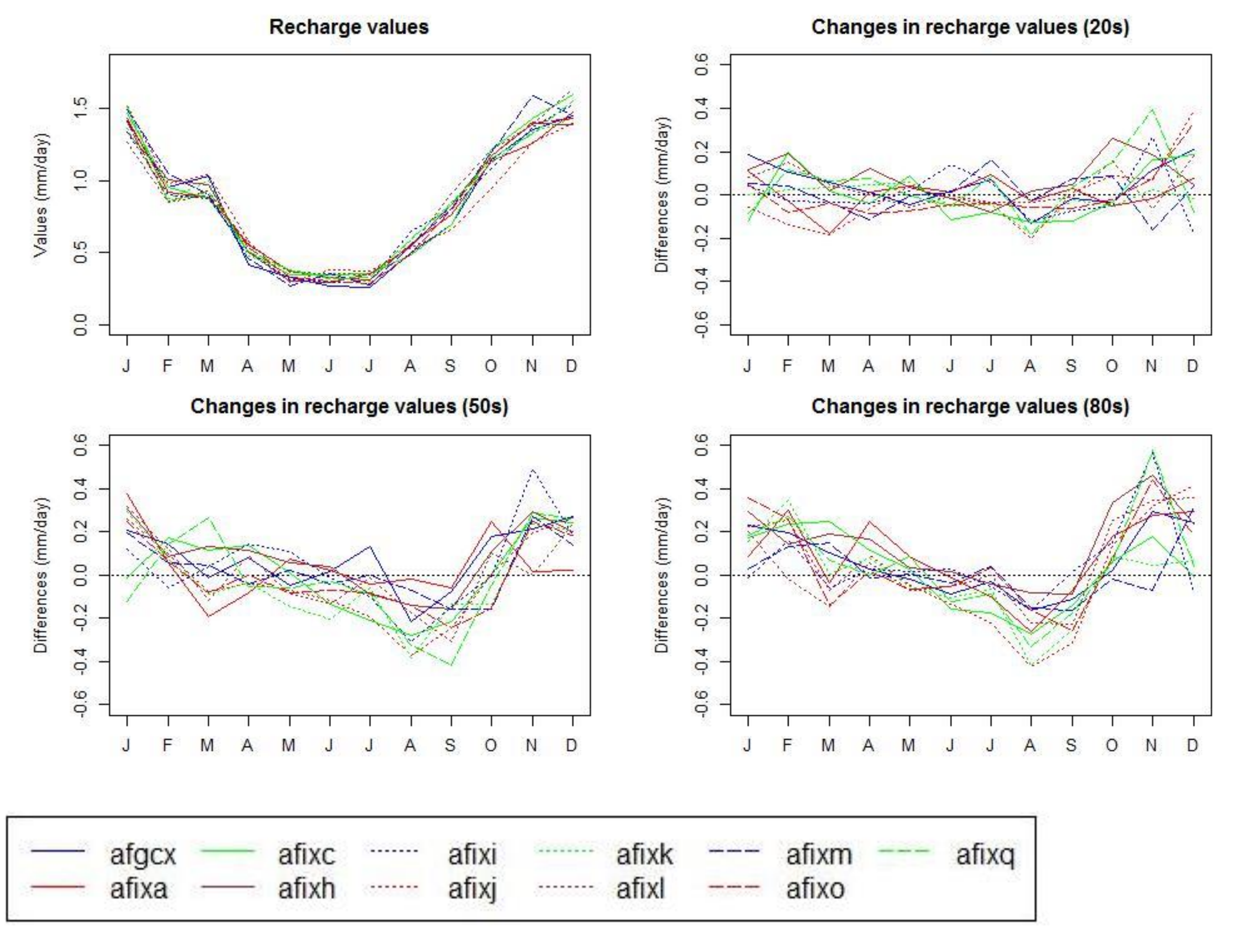


Figure 8. Comparison of historic and future ensemble monthly recharge results for North-west RBMD (12)

Table 3. Recharge volumes for Catchment 12: North-West

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	105.24	102.95	107.38	109.71	107.93	104.77	105.67	109.42	105.76	108.67	106.99	102.95	109.71	106.77
1971-2000	106.12	105.32	108.08	113.47	109.50	105.05	108.34	108.32	109.14	109.39	104.03	104.03	113.47	107.89
20s	110.55	107.53	109.57	117.70	106.13	105.22	105.04	114.72	112.13	105.59	115.18	105.04	117.70	109.94
50s	114.34	111.27	110.51	117.64	111.08	103.00	103.01	110.64	113.48	104.72	107.71	103.00	117.64	109.76
80s	111.53	116.35	111.81	124.74	111.90	107.76	105.14	114.58	112.39	112.53	114.99	105.14	124.74	113.07

Note: Recharge values in 10^6 x Ml/day

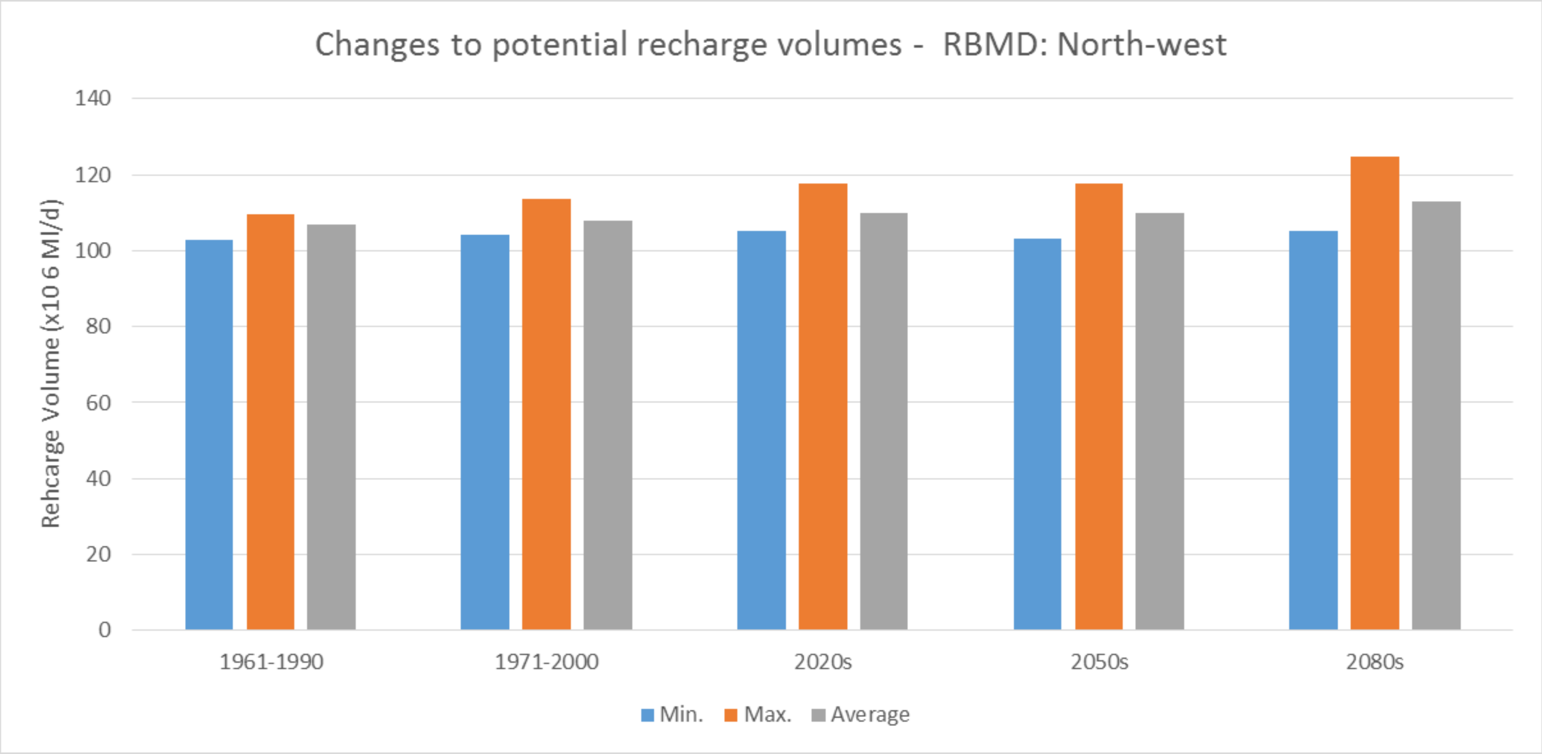


Figure 9. Changes to monthly recharge for North-west RBMD (12)

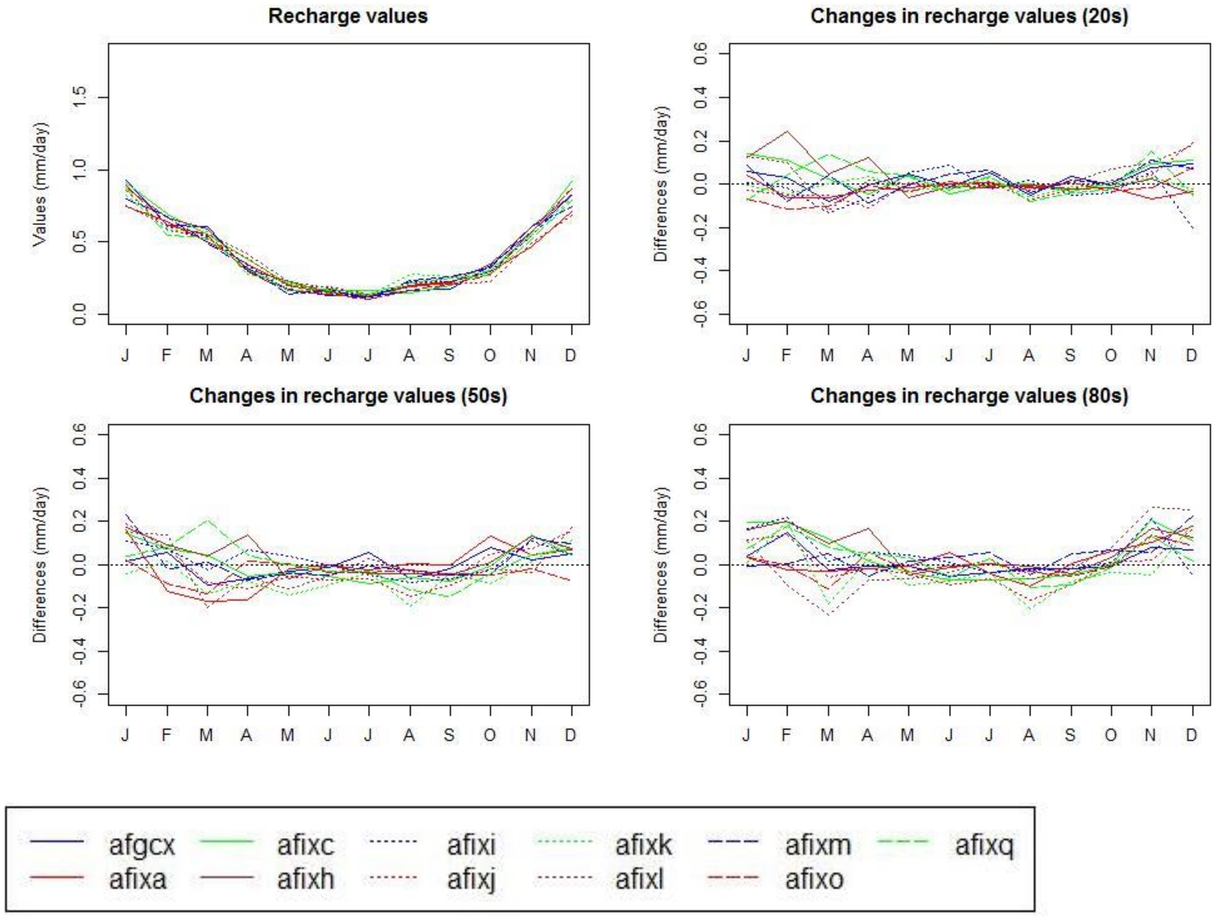


Figure 10. Comparison of historic and future ensemble monthly recharge results for Humber RBMD (4)

Table 4. Recharge volumes for Catchment 4: Humber

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	112.41	108.98	118.00	123.10	115.07	109.50	112.26	121.23	112.65	117.86	112.63	108.98	123.10	114.88
1971-2000	116.05	107.27	119.98	127.61	118.39	116.32	118.13	122.55	109.22	114.74	107.39	107.27	127.61	116.15
20s	122.61	102.30	131.78	129.58	106.31	108.86	114.70	129.74	120.20	107.27	116.49	102.30	131.78	117.26
50s	116.75	106.98	124.18	131.78	118.36	105.00	100.14	121.62	118.44	102.94	115.79	100.14	131.78	114.73
80s	119.71	113.01	134.43	140.09	126.80	107.54	107.76	122.77	124.47	114.74	119.42	107.54	140.09	120.98

Note: Recharge values in 10^6 x Ml/day

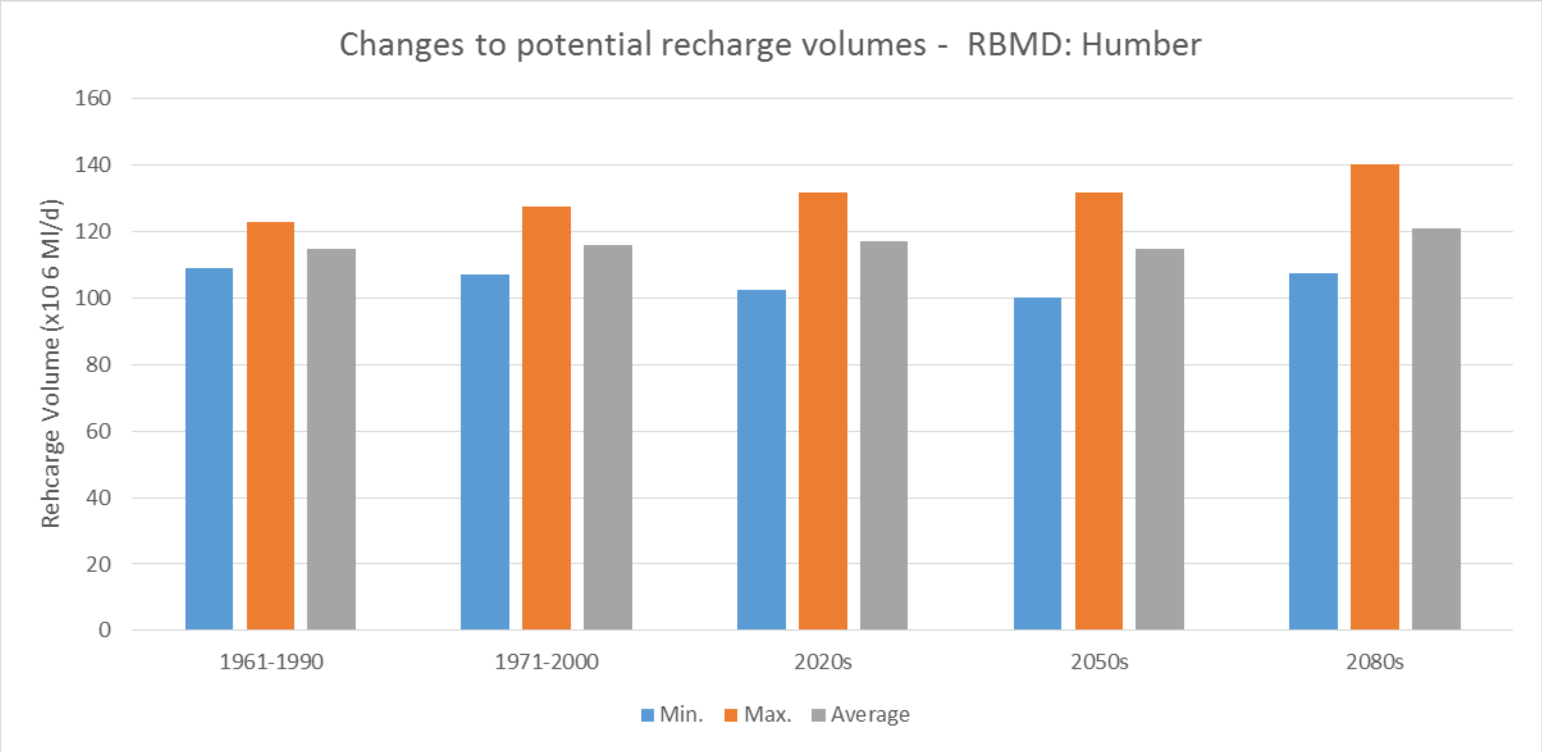


Figure 11. Comparison of historic and future ensemble monthly recharge values for North-west RBMD (12)

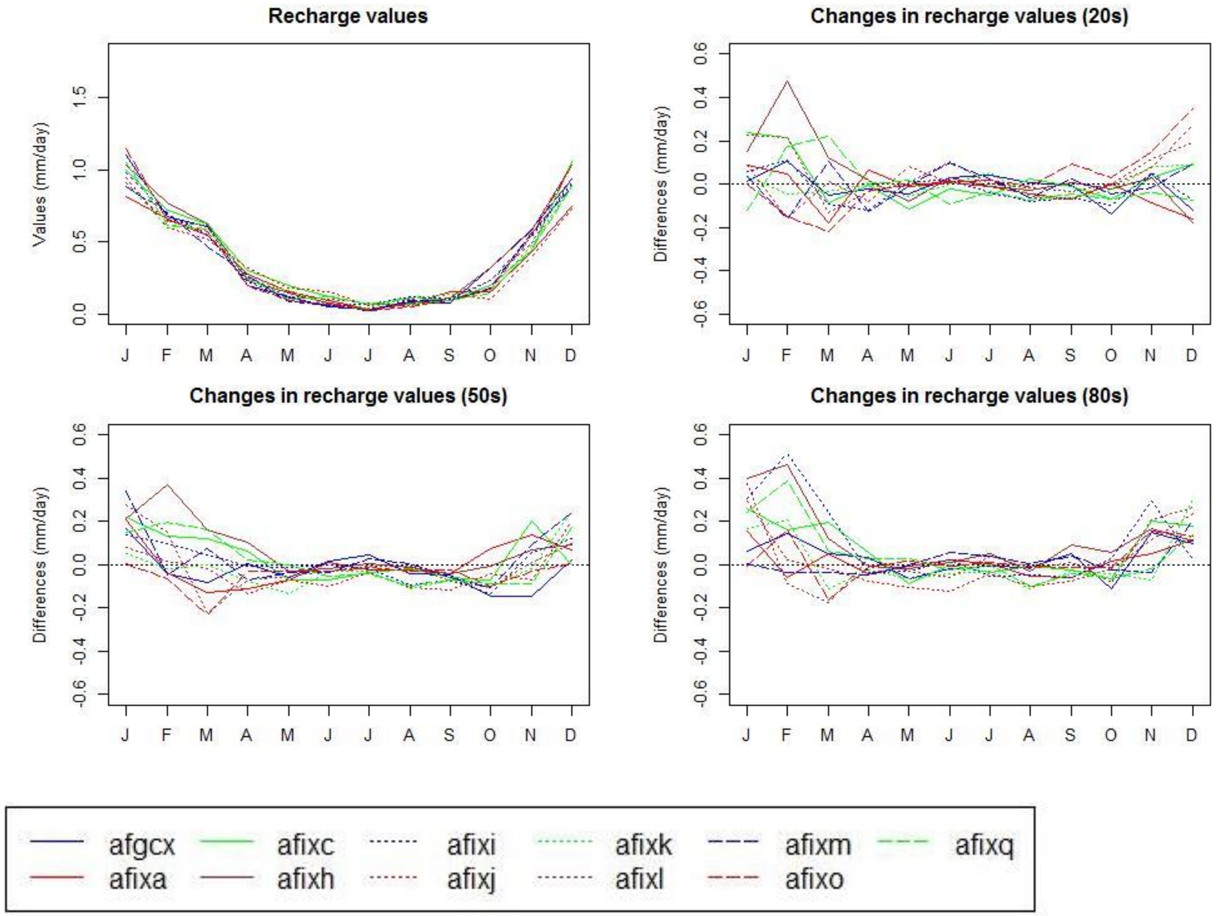


Figure 12. Monthly recharge for Thames RBMD (6)

Table 5. Recharge volumes for Catchment 6: Thames

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	63.69	62.98	69.27	73.05	66.99	62.78	64.65	69.43	63.67	67.85	64.16	62.78	73.05	66.23
1971-2000	69.05	62.16	68.18	78.81	65.74	66.59	67.59	66.13	60.43	69.67	67.23	60.43	78.81	67.42
20s	67.70	54.82	74.84	80.72	62.00	64.77	64.99	75.64	62.23	71.78	62.96	54.82	80.72	67.49
50s	65.53	61.04	77.21	86.57	68.49	56.28	60.90	65.56	69.08	59.53	68.99	56.28	86.57	67.20
80s	74.65	62.53	82.65	93.39	83.39	63.01	66.50	72.57	64.53	70.82	73.65	62.53	93.39	73.43

Note: Recharge values in 10^6 x Ml/day

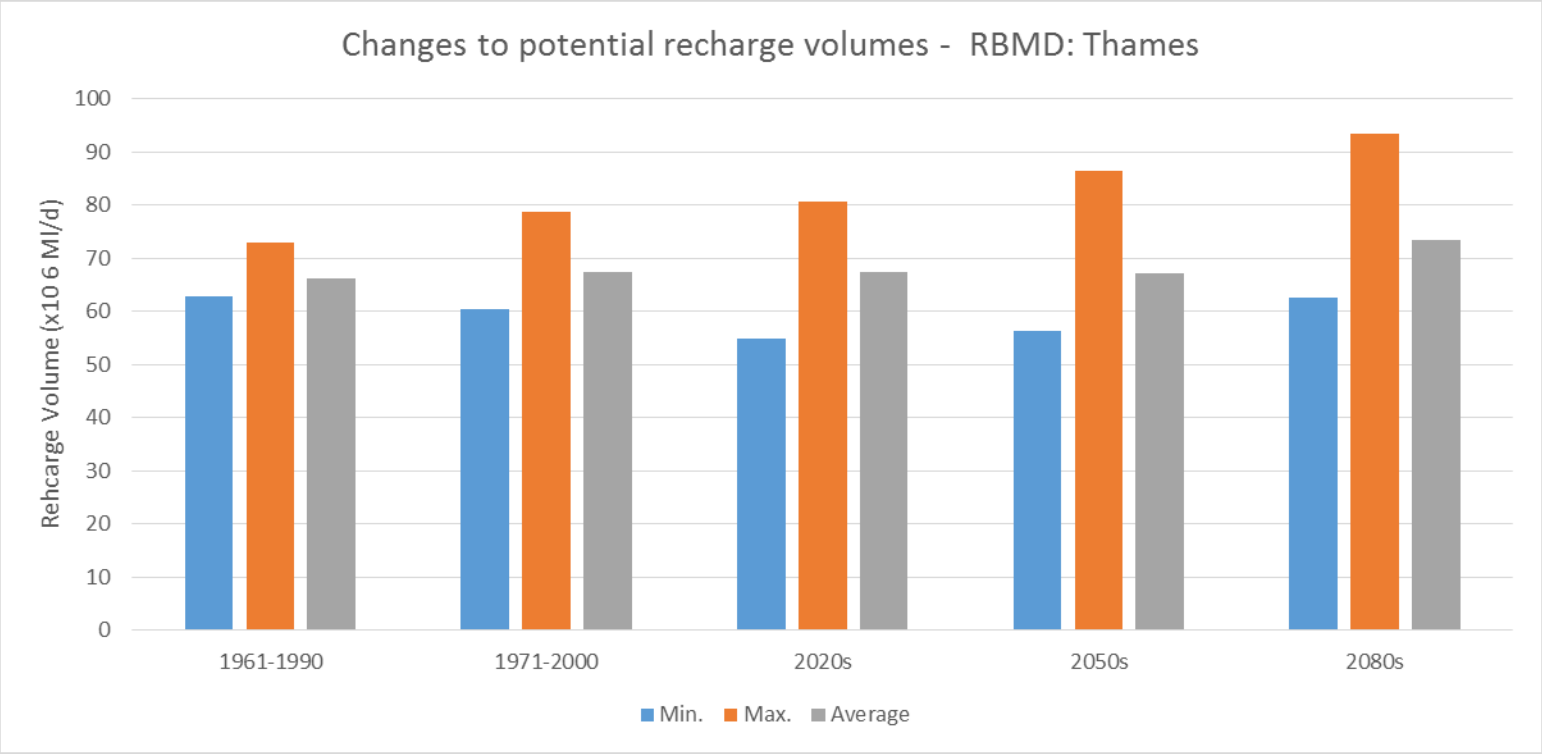


Figure 13. Changes to monthly recharge for Thames RBMD (6)

3.5 SEASONAL AND MONTHLY EMPRICIAL DISTRIBUTION FUNCTIONS

ECDF plots for seasonal long-term recharge totals along with monthly totals for all the RBMD included in this report are presented in Figure 14 and 15 along with median values of long-term total recharge in Table 6. These plots are produced to examine the distribution of the recharge for each year along with how these change from the historic simulation to the future climate change for the 2050s and 2080s. Four 30 year periods are chosen: 1961-90, 1971-2000, 2050s and 2080s to enable direct comparison of the total recharge calculated over the RBMD.

Seasonal: Examining Figure 14 and Table 6 and focussing on the median (50%ile) for each ECDF curve shows a significant increase in winter, small variability during spring and autumn with a significant reduction in summer.

Monthly: Examining Figure 15 the following is highlighted:

- For winter (DJF): Future recharge is greater than the historic simulation.
- For spring (MAM): Similar profiles exist for historic simulation, 2050s and 2080s.
- For summer (JJA): Recharge reduces from historic simulation to future climate (2050s and 2080s).
- For autumn (SON): There is a switch from a reduction in the future in September, neutral in October and an increase in November.

The analysis of seasonal and monthly trends from the historic simulation highlights that summer will become a period of reduced potential recharge. The reduced potential recharge in September (historically the start of the recharge season) suggests that the period of low recharge could be extended by one to two months, thereby shortening the recharge period. This is an important trend to note as prolonged dry weather in a year could have a significant impact on groundwater storage recovery.

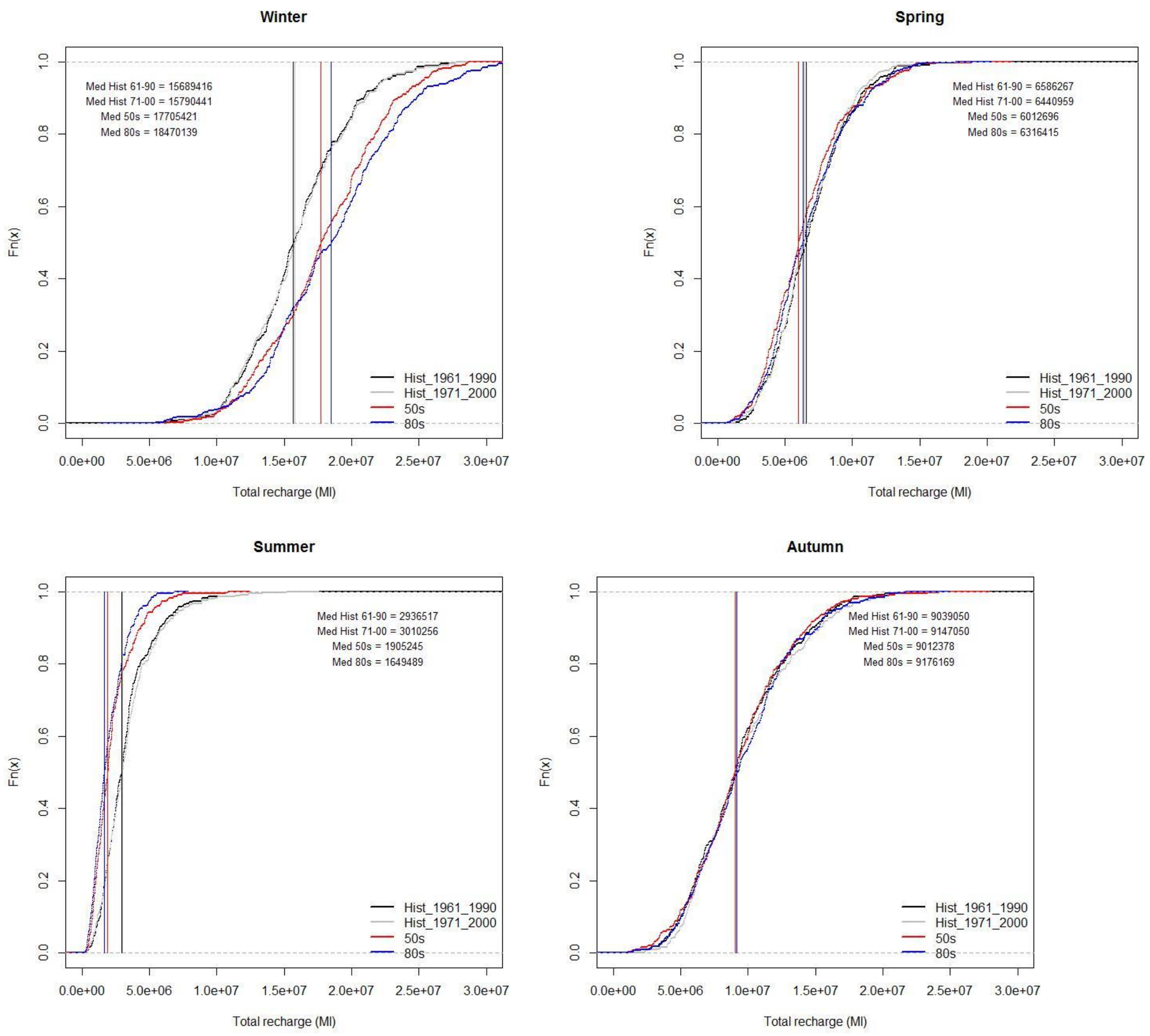
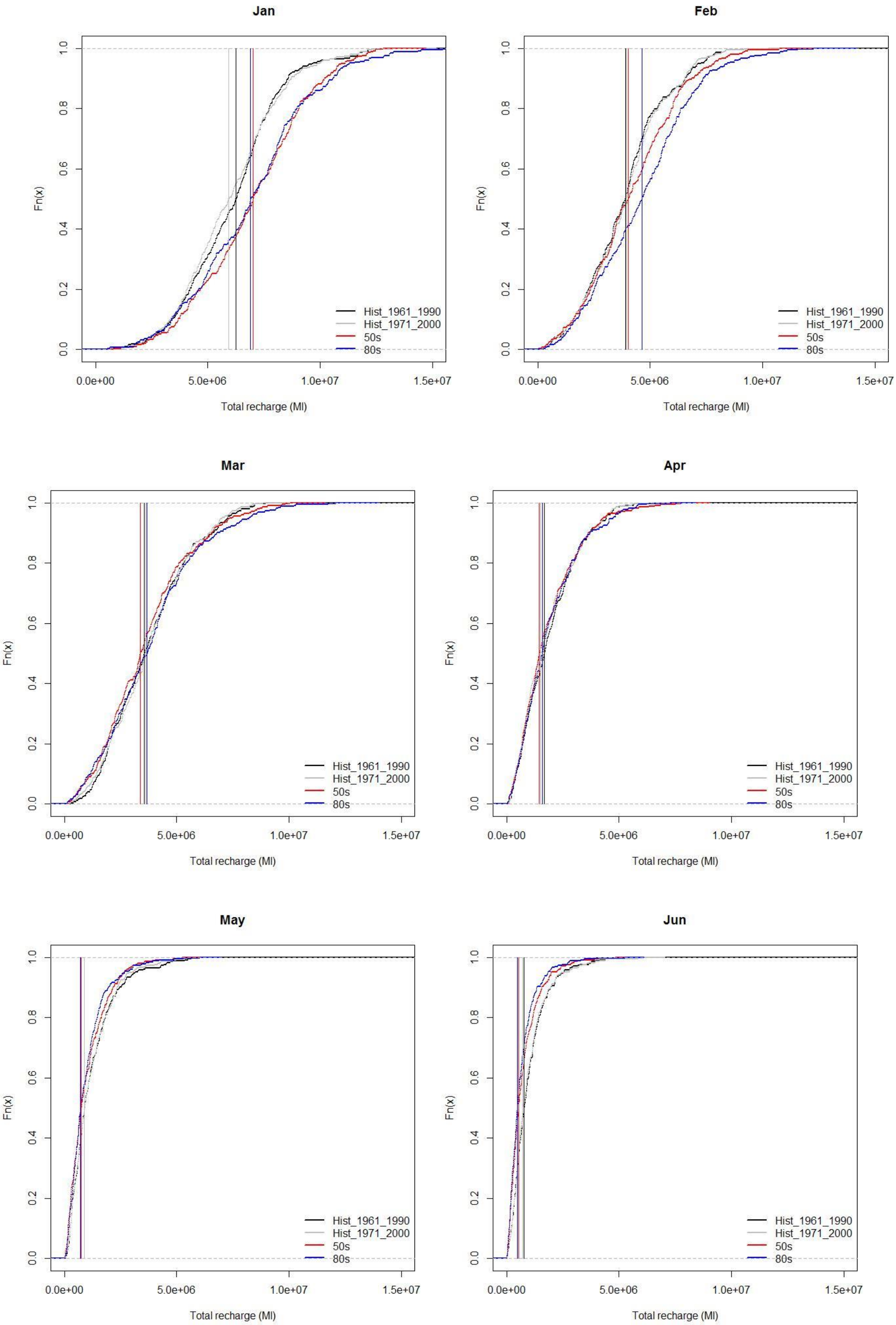


Figure 14. Empirical cumulative distribution function plots for recharge totals (RBMD no. 2-12) over the winter (DJF), spring (MAM), summer (JJA), and autumn (SON) seasons

Table 6. Median values (50%tile) of total recharge (RBMD no. 2-12) for historical simulation and 2050s and 2080s (Ml).

Time period	Winter	Spring	Summer	Autumn
1961-90	15689416	6586268	2936518	9039051
1971-00	15790442	6440959	3010257	9147050
2050s	17705422	6012697	1905246	9012378
2080s	18470139	6316415	1649490	9176169


Jan
Feb
Mar
Apr
May
Jun
Fn(x)
Total recharge (Ml)
0.0e+00
5.0e+06
1.0e+07
1.5e+07
0.0
0.2
0.4
0.6
0.8
1.0
Hist_1961_1990
Hist_1971_2000
50s
80s

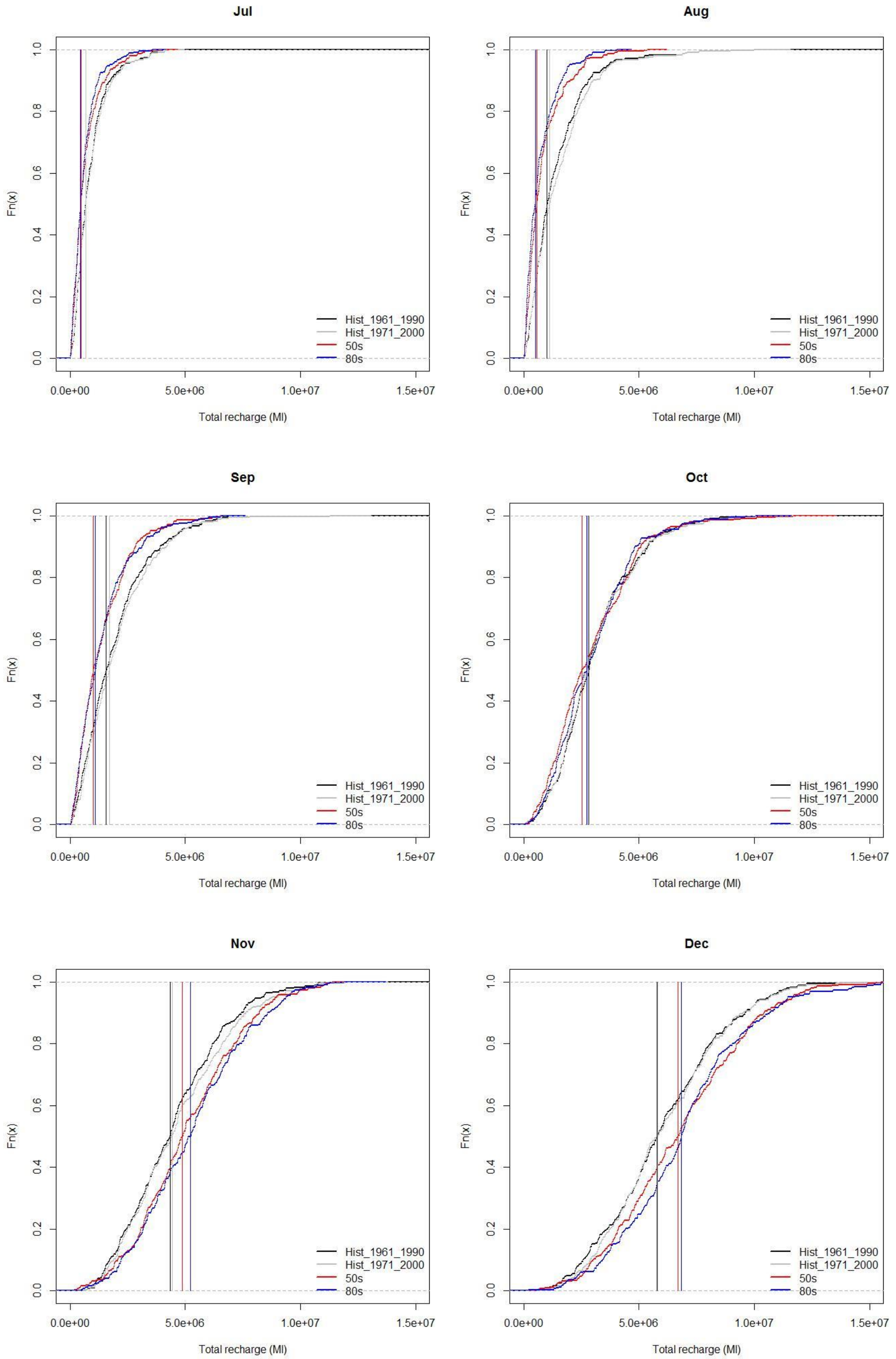


Figure 15. ECDF plots for monthly recharge totals (RBMD no. 2-12): historic simulation, 2050s and 2080s

3.6 SUMMARY

Once the climate change signal becomes more dominant, i.e. 2050s and 2080s, the overall picture is one of shorter recharge season with a similar or increased amount of potential recharge. There are, however, regional variations with basins in the west of England and Wales showing greater changes in late autumn / early winter. The reduction in recharge in the “shoulder” of the recharge season means that more recharge occurs in fewer months. Whilst this means that the groundwater balance is maintained and so is “good news” for water resources, it may make the system more vulnerable to drought if one or two months within the recharge season experience lower than average rainfall.

4 Summary and recommendations for further work

4.1 SUMMARY

4.1.1 Work undertaken

This report has described the application of the BGS distributed recharge model ZOODRM to produce recharge values (potential recharge) for Great Britain (England, Scotland and Wales). Detailed analysis has been completed for England and Wales as part of this project. This model has been run with the rainfall and potential evaporation for the Future Flows Climate datasets (11 ensembles). The following results have been produced:

- For the groundwater bodies in England and Wales:
    - The mean, standard deviation and the following percentiles: 10, 25, 50, 75, 90 have been produced for the Long Term Average (LTA) annual recharge totals of each period; simulated historic (1950-2009), 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
    - The LTA 25th percentile and 75th percentile for the simulated historic for each month has been calculated as mm/d. The daily recharge values calculated by the recharge model were aggregated to monthly values first and the analysis was undertaken using these monthly values (as mm/d). A proportion of recharge values above and below these values for the future climate has been calculated.
    - The LTA mean monthly recharge values were calculated for each month for the simulated historic period. The change in monthly average recharge values (mm/d) in absolute terms was calculated for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
    - Monthly change factors (percentage difference between monthly long-term average recharge for historic simulation and future climate 20s, 50s and 80s) for each groundwater body for each ensemble were produced. These have been summarised in plots which illustrate for each month the minimum, maximum and median monthly change factor from all the ensembles for each groundwater body.
- River Basin Management Districts in England and Wales:
    - The LTA mean monthly recharge value was calculated for each month. The change in recharge value in absolute terms was calculated for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
    - The long-term average total recharge volume as x10^{6} Ml was calculated for 1961-90, 1971-00 and for the 2020s (2010 - 2039), 2050s (2040 - 2069) and 2080s (2070 - 2099).
    - Empirical cumulative distribution functions (ECDF) have been produced for seasonal (spring, summer, autumn and winter) as well as monthly averages for historic simulation (both 1961-1990 and 1971-2000) as well as for the 2020s, 2050s and 2080s.

4.1.2 Summary of findings

The results confirm the dynamic between climate variability and climate change with a stronger climate signal being observed in the 2080s than either of the 2020s or 2050s. This is evidenced by the increasing sign of climate change for the 2080s over the 2020s or 2050s demonstrated by the ECDF plots in Section 3.4.Generally the recharge season is peakier in the future, with greater recharge occurring in fewer months. Typically the recharge season is between five to seven months each year (September to April) during the historical simulation. It appears that this is shortened by one or two months for the future climate predictions. This is seen in both the changes in 25% / 75% recharge values (Appendix 2) and the monthly differences (Section 3.5 and

Appendix 3). There appears to be agreement between the ensemble outputs on this feature of predicted change.

When recharge volumes were produced for the RBMDs (Section 3.4 and Appendix 5), the volumes tend to increase from the historical simulation to the 2020s/2050s, but more significantly in the 2080s. However, the range of possible outcomes also increases and so one possible outcome is that recharge volumes reduce.

The recharge season appears to be forecast to become shorter with a greater amount of recharge "squeezed" into fewer months (e.g. Figure 14 and Section 3.4). This could result in greater "lumpiness" of the recharge signal leading to flashier groundwater level response and potentially greater drought vulnerability. The latter might be the case if rainfall "fails" for one month, since rainfall totals are reliant on fewer months. Furthermore, if potential recharge took place over fewer months the lead in time for reaching drought status could also be reduced. These findings could have implications for water resources managers planning and responding to droughts in future. The increased vulnerability to drought could have knock on impacts for groundwater users and for groundwater dependent rivers, lakes and wetlands. Further groundwater hydrographs may become spikier which may lead to increased risk of groundwater flooding.

Whilst this work offers concrete conclusions, there are limiting assumptions and caveats that need to be observed. These caveats include: the current study has calculated potential recharge as opposed to what actually reaches the water table, it doesn't take into account change in nature of rainfall, i.e. increase intensity and there may be increased amounts of rejected recharge due to a higher water table due to "spikier" groundwater response.

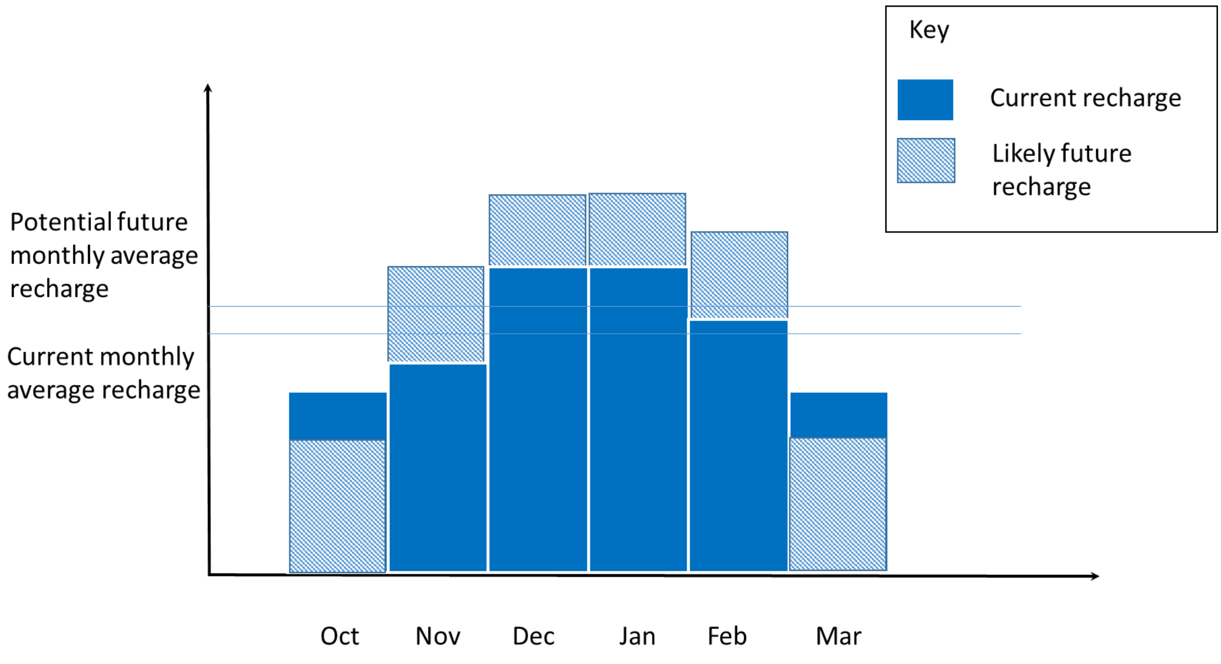


Figure 16. Indicative change in monthly recharge under conditions of climate change

4.2 RECOMMENDATIONS FOR FURTHER ANALYSIS

Given the amount of model outputs produced, a more detailed examination of the results for both groundwater bodies and those produced for the RBMDs would be beneficial. The summary plots produced for the groundwater bodies should be used as a basis for further work. Four issues in particular need to be addressed:

1. Integration of recharge volumes for the River Basin Management Districts – One issue that is clear is that whilst the 2050s and 2080s demonstrate a shorter recharge season, the

volumes from the RBMD show an increase. However, the plots for the summaries of ensembles (Appendix 5) show variation between the groundwater bodies. Further work should be undertaken to examine the impact of changing recharge on water resources and in particular groundwater bodies associated with the outcrops of the primary aquifers: Chalk, Permo-Triassic Sandstone and Jurassic Limestone. Alongside this the results for each time slice (2020s. 2050s and 2080s) for the groundwater bodies should be ranked. This will enable the areas where potential recharge may decrease to be identified.

2. Shortening of recharge season and vulnerability to drought – given the indication that more recharge is occurring in fewer months then the question is “does this make groundwater resources more vulnerable to drought?”. This question needs to be addressed to consolidate the underlying assumption that recharge is predicted to increase.
3. Range of ensembles and likely worse cases – examining the range of recharge volumes for each RBMD for the full set of ensembles show that recharge could decrease under some climate scenarios. The likelihood of this outcome and its implications needs to be examined in more detail.
4. Implications for water resources - Marrying the outputs of the model with either a water balance, e.g. CAMS ledger or producing change factors for recharge. The latter could be used with regional groundwater models or with the current qualitative status of the groundwater bodies and examining how they may change under future projected climate.

Finally whilst the initial analysis has focussed in how recharge will change for water resources, no consideration of groundwater flooding has been included. It is recommended that work on how the frequency of groundwater flooding is affected by climate change be examined.

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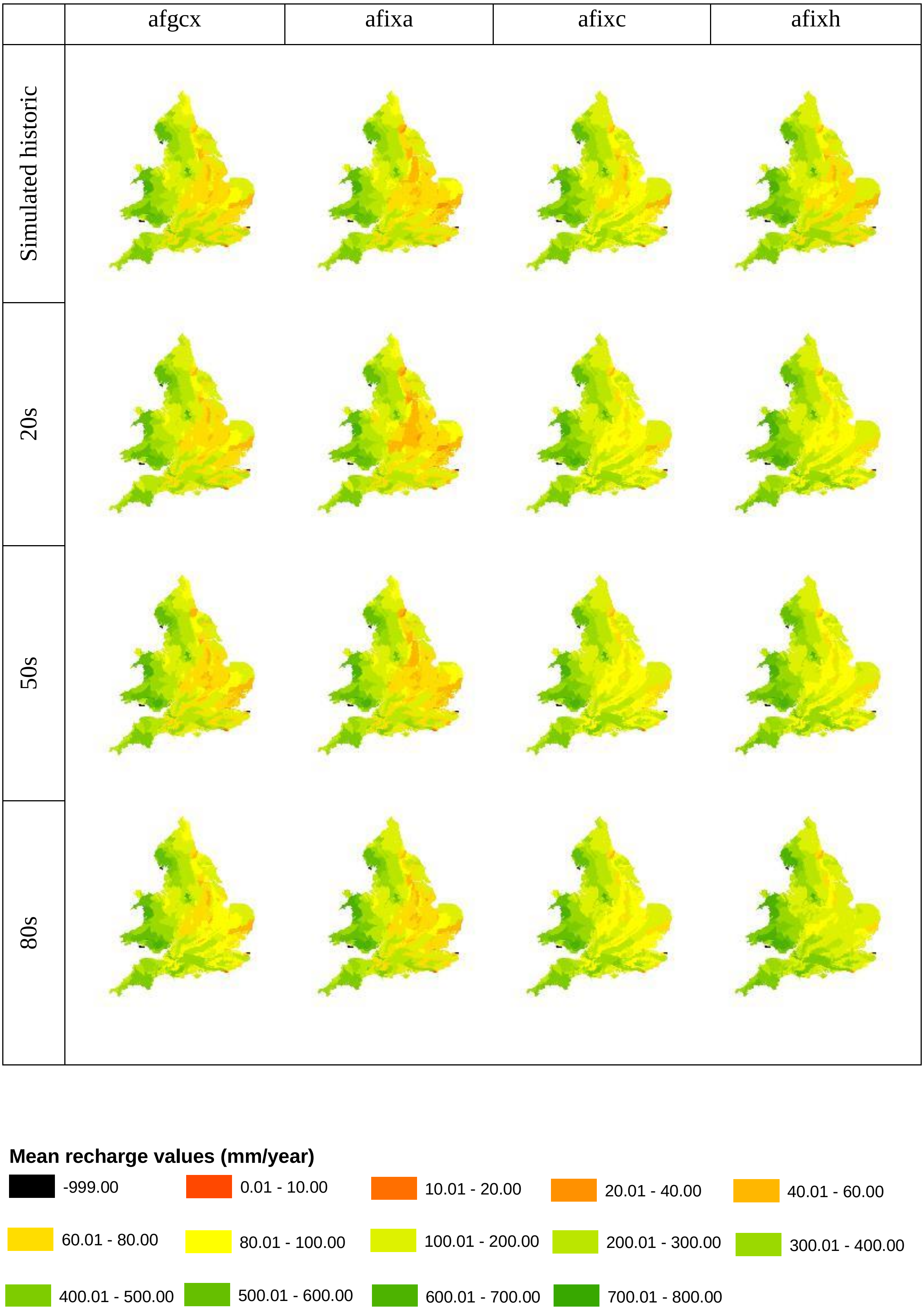
Appendix 1 Mean, standard deviation and percentiles for all recharge values

Figures A1 to A7 show the mean, standard deviation and 10, 25, 50, 75 and 90th percentiles for the historical simulation, 2020s, 2050s, 2080s and the whole simulation for all 11 ensembles. In general whilst this is a useful exercise to undertake, there are limited differences between each ensemble; however, the spatial variation of recharge for each run is much more prevalent.

Examination of Figure A1 shows that for the mean recharge generally speaking lower recharge occurring in the north-east, central and eastern England. For the standard deviation (Figure A16) there is the lowest variability in the north-east and central England with the highest is in southern England.

For the percentiles of recharge (Figures A3 to A7): the spatial distribution is similar for all five percentiles: lowest values in central southern England and the highest in the North-west, Wales, Central and Eastern England. As the percentile increases, as would be expected the absolute values of recharge increase.

Please note that “-999” signifies where data are not available to undertake the recharge calculation.


afgcx
afixa
afixc
afixh
Simulated historic
20s
50s
80s
Mean recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
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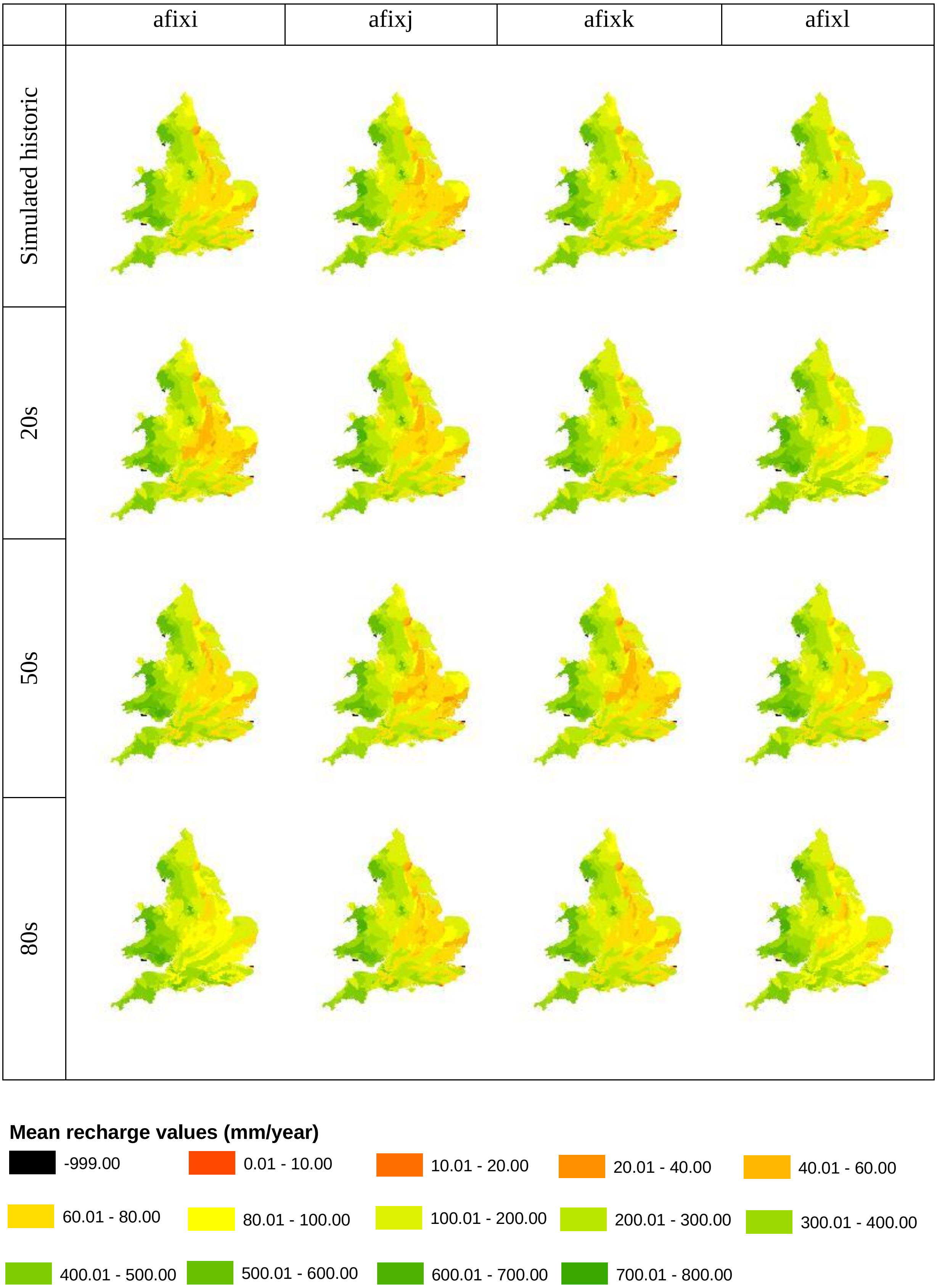
600.01 - 700.00
700.01 - 800.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
Mean recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00

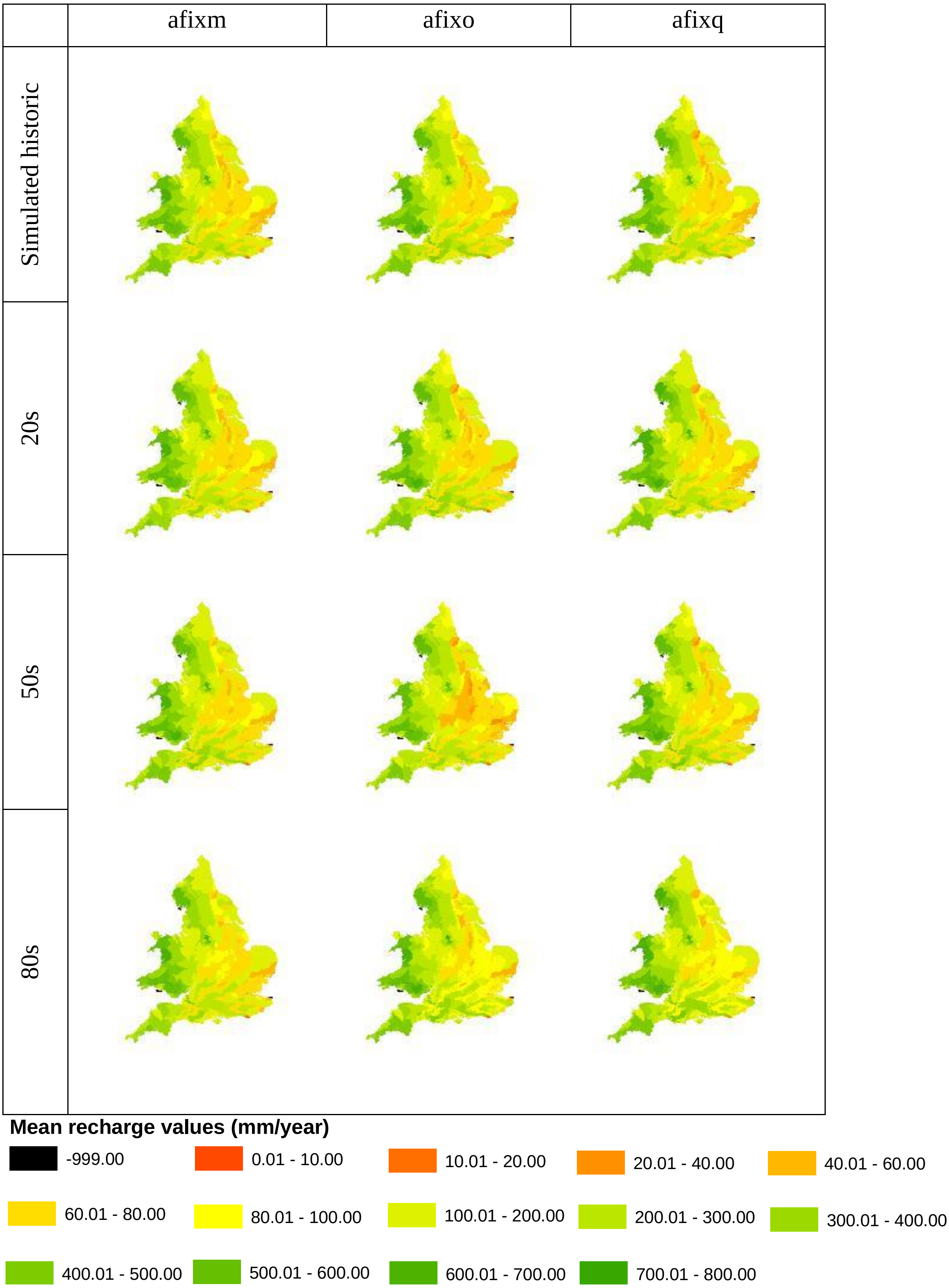
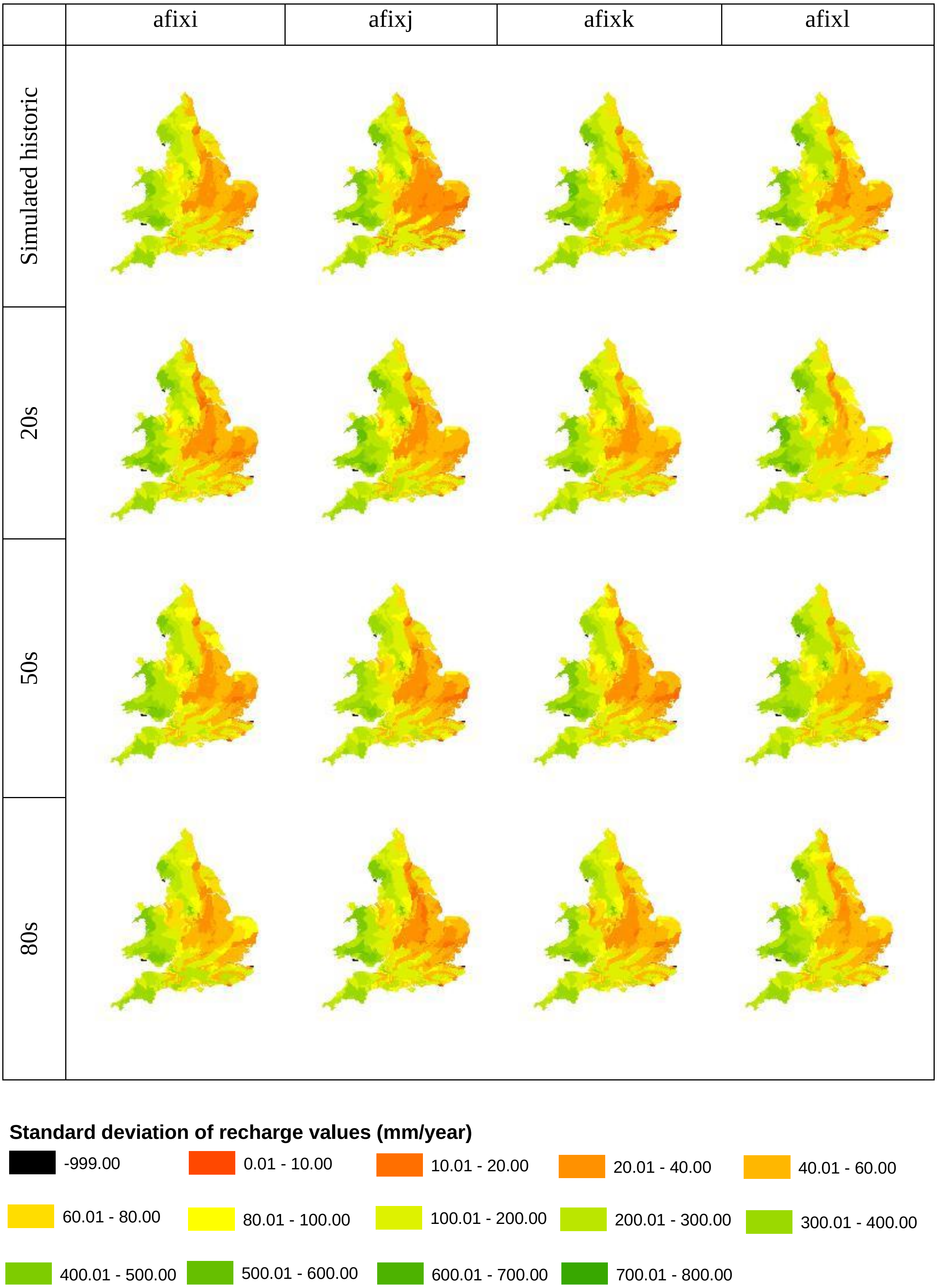


Figure A1. Mean recharge values for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble

	afgcx	afixa	afixc	afixh
Simulated historic				
20s				
50s				
80s				

Standard deviation of recharge values (mm/year)

-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
Standard deviation of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00

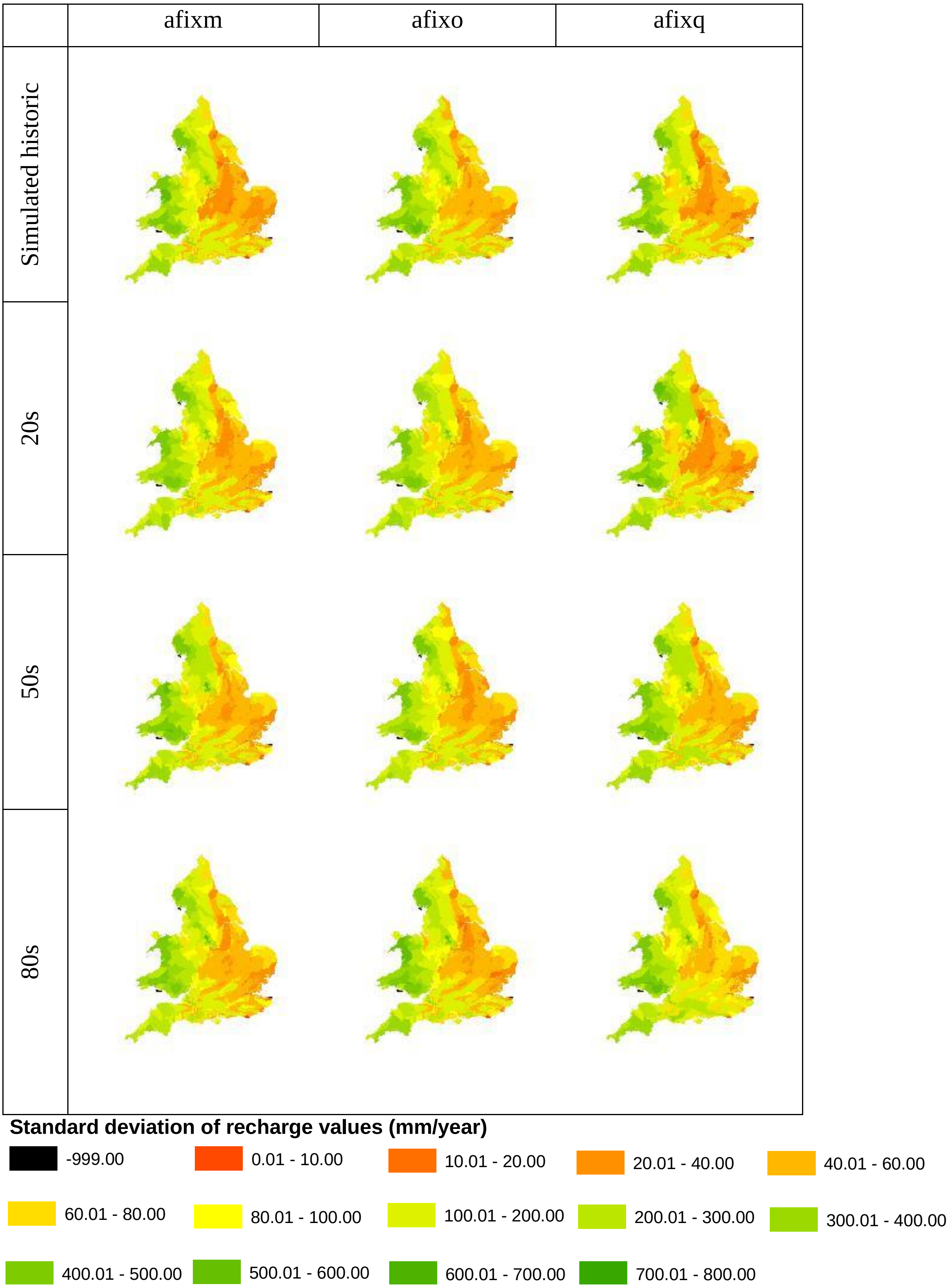
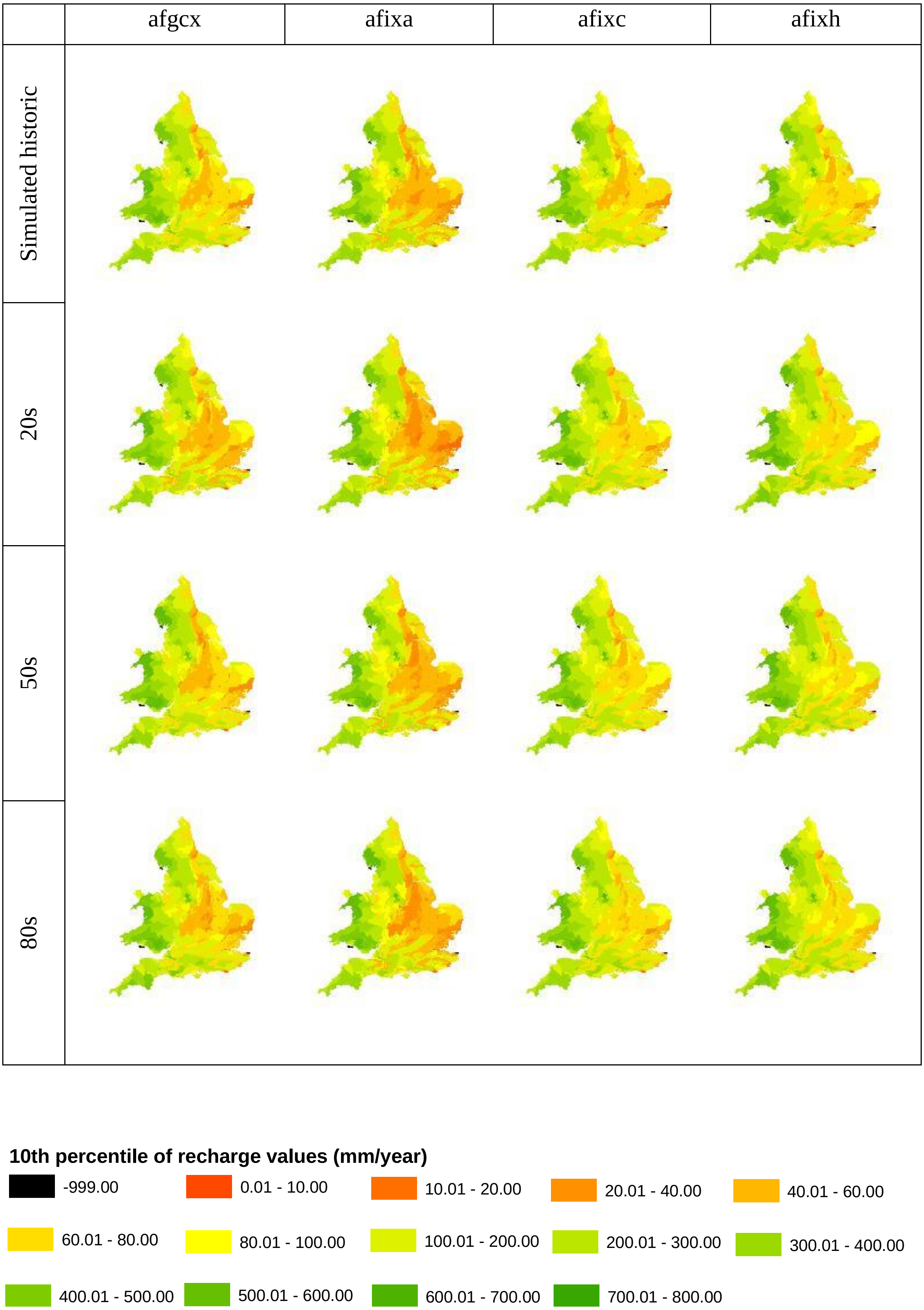
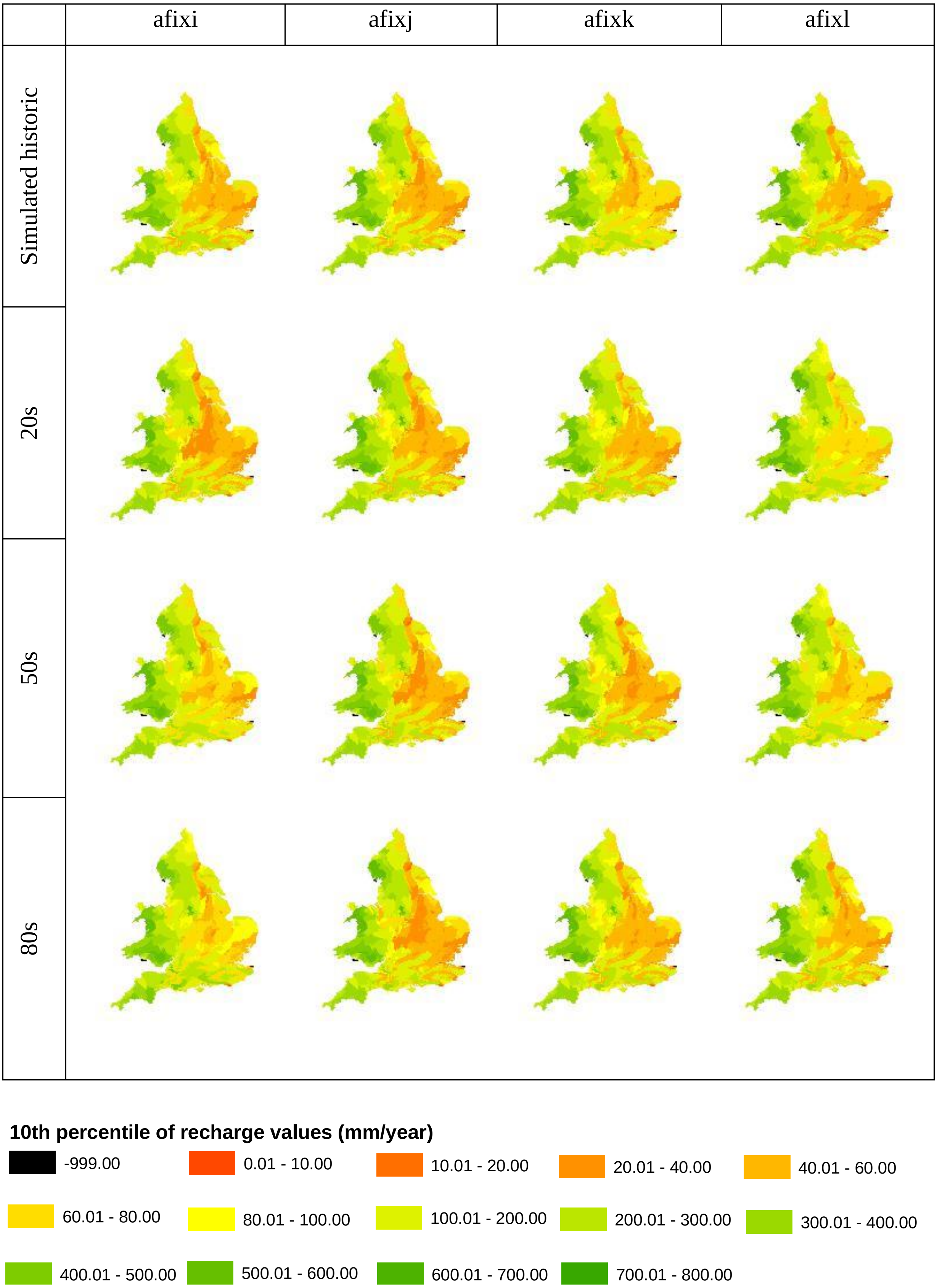


Figure A2. Standard deviation of recharge value for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble


afgcx
afixa
afixc
afixh
Simulated historic
20s
50s
80s
10th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
10th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00

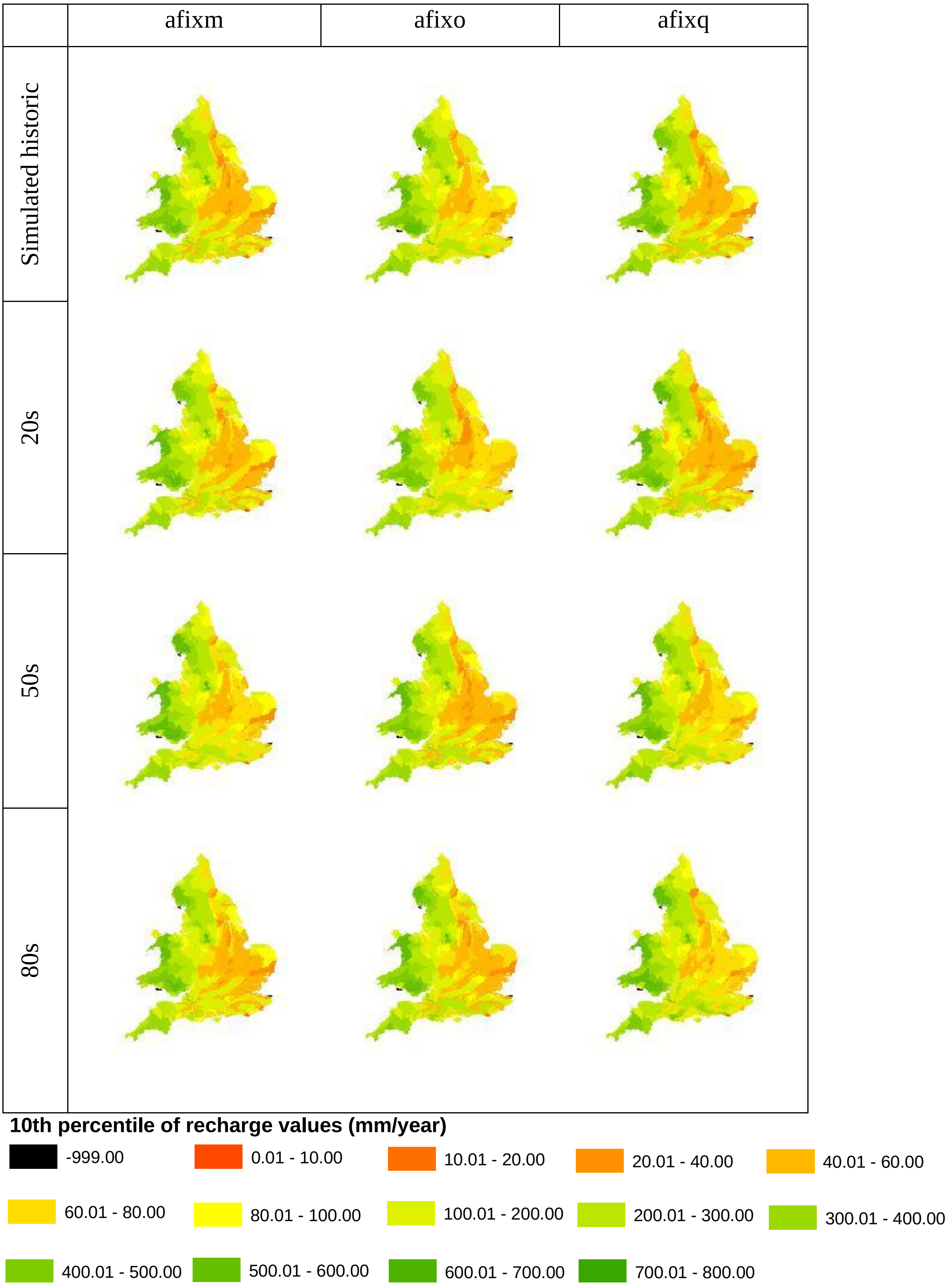
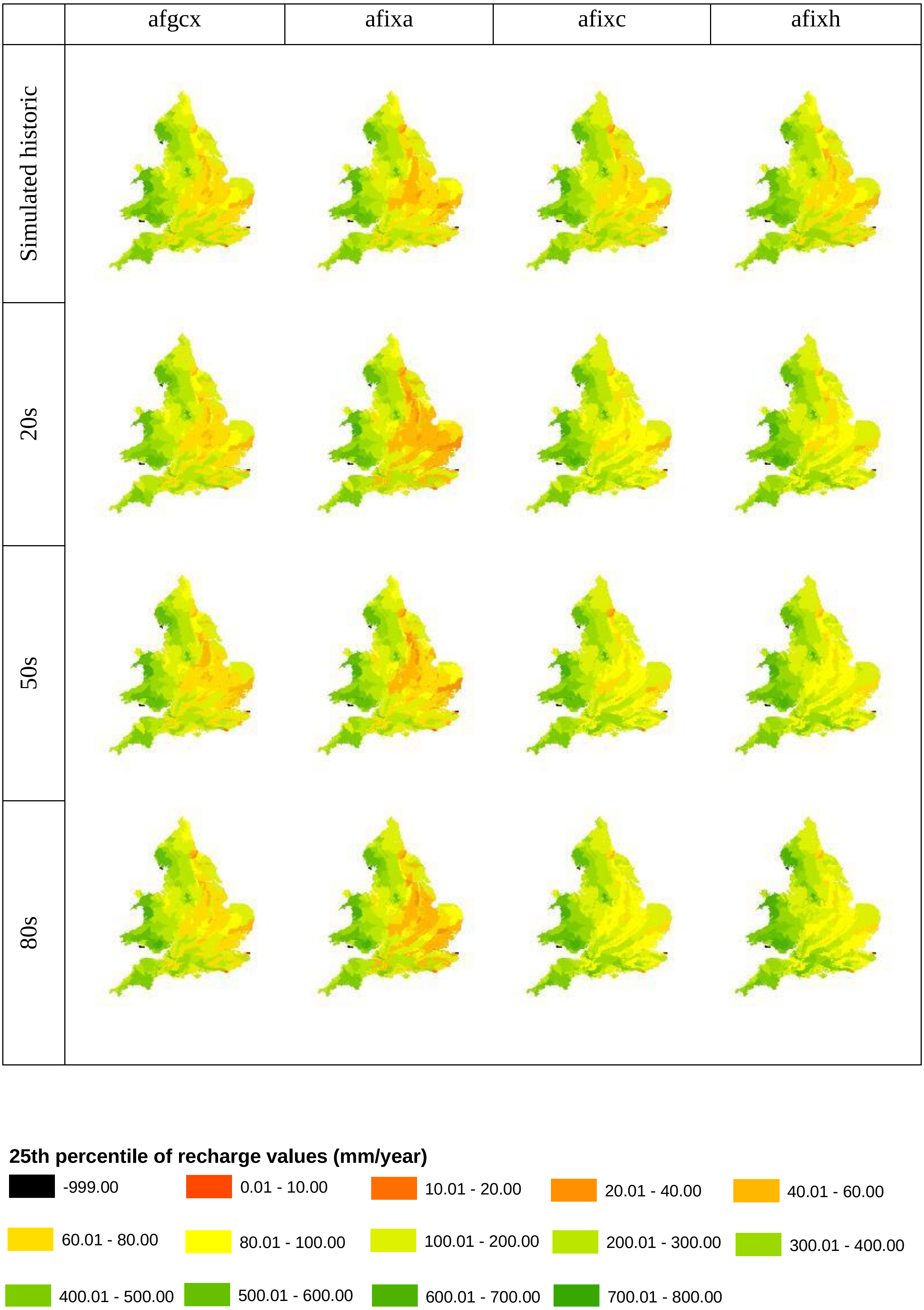
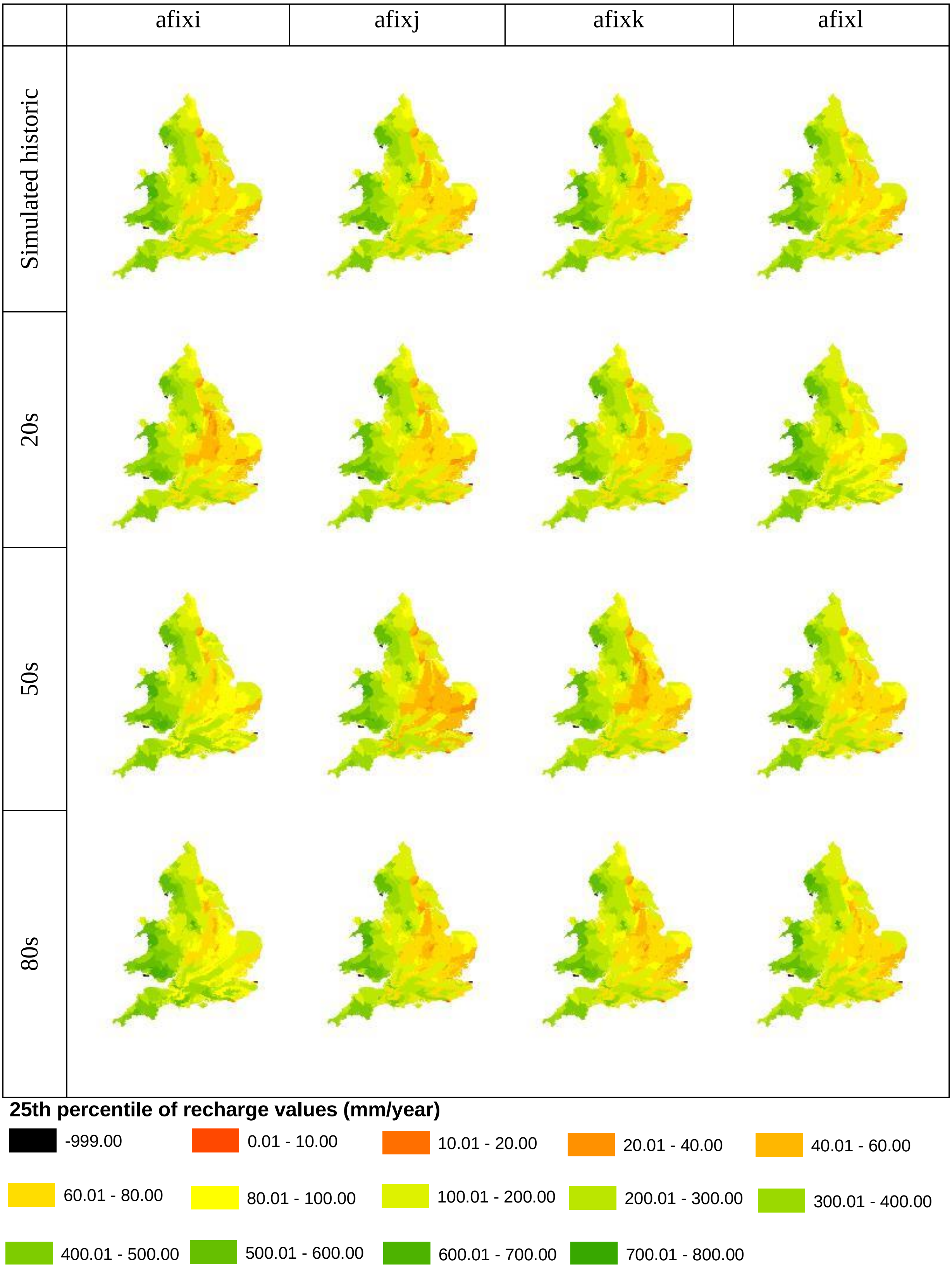


Figure A3. 10th percentile for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble


afgcx
afixa
afixc
afixh
Simulated historic
20s
50s
80s
25th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
25th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00

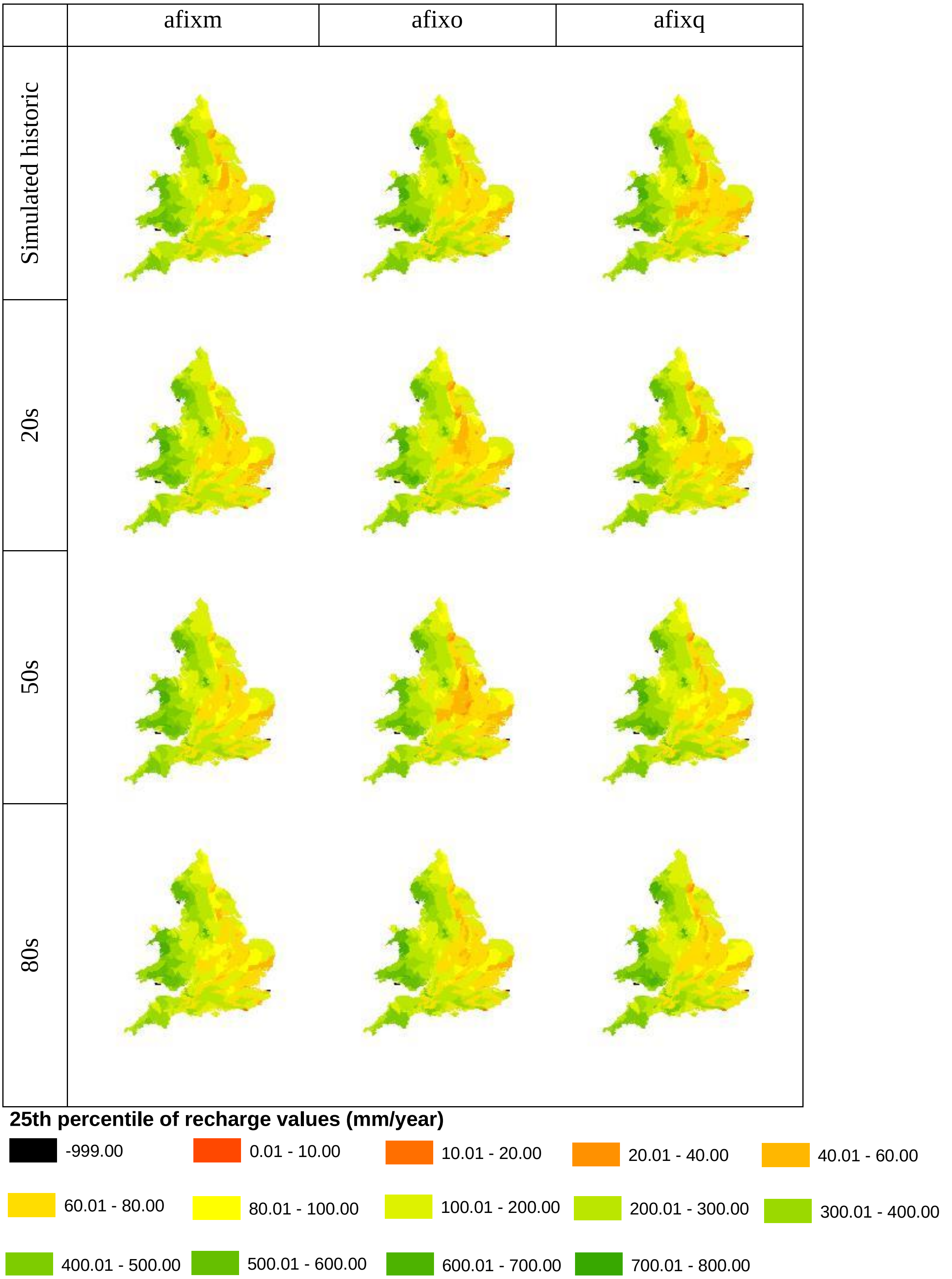
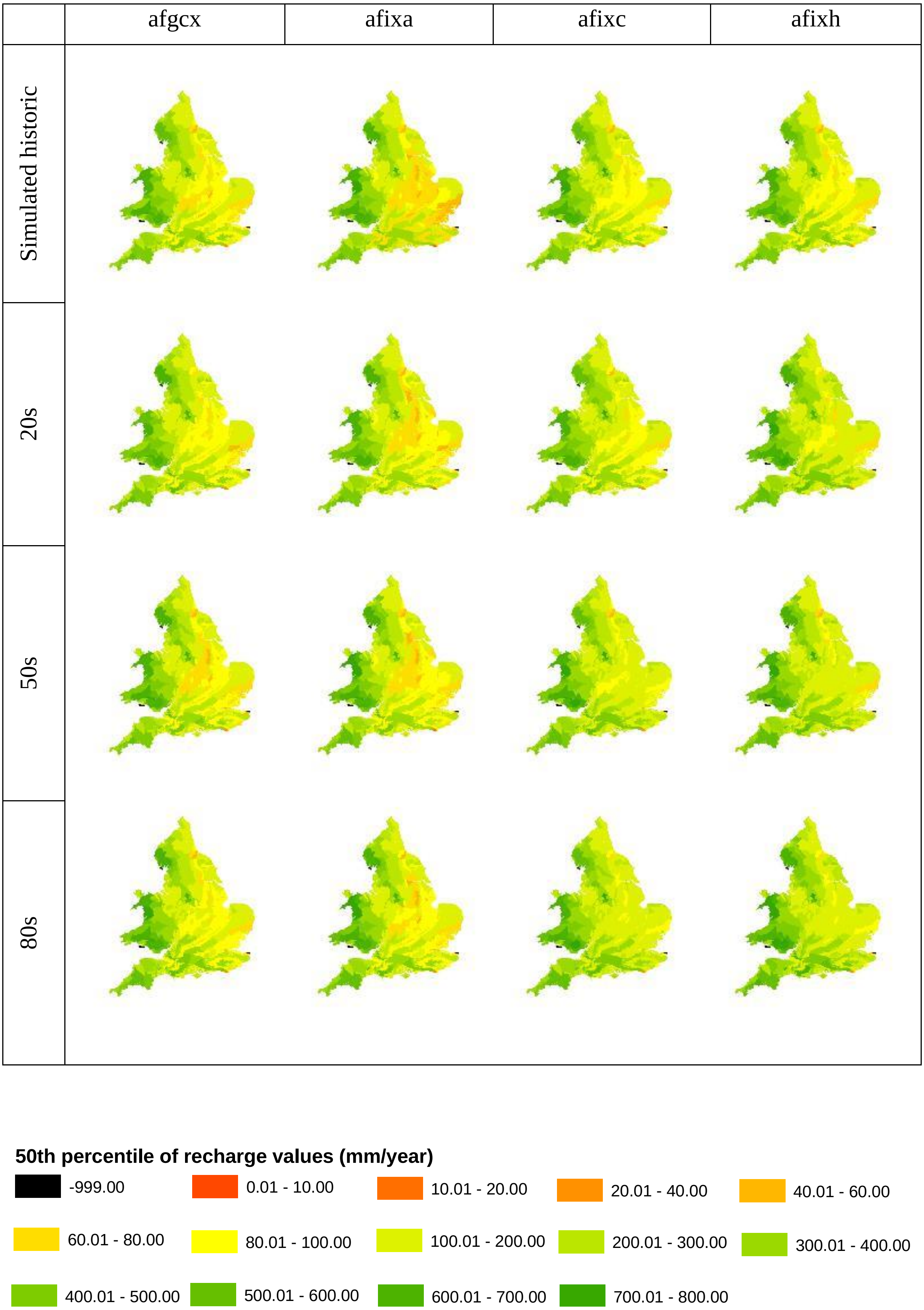
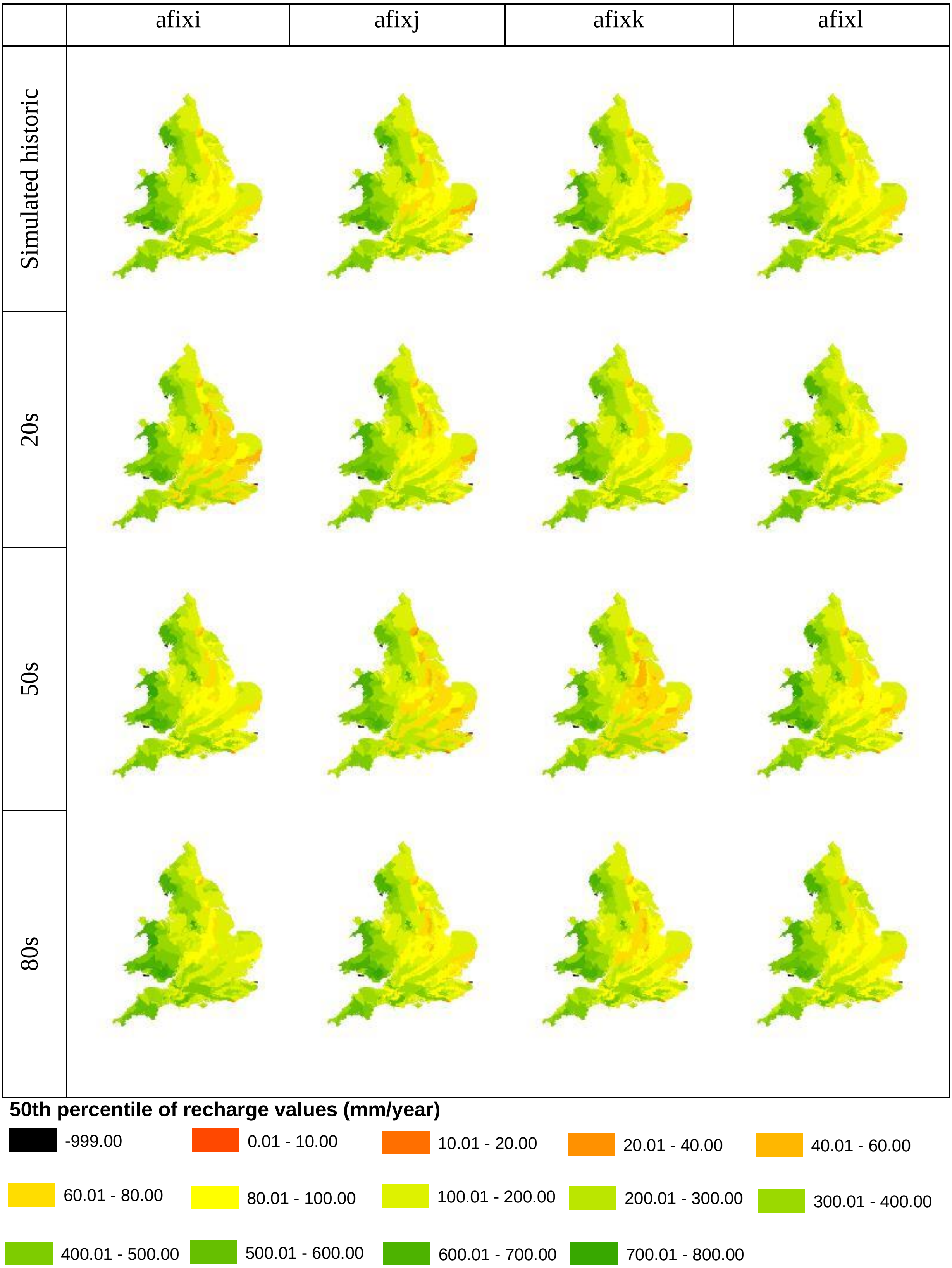


Figure A4. 25th percentile for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble


afgcx
afixa
afixc
afixh
Simulated historic
20s
50s
80s
50th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
50th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 800.00

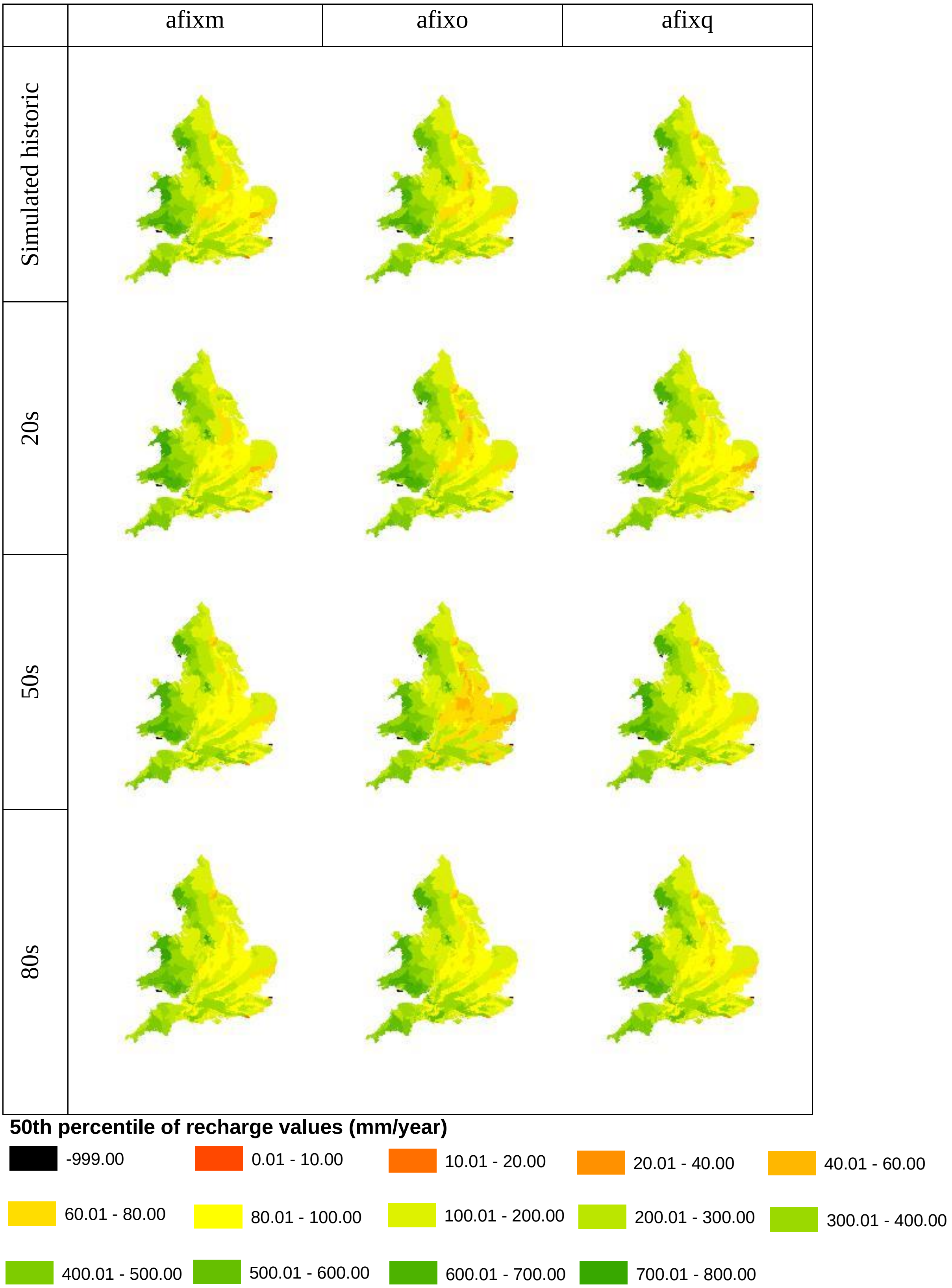
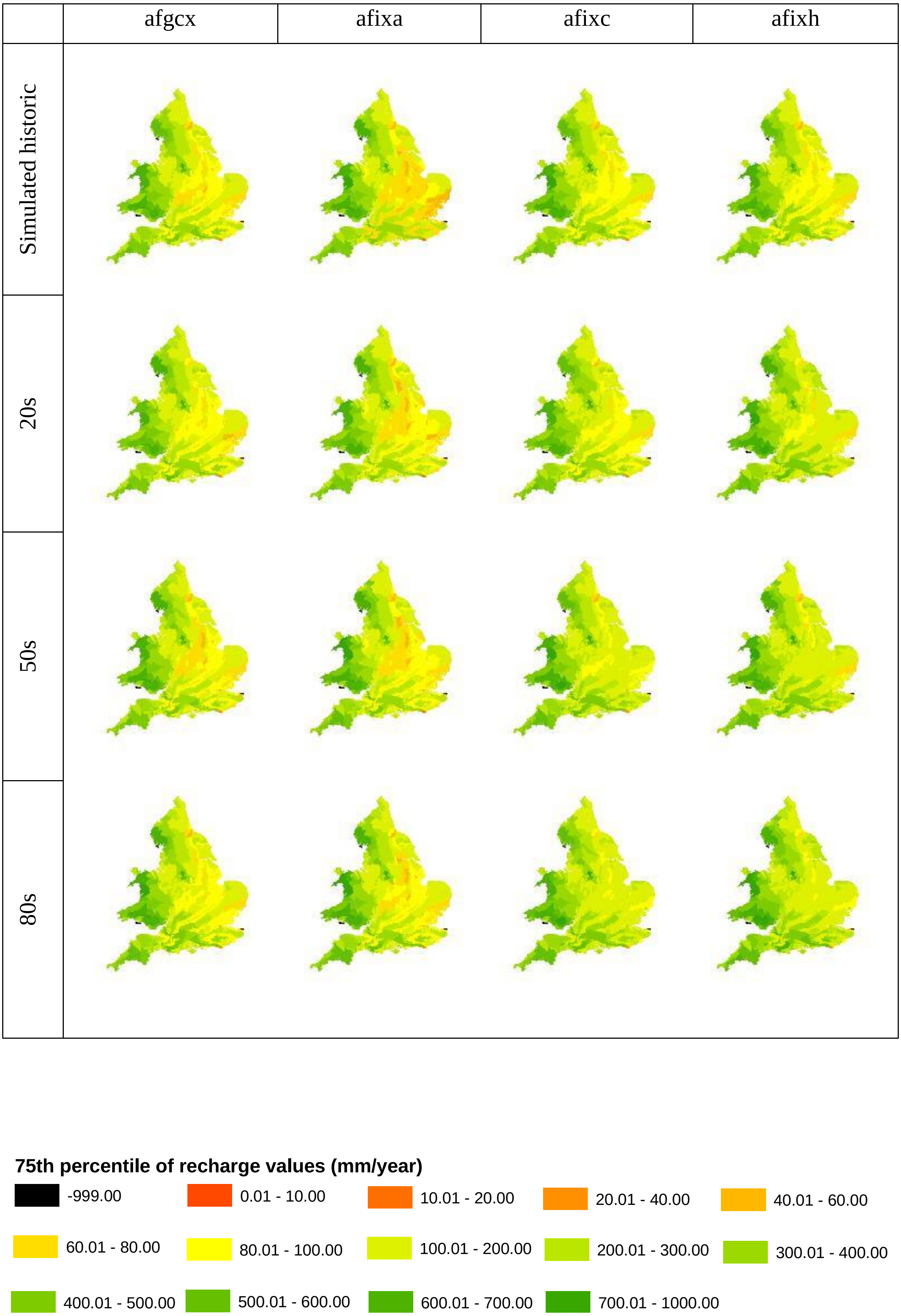
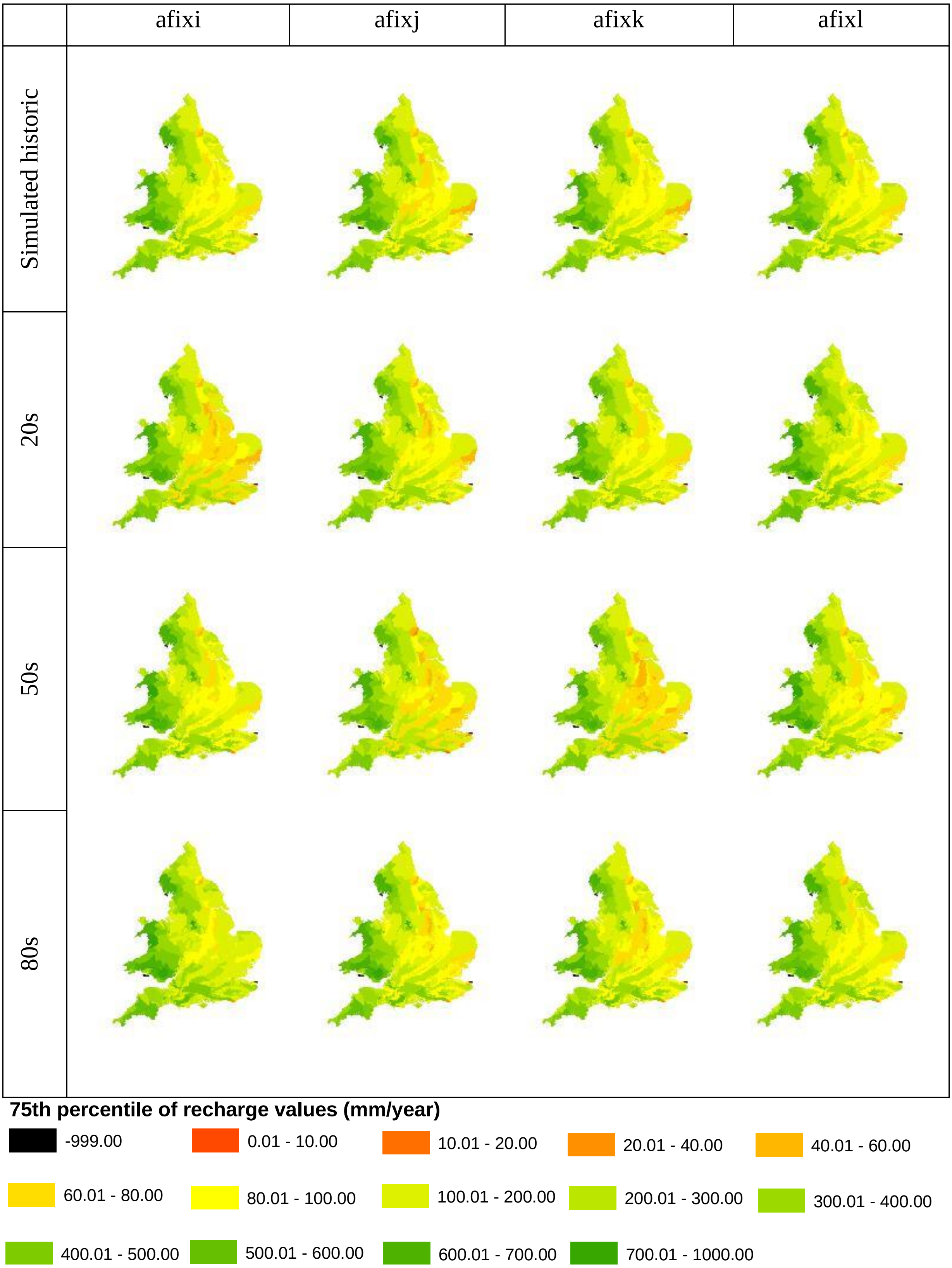


Figure A5. 50th percentile for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble


afgcx
afixa
afixc
afixh
Simulated historic
20s
50s
80s
75th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 1000.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
75th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 1000.00

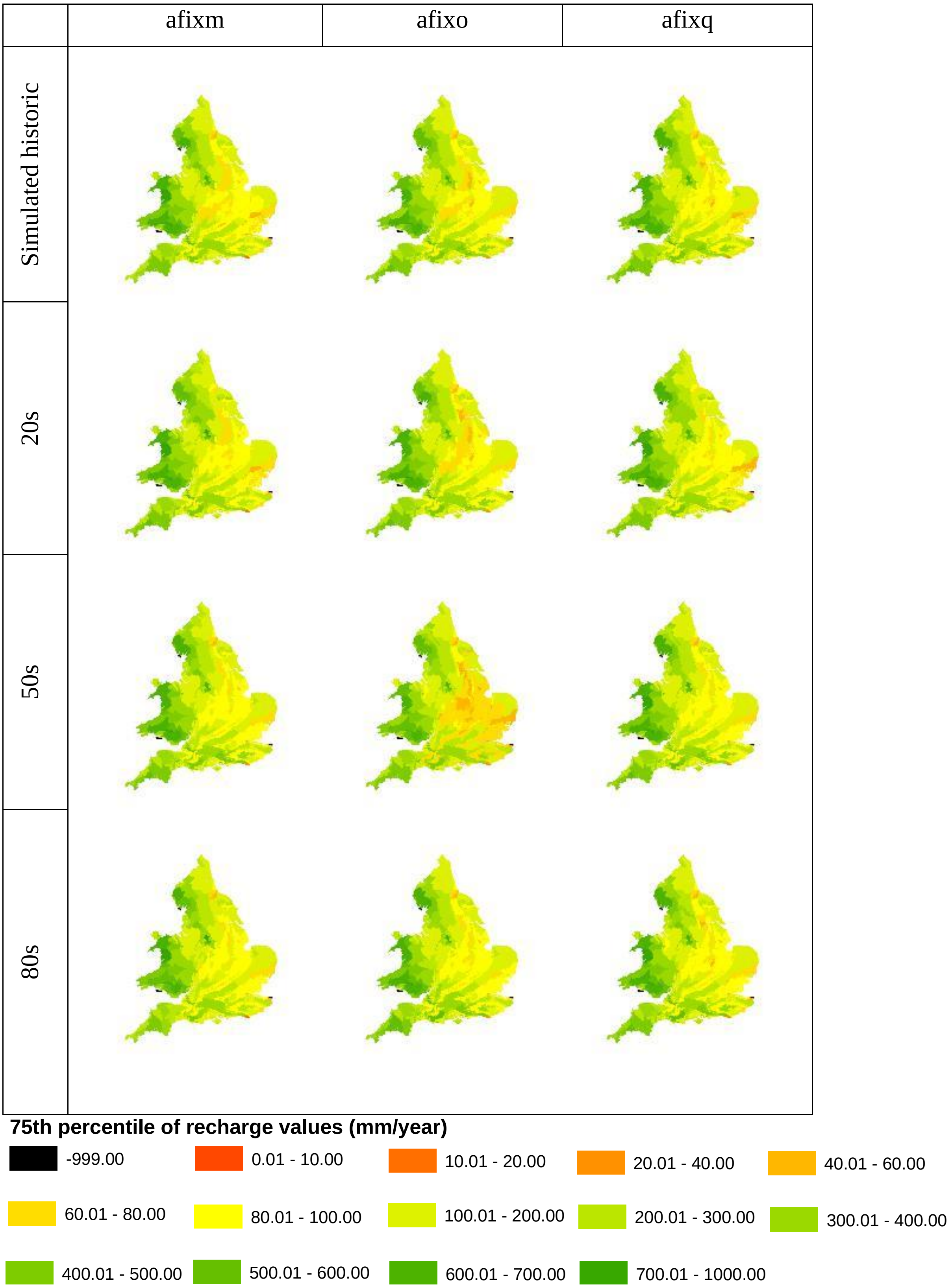
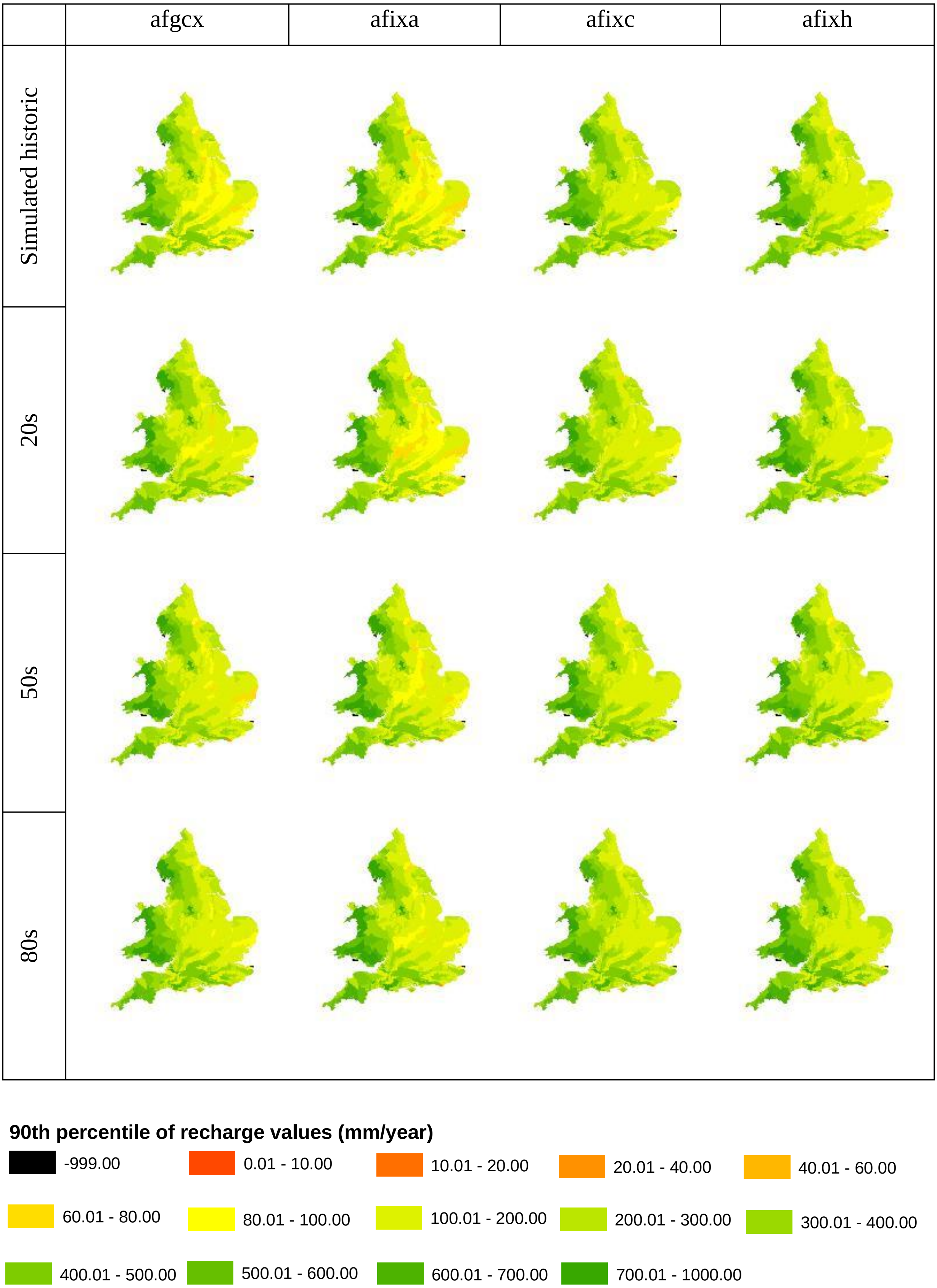
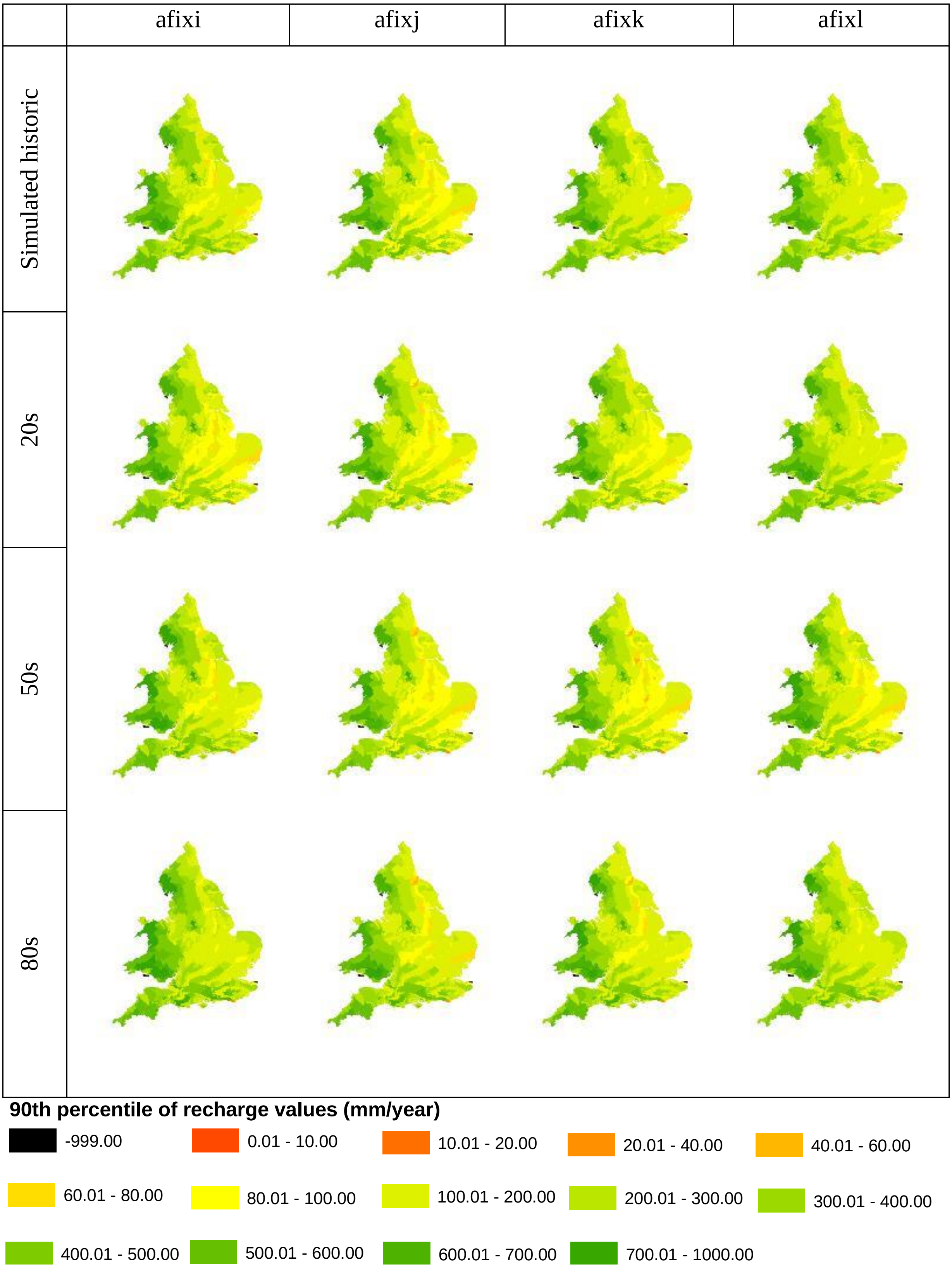


Figure A6. 75th percentile for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble


afgcx
afixa
afixc
afixh
Simulated historic
20s
50s
80s
90th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 1000.00


afixi
afixj
afixk
afixl
Simulated historic
20s
50s
80s
90th percentile of recharge values (mm/year)
-999.00
0.01 - 10.00
10.01 - 20.00
20.01 - 40.00
40.01 - 60.00
60.01 - 80.00
80.01 - 100.00
100.01 - 200.00
200.01 - 300.00
300.01 - 400.00
400.01 - 500.00
500.01 - 600.00
600.01 - 700.00
700.01 - 1000.00

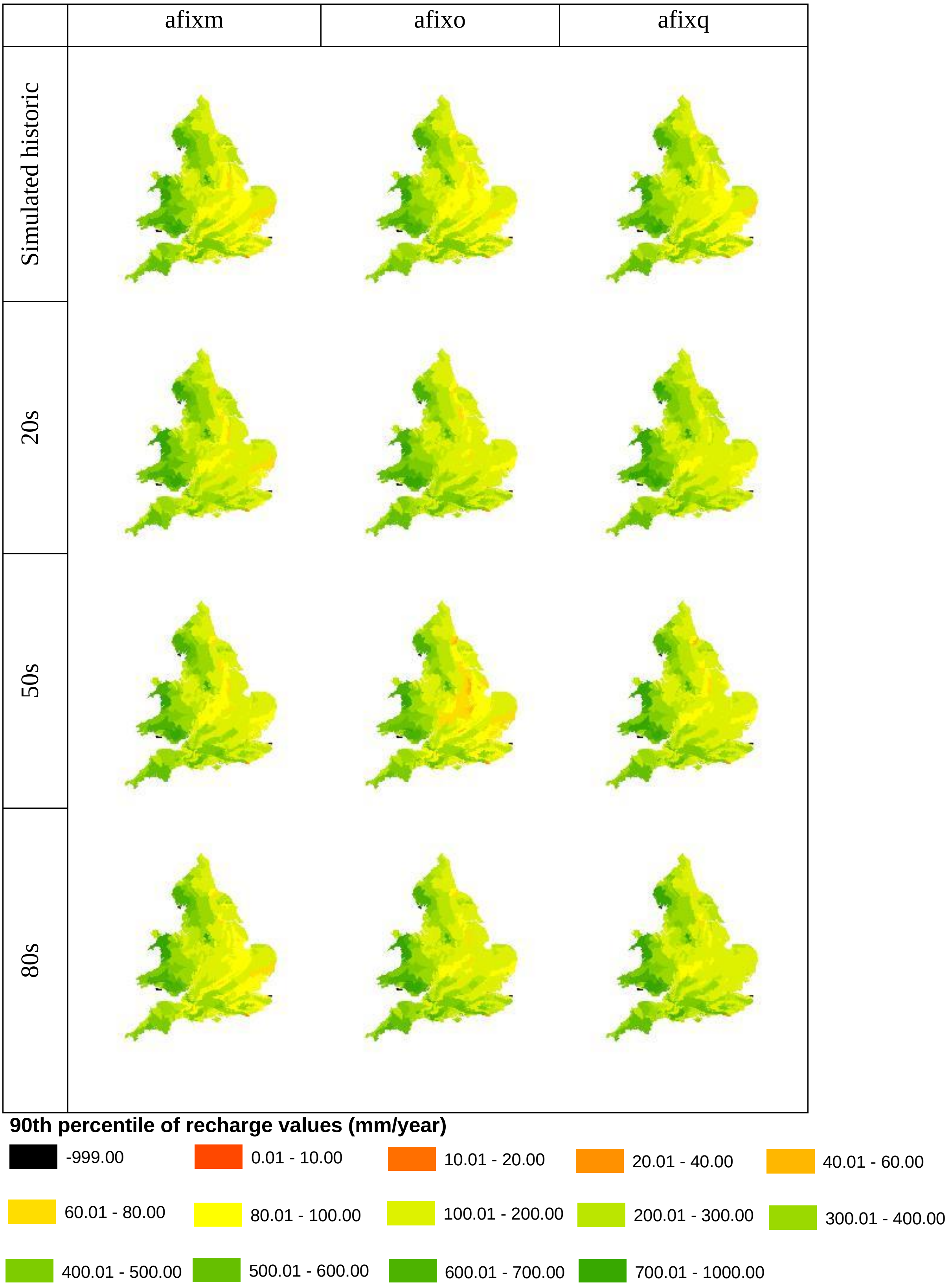


Figure A7. 90th percentile for simulated historic, 2020s, 2050s, 2080s and total model run for each ensemble

Appendix 2 Occurrence under 25% and exceedance of 75% recharge values

Figure A8 to A11 present the results of examining the occurrence of recharge less than 25% month average values for historic recharge and exceedance of 75% for monthly recharge. Any changes to recharge should be examined with respect to the recharge season: September to April, therefore any changes during these months is important. The overall the pattern appears to reflect dryer summers and wetter winters with a recharge season that has a “peakier” response.

A2.1 OCCURRENCE UNDER 25%

Figure A8 shows that generally greater recharge occurs in January, February, March, October, November and December. There is limited variation between the ensembles.

Figure A9 shows the fraction of number of events with future recharge values that are lower than the 25th of the historic recharge values of the 11 ensemble scenarios. A value greater than one means that there are a greater proportion of recharge events below a value of the 25% value, showing decreasing recharge. A fraction less than one shows fewer recharge events less than the 25% and demonstrates a reducing recharge value.

There is no common trend that can be picked up when the results across these scenarios were analysed. For example, scenarios afgcx, afixi and afixq show high number of January dry events to the west of the study area. This is contradicted by the results from scenarios afixa, afixh and afixo, which show high number of dry events for January to the east of the study area. Results from afixi and afixk show high number of dry events across the whole of the study area.

The detailed differences for each ensembles can be summarised as follows:

afgcx: January, November low value (i.e. increased recharge) and December (mixed)

afixa: January, April, November and December all mixed

afixc: January, February and November low

afixh: January, February low with October, November and December low

afixi: February (particularly northern England), October and December low with November very low

afixj: January and February mixed with November low

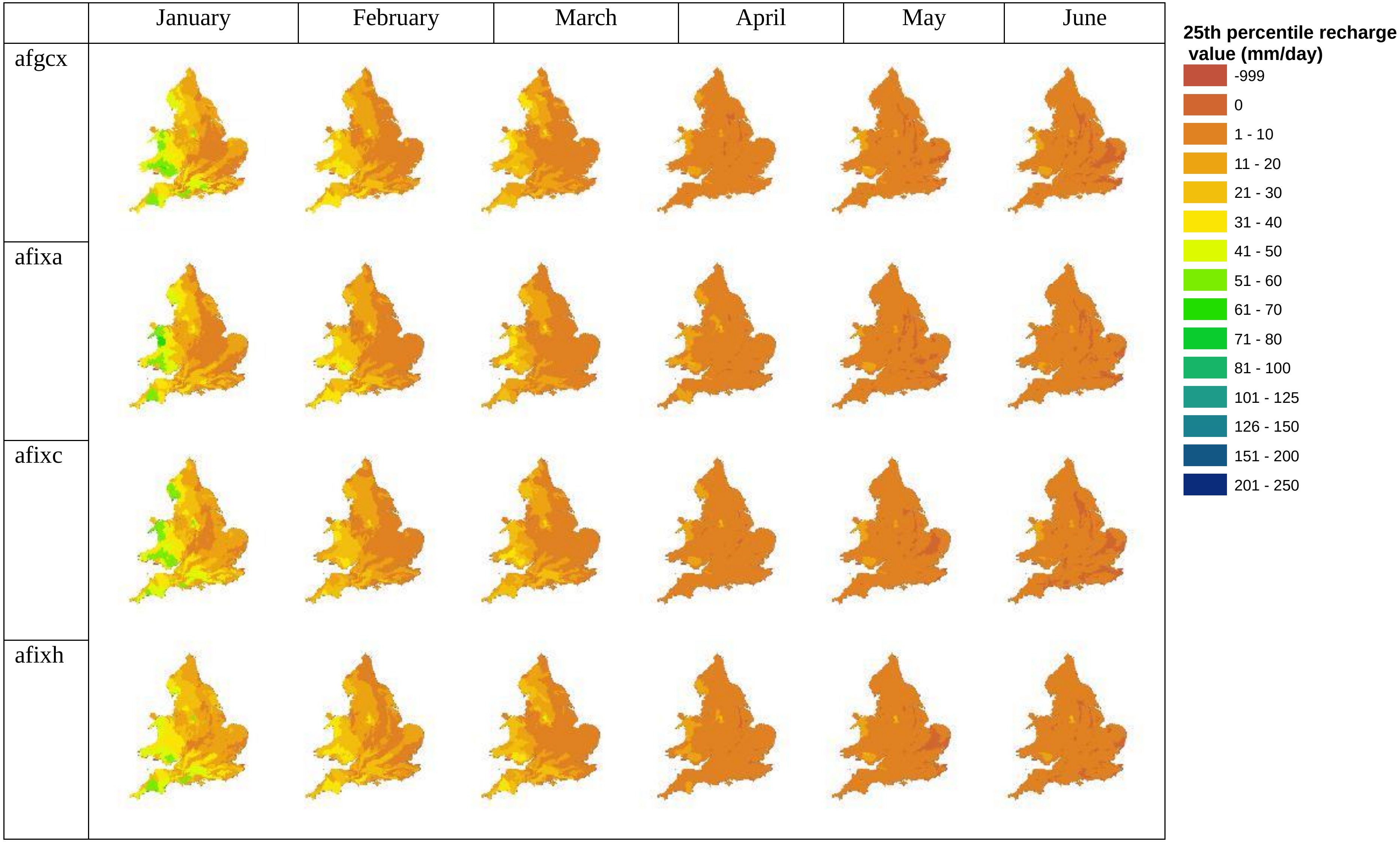
afixk: February low, with October, November and December mixed

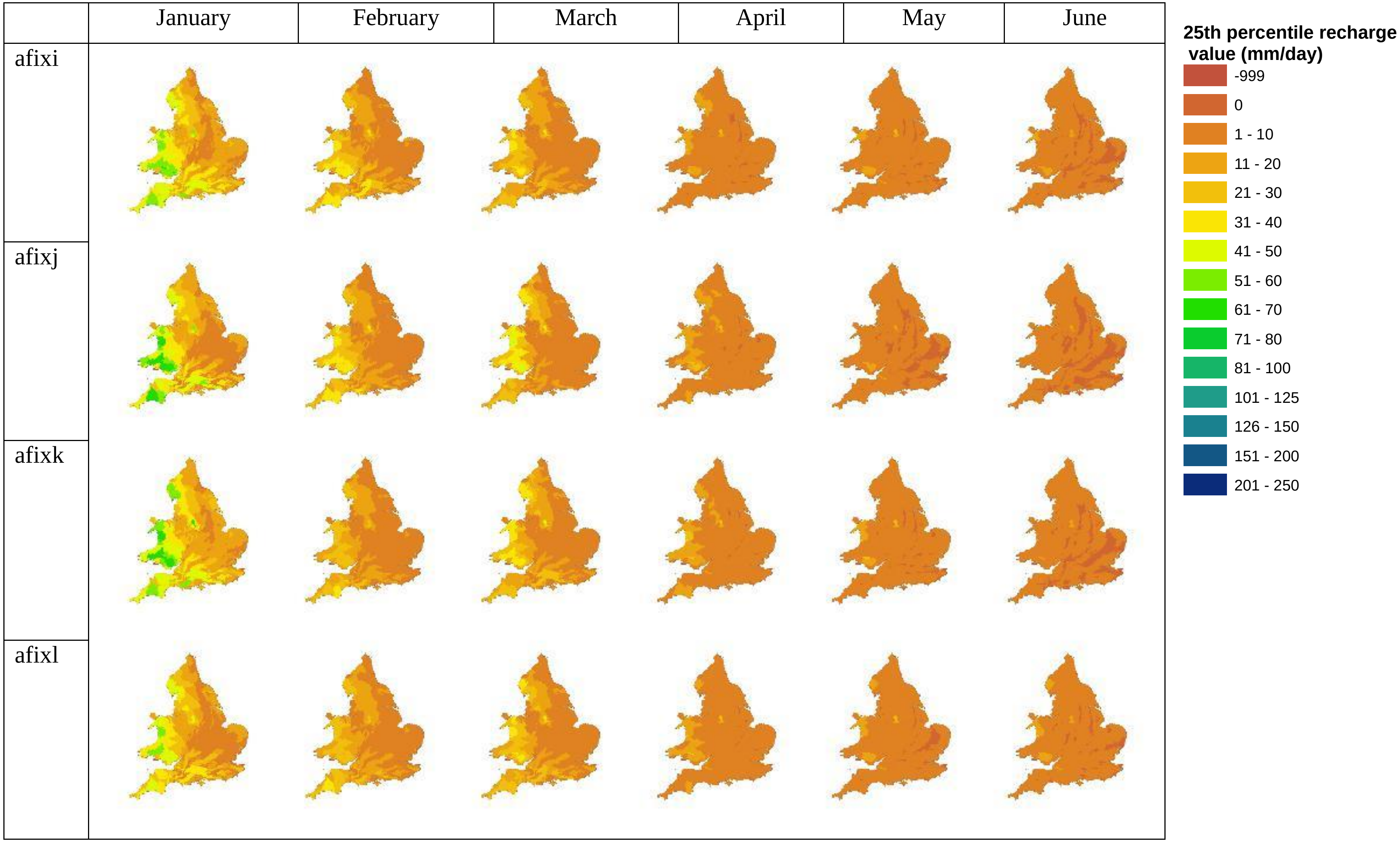
afixl: January, October, November and December low

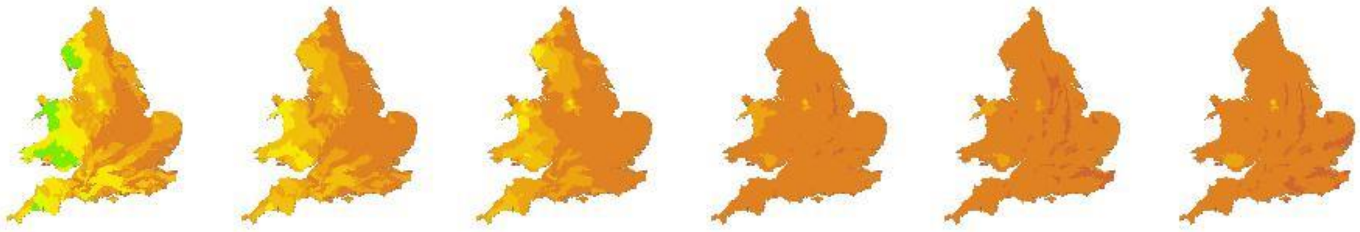
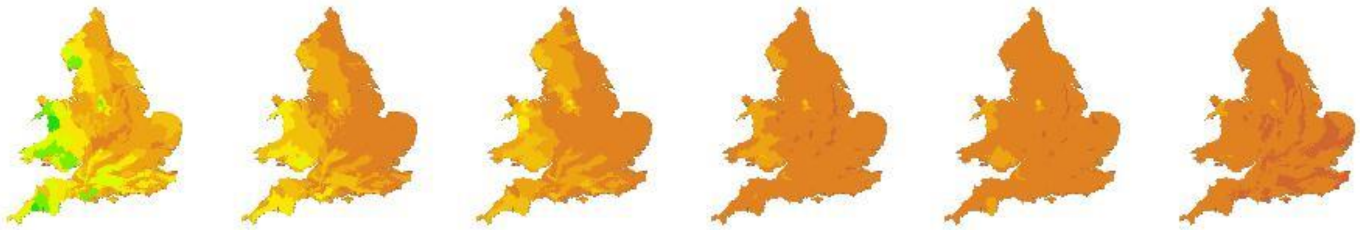
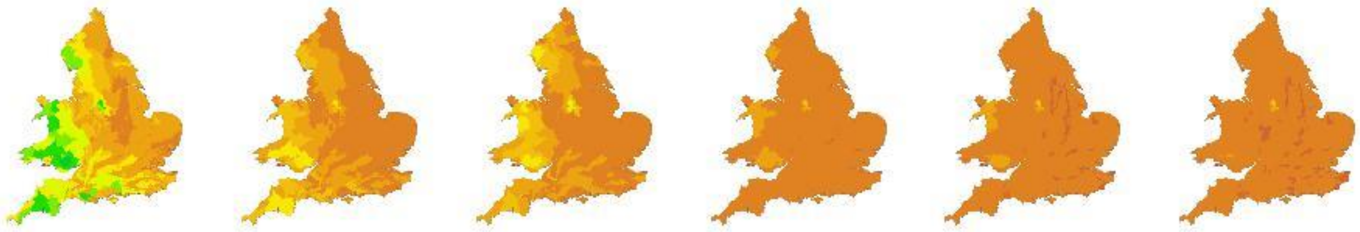
afixm: January , November and December mixed

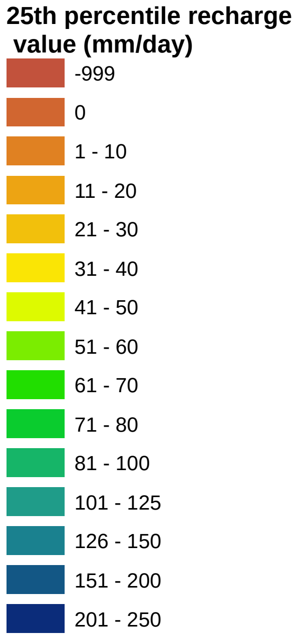
afixo: January, November and December mixed

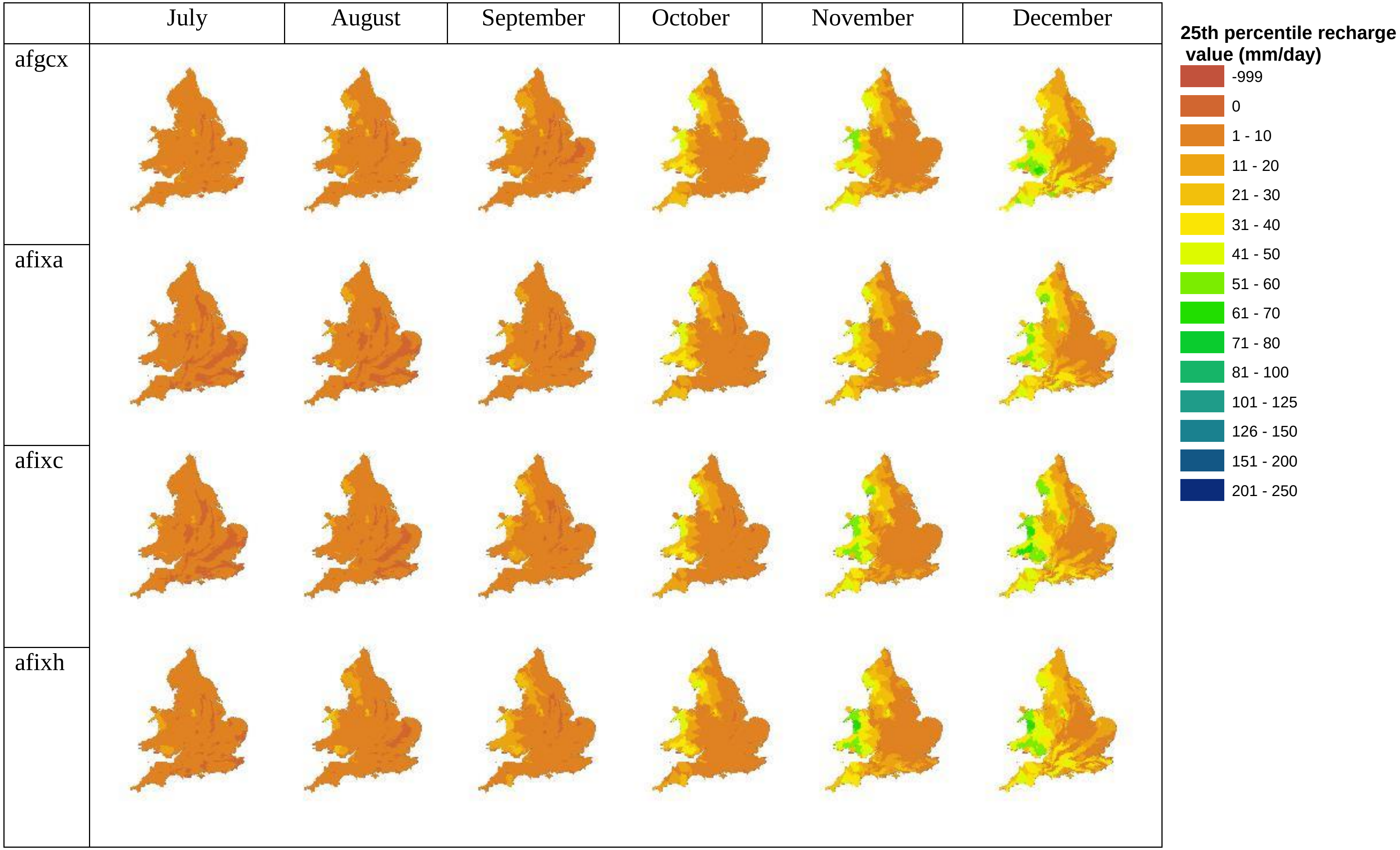
afixq: February, , and November low

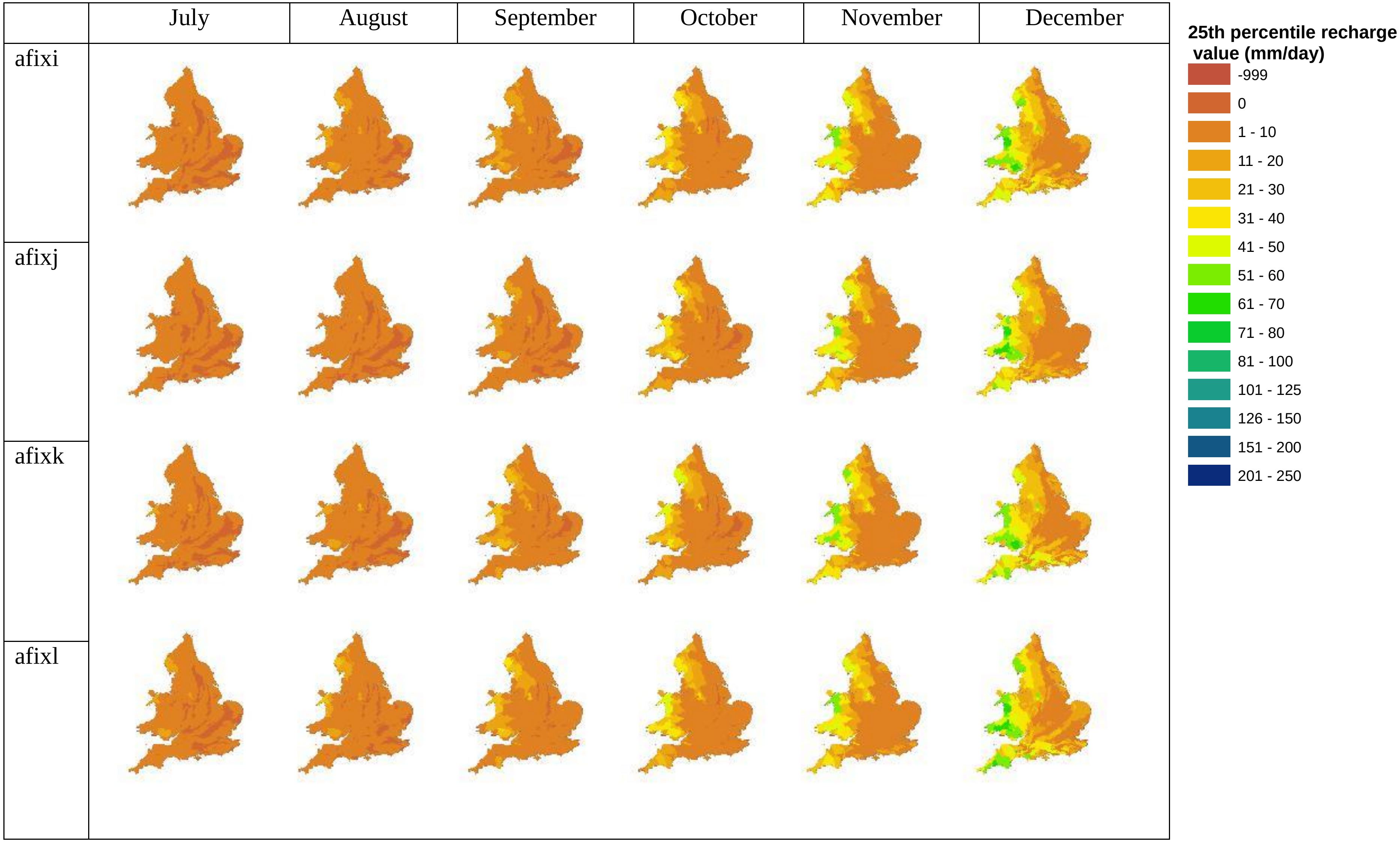

January
February
March
April
May
June
afgcx
afixa
afixc
afixh
25th percentile recharge value (mm/day)
-999
0
1 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 100
101 - 125
126 - 150
151 - 200
201 - 250


January
February
March
April
May
June
afixi
afixj
afixk
afixl
25th percentile recharge value (mm/day)
-999
0
1 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 100
101 - 125
126 - 150
151 - 200
201 - 250

	January	February	March	April	May	June
afixm						
afixo						
afixq						




July
August
September
October
November
December
afgcx
afixa
afixc
afixh
25th percentile recharge value (mm/day)
-999
0
1 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 100
101 - 125
126 - 150
151 - 200
201 - 250


July
August
September
October
November
December
afixi
afixj
afixk
afixl
25th percentile recharge value (mm/day)
-999
0
1 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 100
101 - 125
126 - 150
151 - 200
201 - 250

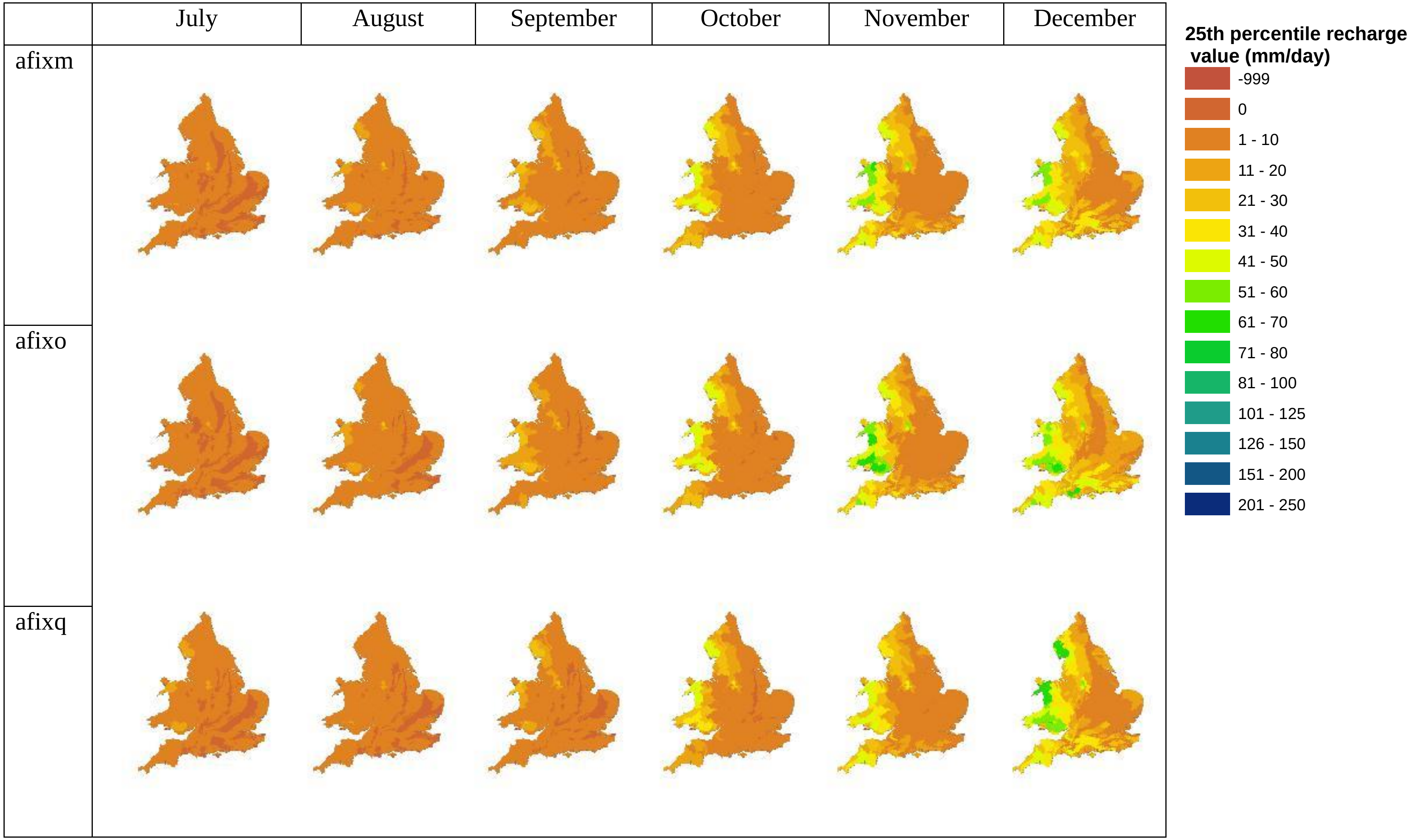
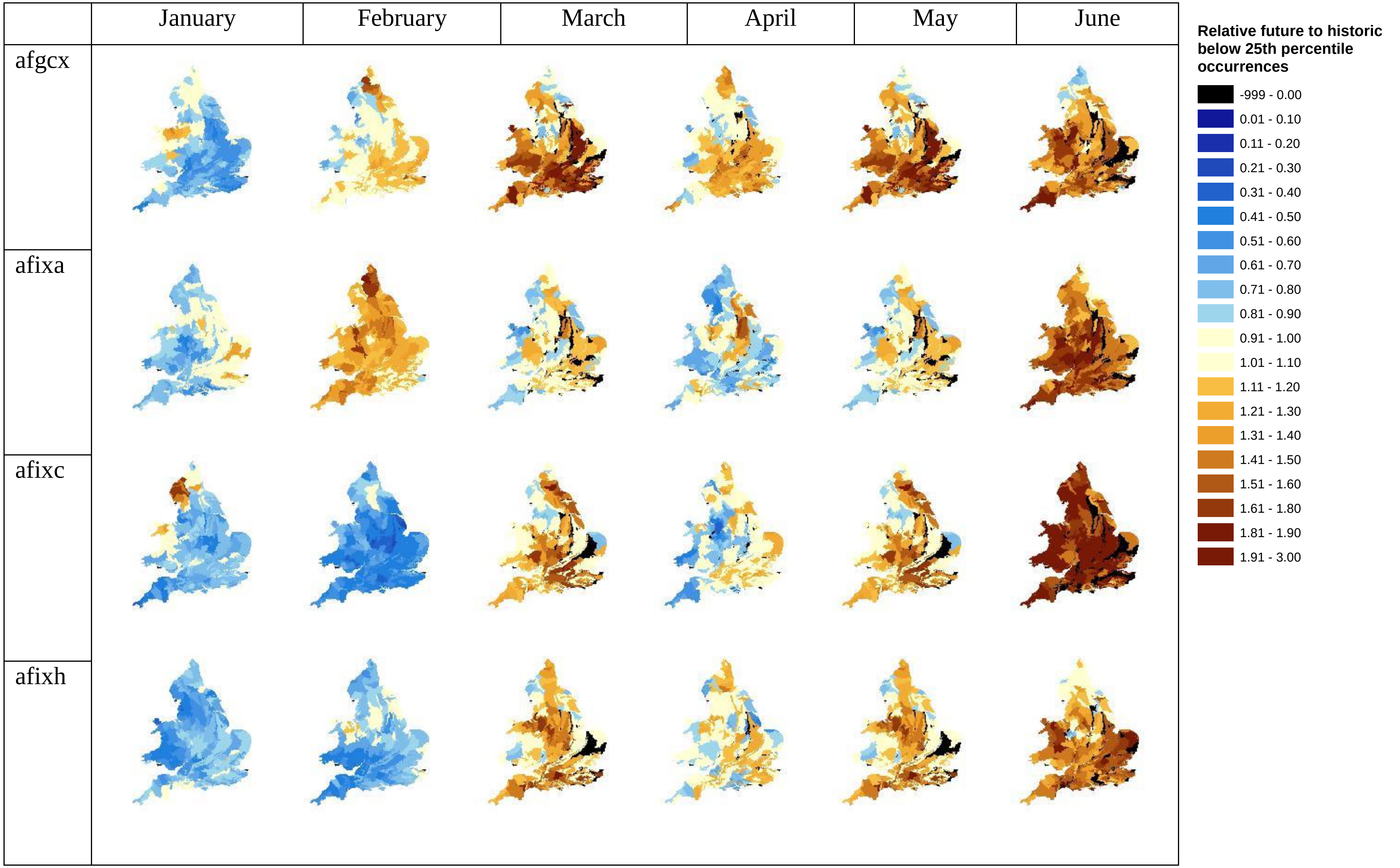
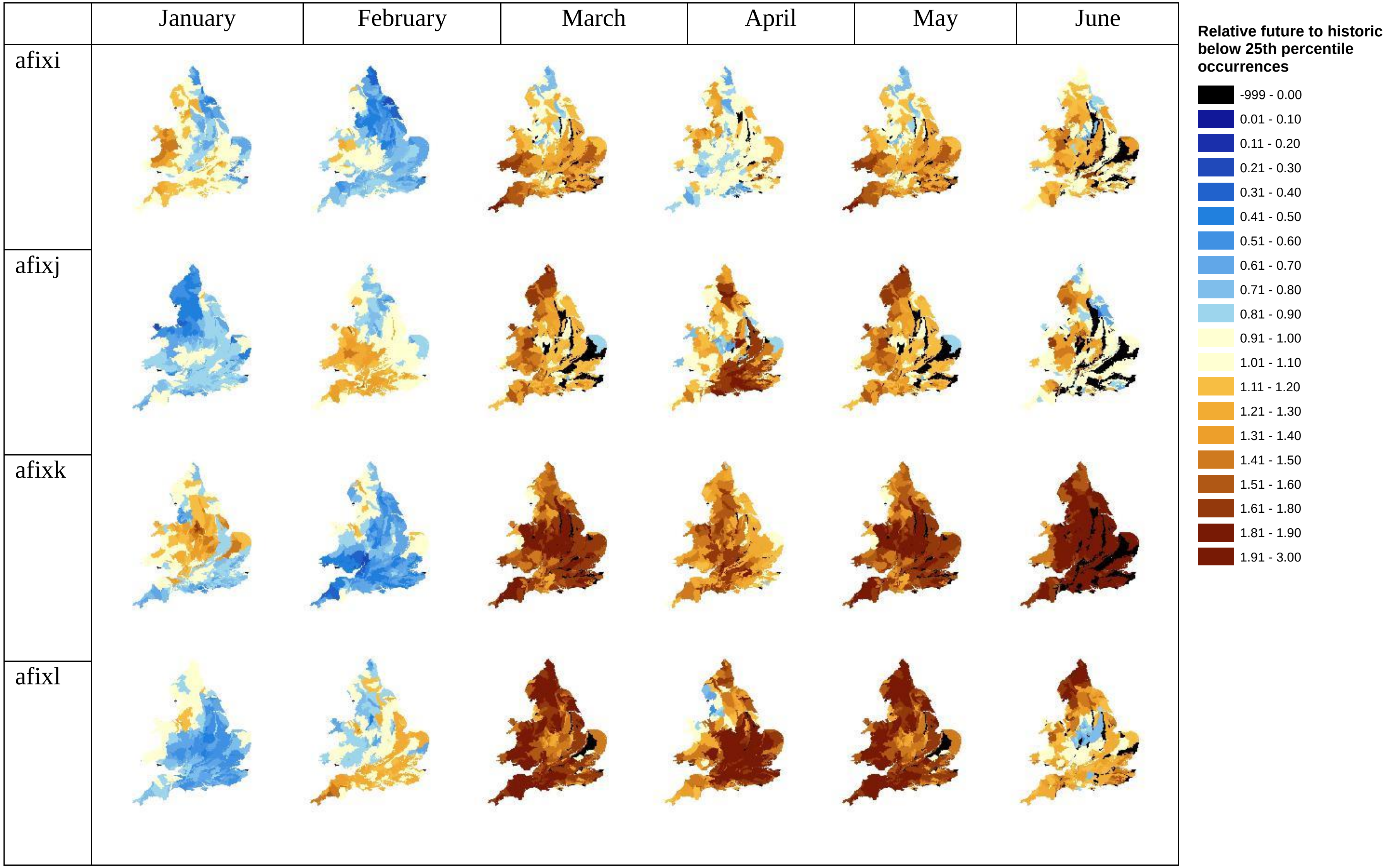
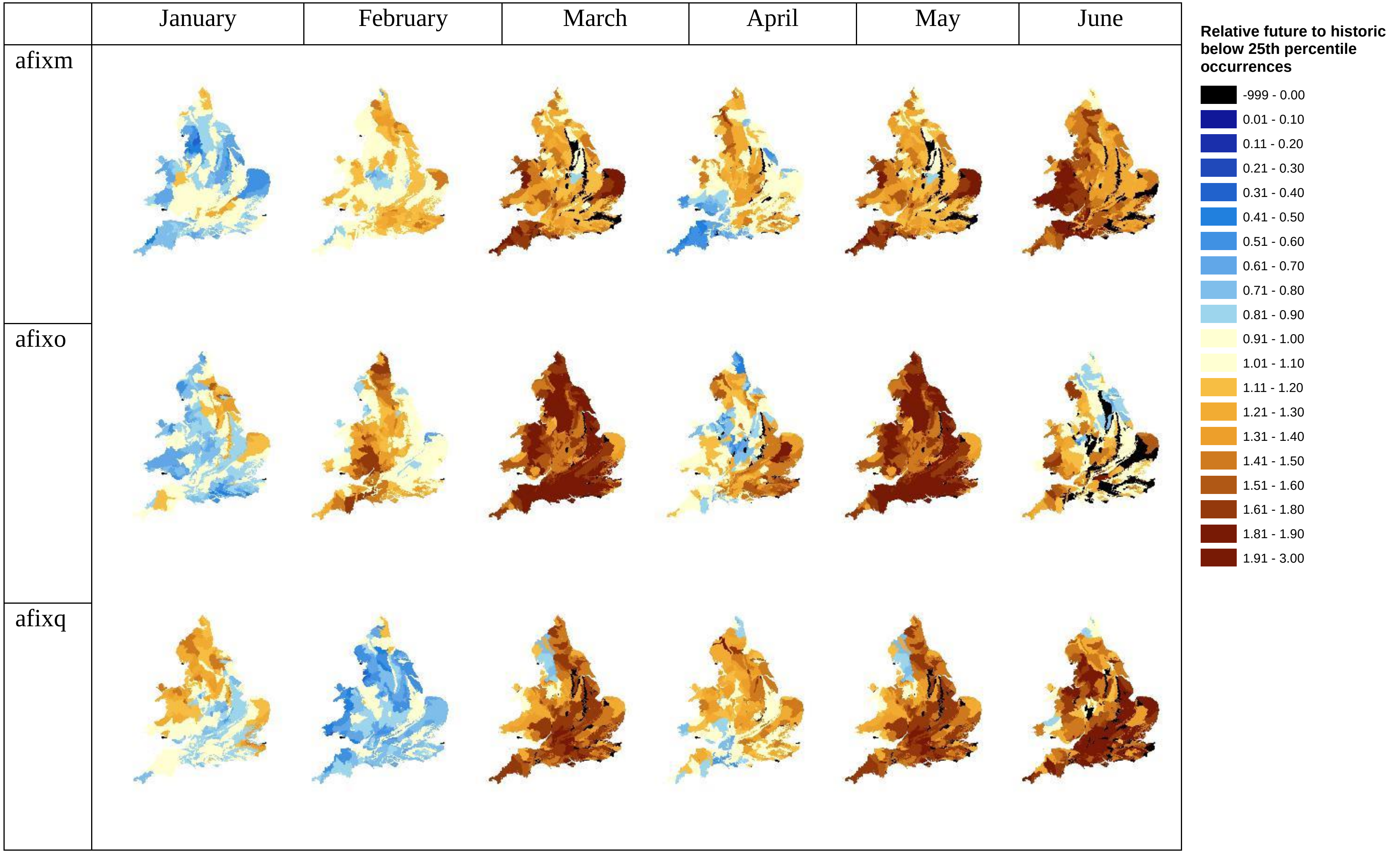
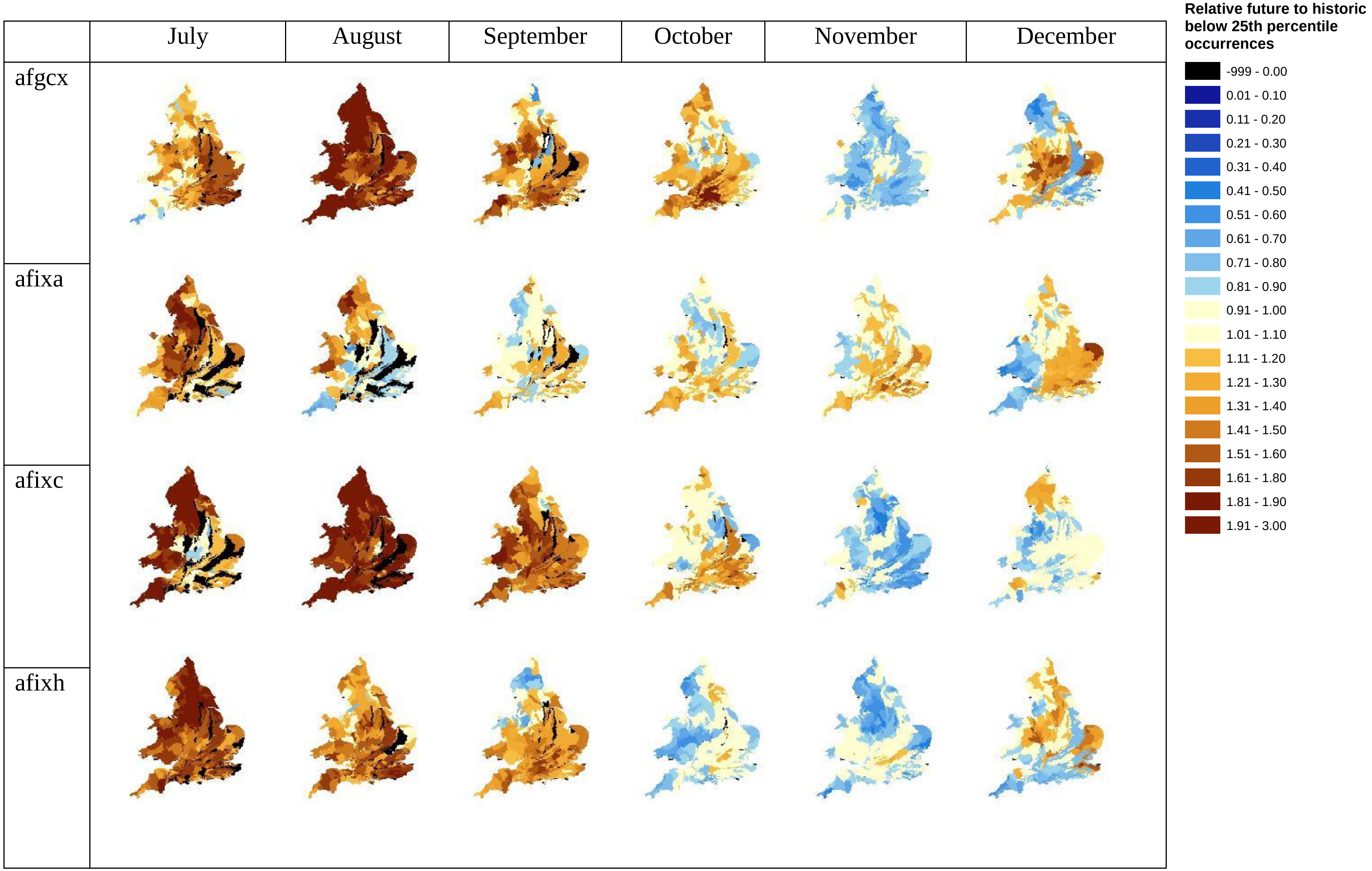


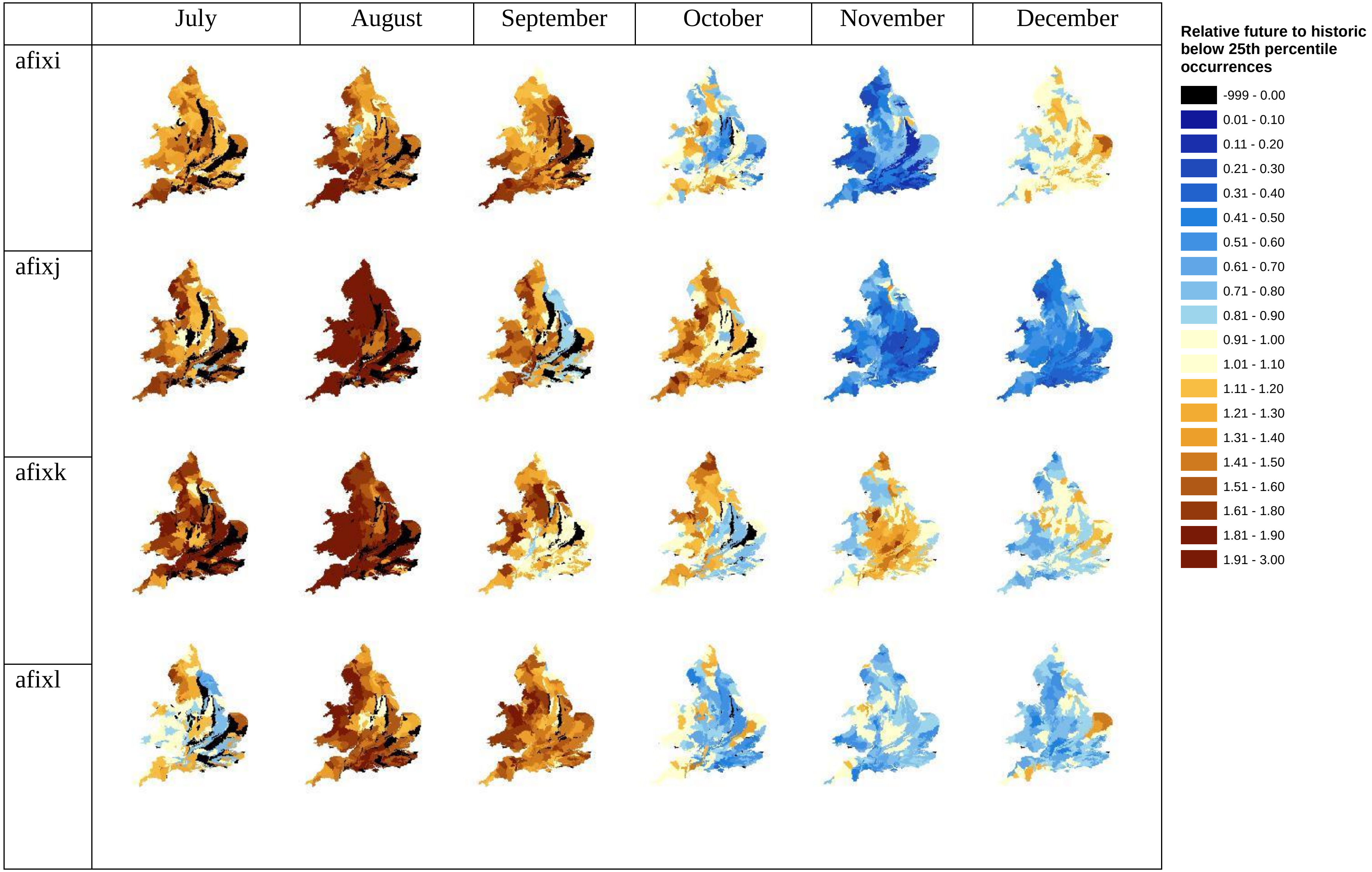
Figure A8. 25th percentile simulated historic values by month for each ensemble


January
February
March
April
May
June
afgcx
afixa
afixc
afixh
Relative future to historic below 25th percentile occurrences
-999 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00


January
February
March
April
May
June
afixi
afixj
afixk
afixl
Relative future to historic below 25th percentile occurrences
-999 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00


January
February
March
April
May
June
afixm
afixo
afixq
Relative future to historic below 25th percentile occurrences
-999 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00


July
August
September
October
November
December
afgcx
afixa
afixc
afixh
Relative future to historic below 25th percentile occurrences
-999 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00


July
August
September
October
November
December
afixi
afixj
afixk
afixl
Relative future to historic below 25th percentile occurrences
-999 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00

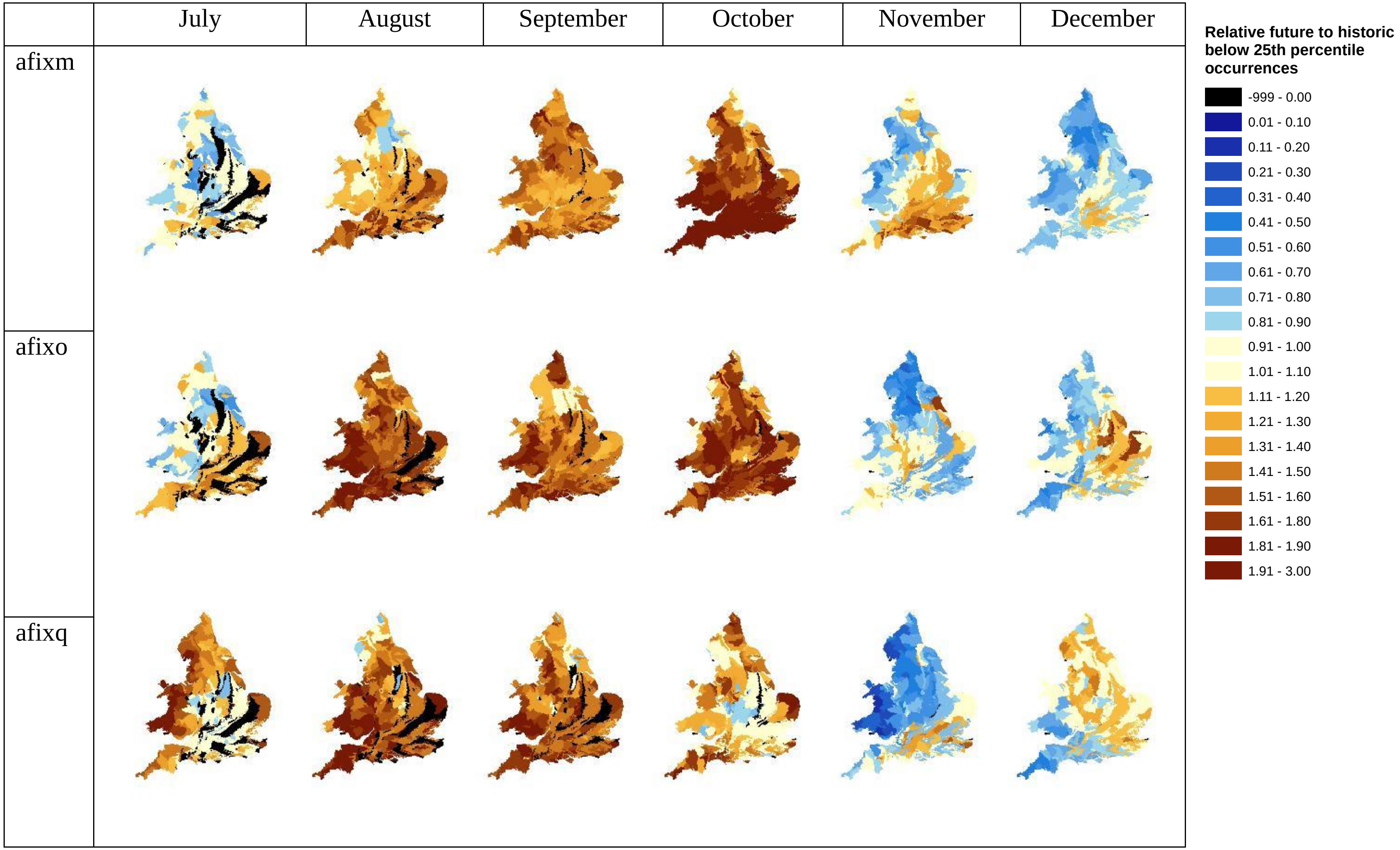


Figure A9. Proportion of recharge value less than the 25th percentile of simulates historic recharge values for each ensemble

A2.2 EXCEEDANCE OVER 75%

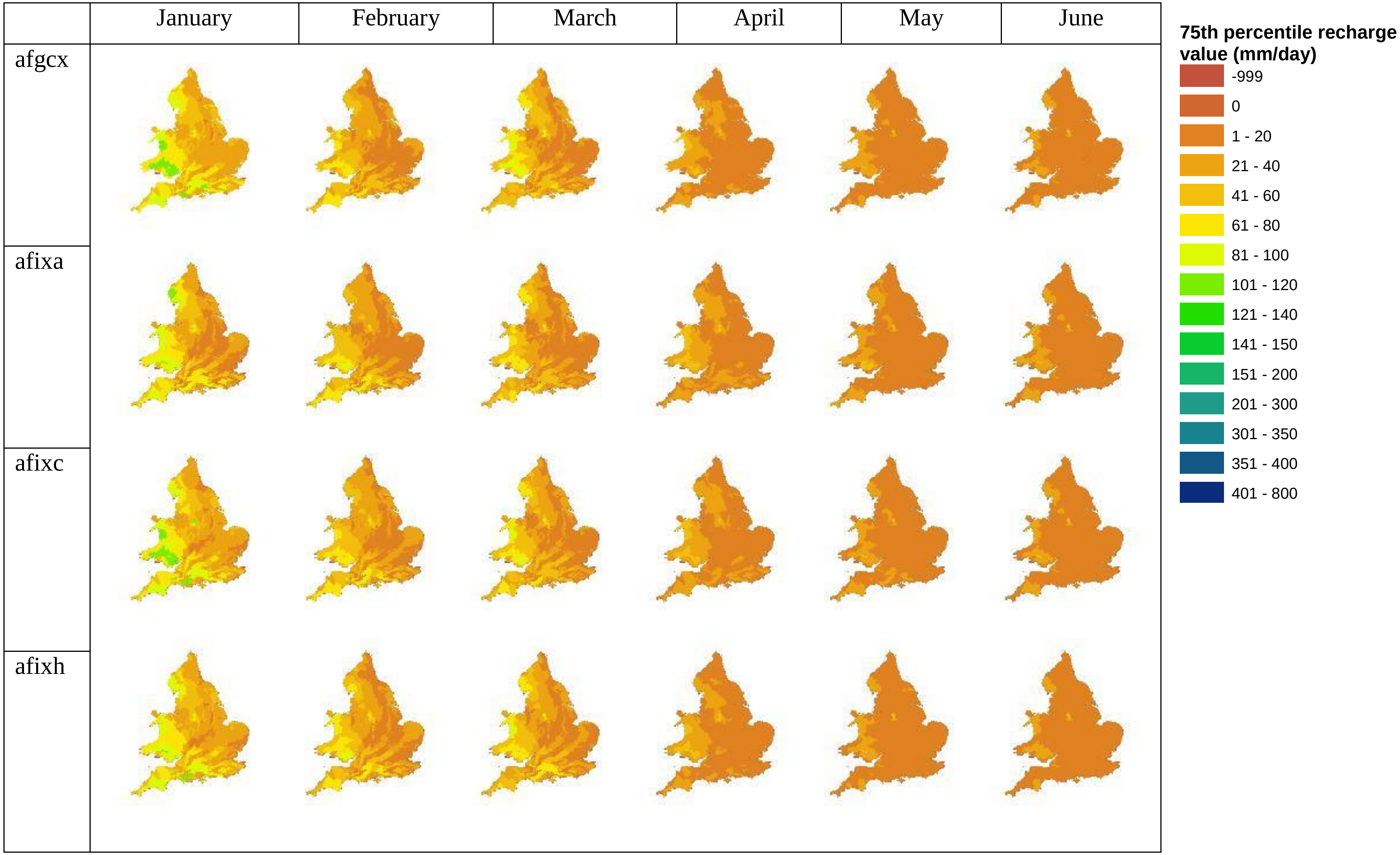
Figure A10 shows that the pattern is similar that observed for the 25% value, generally greater recharge occurs in January, February, March, October, November and December. Of these months the greatest occurs in January, November and December. April through to September has < 40 mm/d. There is limited variation between the 11 ensembles.

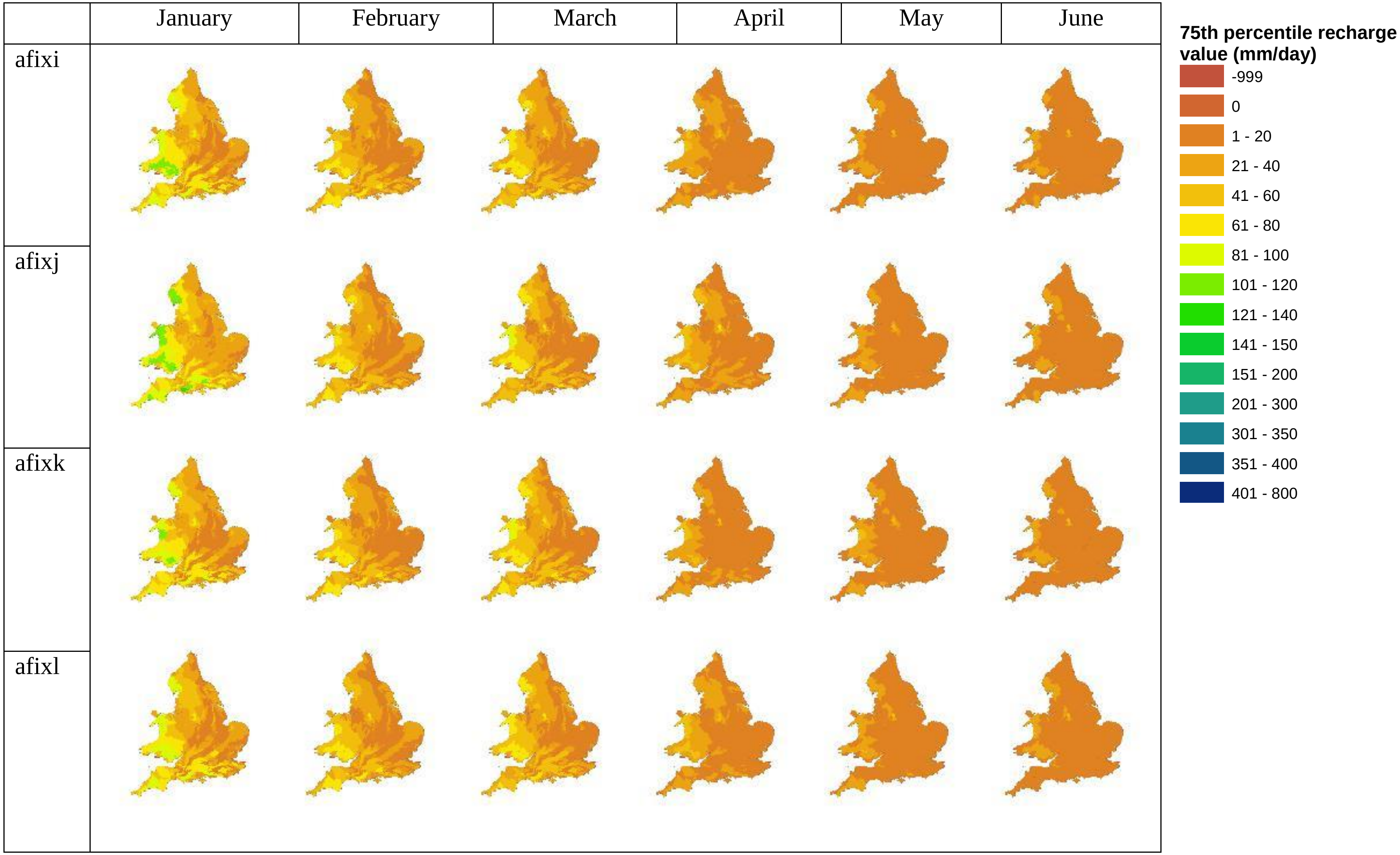
Figure A11 shows the fraction of future recharge values that are higher than the 75th percentile of the historic recharge values of the 11 ensemble scenarios. A value greater than 1 means there are greater number of recharge events with a value more than the 75%. This indicates increasing recharge. A value less than one means fewer events with a recharge value of 75% of the historic simulated. This indicates reducing recharge compared to the historic simulated.

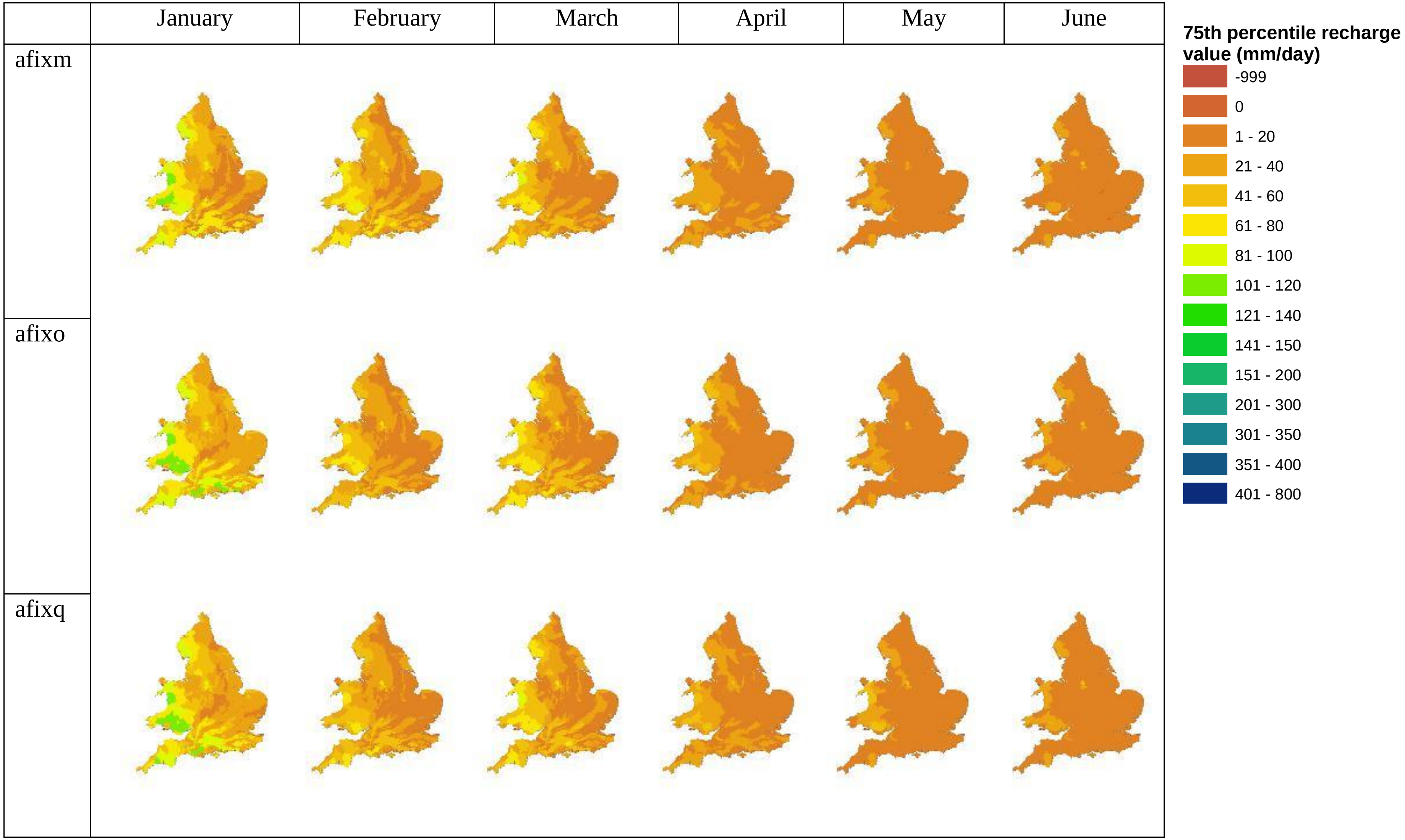
Figure A11 shows that all scenarios are showing a general trend of significant increase in the number events (fraction greater than one) during the winter months, January and December, to the south of England than to the north of England with the exception of scenario afixo for January and scenarios afixc and afixh for December. As for the summer months, there is no general trend that can be picked up from the results of the different scenarios, for example scenarios afgcx, afixm and afixo show high number of events to the east of England, scenarios afixi and afixq show high number of events to the north of England and over Wales.

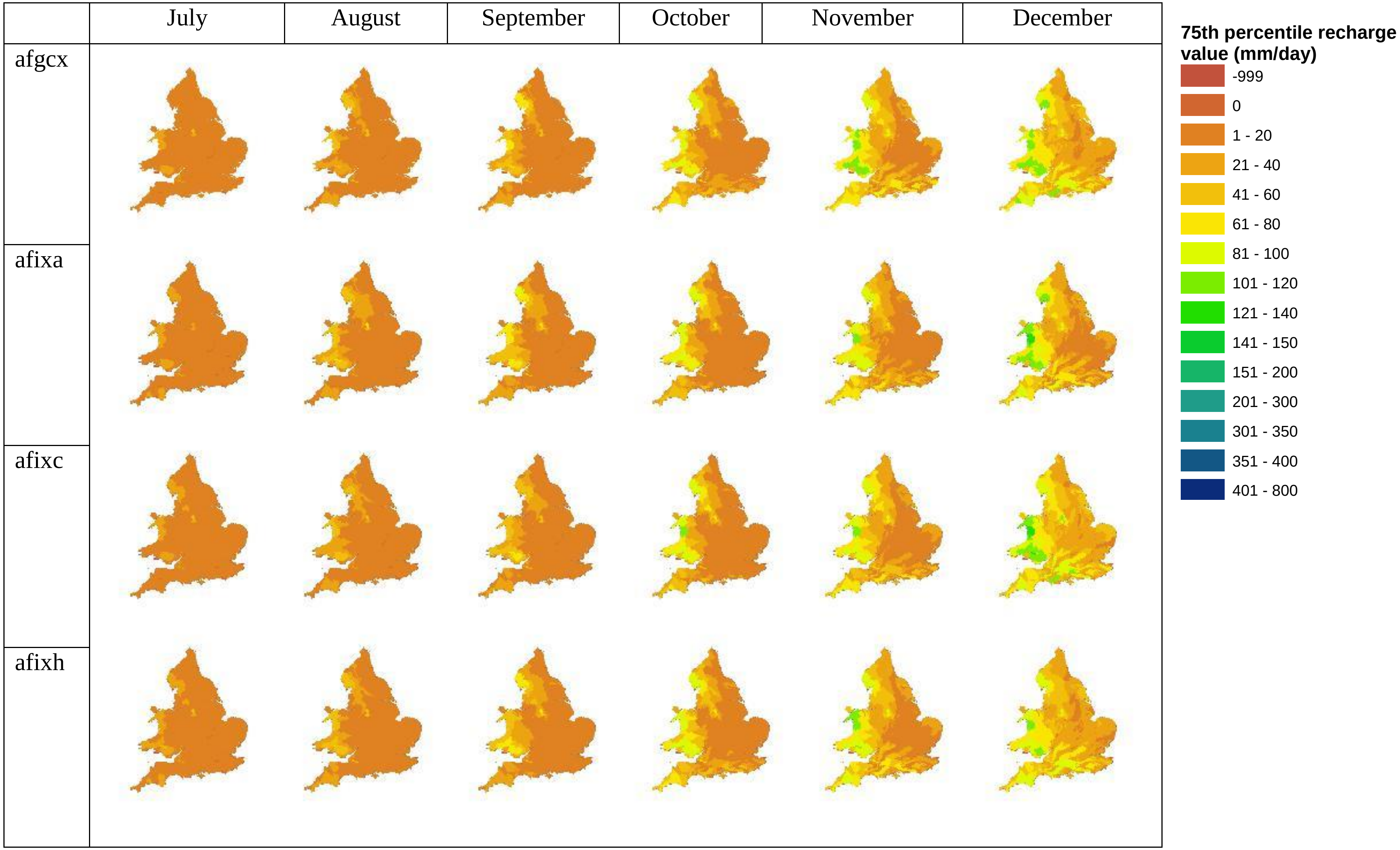
The monthly change by ensembles can be summarised as follows:

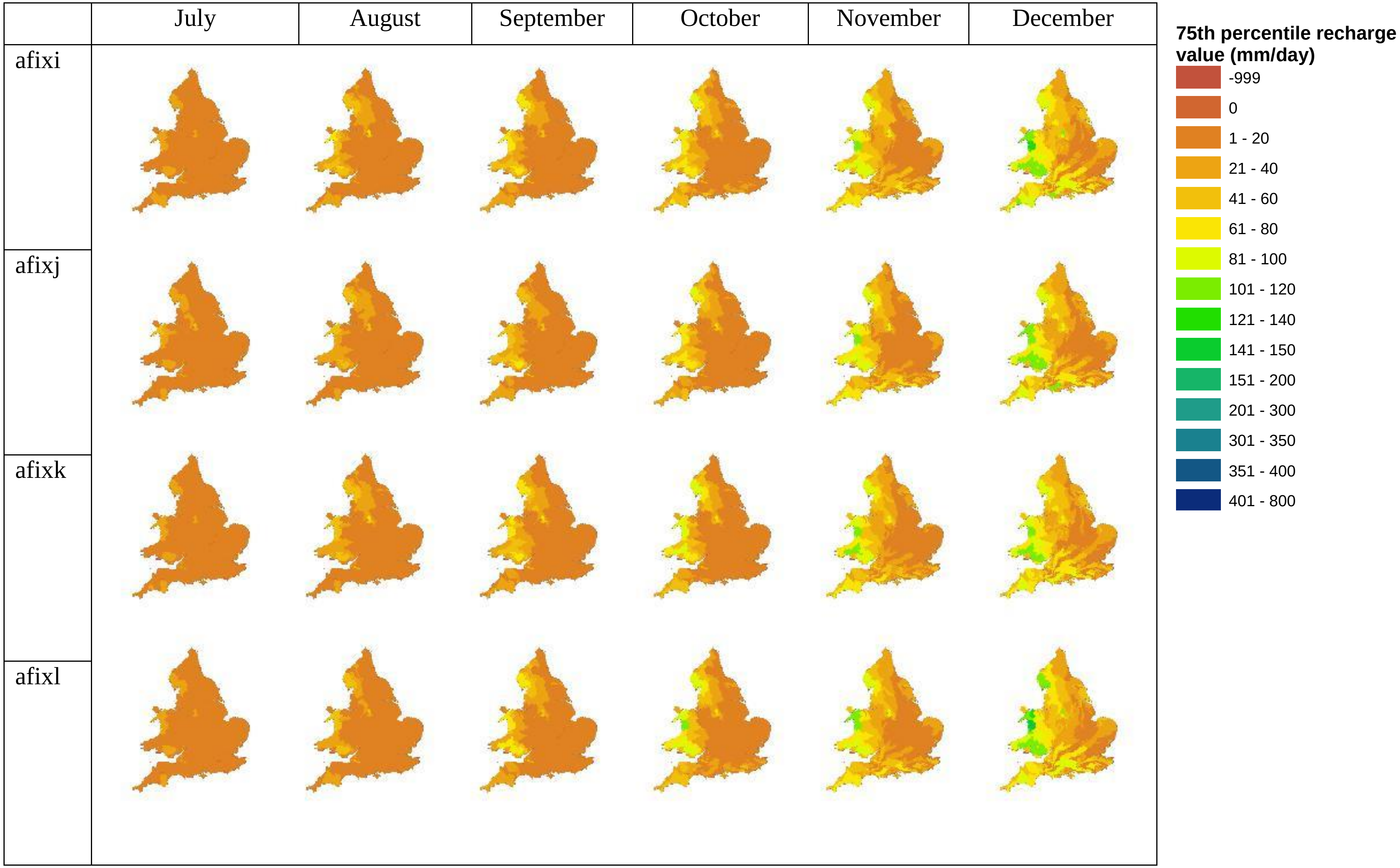
- afgcx: January, February high (i.e. increased recharge value) with November and December mixed value
- afixa: January, October, November and December high
- afixc: January, February, and November high
- afixh: January, February, March, April, and November high, October and December mixed
- afixi: January, February, March (south and east), November high and December mixed
- afixj: January, February, November all mixed with December high
- afixk: January, February, November all mixed with December high
- afixl: January, February, November and December high with October mixed
- afixm: January and December high and November mixed
- afixo: January, February, November and December all mixed
- afixq: January, February and March all high with November and December mixed


January
February
March
April
May
June
afgcx
afixa
afixc
afixh
75th percentile recharge value (mm/day)
-999
0
1 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 150
151 - 200
201 - 300
301 - 350
351 - 400
401 - 800


January
February
March
April
May
June
afixi
afixj
afixk
afixl
75th percentile recharge value (mm/day)
-999
0
1 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 150
151 - 200
201 - 300
301 - 350
351 - 400
401 - 800


January
February
March
April
May
June
afixm
afixo
afixq
75th percentile recharge value (mm/day)
-999
0
1 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 150
151 - 200
201 - 300
301 - 350
351 - 400
401 - 800


July
August
September
October
November
December
afgcx
afixa
afixc
afixh
75th percentile recharge value (mm/day)
-999
0
1 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 150
151 - 200
201 - 300
301 - 350
351 - 400
401 - 800


July
August
September
October
November
December
afixi
afixj
afixk
afixl
75th percentile recharge value (mm/day)
-999
0
1 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 150
151 - 200
201 - 300
301 - 350
351 - 400
401 - 800

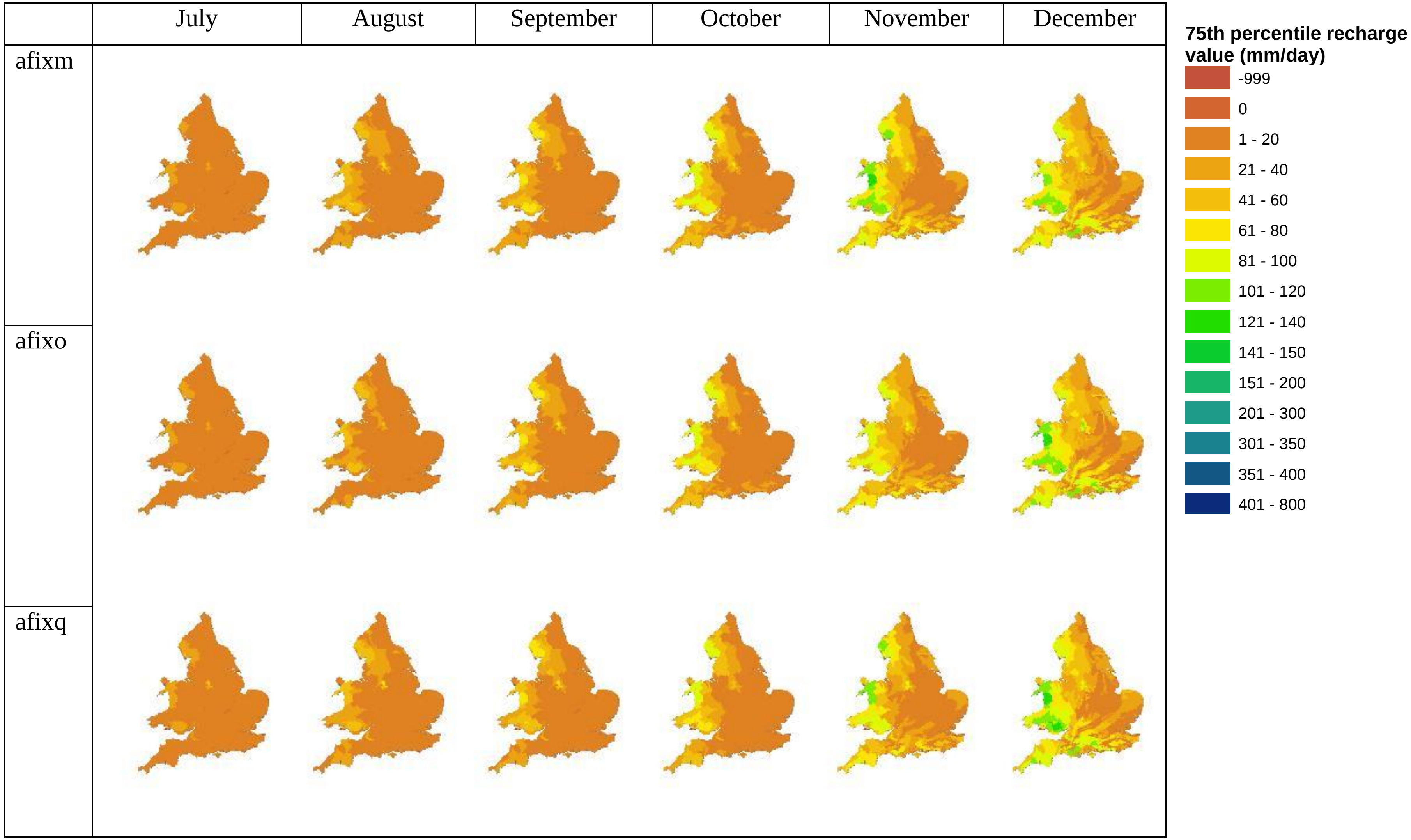
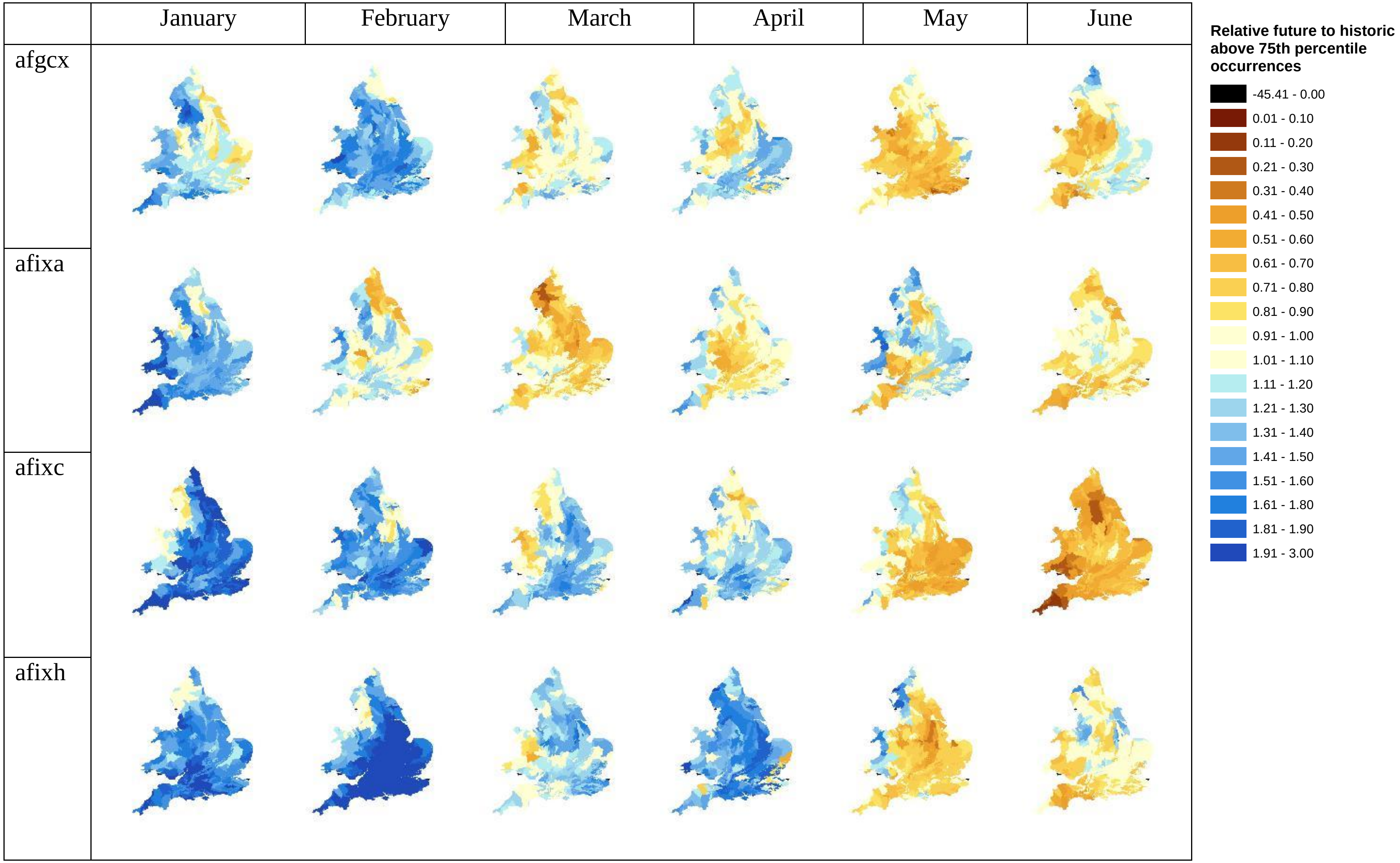
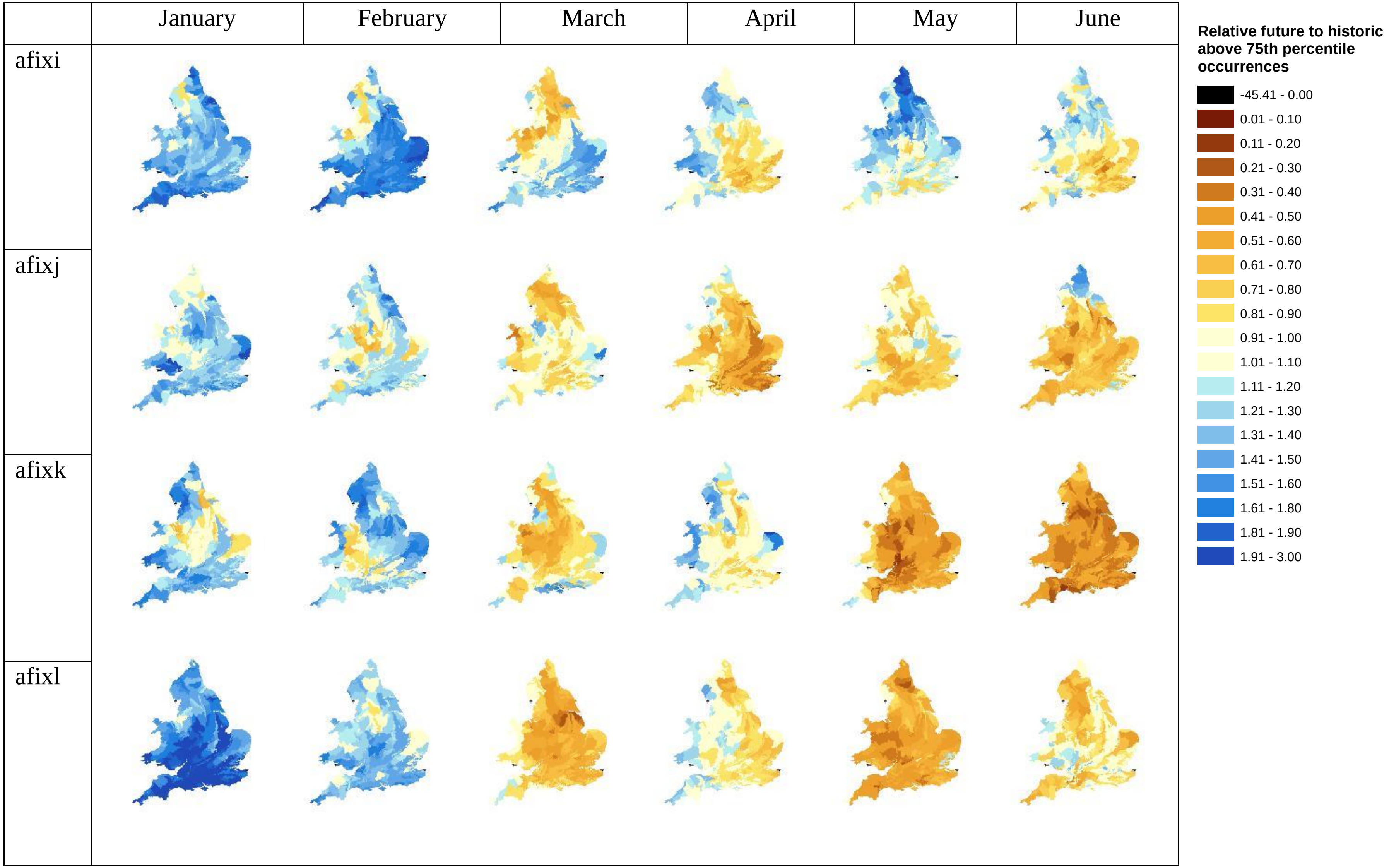
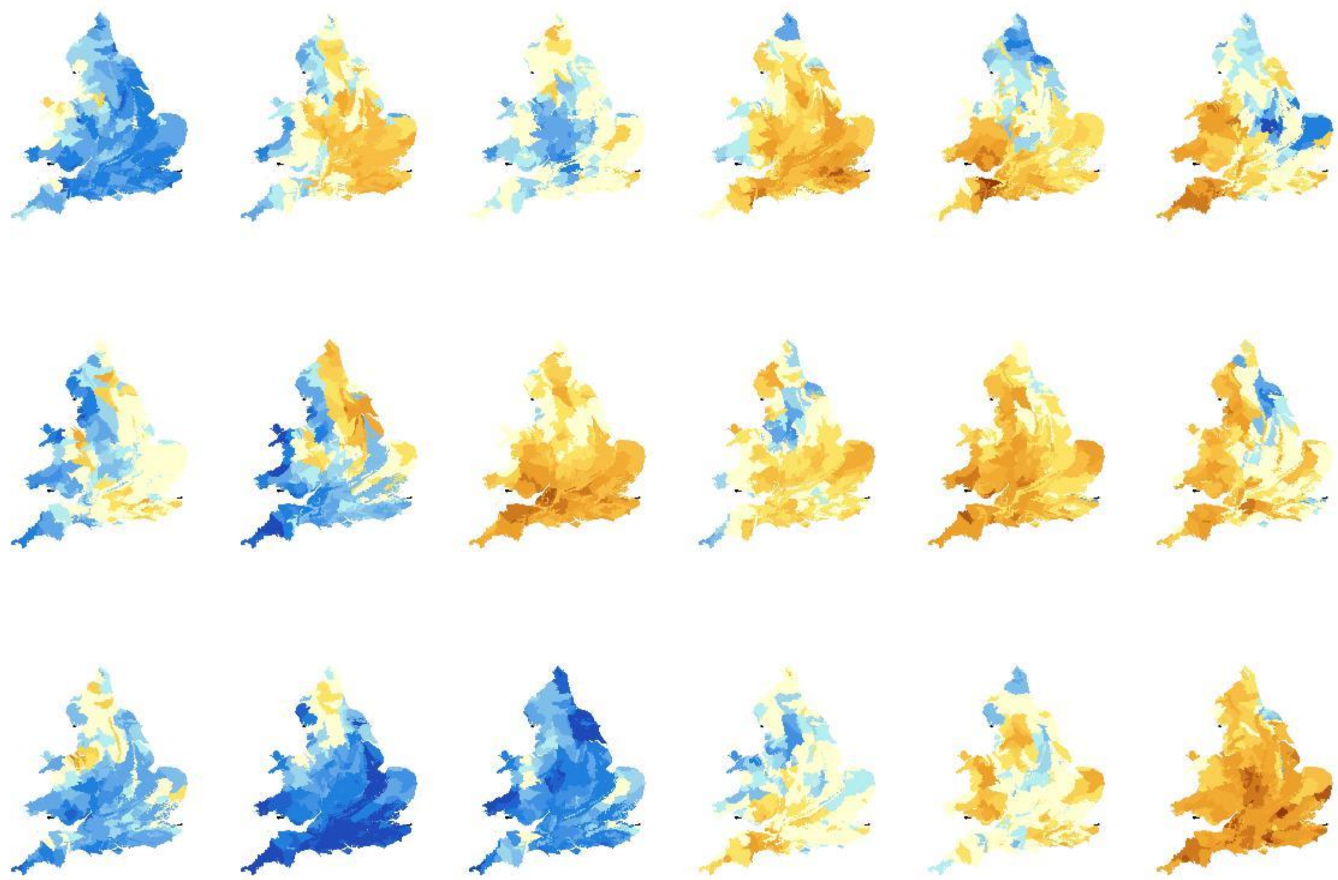


Figure A10. 75th percentile simulated historic values by month for each ensemble


January
February
March
April
May
June
afgcx
afixa
afixc
afixh
Relative future to historic above 75th percentile occurrences
-45.41 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00

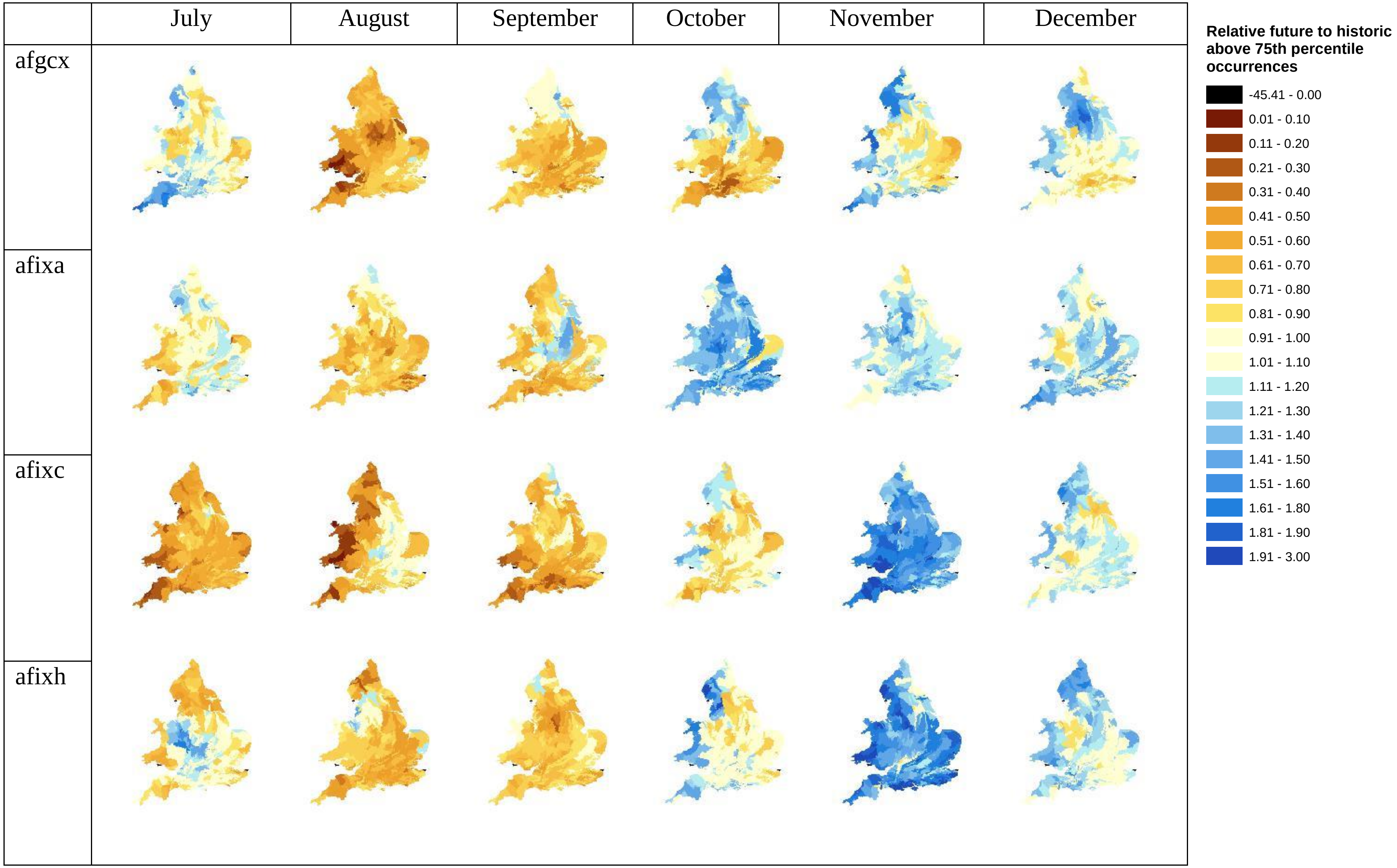

January
February
March
April
May
June
afixi
afixj
afixk
afixl
Relative future to historic above 75th percentile occurrences
-45.41 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00

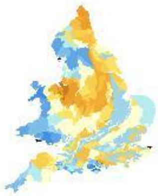
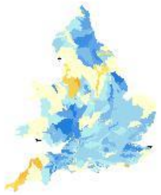
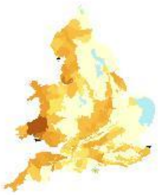
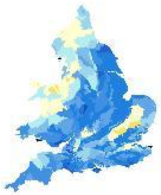
	January	February	March	April	May	June
afixm						
afixo						
afixq						



Relative future to historic above 75th percentile occurrences

- -45.41 - 0.00
- 0.01 - 0.10
- 0.11 - 0.20
- 0.21 - 0.30
- 0.31 - 0.40
- 0.41 - 0.50
- 0.51 - 0.60
- 0.61 - 0.70
- 0.71 - 0.80
- 0.81 - 0.90
- 0.91 - 1.00
- 1.01 - 1.10
- 1.11 - 1.20
- 1.21 - 1.30
- 1.31 - 1.40
- 1.41 - 1.50
- 1.51 - 1.60
- 1.61 - 1.80
- 1.81 - 1.90
- 1.91 - 3.00


July
August
September
October
November
December
afgcx
afixa
afixc
afixh
Relative future to historic above 75th percentile occurrences
-45.41 - 0.00
0.01 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.20
1.21 - 1.30
1.31 - 1.40
1.41 - 1.50
1.51 - 1.60
1.61 - 1.80
1.81 - 1.90
1.91 - 3.00

	July	August	September	October	November	December
afixi						
afixj						
afixk						
afixl						

Relative future to historic above 75th percentile occurrences

- -45.41 - 0.00
- 0.01 - 0.10
- 0.11 - 0.20
- 0.21 - 0.30
- 0.31 - 0.40
- 0.41 - 0.50
- 0.51 - 0.60
- 0.61 - 0.70
- 0.71 - 0.80
- 0.81 - 0.90
- 0.91 - 1.00
- 1.01 - 1.10
- 1.11 - 1.20
- 1.21 - 1.30
- 1.31 - 1.40
- 1.41 - 1.50
- 1.51 - 1.60
- 1.61 - 1.80
- 1.81 - 1.90
- 1.91 - 3.00

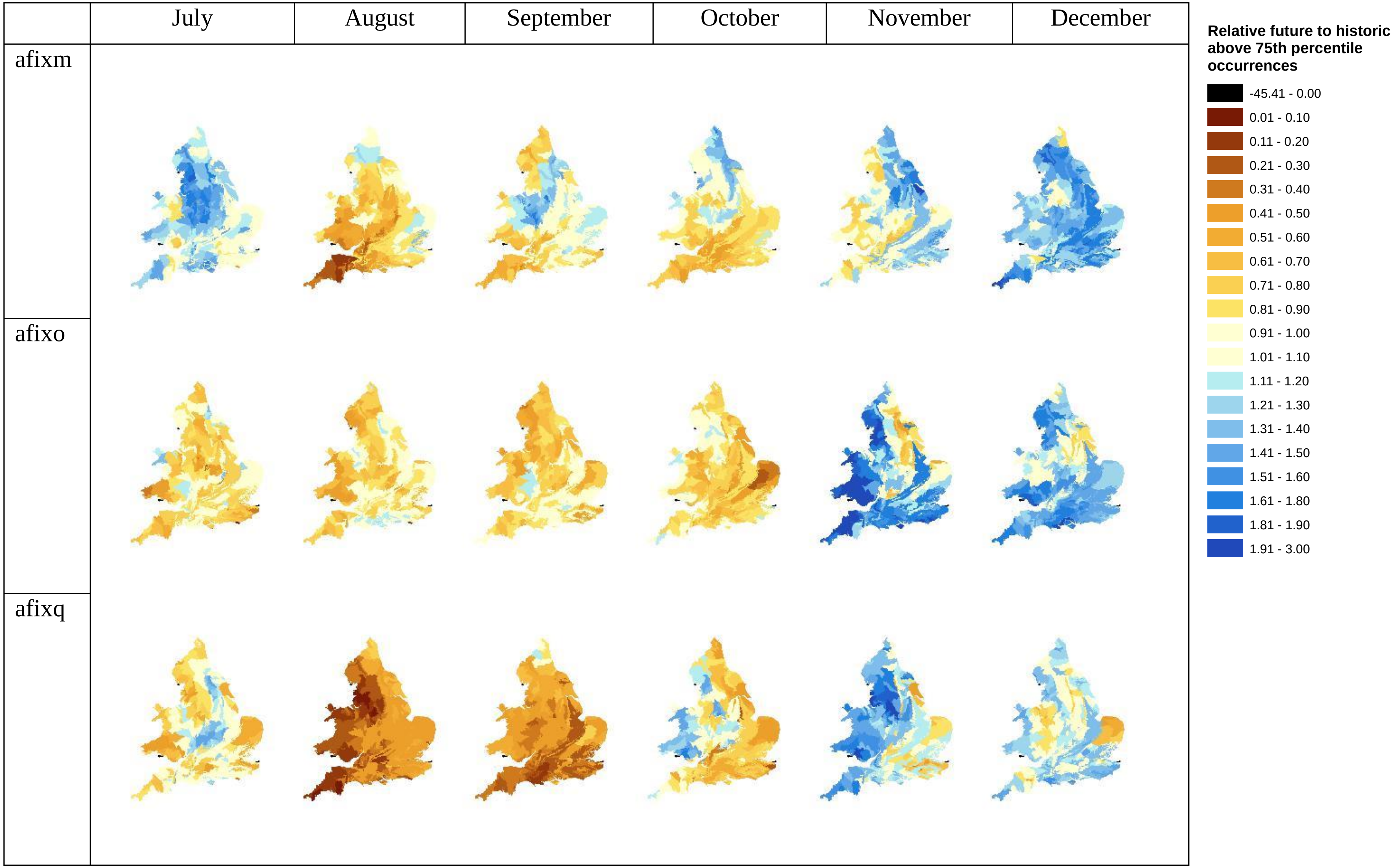


Figure A11. Proportion of recharge values greater than the 75th percentile of simulates historic recharge values for each ensemble

Appendix 3 Mean monthly change

As discussed above (Section 2) the recharge season generally considered as being from September through to April so the change in monthly recharge has been assessed for these months.

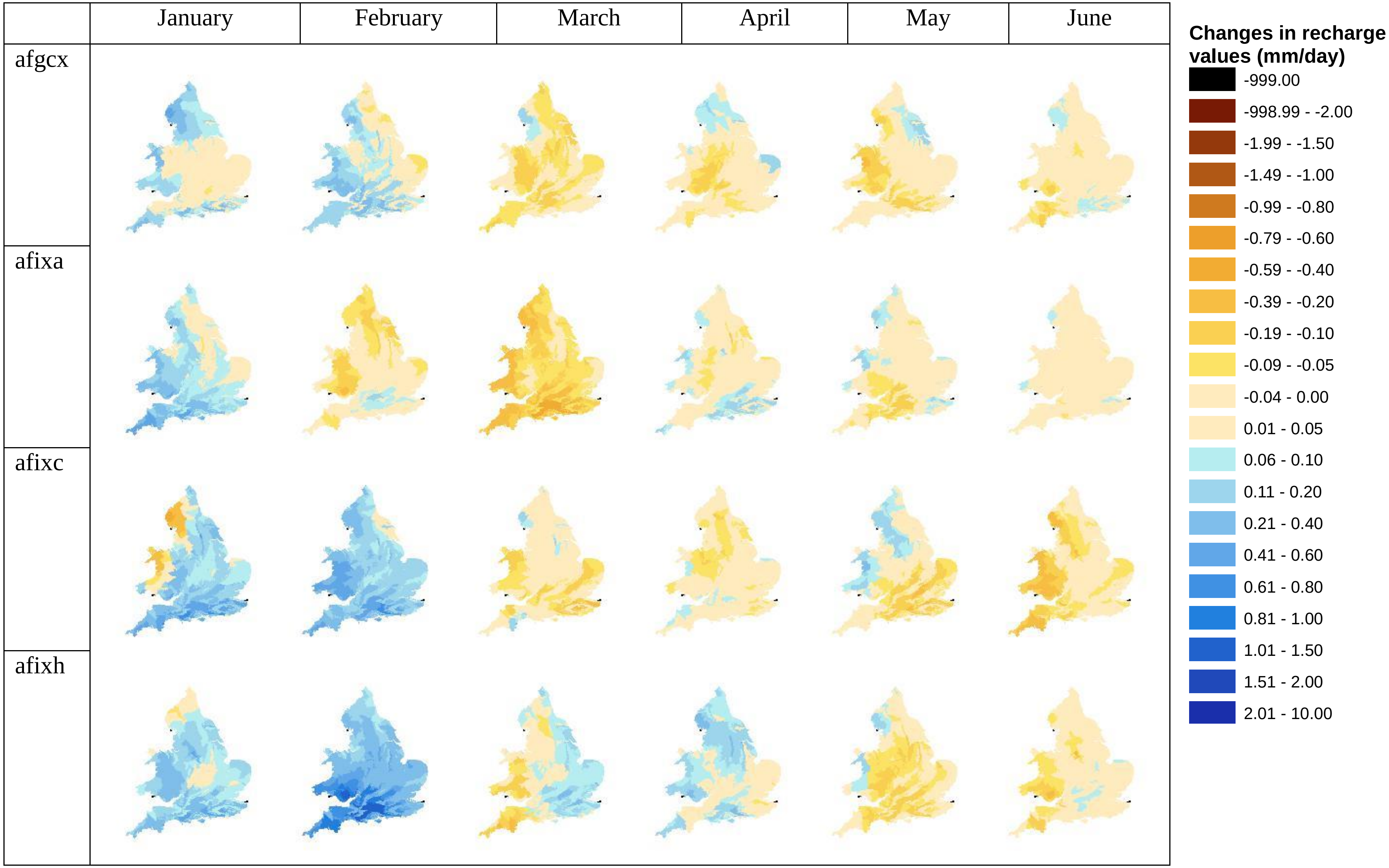
A3.1 MONTHLY CHANGES DURING THE 2020S

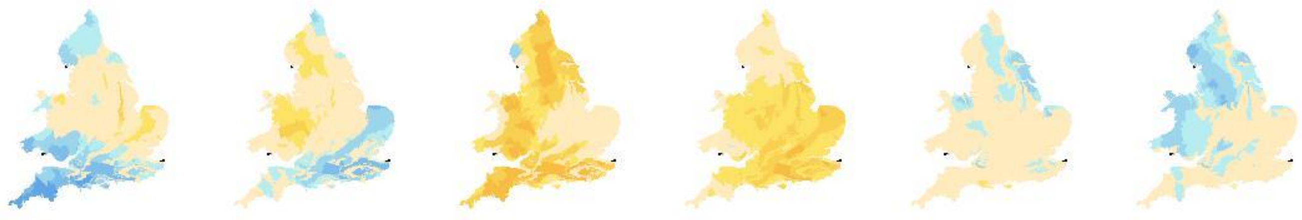
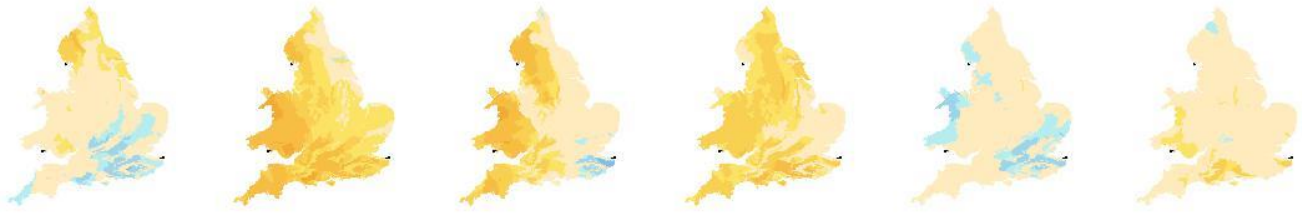
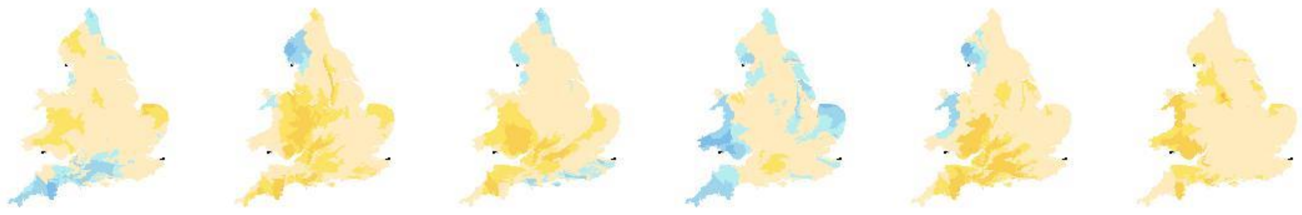
Figure A12 shows the differences between the monthly recharge values calculated for the period between 2010 and 2039 and the simulated historic recharge values calculated between 1961 and 2009. The legend is set to negative values, i.e. future values less than historical values, are represented by a shade of colours from light brown /yellow to dark brown. Positive difference values, i.e. future values greater than historical values, are shown with colours ranging from light blue to dark blue. This figure shows that there is a general trend of increased recharge values for almost all months except for March and April where the trend is a reduction in future recharge values.

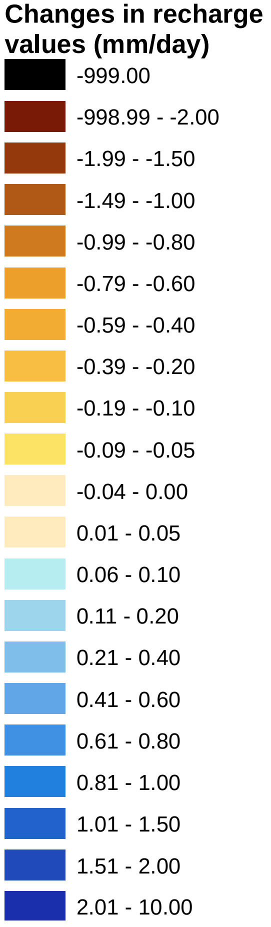
In addition, it can be inferred from Figure A12 that all scenarios produce future recharge values, the 20s recharge values, which are higher than the historical recharge values. However, detailed inspection, especially when interpreting the spatial variations of recharge values, reveals a more complex conclusion. For example, almost all scenarios show that there is increase in January recharge values across the study area especially to the south of England except scenarios afixo and afixq. However, scenarios afixc, afixj and afixk show reduction in January recharge over the north of England and north of Wales. In addition, scenarios afixh and afixl show significant increase in February recharge to the southwest of England, this is contradicted by the results obtained from scenarios afixj, afixk and afixm, which show reduction in February recharge values.

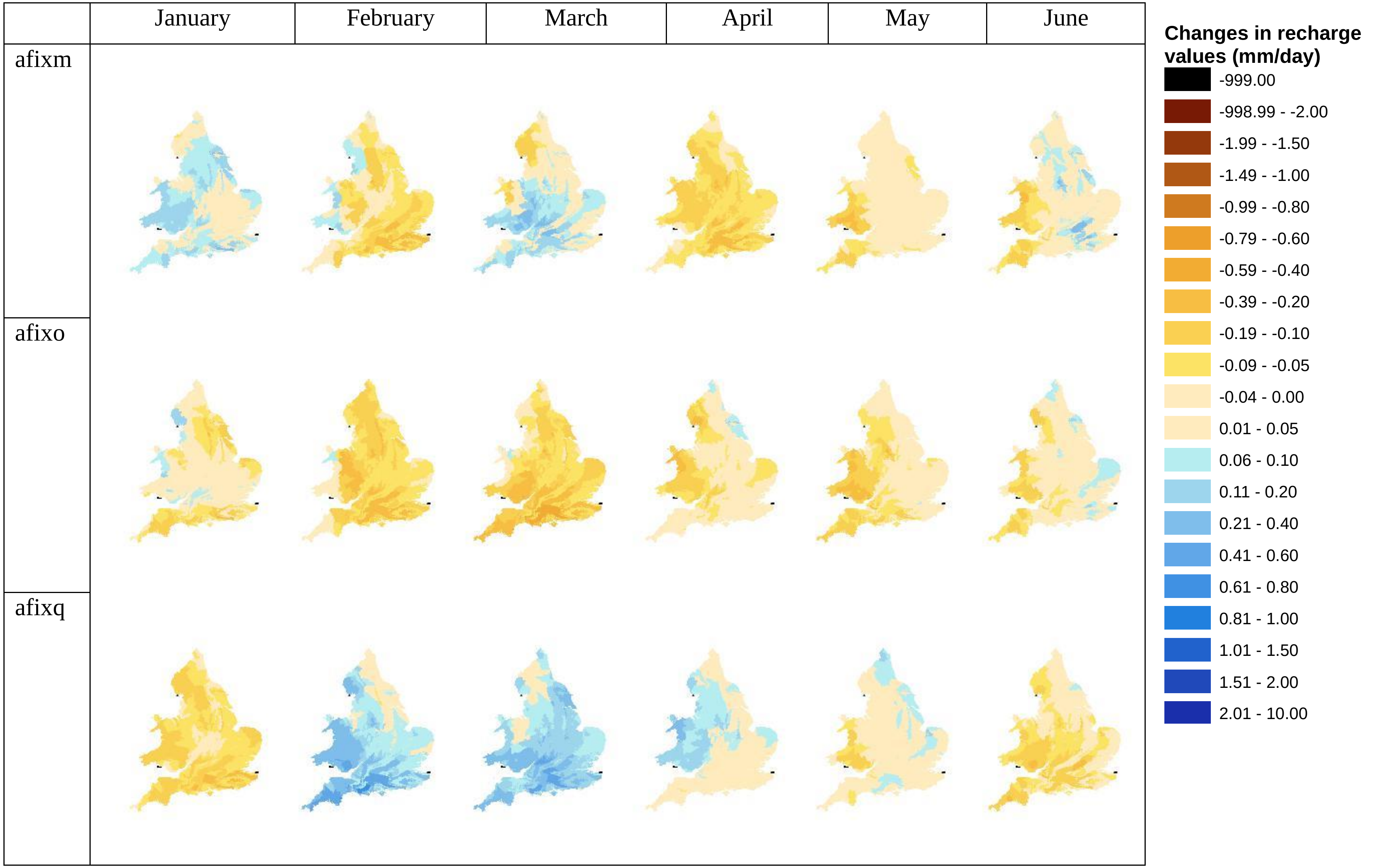
The monthly change by ensembles can be summarised as follows:

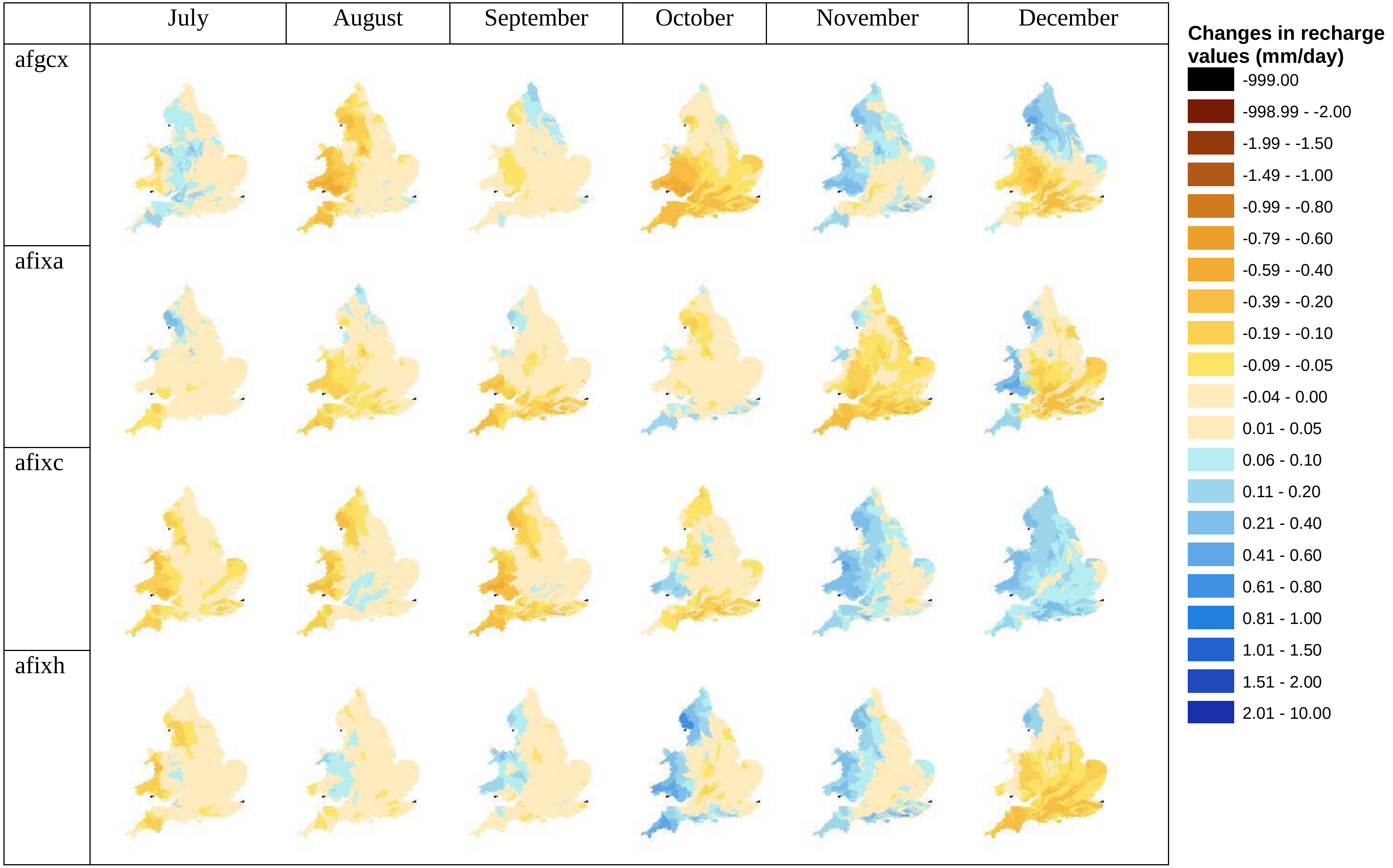
- afgcx reduction in March and April
- afixa reduction in March, February, November and December
- afixc reduction in March, April, September and October, but with increases in Januar,y February and December
- afixh reduction in December
- afixi reduction in March, April, October and December
- afixj and afixk reduction January through to April, with January being the worse case. afixj shows an increase in December
- afixl reduction in March, but with increases in recharge in January, February, November and December
- afixm reduction in February, October and November
- afixo reduction from January to March, but increased recharge in December
- afixq reduction January, October and December but greater recharge in February to April

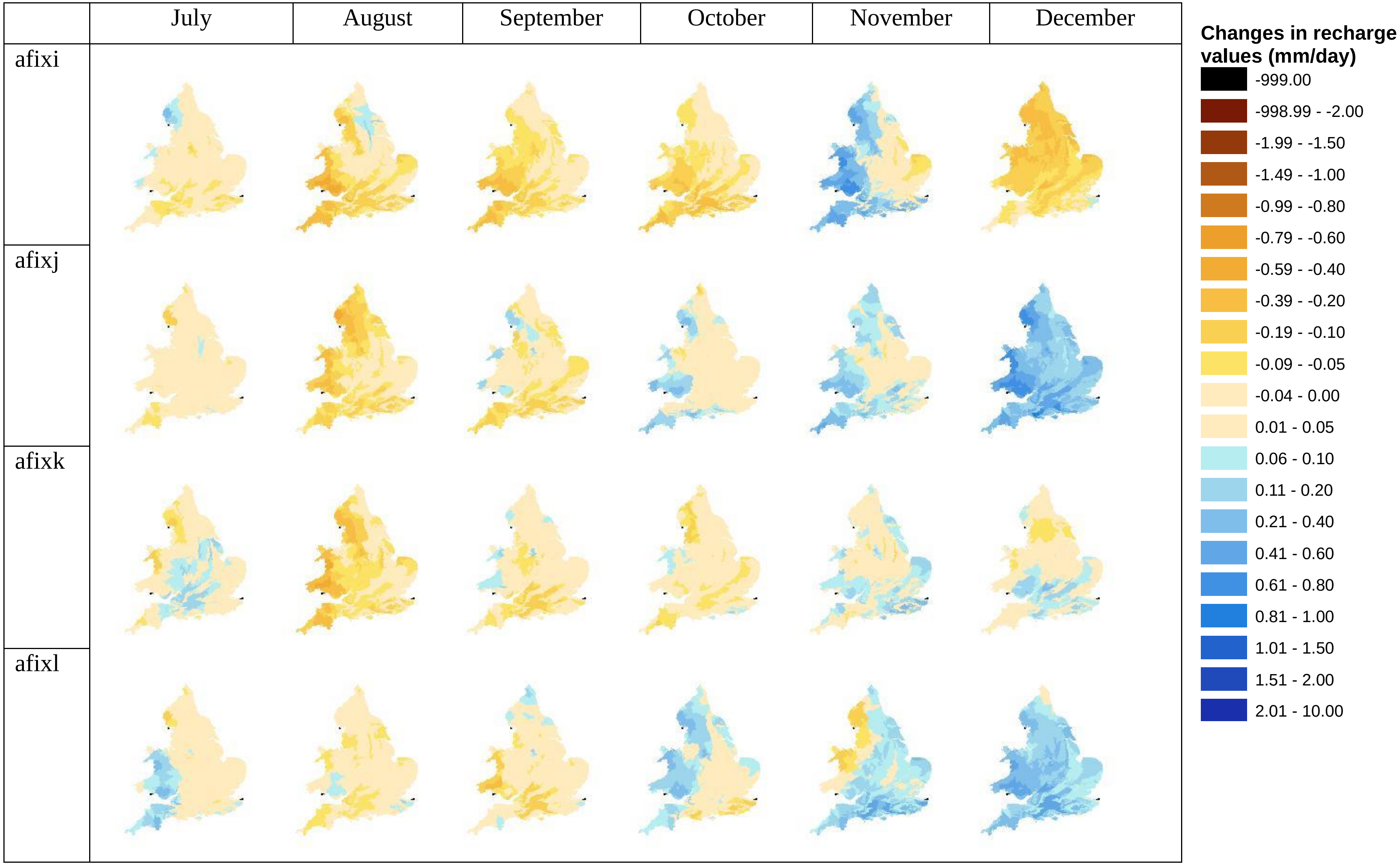

January
February
March
April
May
June
afgcx
afixa
afixc
afixh
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

	January	February	March	April	May	June
afixi						
afixj						
afixk						
afixl						




January
February
March
April
May
June
afixm
afixo
afixq
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00


July
August
September
October
November
December
afgcx
afixa
afixc
afixh
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00


July
August
September
October
November
December
afixi
afixj
afixk
afixl
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

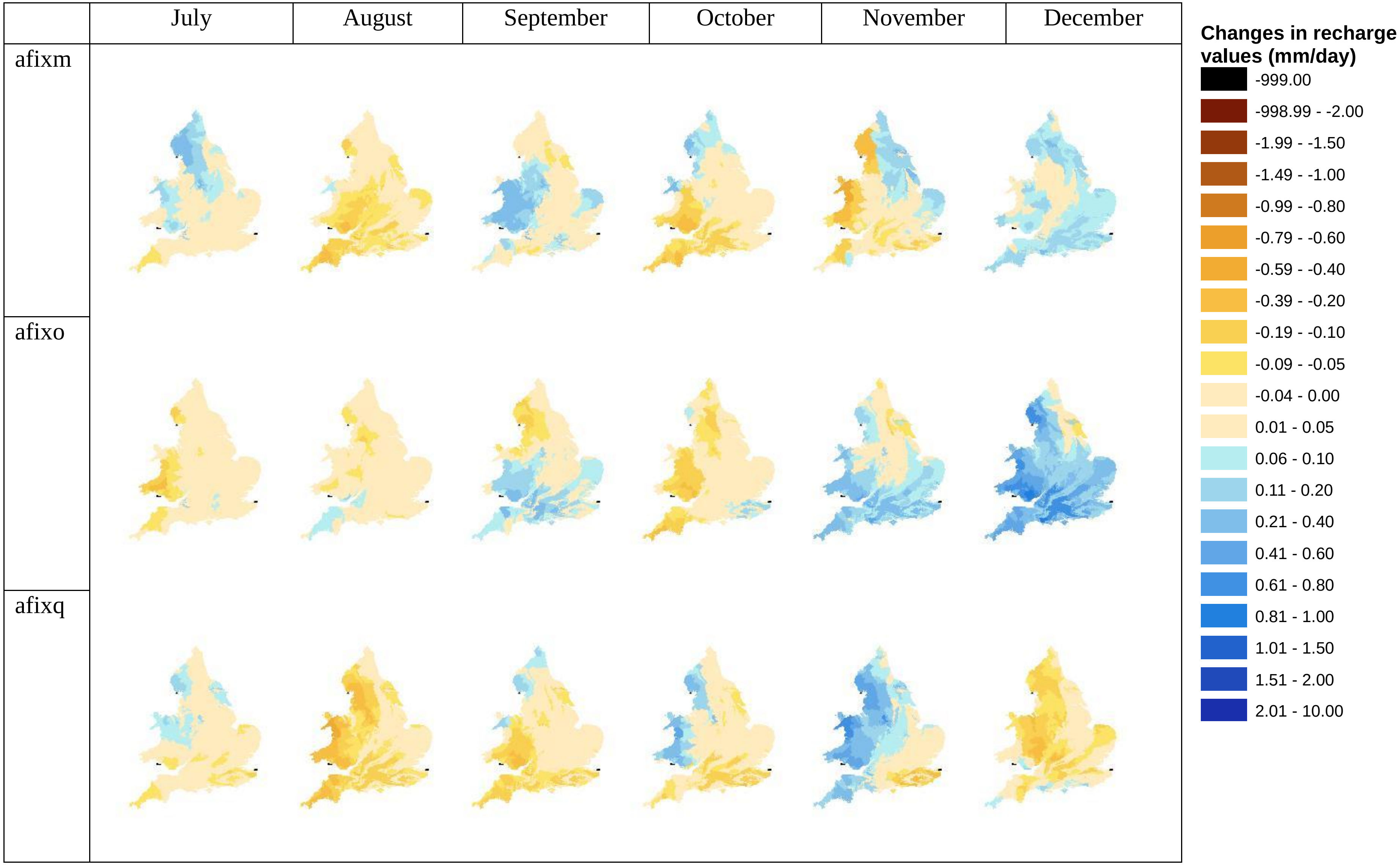


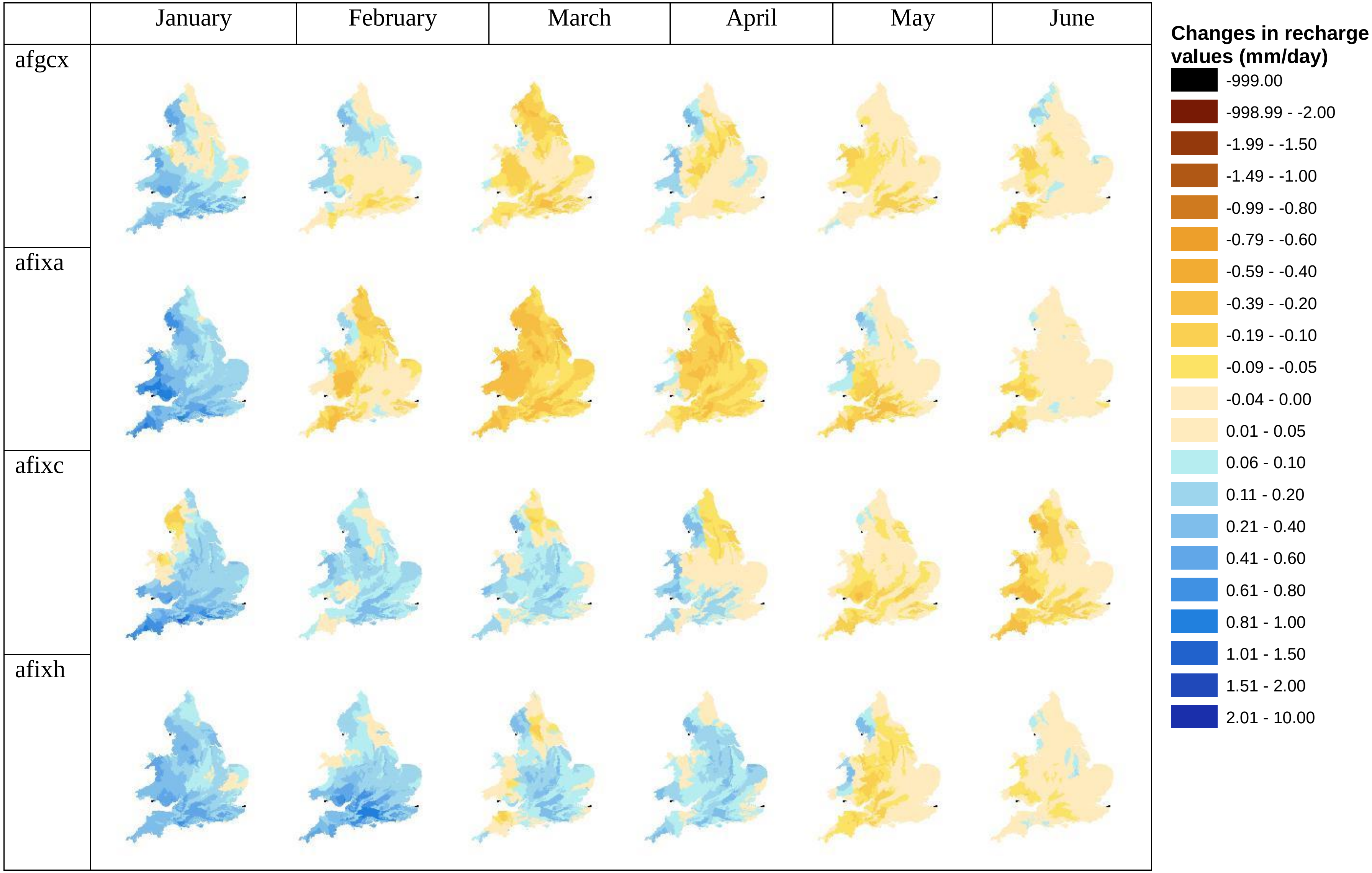
Figure A12. Changes in monthly recharge for the 2020s for all ensembles

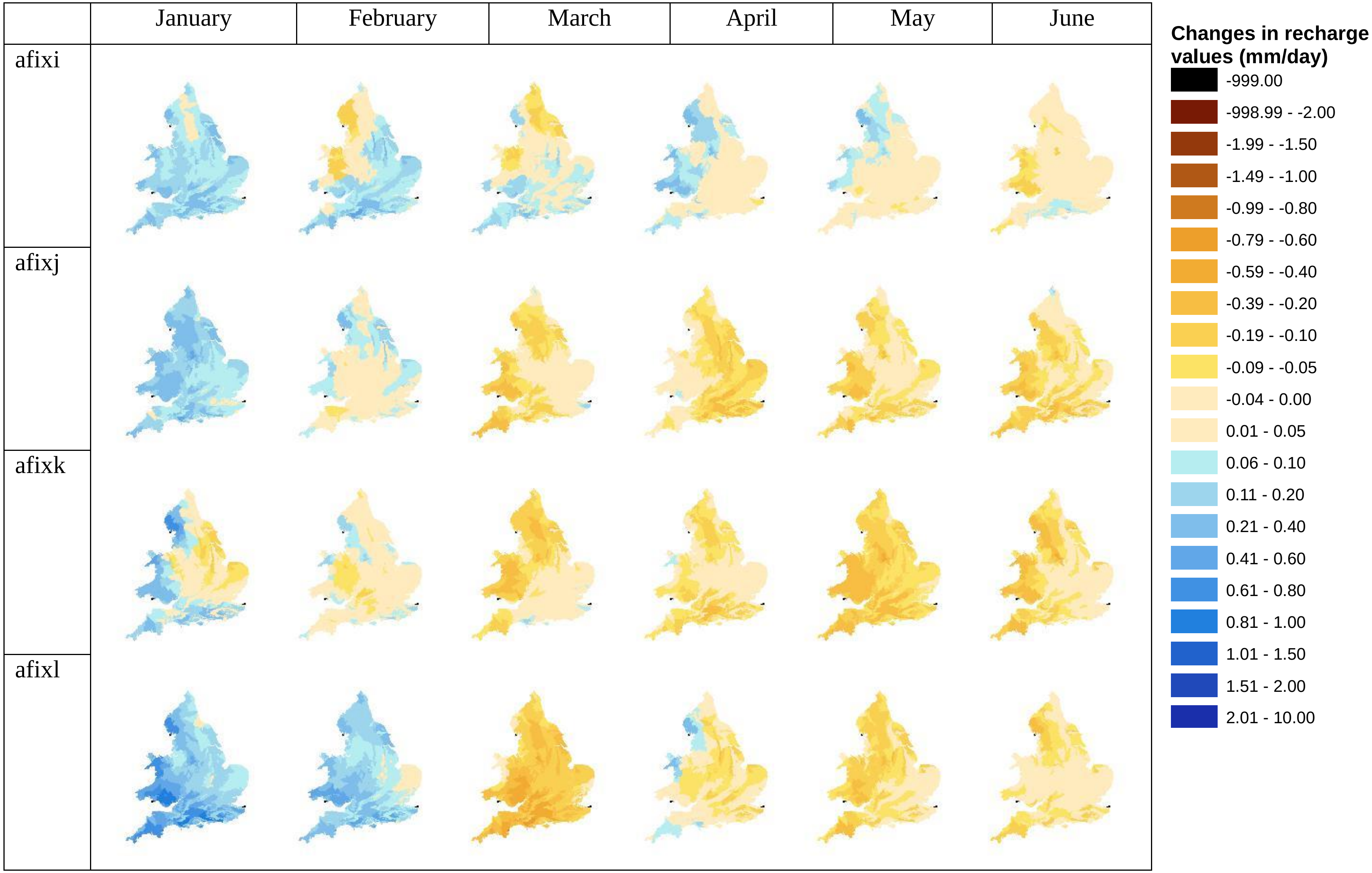
A3.2 MONTHLY CHANGES DURING THE 2050S

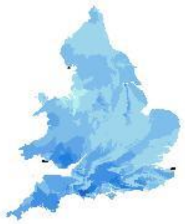
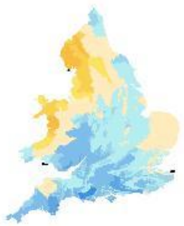
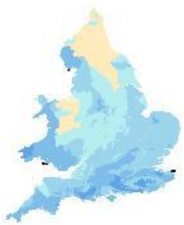
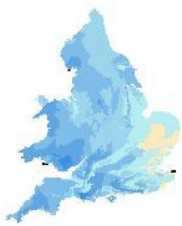
Figure A13 shows the differences between the monthly recharge values calculated for the period between 2040 and 2069 and the simulated historic recharge values calculated between 1961 and 2009. The legend is same as the one used in the previous Section (A3.1). This figure shows that there is a general trend of increased recharge values for winter months of November, December, January and February and that there is a decrease in recharge values of May, June and August. There is an agreement between the scenarios, however, for recharge values to be higher during January, July and December in the future. This agreement between scenarios is more pronounced for this period, the 50s, than for the 20s discussed above. In addition, recharge values calculated for May are shown to be lower during the 50s than during the 20s. However, and similar to the in the previous section, it is difficult to infer one clear trend from the results obtained from all these scenarios when detailed inspection of the spatial variations of recharge values is undertaken.

The monthly change by ensembles can be summarised as follows:

- afgcx reduction in March, September with increased recharge in January
- afixa reduction in February, March and September with increased recharge in January, October, November and December. The latter two months the increases occur mainly in south-east England.
- afixc and afixh greater recharge in January, February and March along with increases in November and December
- afixi increased recharge in January to April with a reduction in September and October but with increases in November and December
- afixj, afixk and afixl increased recharge in January and February reduced in March and April with a reduction in September and October but with increases in November and December
- afixm greater recharge in January with a reduction in September and October but with increases in November and December
- afixo reduction in recharge in February and March as well as a reduction in September and October but with increases in November and December
- afixq greater recharge in January to March with a reduction in September and October but with increases in November and December

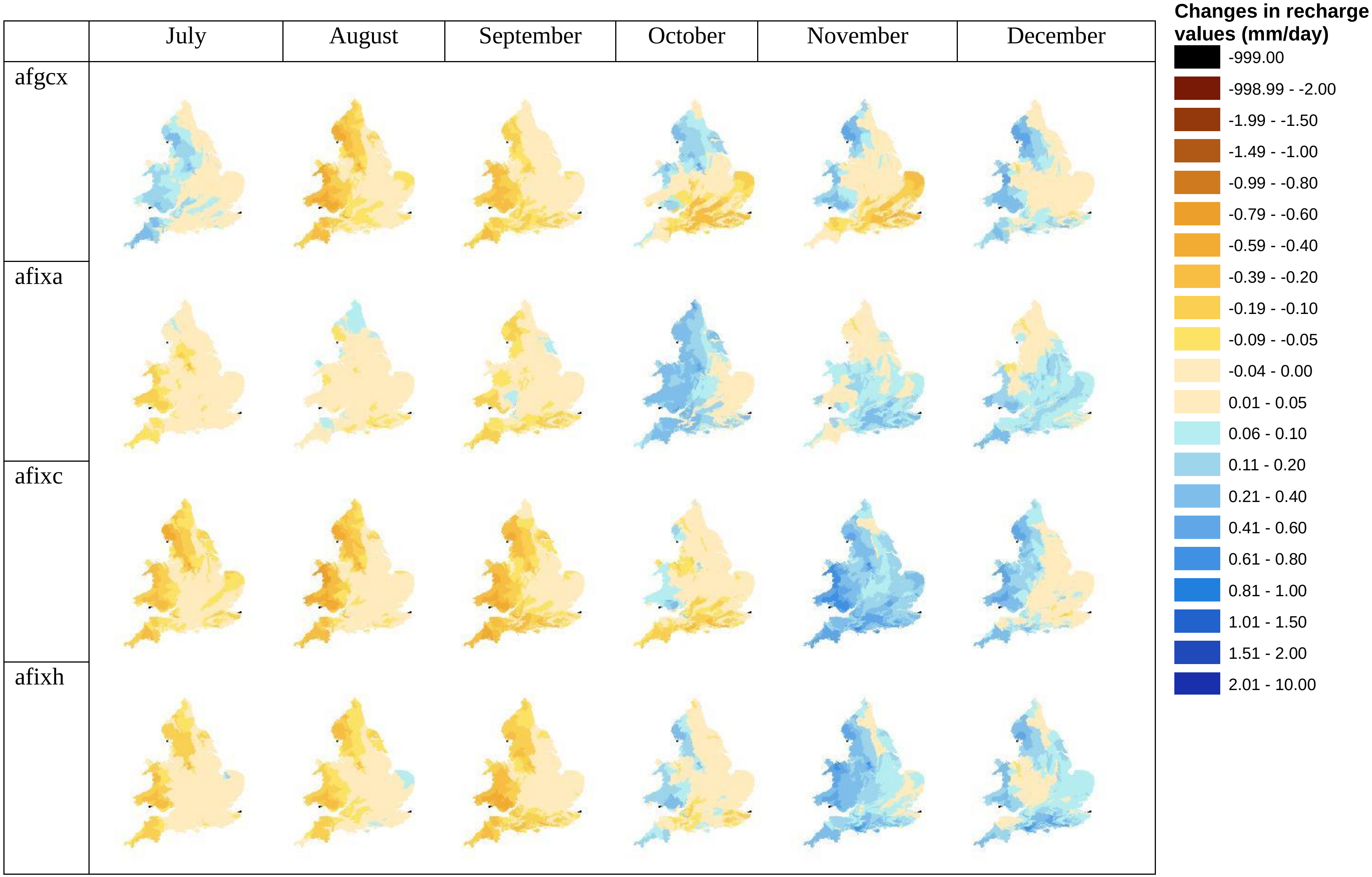

January
February
March
April
May
June
afgcx
afixa
afixc
afixh
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

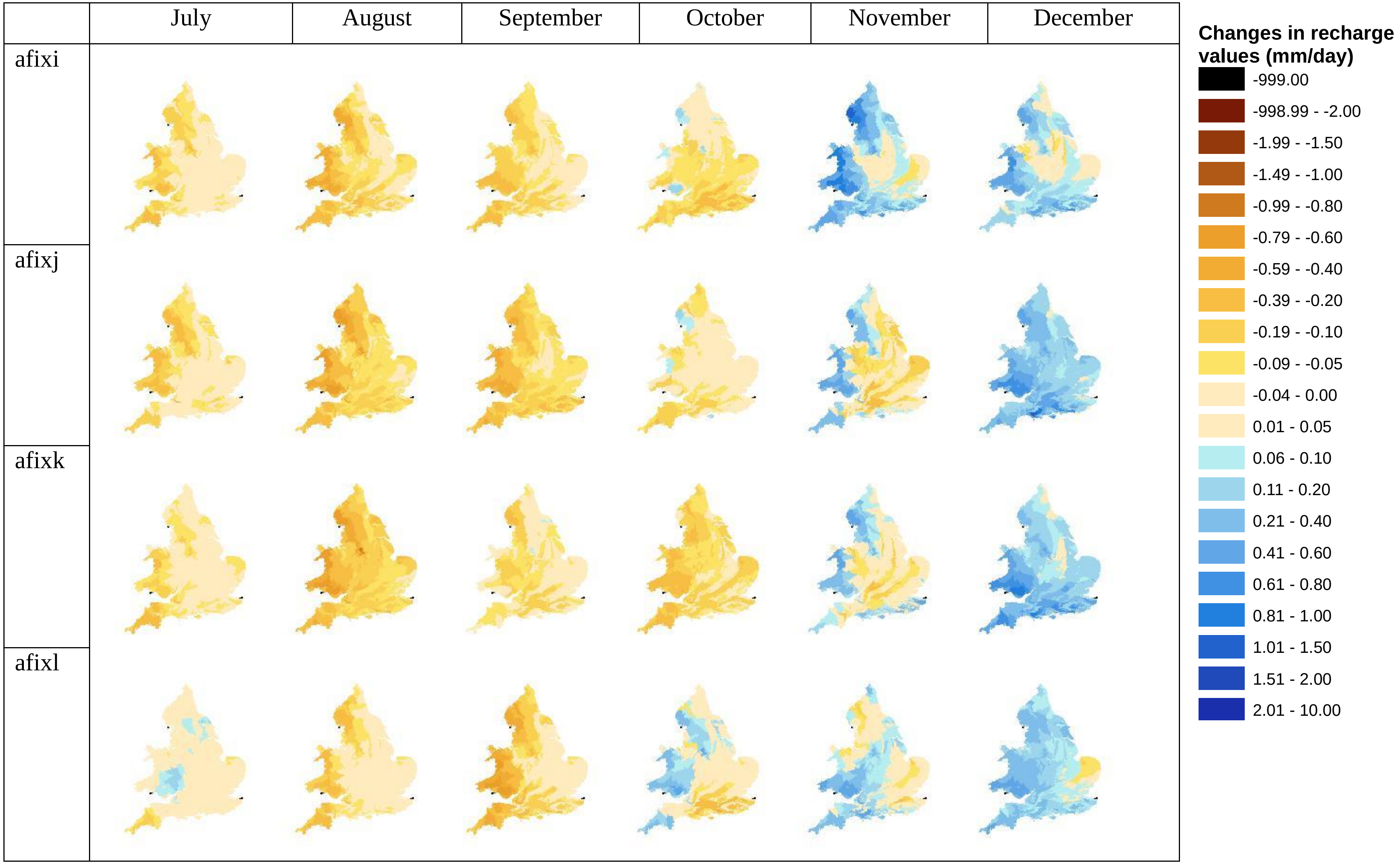

January
February
March
April
May
June
afixi
afixj
afixk
afixl
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

	January	February	March	April	May	June
afixm						
afixo						
afixq						

Changes in recharge values (mm/day)

- -999.00
- -998.99 - -2.00
- -1.99 - -1.50
- -1.49 - -1.00
- -0.99 - -0.80
- -0.79 - -0.60
- -0.59 - -0.40
- -0.39 - -0.20
- -0.19 - -0.10
- -0.09 - -0.05
- -0.04 - 0.00
- 0.01 - 0.05
- 0.06 - 0.10
- 0.11 - 0.20
- 0.21 - 0.40
- 0.41 - 0.60
- 0.61 - 0.80
- 0.81 - 1.00
- 1.01 - 1.50
- 1.51 - 2.00
- 2.01 - 10.00


July
August
September
October
November
December
afgcx
afixa
afixc
afixh
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00


July
August
September
October
November
December
afixi
afixj
afixk
afixl
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

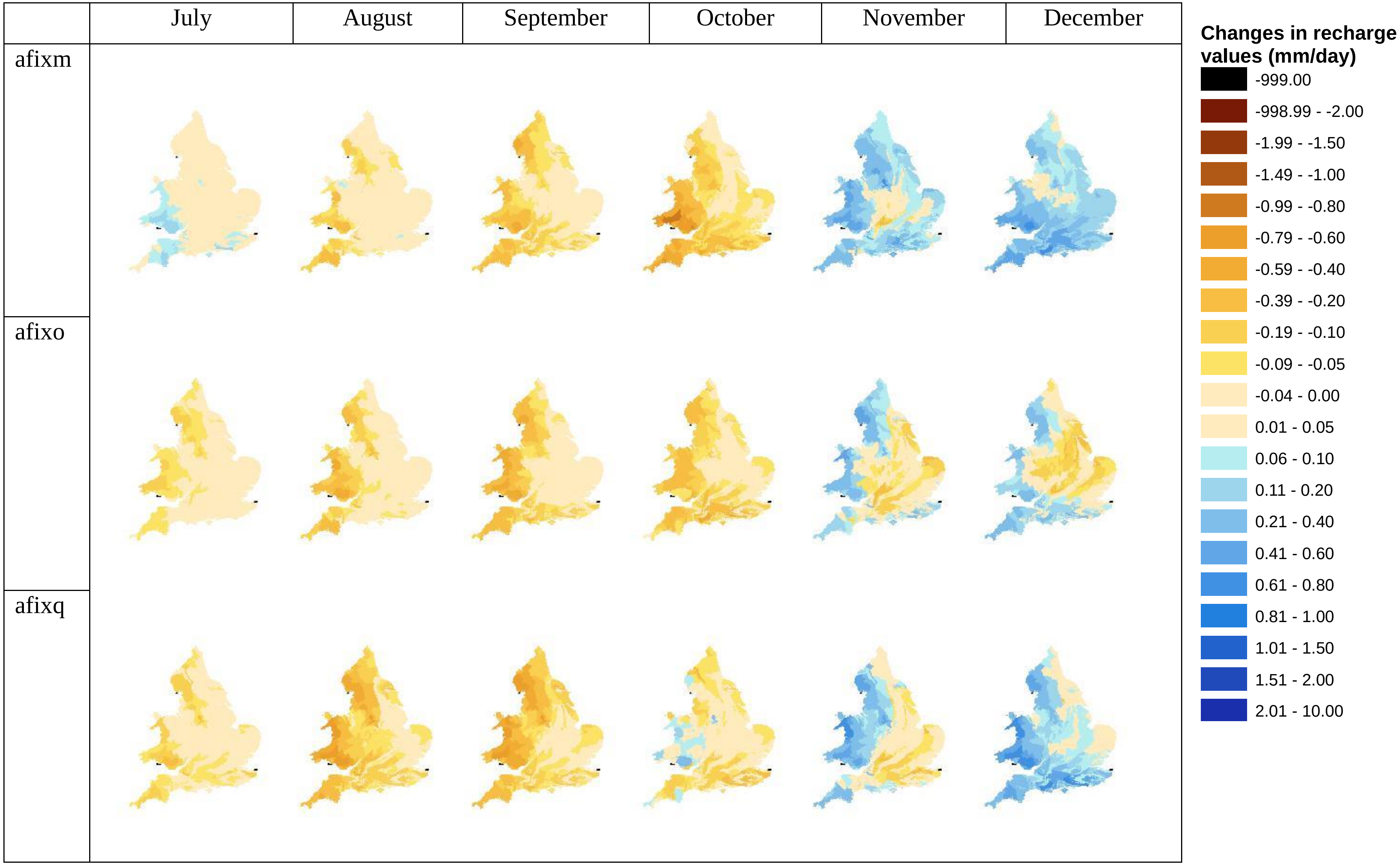


Figure A13. Changes in monthly recharge for the 2050s for all ensembles

A3.3 MONTHLY CHANGES DURING THE 2080S

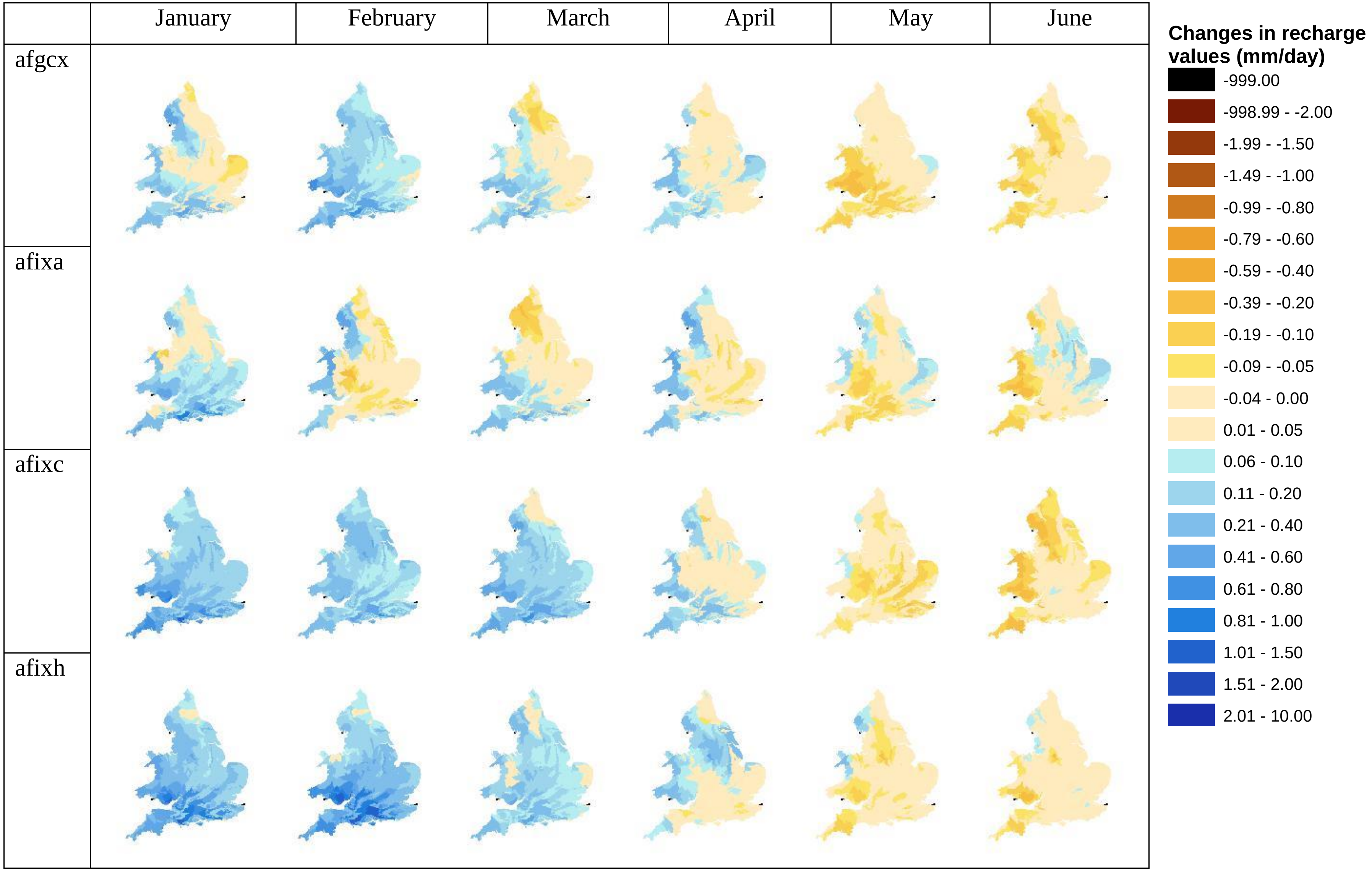
Figure A14 shows the differences between the monthly recharge values calculated for the period between 2070 and 2099 and the simulated historic recharge values calculated between 1961 and 2009. The legend is same as the one used in the previous Section (A3.2). Figure A14 shows that there is a general trend of increased recharge values for almost all months of the year except for August for which future calculated recharge values are in general lower than the historical recharge values.

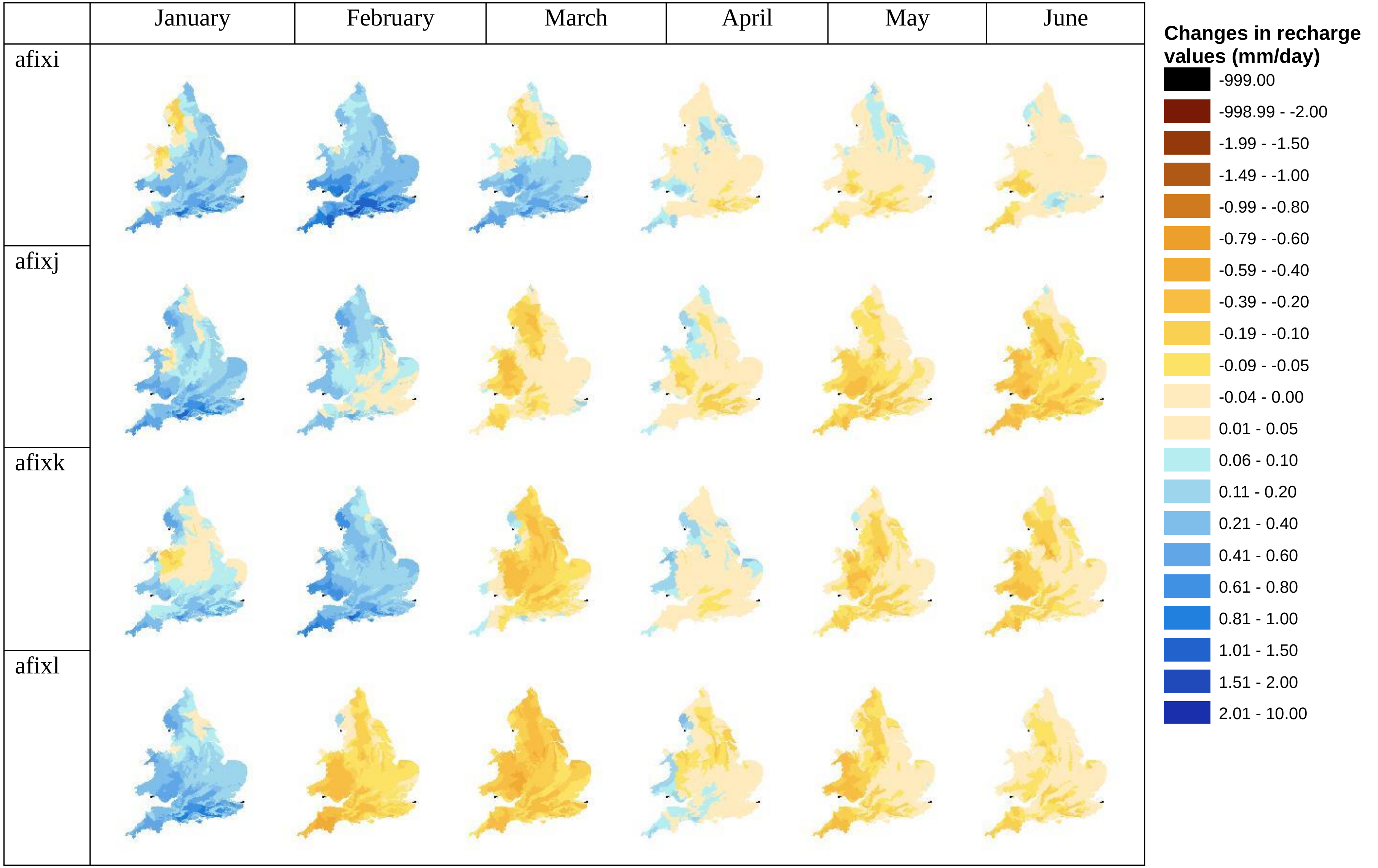
There is a noticeable conclusion from this set of results, which is a more consistency of higher future recharge values across all models and for all months. Comparing with the 20s and 50s recharge values, the recharge values calculated over May and June are much higher in the 80s. A major outcome from the analysis of the results of this period is that it is most likely that more recharge is available during the 80s; however, it is very difficult to infer a general conclusion that describes all the spatial variations of recharge values.

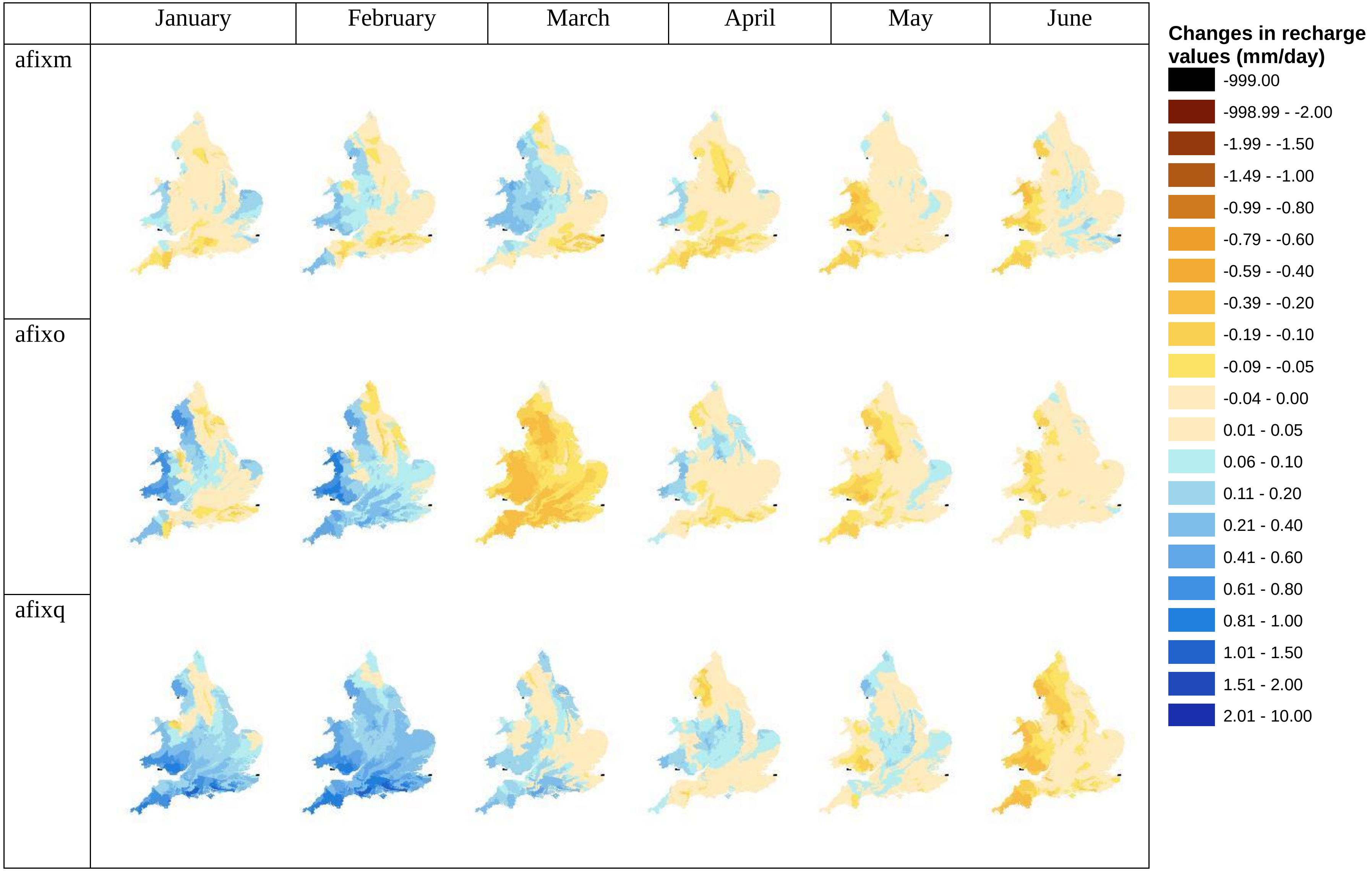
The monthly change by ensembles can be summarised as follows:

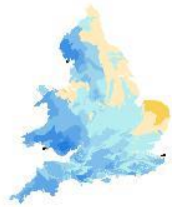
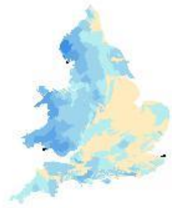
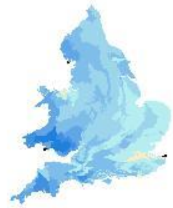
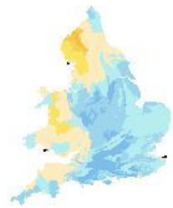
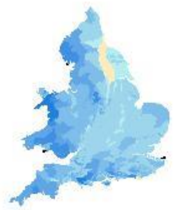
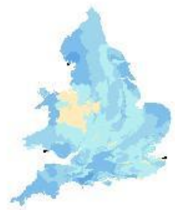
- afgcx greater recharge in February with a reduction in recharge in September and October and an increase in November and December
- afixa greater recharge in January and September and an increase in October, November and December
- afixc and afixh both show a greater recharge in January to March with a reduction in recharge in September and October and an increase in November and December
- afixi greater recharge in January to February but reduction in March in the NW of England and reduction in April; reduction in September, October and December and with a greatly increased recharge in November
- afixj and afixk greater recharge January and February reduction in March and April and September with an increased very much increased recharge in December
- afixl greater recharge in January, reduction in February, March and April as well as in September and October but with a very much increased recharge in November and December
- afixm predominantly mixed spatial pattern of decreased and increased recharge January, February and March reduction in April, September, October and November but with an increase in December
- afixo increased recharge in February, reduction in March, September and October with increased November and December

afixq increased in January and February, more modest increases in March and April reduction in September and October and increases in November and December


January
February
March
April
May
June
afgcx
afixa
afixc
afixh
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

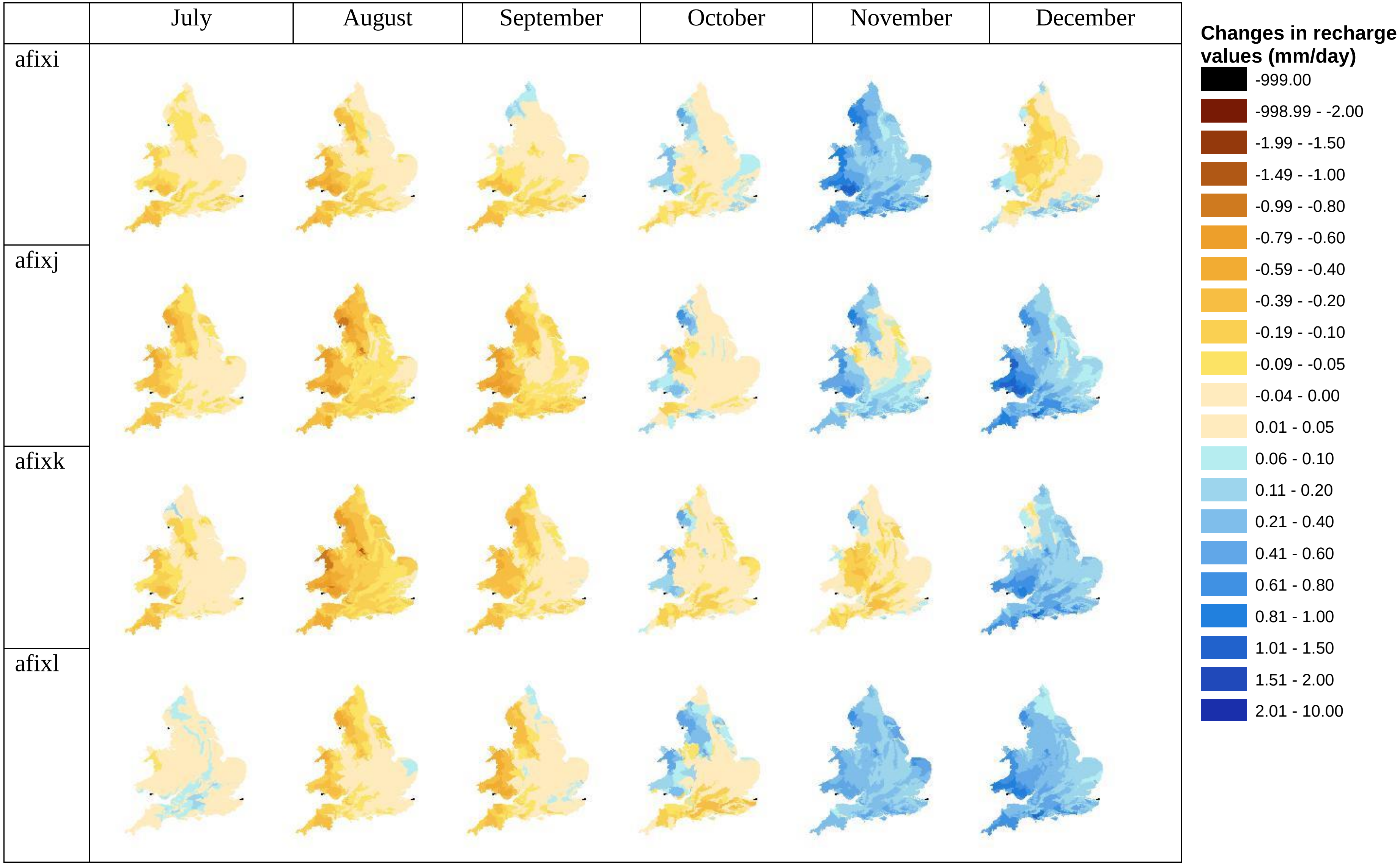

January
February
March
April
May
June
afixi
afixj
afixk
afixl
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00


January
February
March
April
May
June
afixm
afixo
afixq
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

	July	August	September	October	November	December
afgcx						
afixa						
afixc						
afixh						

Changes in recharge values (mm/day)

- -999.00
- -998.99 - -2.00
- -1.99 - -1.50
- -1.49 - -1.00
- -0.99 - -0.80
- -0.79 - -0.60
- -0.59 - -0.40
- -0.39 - -0.20
- -0.19 - -0.10
- -0.09 - -0.05
- -0.04 - 0.00
- 0.01 - 0.05
- 0.06 - 0.10
- 0.11 - 0.20
- 0.21 - 0.40
- 0.41 - 0.60
- 0.61 - 0.80
- 0.81 - 1.00
- 1.01 - 1.50
- 1.51 - 2.00
- 2.01 - 10.00


July
August
September
October
November
December
afixi
afixj
afixk
afixl
Changes in recharge values (mm/day)
-999.00
-998.99 - -2.00
-1.99 - -1.50
-1.49 - -1.00
-0.99 - -0.80
-0.79 - -0.60
-0.59 - -0.40
-0.39 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - 0.00
0.01 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 10.00

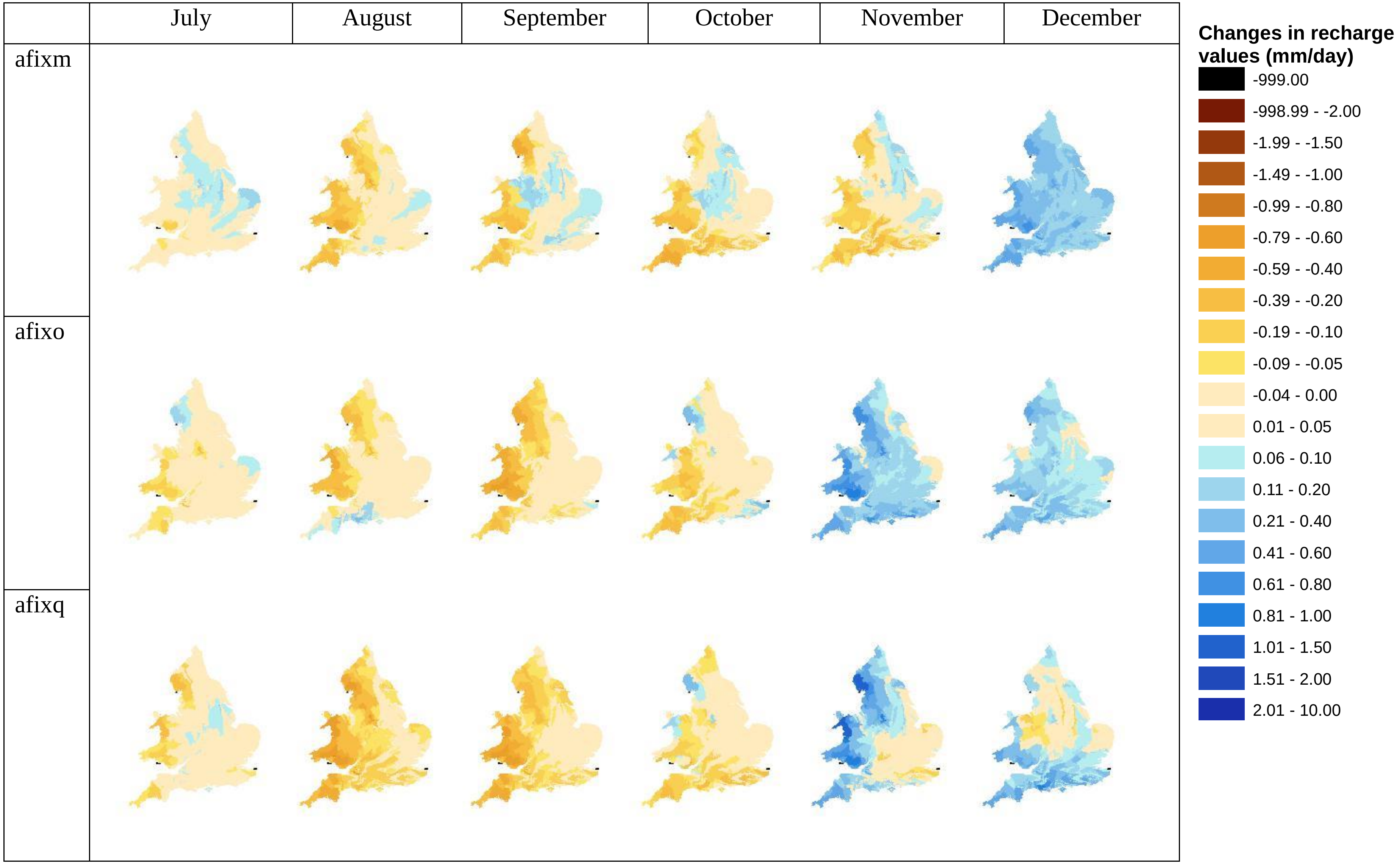


Figure A14. Changes in monthly recharge for the 2080s for all ensembles

Appendix 4 Change factors

To summarise the plethora of results produced by the 11 ensembles, the results for each groundwater body have been summarised by choosing an extreme value (minimum or maximum) or median for monthly values for each ensemble (see Section 2.3.1 for details). The aim is to present the minimum, maximum of the change factors for each ensemble for both the historic simulation and future climate scenarios. To demonstrate the baseline conditions the monthly minimum, maximum and media are presented for the historical simulation (Figure A15). Two sets of monthly summary plots are presented for the 2050s (Figure A16) and the 2080s (Figure A17)

A4.1 Historical simulation

Figure A15 shows that there is a distinct recharge season within the historical simulation: for all three sets of plots (minimum, maximum and median) April to October show a significant proportion of England and Wales with very low or zero recharge. The recharge season can be thought of, therefore, November through to March. In general very little difference can be observed for each month between the minimum, maximum and the median values. This is understandable given that the aim of the historical simulation for each ensemble is to produce very similar rainfall and PE for the period between 1951 and 2009. This appears to be reflected in the recharge calculation.

A4.2 Change factors for 2050s

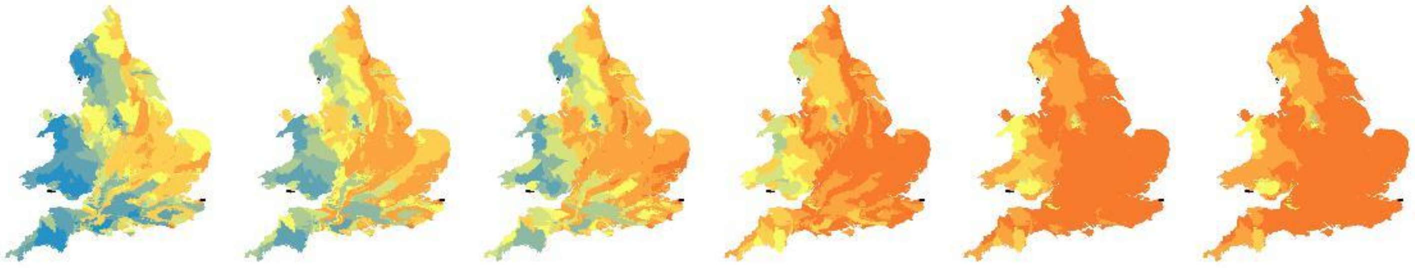
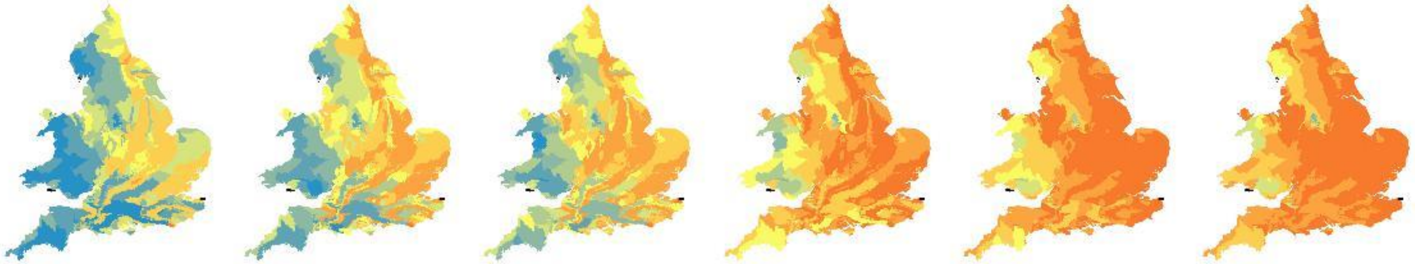
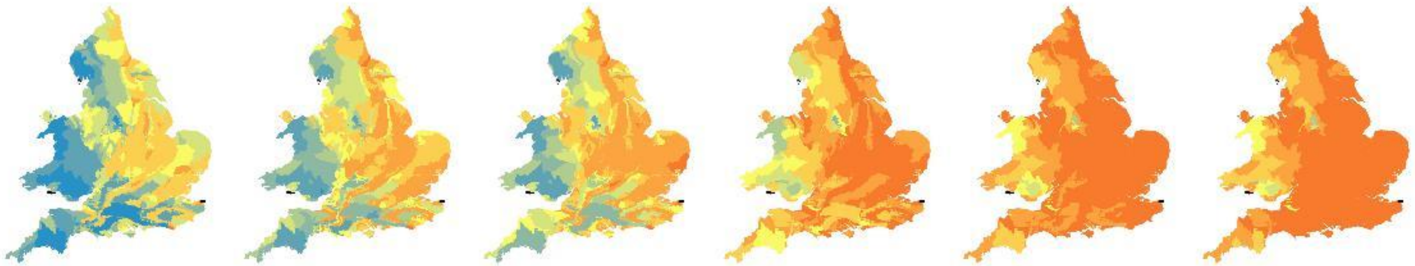
Compared with the baseline, the plots for the 2050s (see Figure A16) show much more variation between minimum, maximum and median, which given that they represent a future predicted climate is understandable. The minimum change factor for the ensembles shows that the likely percentage change will occur between May to September, the months that for the historical simulation (Figure A15) show the lowest recharge. Of more interest are January and December where the minimum change factors are positive (light blue on the plots). This means that recharge is predicted to increase in some parts of the country whatever ensemble is chosen.

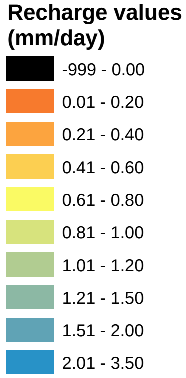
The maximum plots are mostly all positive values, again as would be expected, however May, June, August and September show negative values as their maximum which indicates that recharge is predicted to decrease whatever ensemble is chosen. However, these months have a very low recharge anyway and for only selected geographical areas.

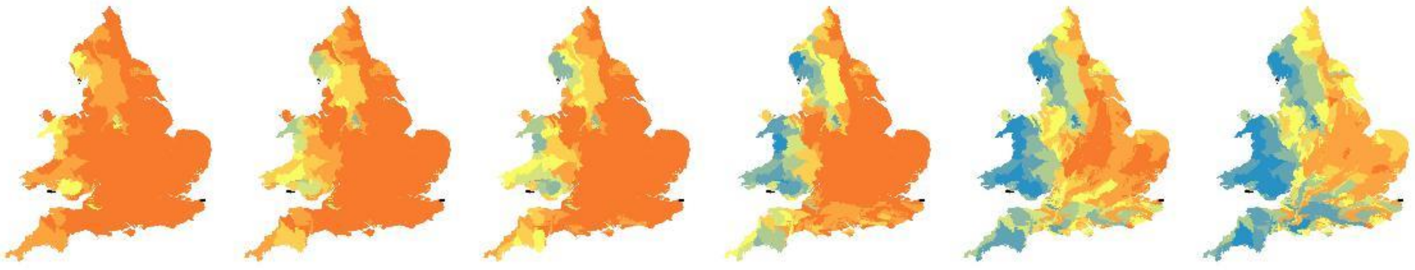
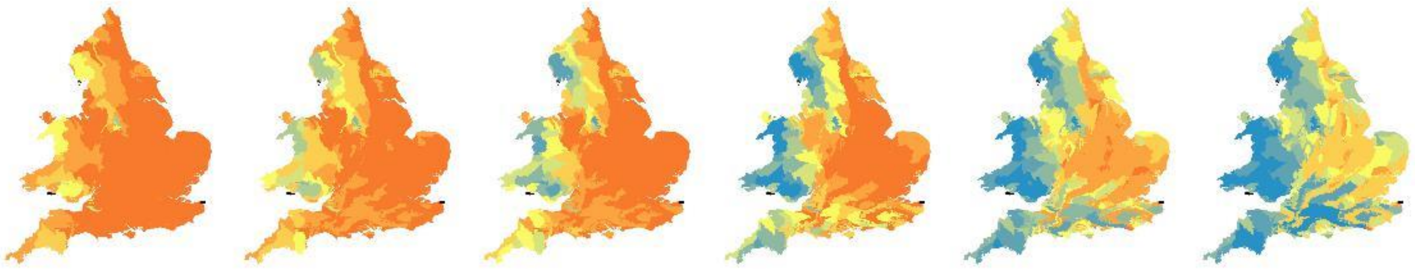
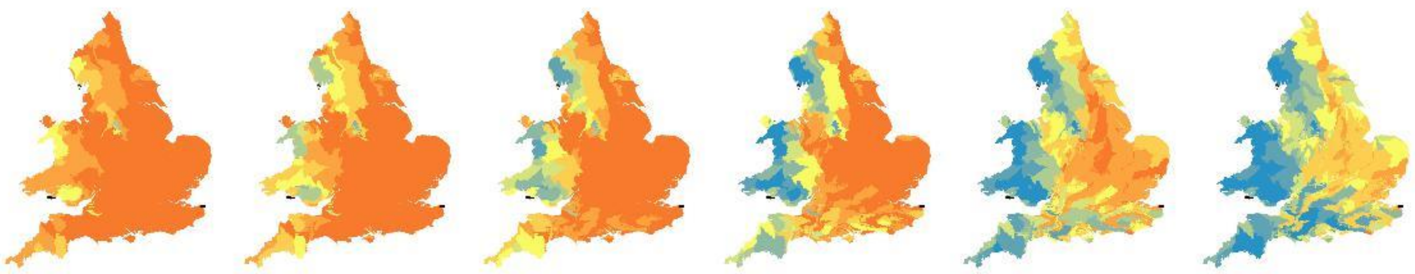
The median percentage change values show three categories of responses: January, February, November and December are predominantly positive; May to September are predominantly negative and February, March and October as geographically mixed.

A4.3 Change factors for the 2080s

The plots for the 2080s (Figure A17) shows a response that is very similar to that displayed for the 2050s (Figure A16). There are variations in geographical extent of the changes, reflecting subtle changes in rainfall patterns. Particularly for the median case January, February, November and December show a more definite positive signature.

	January	February	March	April	May	June
Simulated historic minimum						
Simulated historic maximum						
Simulated historic median						



	July	August	September	October	November	December
Simulated historic minimum						
Simulated historic maximum						
Simulated historic median						

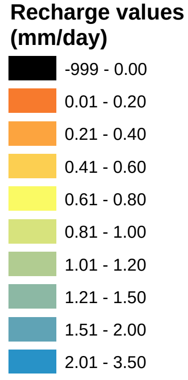
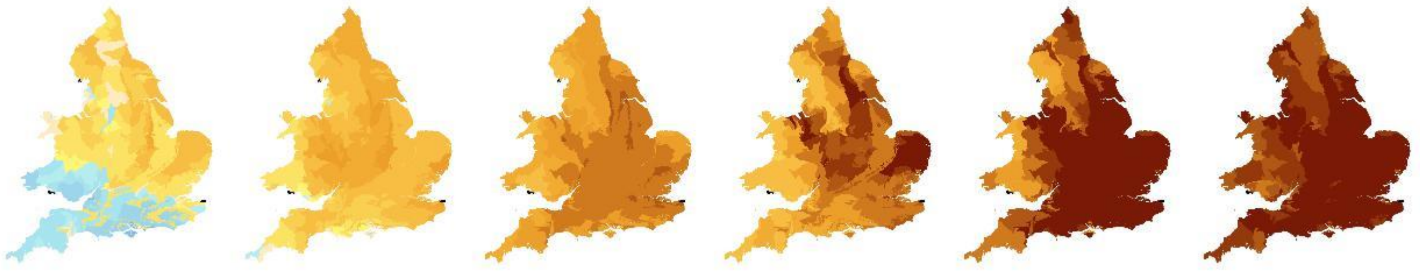
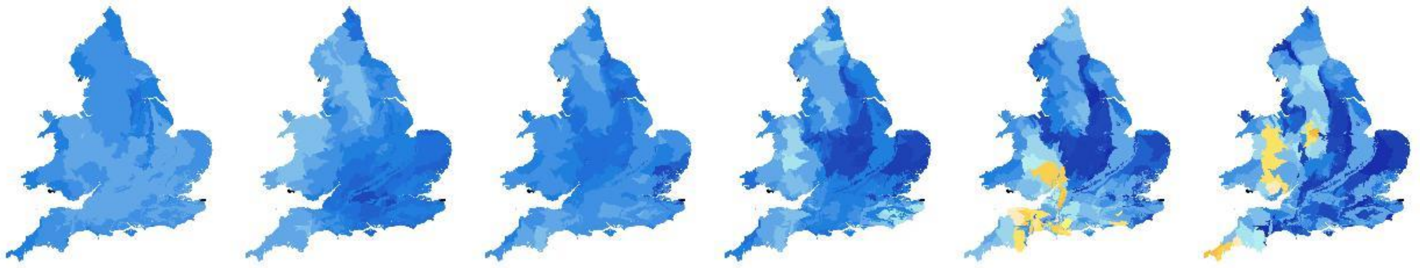
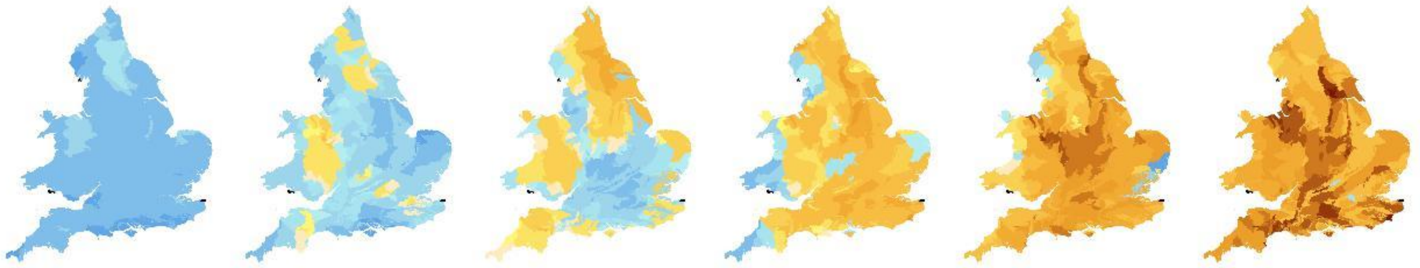
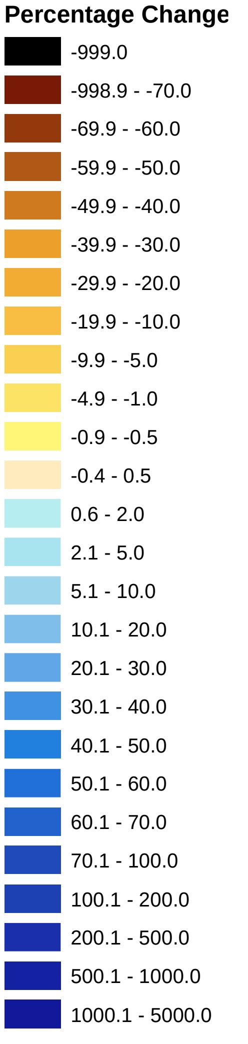


Figure A15. Minimum, maximum and median changes for the historical simulation (1961-90)

	January	February	March	April	May	June
50s Percentage changes minimum						
50s Percentage changes maximum						
50s Percentage changes median						



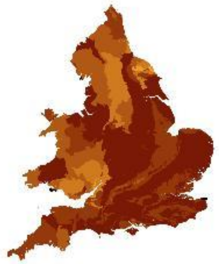
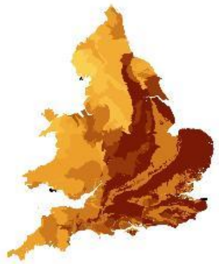
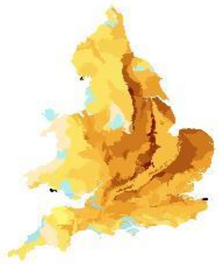
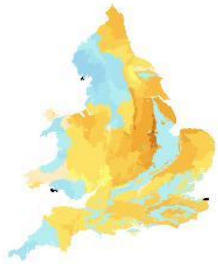
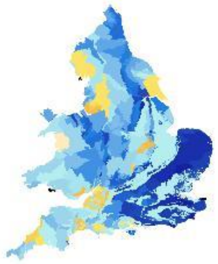
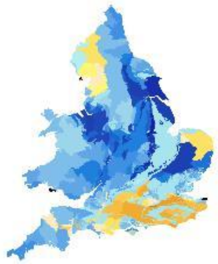
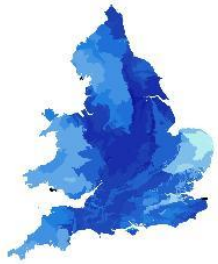
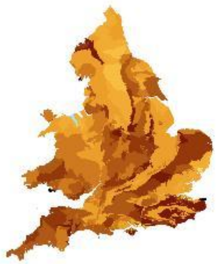
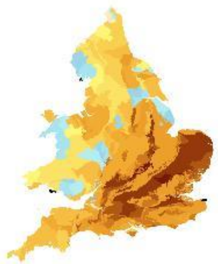
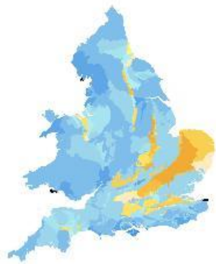
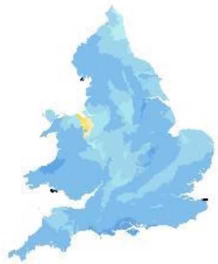
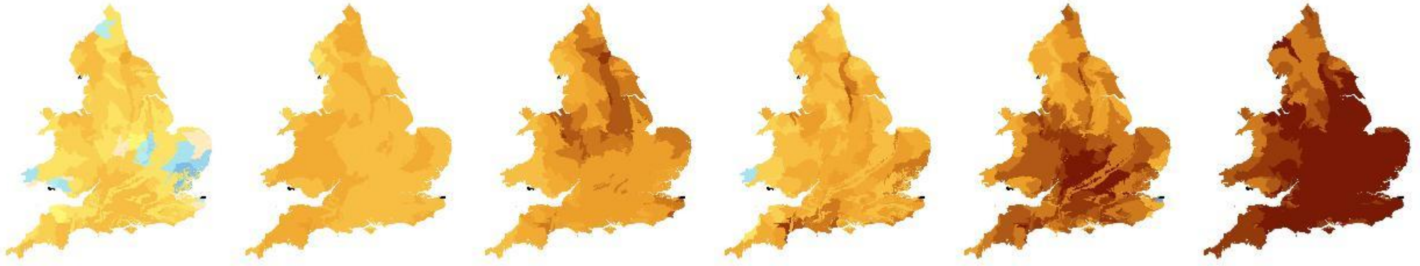
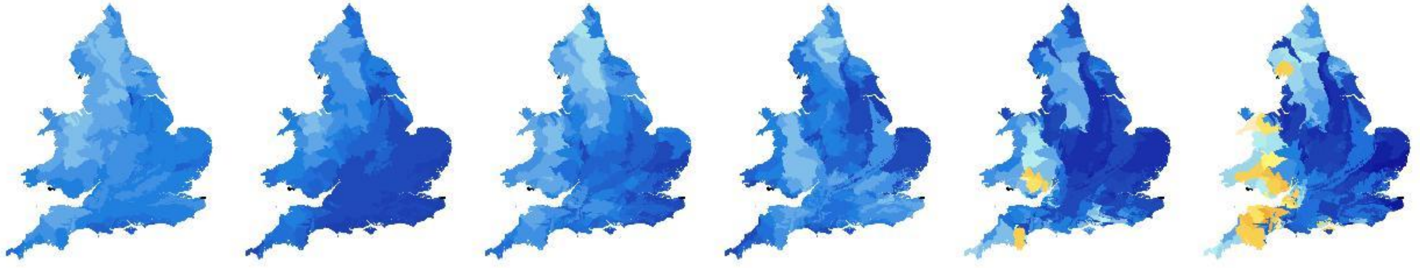
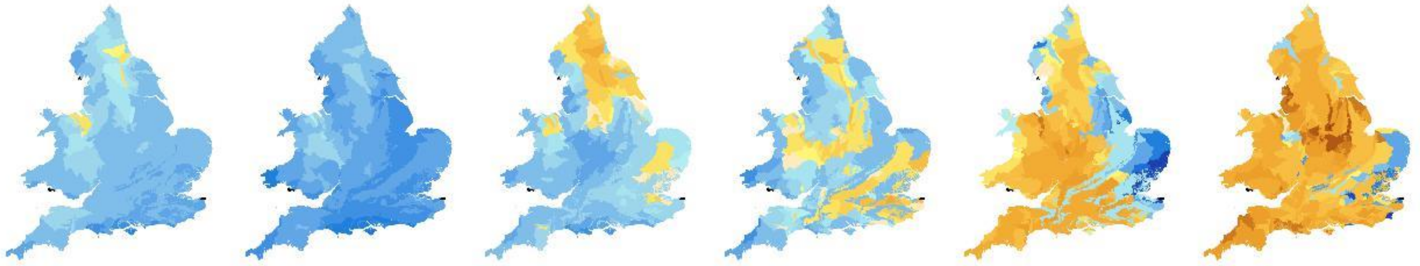
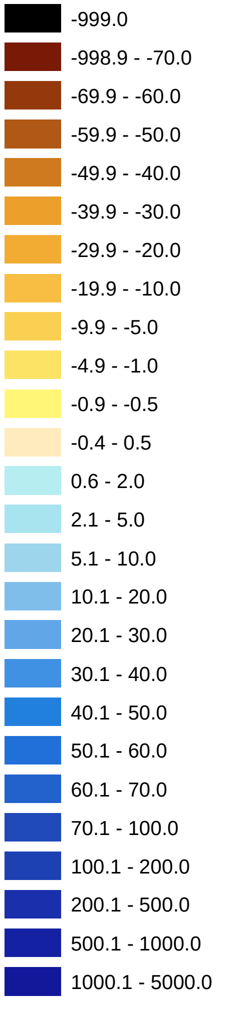
	July	August	September	October	November	December
50s Percentage changes minimum						
50s Percentage changes maximum						
50s Percentage changes median						

Figure A16. Minimum, maximum and median changes for the 2050s

	January	February	March	April	May	June
80s Percentage changes minimum						
80s Percentage changes maximum						
80s Percentage changes median						

Percentage Change



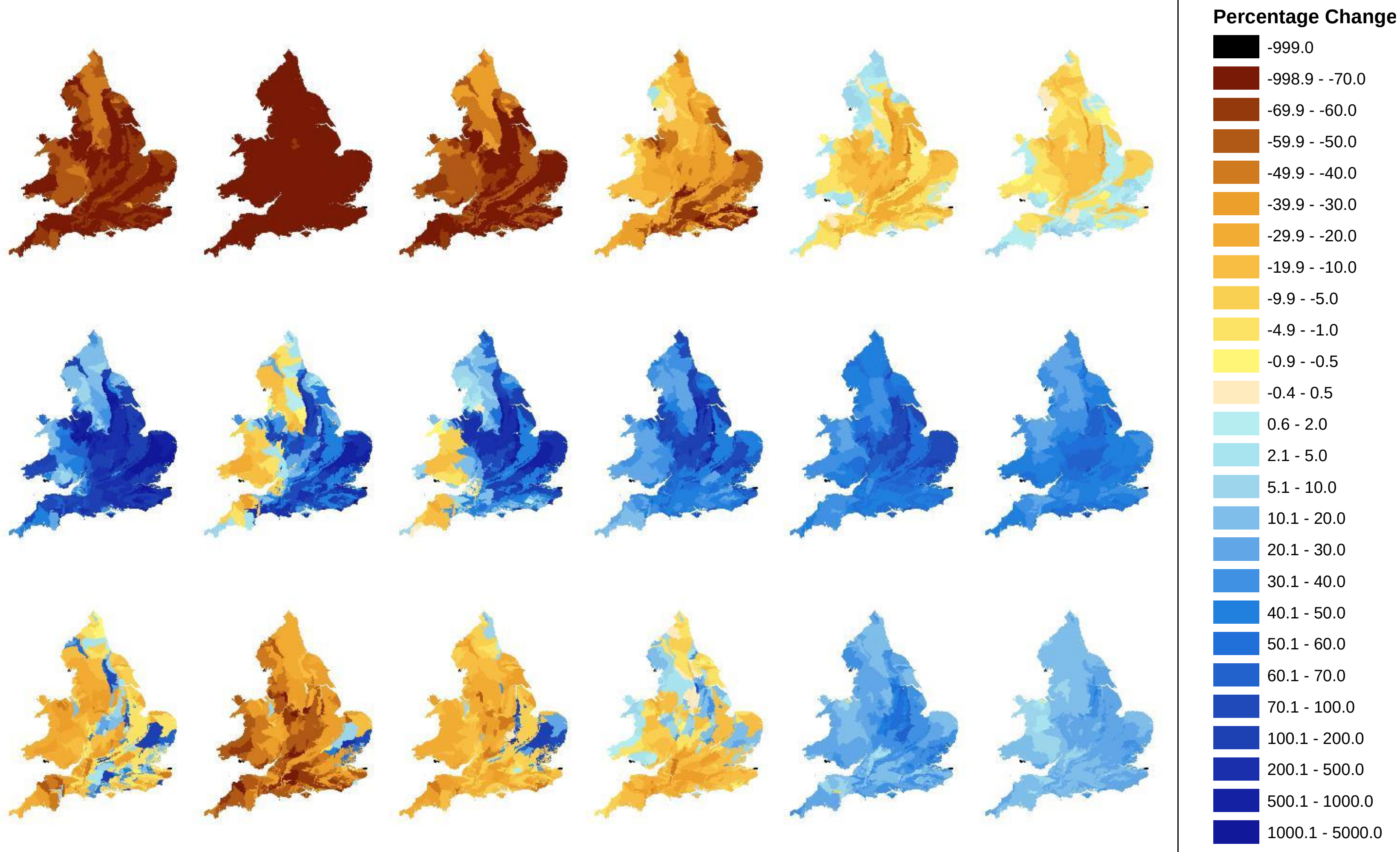
	July	August	September	October	November	December
80s Percentage changes minimum						
80s Percentage changes maximum						
80s Percentage changes median						

Figure A17. Minimum, maximum and median changes for the 2080s

Appendix 5 River basin management districts

A5.1 GENERAL

Figure A18 to A39 display four plots for each of the eleven River Basin Management Districts (RBMD) covering England and Wales. The plots (clockwise from top left) are the average monthly recharge values for the historical simulation for each RBMD, average monthly change for each RBMD for the 2020s, average monthly change for the 2080s and average monthly change for the 2050s. There are different responses for each RBMD, but in general the 2020s are exhibit less variability than the 2050s and 2080s. Variability of the monthly change also exhibits an east-west split, with the western catchments demonstrating greater variability than the eastern ones. Finally the variability in the recharge season: September to April is generally greater than for the rest of the year (May to August).

To quantify the impact of climate change on total recharge and how this may change the total volume for 30 year periods both within the historical simulation and predicted future scenarios were calculated for each RBMD. Two 30 year periods (1961-90 and 1971-00) were chosen within the historical simulation. This enables any variability within these periods to be understood. These results were then compared to total recharge volumes for the 2020s, 2050s and 2080s for each RBMD. The results are summarised for each ensemble for each RBDM in Tables A1 to A11. and diagrammatically in Figures A18 to A39. To enable a comparison to be undertaken the minimum, maximum and average value is calculated for each time period.

The individual response for both recharge rates and volumes for each RBMD are detailed below.

A5.2 RBMD 2 – SOLWAY TWEED

There is relative high recharge in the historical simulation (Figure A18). The comparison of ensembles for 2020s show a mixed response (some decreases and some increases over the year). For the 2050s there are increases earlier in the year, mixed in the summer, reduction in July, August, September, and increases in October November and December. The 2080s follow a similar pattern to the 2050s. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A19).

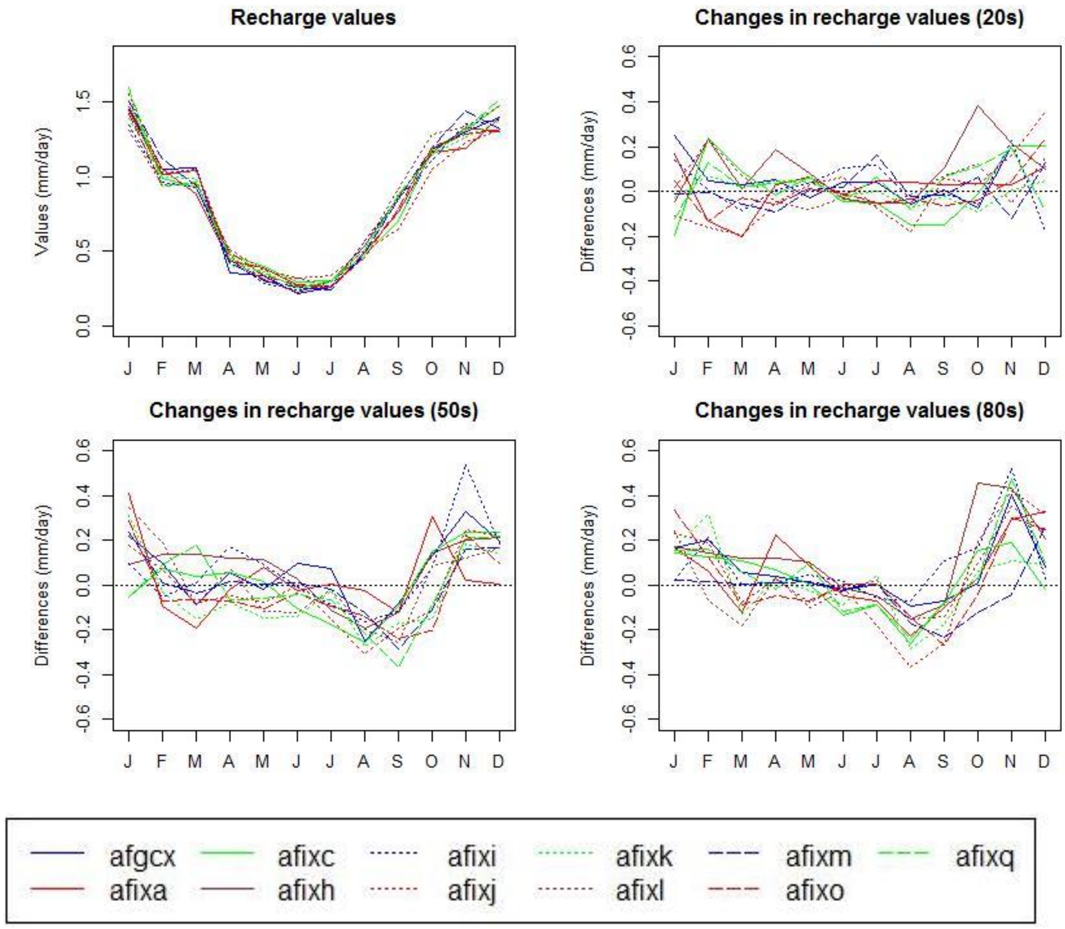


Figure A18. Monthly recharge the Solway Tweed RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

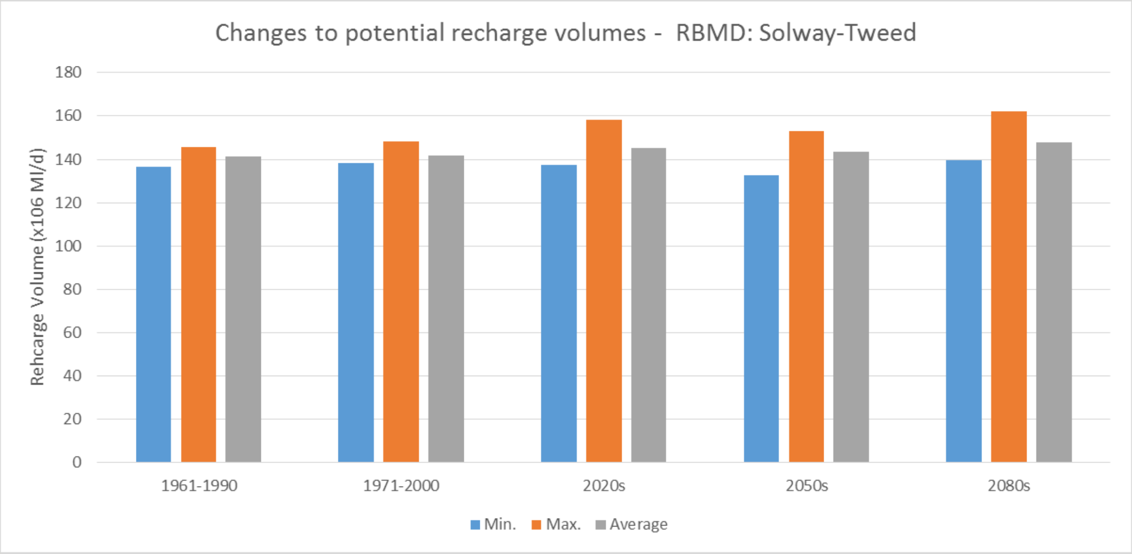


Figure A19. Minimum, average and maximum recharge the Solway Tweed RBMD for historic simulated and for 2020s, 2050s and 2080s

Table A1 shows that average recharge for all the 11 ensembles is very similar for the historical simulation and the 2020s and 2050s. An increase is observed for the 2080s. As would be expected range (difference between minimum and maximum) increases between historical simulation and future forecasts. So it is worth noting that under some future scenarios (afixj and afixo) recharge volume decreases compared to the historical simulation.

A5.3 RBMD 3 – NORTHUMBRIA

There is relative low recharge in the historical simulation (Figure A20). For the 2020s, 2050s and the 2080s there is a mixed response (some decreases and some increases over the year). The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A21).

This is a small catchment so variability in average recharge volumes is limited (Table A2) with possibly a reduction in reduction from historical simulation to future.

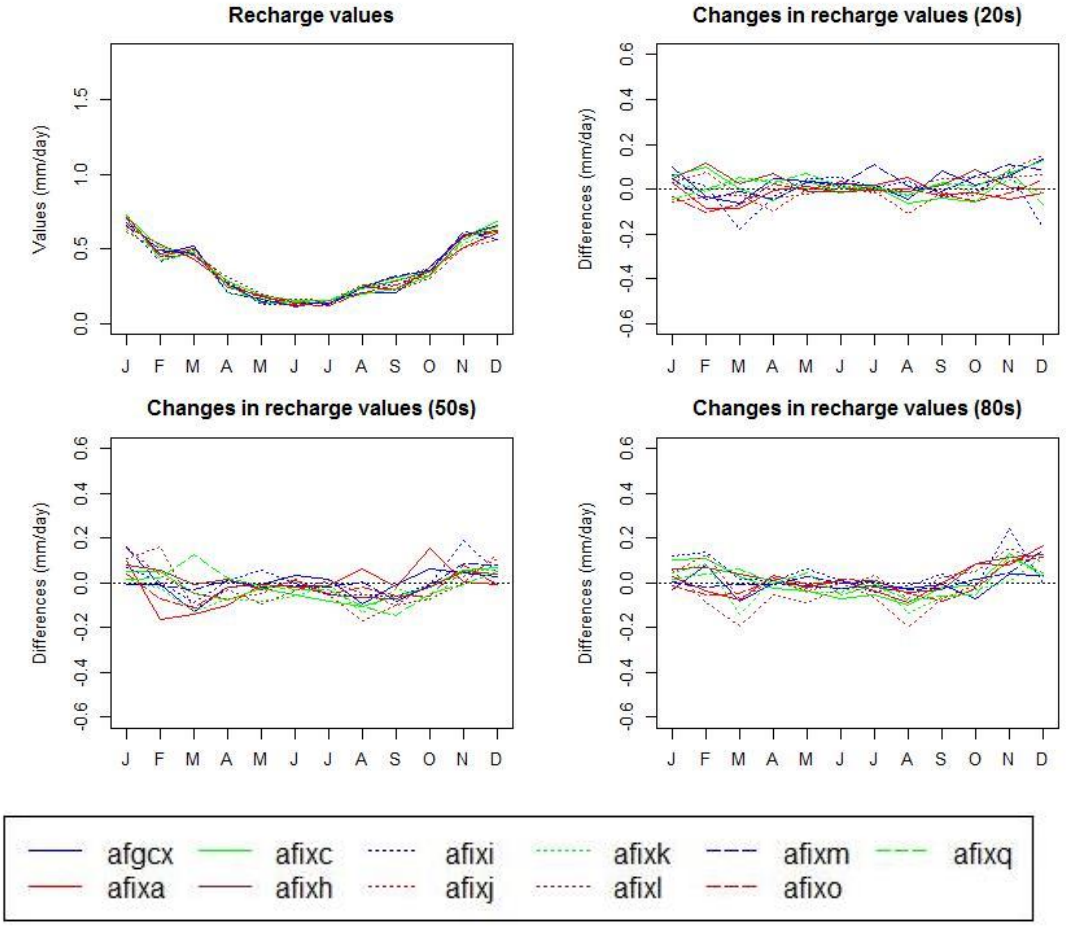


Figure A20. Monthly recharge the Northumbria RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

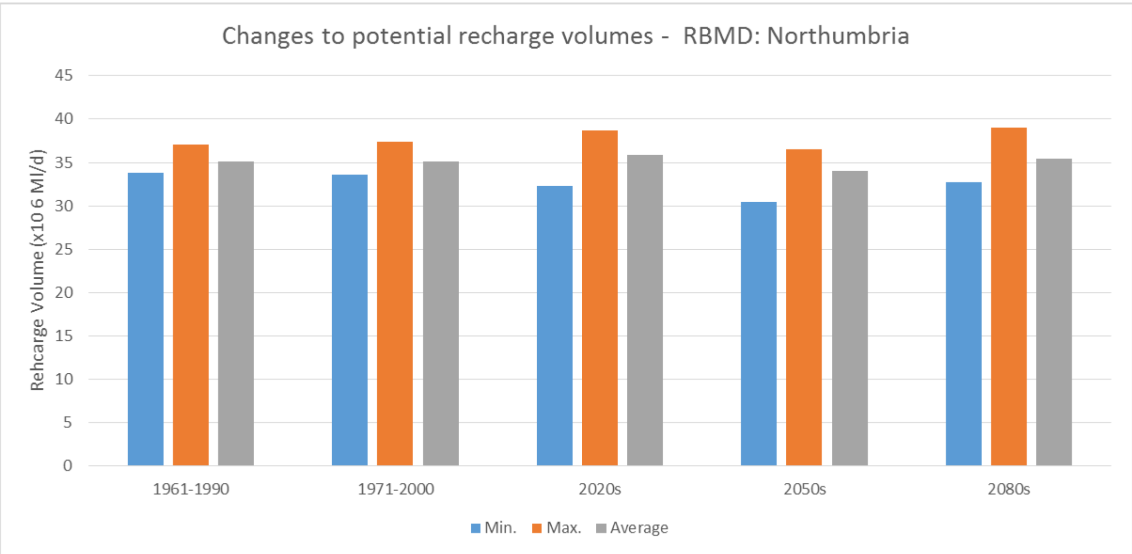


Figure A21. Minimum, average and maximum recharge the Northumbria RBMD for historic simulated and for 2020s, 2050s and 2080s

A5.4 RBMD 4 – HUMBER

There is a relative low recharge in the historical simulation (Figure A22). For the 2020s mixed response (some decreases and some increases over the year). The 2050s demonstrated increases earlier in the year, mixed in the summer, reduction in July, August, September, and increases in October, November and December. The 2080s follow a similar pattern to the 2050s. Note: due to lower historical simulated recharge then variability is perhaps more muted. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A23).

Table A3 shows that average recharge for all the 11 ensembles is very similar for the historical simulation and the 2020s and 2050s. However a marked increase is observed for the 2080s**.**

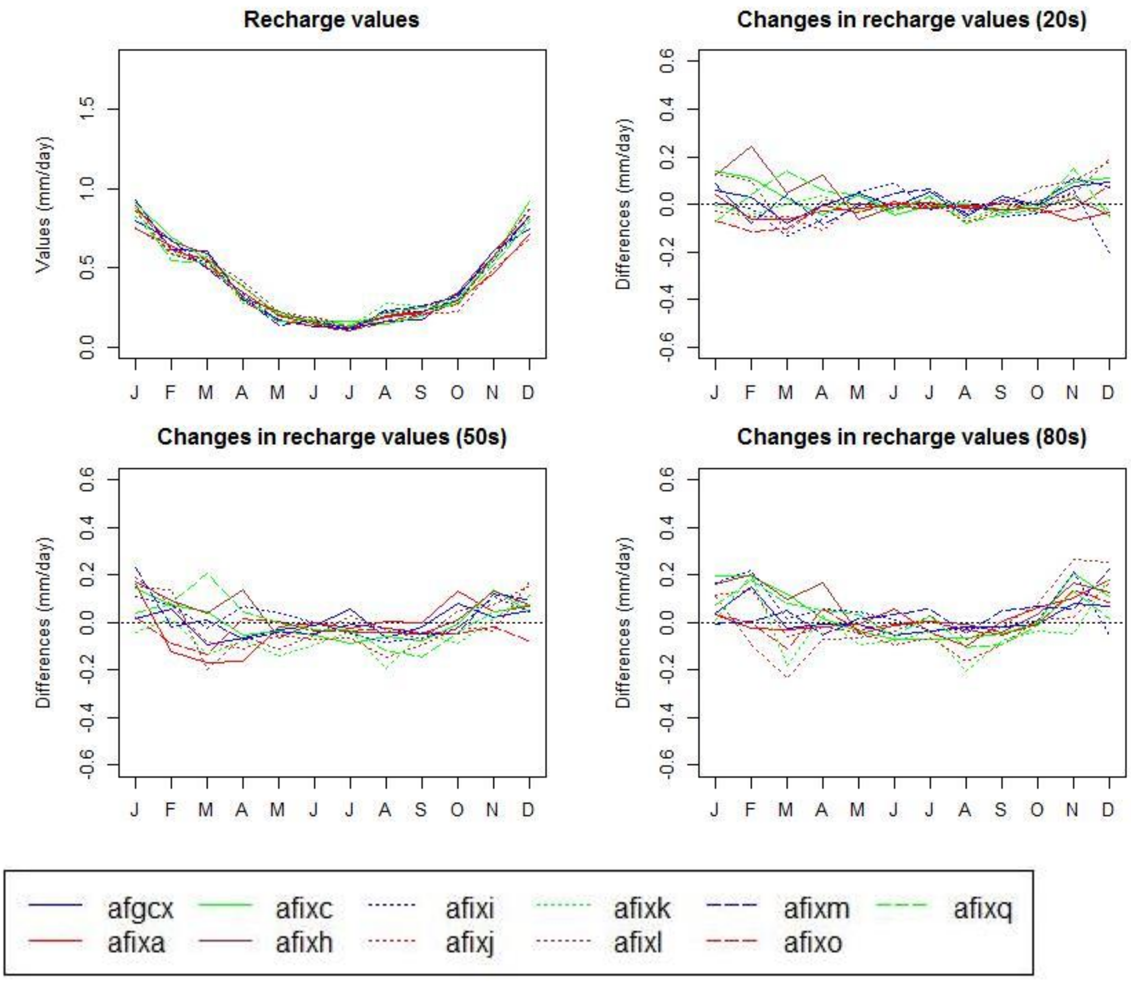


Figure A22. Monthly recharge the Humber RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

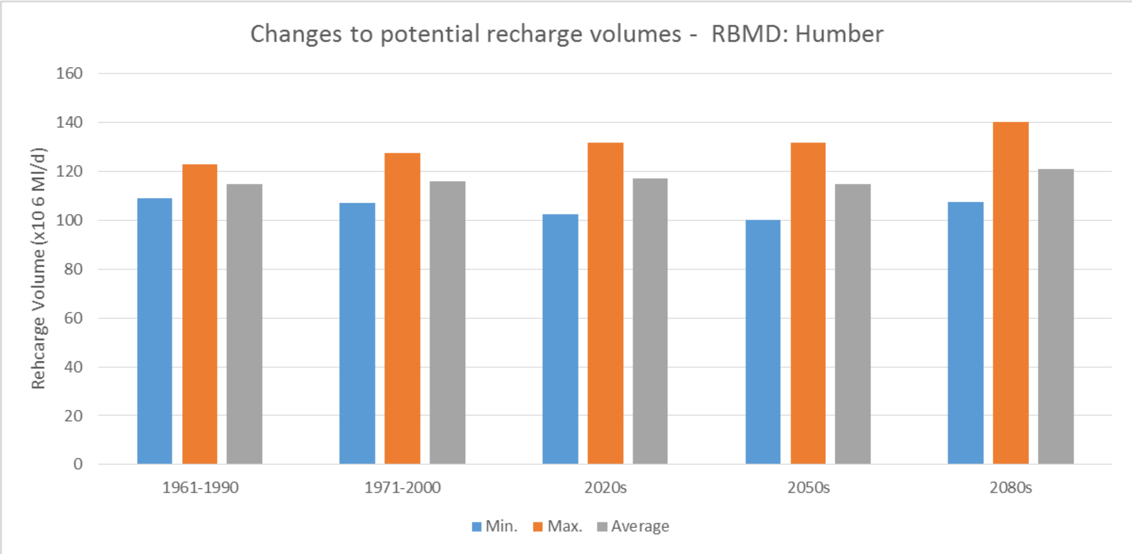


Figure A23. Minimum, average and maximum recharge the Humber RBMD for historic simulated and for 2020s, 2050s and 2080s

Table A1. Recharge volumes for Catchment 2: Solway Tweed

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	139.55	136.35	142.67	145.82	142.11	137.94	139.68	145.21	140.20	143.78	141.58	136.35	145.82	141.35
1971-2000	140.76	138.95	142.81	148.04	139.00	138.37	143.13	144.50	140.10	144.52	139.51	138.37	148.04	141.79
20s	149.59	142.24	145.40	158.02	142.39	138.72	139.85	150.79	144.63	137.57	150.39	137.57	158.02	145.42
50s	150.07	144.33	144.99	152.82	149.35	135.77	132.70	148.12	144.07	132.74	142.07	132.70	152.82	143.37
80s	149.56	147.08	145.34	162.15	152.08	144.29	140.60	149.53	139.42	142.80	152.33	139.42	162.15	147.74

Note: Recharge values in 10^6 x Ml/day

Table A2. Recharge volumes for Catchment 3 – Northumbria

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	34.39	33.95	35.73	37.02	34.86	34.35	33.77	36.47	34.69	35.87	34.64	33.77	37.02	35.07
1971-2000	35.48	33.57	35.54	37.34	35.30	36.12	34.48	36.58	33.64	34.96	33.55	33.55	37.34	35.14
20s	38.14	32.82	37.34	38.64	33.47	33.41	35.37	38.03	38.19	32.34	36.31	32.34	38.64	35.82
50s	34.46	33.13	34.02	36.02	35.36	32.77	30.49	36.11	36.48	31.55	34.05	30.49	36.48	34.04
80s	33.95	35.30	36.41	39.03	38.67	33.74	32.75	35.28	36.24	33.53	35.44	32.75	39.03	35.49

Note: Recharge values in 10^6 x Ml/day

Table A3. Recharge volumes for Catchment 4 – Humber

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	112.41	108.98	118.00	123.10	115.07	109.50	112.26	121.23	112.65	117.86	112.63	108.98	123.10	114.88
1971-2000	116.05	107.27	119.98	127.61	118.39	116.32	118.13	122.55	109.22	114.74	107.39	107.27	127.61	116.15
20s	122.61	102.30	131.78	129.58	106.31	108.86	114.70	129.74	120.20	107.27	116.49	102.30	131.78	117.26
50s	116.75	106.98	124.18	131.78	118.36	105.00	100.14	121.62	118.44	102.94	115.79	100.14	131.78	114.73
80s	119.71	113.01	134.43	140.09	126.80	107.54	107.76	122.77	124.47	114.74	119.42	107.54	140.09	120.98

Note: Recharge values in 10^6 x Ml/day

A5.5 RBMD 5 – ANGLIAN

There is relative low recharge in the historical simulation (Figure A24). For the 2020s there are increases in recharge season, but with some ensembles showing lower recharge. The summer months exhibit a very flat response. The 2050s and 2080s very similar pattern, but with 2080s showing increase in variability from April to September. The recharge totals increase from the historical simulation to the 2020s, increasing for the 2050s and increasing markedly in the 2080s (see Figure A25).

Table A4 shows that average recharge for all the 11 ensembles is very similar for the historical simulation and the 2020s and 2050s. Similarly for the Humber RBMD, a significant increase is observed for the 2080s**.**

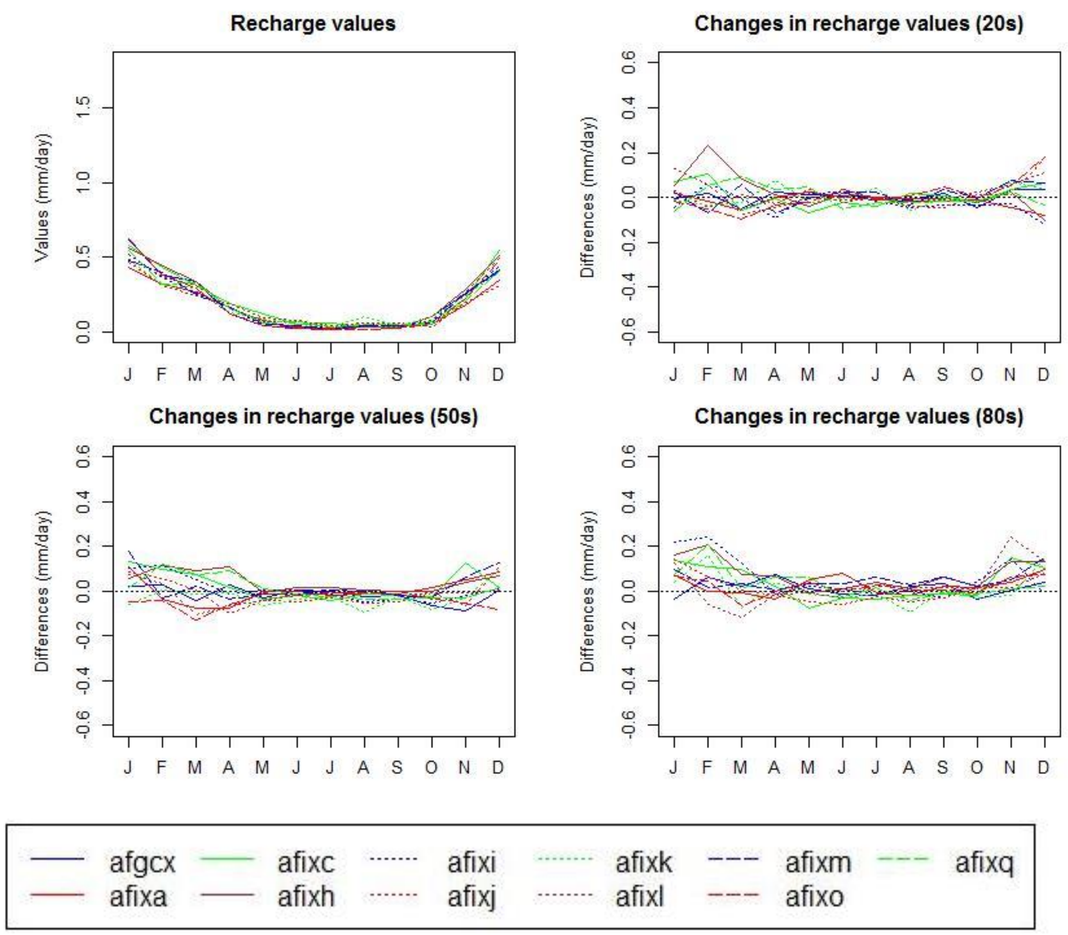


Figure A24. Monthly recharge the Anglian RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

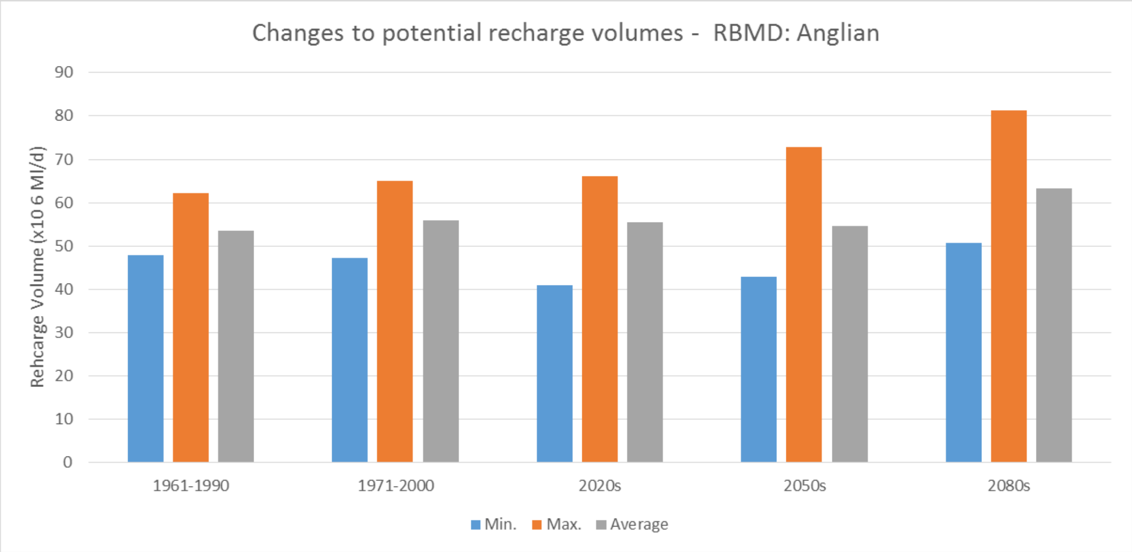


Figure A25. Minimum, average and maximum recharge the Anglia RBMD for historic simulated and for 2020s, 2050s and 2080s

A5.6 RBMD 6 – THAMES

The recharge is moderate in the historical simulation (Figure A26). For the future scenarios, the monthly variability of change in recharge values increases for all three time slices with January to March and November and December exhibiting the greatest changes. The recharge totals increase from the historical simulation to the 2020s, increasing again to the 2050s and onwards to 2080s (see Figure A27).

Table A5 shows that average recharge for all the 11 ensembles is very similar for the historical simulation and the 2020s and 2050s. Again for the Humber and Anglian RBMDs, a significant increase is observed for the 2080s.

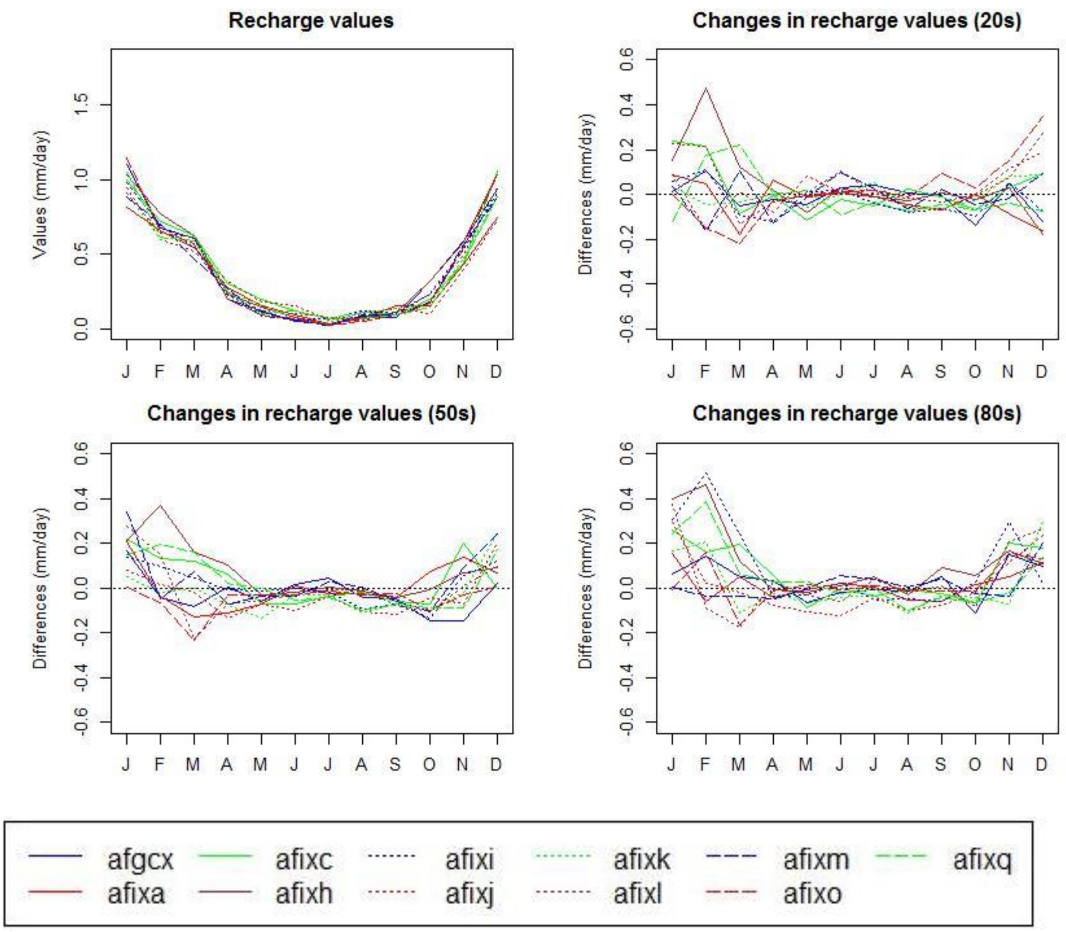


Figure A26. Monthly recharge the Thames RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

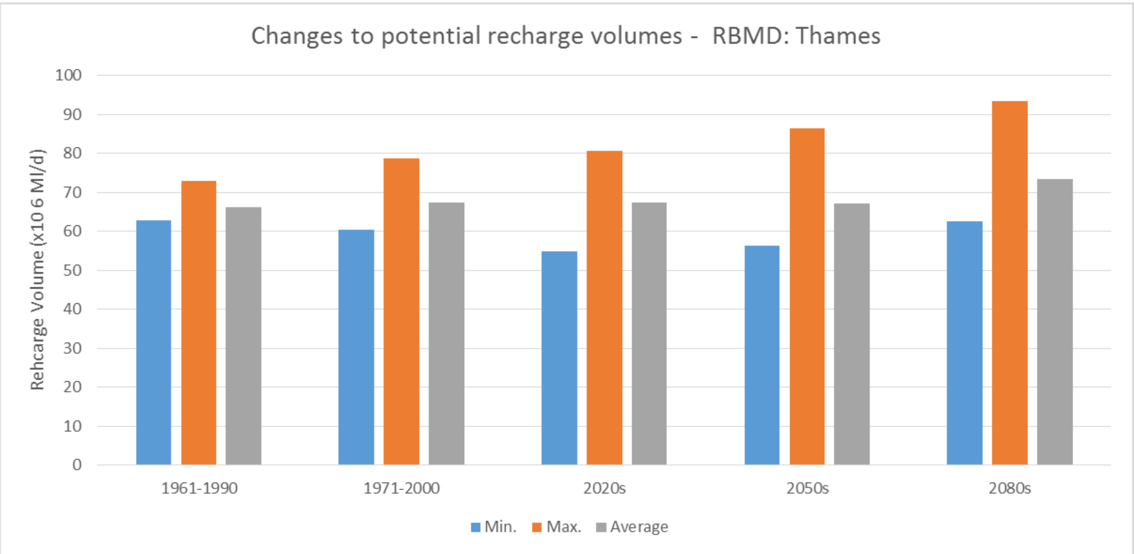


Figure A27. Minimum, average and maximum recharge the Thames RBMD for historic simulated and for 2020s, 2050s and 2080s

A5.7 RBMD 7 - SOUTH EAST

The recharge is high in the historical simulation (Figure 28). For the ensembles, the monthly variability of change in recharge values increases for all three time slices with January to March and November and December exhibiting the greatest changes. Some of the ensembles show a reduction in September and October. The recharge totals increase from the historical simulation to the 2020s, increasing for the 2050s and increasing again in the 2080s (see Figure A29).

Table A6 shows that average recharge for all the 11 ensembles increases from historical simulation marginally to the 2020s and 2050s. Following a similar pattern for the other larger RBMDs, a significant increase is observed for the 2080s.

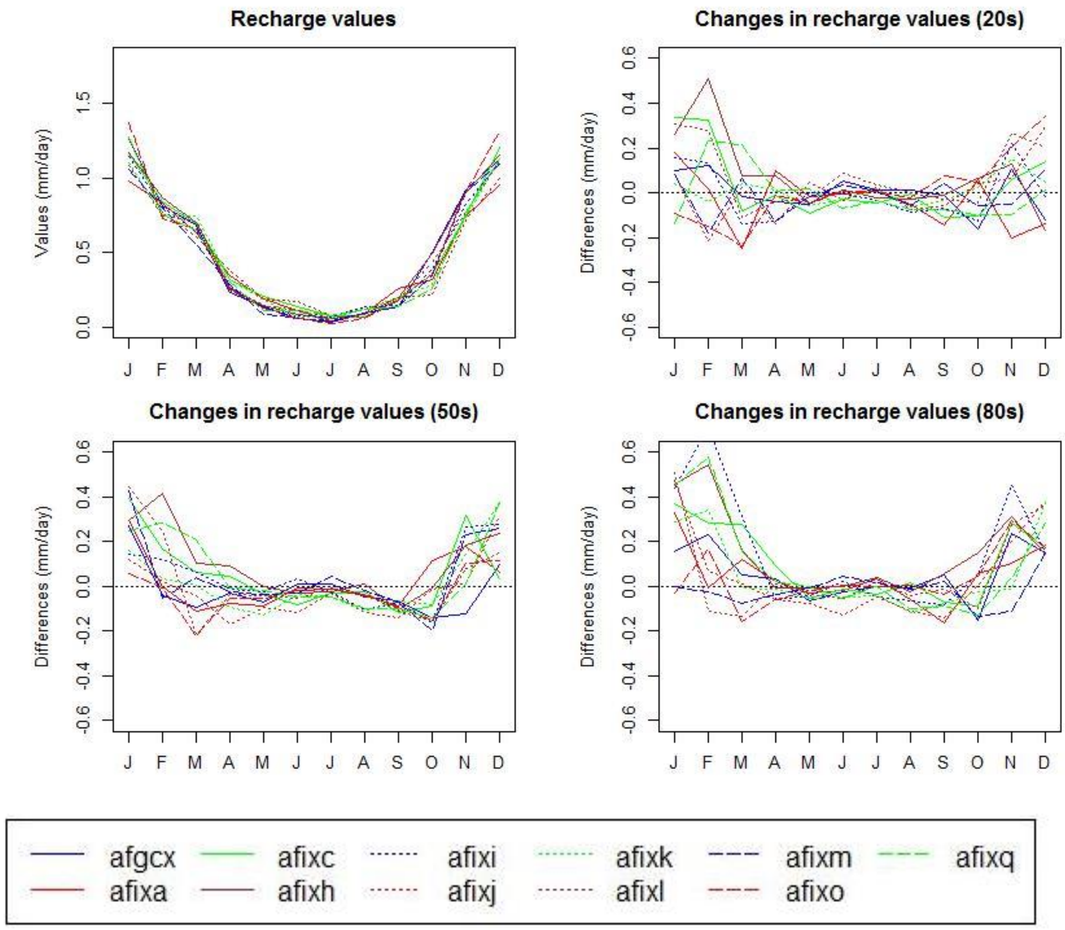


Figure A28. Monthly recharge the South east RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

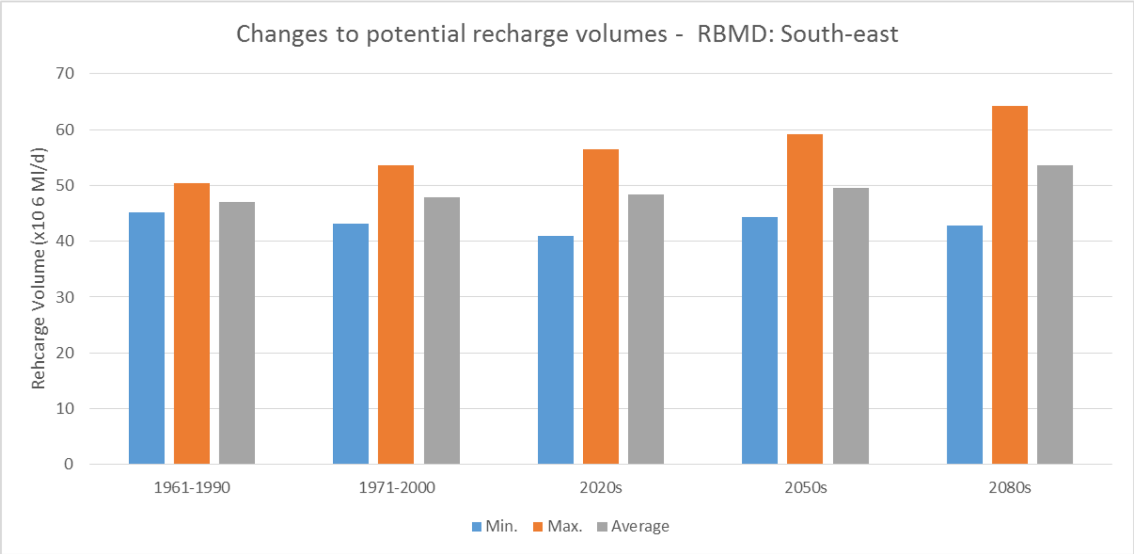


Figure A29. Minimum, average and maximum recharge the South-east RBMD for historic simulated and for 2020s, 2050s and 2080s

Table A4. Recharge volumes for Catchment 5: Anglian

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	50.84	47.86	57.66	62.12	53.83	48.30	52.58	58.18	51.49	55.62	51.31	47.86	62.12	53.62
1971-2000	56.54	47.26	60.56	64.95	55.69	55.06	56.79	58.98	49.83	55.21	53.22	47.26	64.95	55.82
20s	57.40	40.86	64.22	66.11	46.06	51.18	55.02	62.26	55.05	57.05	54.24	40.86	66.11	55.40
50s	52.36	46.75	69.41	72.75	56.21	45.48	46.07	52.75	57.85	42.94	57.24	42.94	72.75	54.53
80s	60.31	53.01	71.82	81.37	70.67	50.62	55.90	64.39	65.45	59.97	61.97	50.62	81.37	63.22

Note: Recharge values in 10^6 x Ml/day

Table A5. Recharge volumes for Catchment 6: Thames

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	63.69	62.98	69.27	73.05	66.99	62.78	64.65	69.43	63.67	67.85	64.16	62.78	73.05	66.23
1971-2000	69.05	62.16	68.18	78.81	65.74	66.59	67.59	66.13	60.43	69.67	67.23	60.43	78.81	67.42
20s	67.70	54.82	74.84	80.72	62.00	64.77	64.99	75.64	62.23	71.78	62.96	54.82	80.72	67.49
50s	65.53	61.04	77.21	86.57	68.49	56.28	60.90	65.56	69.08	59.53	68.99	56.28	86.57	67.20
80s	74.65	62.53	82.65	93.39	83.39	63.01	66.50	72.57	64.53	70.82	73.65	62.53	93.39	73.43

Note: Recharge values in 10^6 x Ml/day

Table A6. Recharge volumes for Catchment 7: South-East

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	45.96	45.22	48.47	50.39	47.77	46.17	45.84	48.07	45.98	48.02	46.05	45.22	50.39	47.08
1971-2000	48.20	47.21	47.41	53.61	45.42	49.10	47.35	46.44	43.10	50.77	47.69	43.10	53.61	47.84
20s	48.82	41.01	51.79	56.52	45.91	47.08	47.37	54.02	43.35	50.37	45.56	41.01	56.52	48.34
50s	47.14	46.56	53.91	59.19	50.80	44.40	47.77	48.57	49.22	46.17	51.75	44.40	59.19	49.59
80s	53.73	49.09	58.39	64.19	61.08	50.68	50.95	51.78	42.79	51.80	55.23	42.79	64.19	53.61

Note: Recharge values in 10^6 x Ml/day

A5.8 RBMD 8 - SOUTH WEST

The recharge is high in the historical simulation (Figure A30). For the ensembles, the monthly variability of change in recharge values increases for all three time slices with January to March and November and December exhibiting the greatest changes. Some of the ensembles show a reduction in September and October. The 2050s and 2080s show a reduction in recharge between April and October. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A31).

Table A7 shows that average recharge for all the 11 ensembles increases from historical simulation marginally to the 2020s and 2050s. Again, a significant increase is observed for the 2080s.

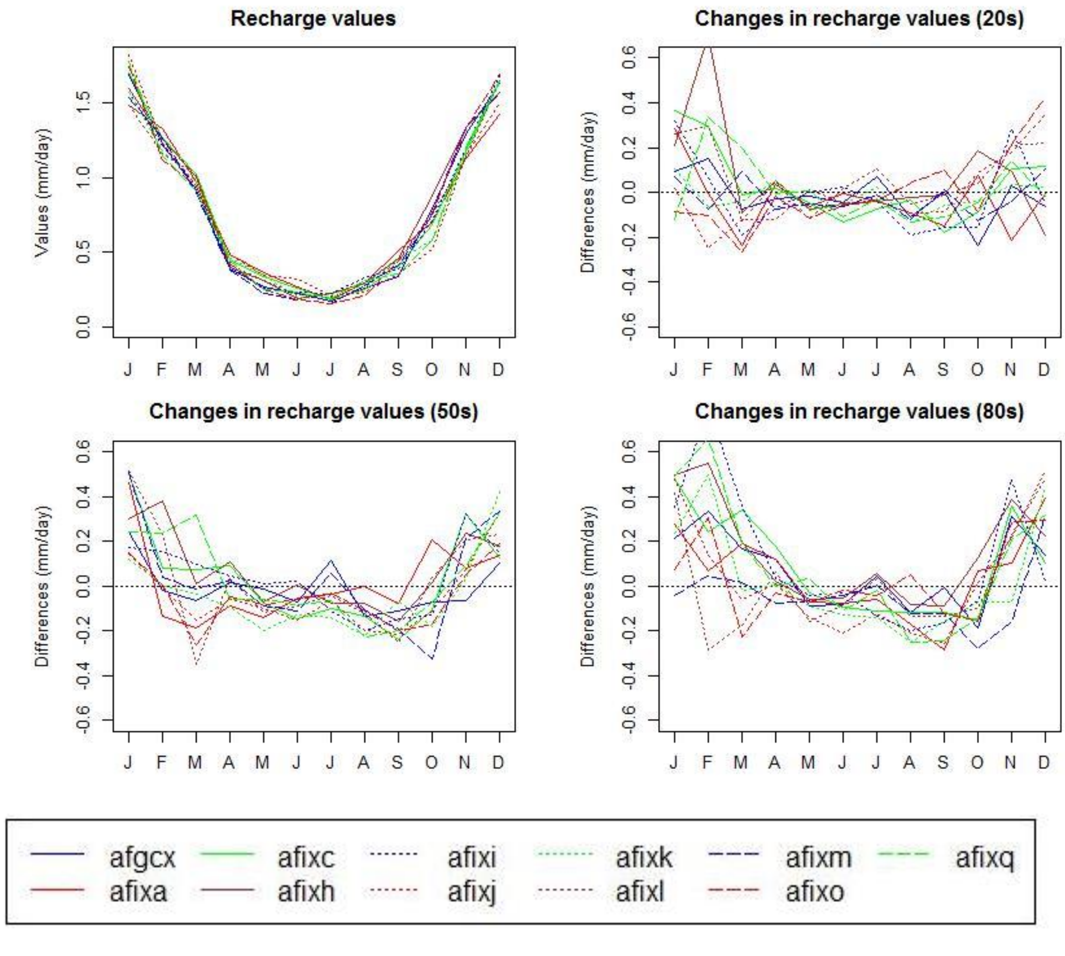


Figure A30. Monthly recharge the South-west RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

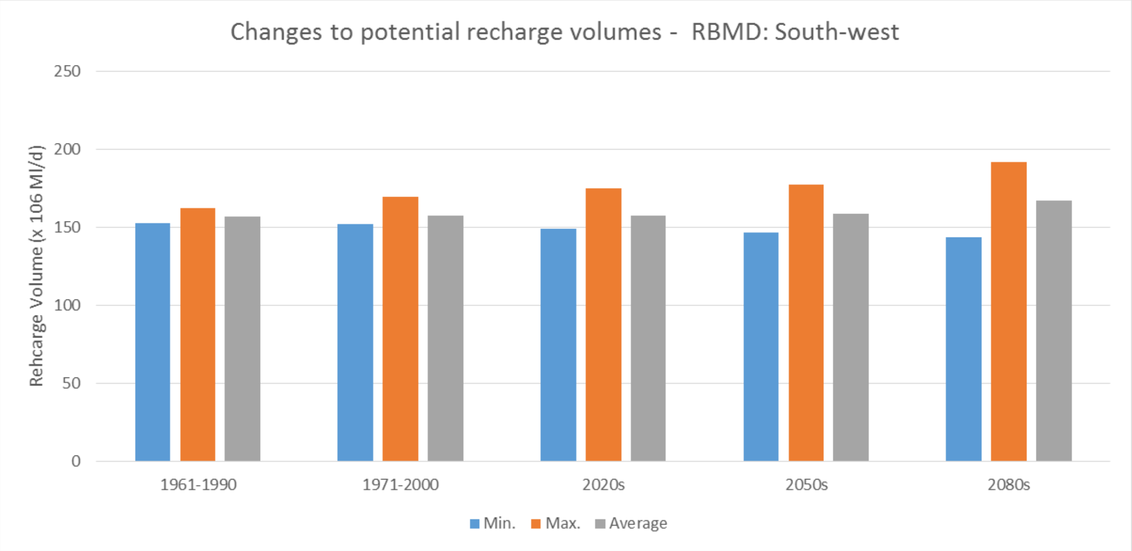


Figure A31. Minimum, average and maximum recharge the South-west RBMD for historic simulated and for 2020s, 2050s and 2080s

A5.9 RBMD 9- SEVERN

The recharge is high in the historical simulation (Figure A32). For the ensembles, the monthly variability of change in recharge values increases for all three time slices with January to March and November and December exhibiting the greatest changes. Some of the ensembles show a reduction in September and October. The 2050s and 2080s show a reduction in recharge between April and October. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A33).

Table A8 shows that average recharge for all the 11 ensembles is very similar for the historical simulation and the 2020s and 2050s. As is observed for the other RBMDs an increase is observed for the 2080s.

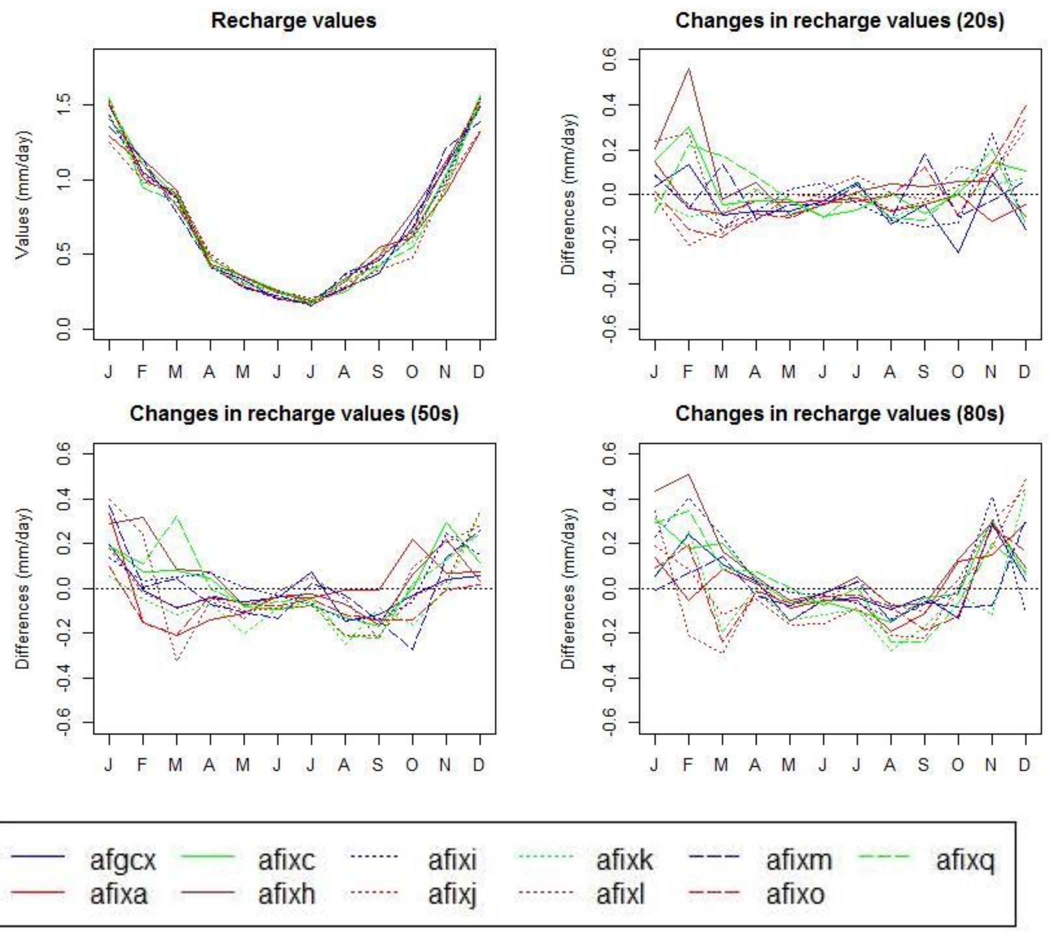


Figure A32. Monthly recharge the Severn RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

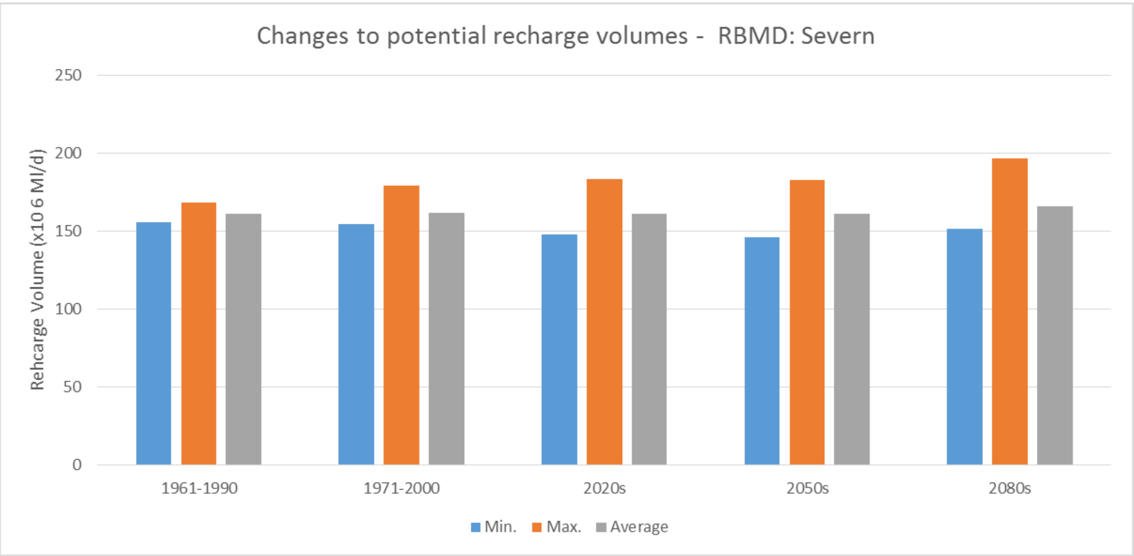


Figure A33. Minimum, average and maximum recharge the Severn RBMD for historic simulated and for 2020s, 2050s and 2080s

A5.10 RBMD 10 - WESTERN WALES

The recharge is very high in the historical simulation (Figure A34). For the 2020s variability with the majority of the ensembles increasing January and February as well as October, November and

December. For both the 2050s and 2080s then the trend appears to be from an increase to a decrease from January to September followed by a sharp increase from September to the end of the year. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A35).

Table A9 shows that average recharge for all the 11 ensembles increases from historical simulation marginally to the 2020s and 2050s. A significant increase is observed for the 2080s

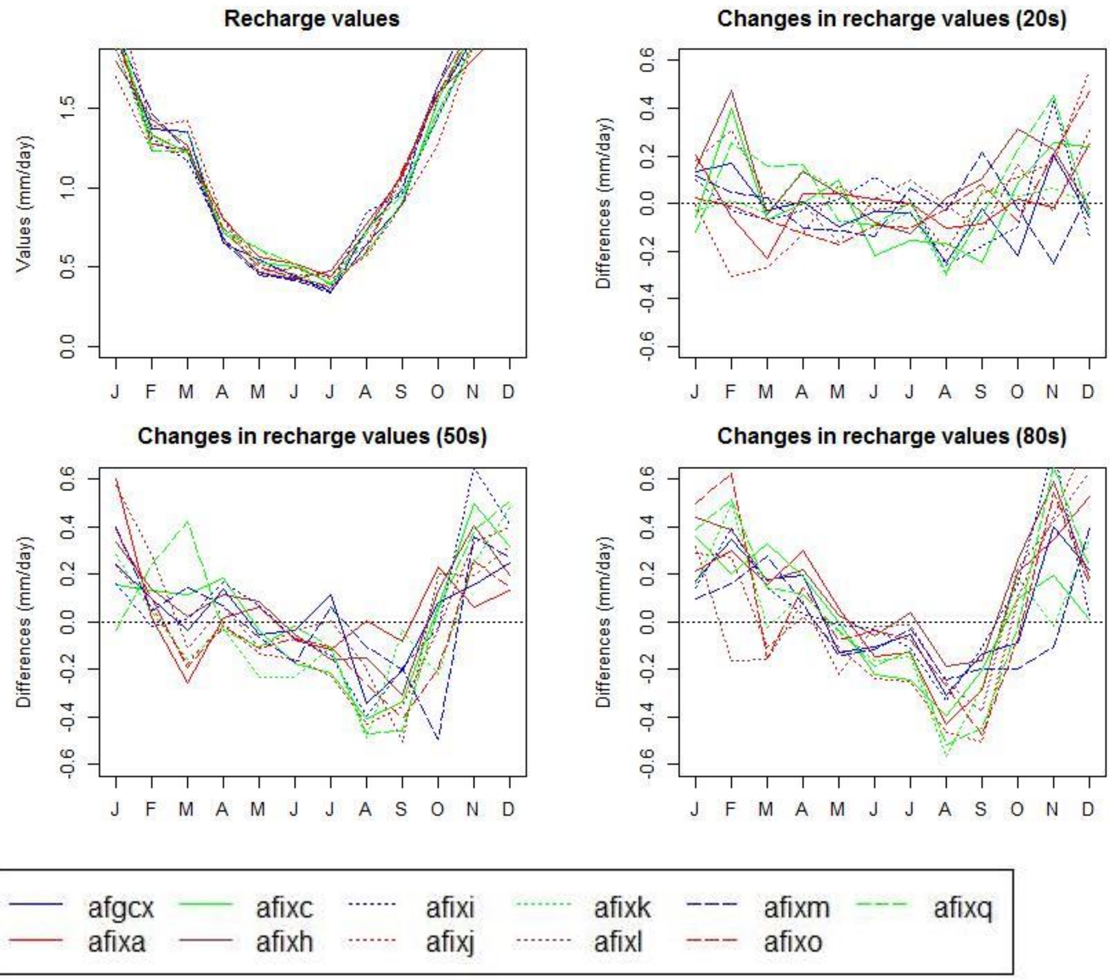


Figure A34. Monthly recharge the Western Wales RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

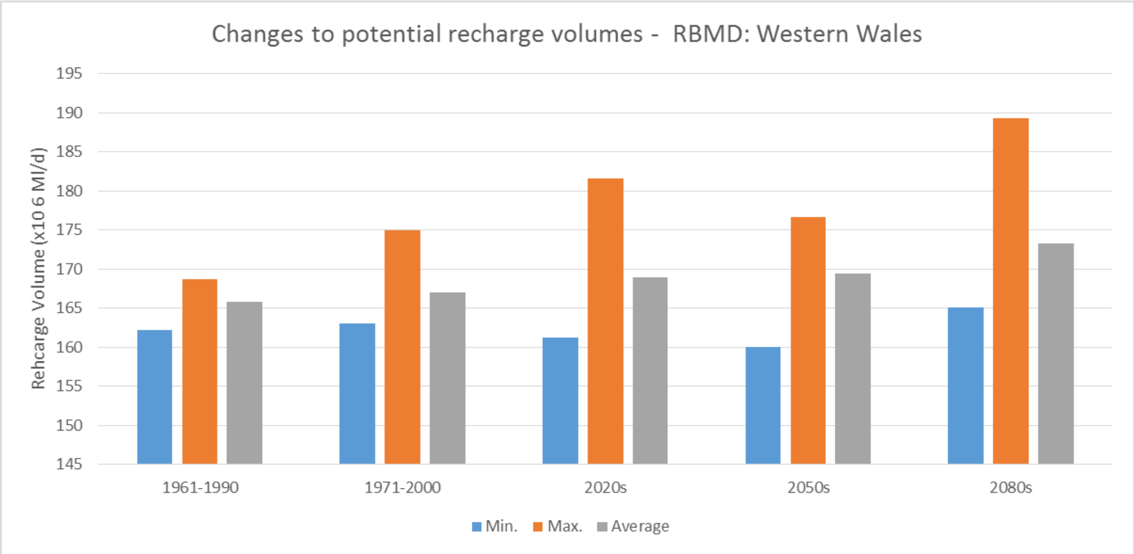


Figure A35. Minimum, average and maximum recharge the Western Wales RBMD for historic simulated and for 2020s, 2050s and 2080s

Table A7. Recharge volumes for Catchment 8: South-West

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	154.69	152.97	158.71	162.35	159.66	156.11	153.76	159.69	155.22	157.62	154.81	152.97	162.35	156.87
1971-2000	156.68	158.88	155.93	170.01	155.08	162.05	158.47	155.52	153.06	158.78	152.32	152.32	170.01	157.89
20s	153.03	149.26	166.05	175.29	153.73	154.74	151.42	169.74	149.44	159.02	156.34	149.26	175.29	158.01
50s	156.12	159.64	167.37	177.37	163.05	147.21	146.94	159.47	160.18	148.84	162.43	146.94	177.37	158.97
80s	170.35	164.97	177.58	191.92	178.89	161.27	157.72	156.82	143.79	162.88	172.26	143.79	191.92	167.13

Note: Recharge values in 10^6 x Ml/day

Table A8. Recharge volumes for Catchment 9: Severn

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	158.39	156.16	163.54	168.44	161.83	157.68	158.92	166.12	159.26	163.59	158.83	156.16	168.44	161.16
1971-2000	162.16	154.58	160.16	179.36	161.77	158.94	164.56	160.80	156.41	164.13	155.29	154.58	179.36	161.65
20s	151.68	148.26	171.90	183.79	152.34	153.92	155.81	175.50	161.40	162.12	159.92	148.26	183.79	161.51
50s	159.11	155.94	169.67	183.10	164.57	150.28	147.92	168.13	162.74	146.19	165.00	146.19	183.10	161.15
80s	166.10	159.95	176.35	196.77	174.46	153.73	151.98	163.66	161.09	160.36	164.95	151.98	196.77	166.31

Note: Recharge values in 10^6 x Ml/day

Table A9. Recharge volumes for Catchment 10: Western Wales

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	164.21	162.21	167.17	168.77	167.21	165.04	163.90	168.14	164.86	167.42	165.41	162.21	168.77	165.85
1971-2000	167.30	166.91	164.29	175.00	167.27	165.27	168.32	163.45	168.16	168.26	163.05	163.05	175.00	167.03
20s	161.28	169.65	168.69	181.57	161.92	166.95	163.57	174.89	167.23	167.68	175.69	161.28	181.57	169.01
50s	169.20	175.72	170.52	176.69	170.94	160.42	160.04	173.59	172.67	160.64	173.32	160.04	176.69	169.43
80s	171.40	180.60	169.77	189.26	174.47	167.93	165.09	170.09	167.56	174.46	175.95	165.09	189.26	173.33

Note: Recharge values in 10^6 x Ml/day

A5.11 RBMD 11 – DEE

The recharge is high in the historical simulation (Figure A36). For the ensembles, the monthly variability of change in recharge values increases for all three time slices with January to March and November and December exhibiting the greatest changes. Some of the ensembles show a reduction in September and October. The 2050s and 2080s show a reduction n recharge between April and October. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A37).

This is a small catchment so variability in average recharge is limited (see Table A10) with possibly a reduction in reduction from historical simulation to future.

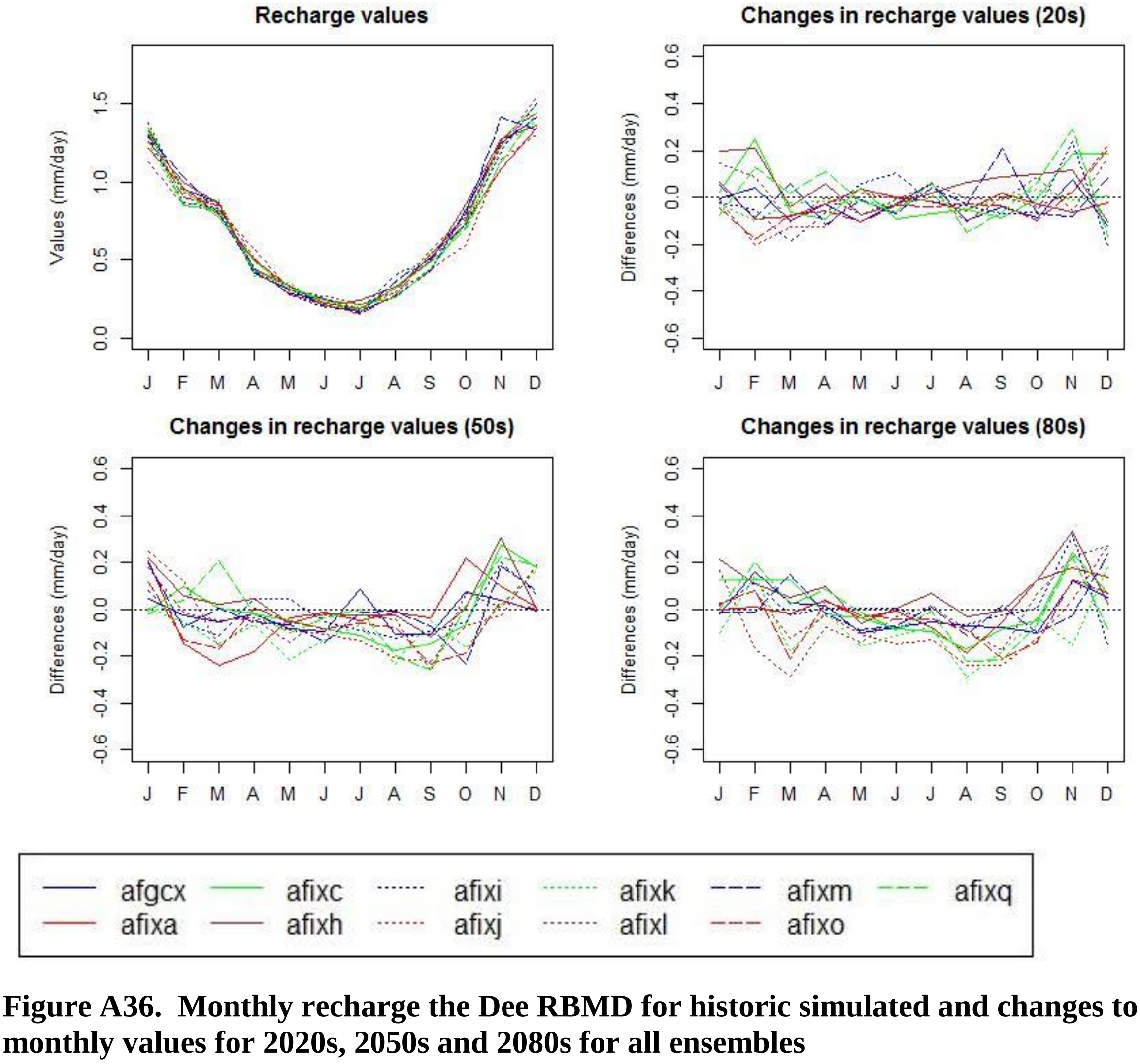


Figure A36. Monthly recharge the Dee RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

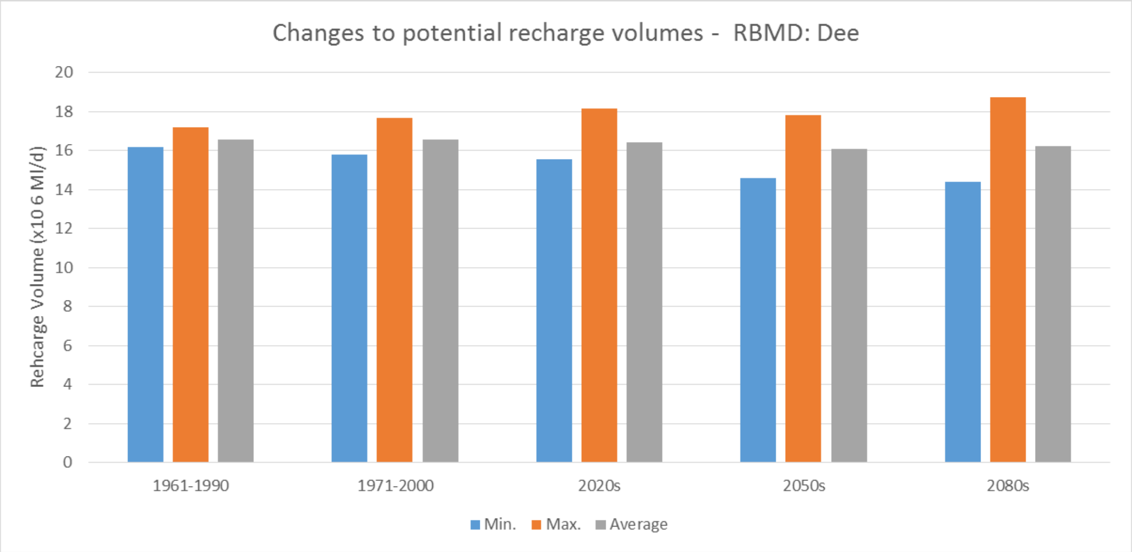


Figure A37. Minimum, average and maximum recharge the Dee RBMD for historic simulated and for 2020s, 2050s and 2080s

A5.12 RBMD 12 - NORTH WEST

The recharge is high in the historical simulation (Figure 38). For the 2020s variability with the majority of the ensembles increasing January and February as well as October, November and December. For both the 2050s and 2080s then the trend appears to be from an increase to a decrease from January to September followed by a sharp increase from September to the end of the year. The recharge totals increase from the historical simulation to the 2020s, reducing for the 2050s and increasing again in the 2080s (see Figure A39).

Table A11 shows that average recharge for all the 11 ensembles increases from historical simulation marginally to the 2020s and 2050s. A significant increase is observed for the 2080s.

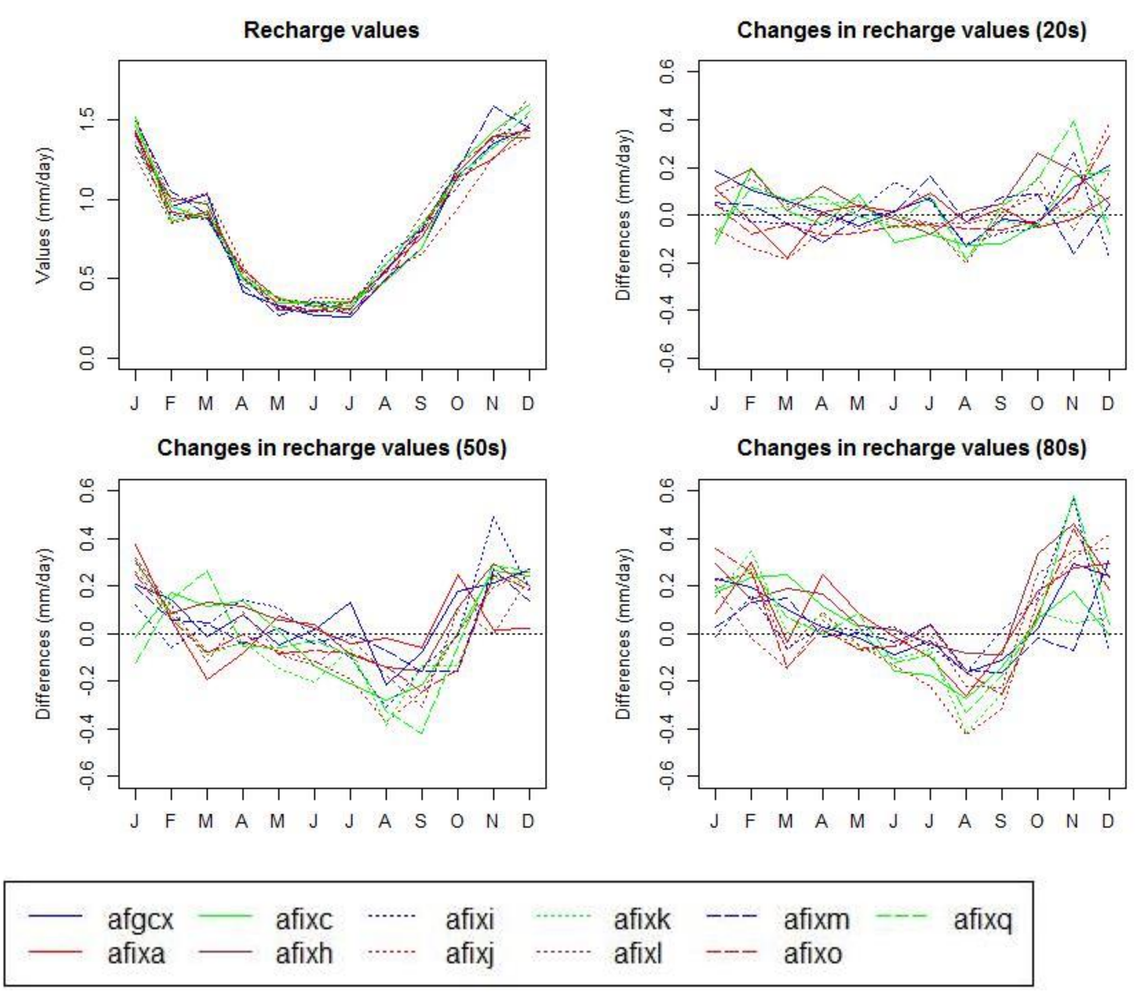


Figure A38. Monthly recharge the North-west RBMD for historic simulated and changes to monthly values for 2020s, 2050s and 2080s for all ensembles

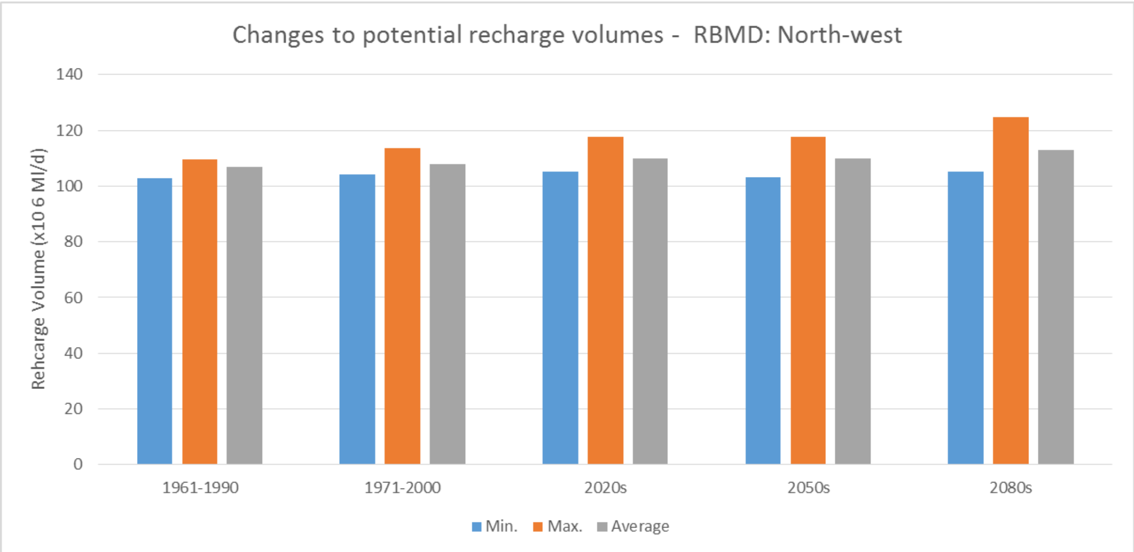


Figure A39. Minimum, average and maximum recharge the North-west RBMD for historic simulated and for 2020s, 2050s and 2080s

Table A10. Recharge volumes for Catchment 11: Dee

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	16.27	16.22	16.72	17.20	16.62	16.16	16.29	17.00	16.45	16.86	16.40	16.16	17.20	16.56
1971-2000	16.66	15.80	16.41	17.69	17.15	16.19	16.67	16.57	16.49	16.88	15.81	15.80	17.69	16.58
20s	15.68	15.64	17.21	18.17	15.92	15.56	16.00	17.36	17.00	15.69	16.46	15.56	18.17	16.43
50s	16.10	15.84	16.57	17.83	16.25	15.08	14.61	16.64	16.64	14.95	16.28	14.61	17.83	16.07
80s	16.21	16.27	16.94	18.72	16.69	14.70	14.39	16.23	16.84	15.61	15.74	14.39	18.72	16.21

Note: Recharge values in 10^6 x Ml/day

Table A11. Recharge volumes for Catchment 12: North-West

	afgcx	afixa	afixc	afixh	afici	afixj	afixk	afixl	afixm	afixo	afixq	Min.	Max.	Average
1961-1990	105.24	102.95	107.38	109.71	107.93	104.77	105.67	109.42	105.76	108.67	106.99	102.95	109.71	106.77
1971-2000	106.12	105.32	108.08	113.47	109.50	105.05	108.34	108.32	109.14	109.39	104.03	104.03	113.47	107.89
20s	110.55	107.53	109.57	117.70	106.13	105.22	105.04	114.72	112.13	105.59	115.18	105.04	117.70	109.94
50s	114.34	111.27	110.51	117.64	111.08	103.00	103.01	110.64	113.48	104.72	107.71	103.00	117.64	109.76
80s	111.53	116.35	111.81	124.74	111.90	107.76	105.14	114.58	112.39	112.53	114.99	105.14	124.74	113.07

Note: Recharge values in 10^6 x Ml/day