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New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies

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Abstract

Under enhanced greenhouse conditions, climate models suggest an increase in rainfall intensities in the northern Hemisphere. Major flood events in the UK during autumn 2000 and central Europe in August 2002, have focussed attention on the dramatic impacts these changes may have on many sectors of society. In the companion paper [Fowler et al., J. Hydrol. (2004) this issue], we suggested that the HadRM3H model may be used with some confidence to estimate extreme rainfall distributions, showing good predictive skill in estimating statistical properties of extreme rainfall during the baseline period, 1961–1990. In this study, we use results from the future integration of HadRM3H (following the IPCC SRES scenario A2 for 2070–2100) to assess possible changes in extreme rainfall across the UK using two methods: regional frequency analysis and individual grid box analysis. Results indicate that for short duration events (1–2 days), event magnitude at a given return period will increase by 10% across the UK. For longer duration events (5–10 days), event magnitudes at given return periods show large increases in Scotland (up to +30%), with greater relative change at higher return periods (25–50 years). In the rest of the UK, there are small increases in the magnitude of more frequent events (up to +10%) but reductions at higher return periods (up to −20%). These results provide information to alter design storm depths to examine climate change impacts on various structures. The uncertainty bounds of the estimated changes and a ‘scaling’ methodology are additionally detailed. This allows the estimation of changes for the 2020s, 2050s and 2080s, and gives some confidence in the use of these estimates in impact studies.

Keywords: Rainfall; Extremes; Climate change; Regional climate models; Floods; UK

1. Introduction

Climate model integrations suggest increases in both the frequency and intensity of heavy rainfall in high latitudes of the northern Hemisphere under enhanced

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greenhouse conditions (McGuffie et al., 1999; Palmer and Räisänen, 2002; Jones and Reid, 2001). This is consistent with recent increases in rainfall intensity seen in the UK (Osborn et al., 2000; Osborn and Hulme, 2002; Fowler and Kilsby, 2003a,b) and worldwide (Groisman et al., 1999; Karl and Knight, 1998; Frich et al., 2002), although it is not possible to assign a cause–effect relationship. The autumn and calendar year 2000 were the wettest in the England and Wales record back to 1766 (Alexander and Jones, 2001), with several other regions in western Europe receiving twice their long-term annual average rainfall (Lawrimore et al., 2001). This caused widespread severe flooding (Lawrimore et al., 2001; Marsh, 2001) and prompted public debate on the apparent increased frequency of extreme rainfall amounts.

The Intergovernmental Panel on Climate Change (Giorgi et al., 2001) suggest that in the future there may be more intense rainfall events over many areas in Europe. Changes to the magnitude, character and spatial distribution of extreme rainfall may have serious impacts upon many sectors such as agriculture, industry, transport, power generation, the built environment and ecosystems. Similarly, changes in many of these sectors will affect hydrology and water resources by altering the flow paths of both surface and groundwater. Recent extreme rainfall events have pushed urban structures beyond their design limits (Pagliara et al., 1998) and caused failure of many systems, including fluvial flood defences (Lawrimore et al., 2001). A possible increase in the occurrence of such events under climate change may exacerbate these impacts. It is important therefore, to understand not only the current spatial and temporal patterns of extreme rainfall (Osborn et al., 2000; Osborn and Hulme, 2002) but also how they are changing (Fowler and Kilsby, 2003a,b) and how the distributions may further change during the planning horizon for system design (~20–100 years). Moreover, uncertainties in these future estimates should be assessed simultaneously to incorporate the uncertainty in climate impacts (Boorman and Sefton, 1997; Katz, 1999). Estimations of uncertainty in extreme rainfall with climate change are important but have tended to be ignored; rare exceptions being Kharin and Zwiers (2000), Booij (2002), Durman et al. (2001), and Huntingford et al. (2003).

In previous studies, global climate model (GCM) simulations have been used to assess changes in extreme rainfall under enhanced greenhouse conditions (Durman et al., 2001; Zwiers and Kharin, 1998). However, whilst GCMs simulate a coarse resolution world, the issues that are most relevant to water management generally work on much smaller scales. This regional detail can however be obtained from the coarse-scale outputs of global models by using simple interpolation, statistical downscaling or high-resolution dynamical modelling. These approaches have a fundamental difference, whilst simple interpolation simply reproduces the change patterns of the GCMs, statistical and dynamic modelling approaches can produce local climate changes that are different from the large-scale estimates.

The greatest advantage of using regional climate models (RCMs) in hydrological studies (Durman et al., 2001; Jones and Reid, 2001; Huntingford et al., 2003) is that very highly resolved information (spatial and temporal) can be derived from these physically based models. The first analysis of prospective changes in extreme rainfall over the UK was provided by Jones and Reid (2001) using results from the HadRM2 RCM (Murphy, 1999). Their research suggested that there would be dramatic increases in the heaviest rainfall events by the end of the 21st century. This conclusion was echoed by Huntingford et al. (2003) who suggested, using results from HadRM2, that for longer duration events there will be even larger increases. Recently, a more comprehensive set of climate scenarios has been produced for the UK, the UK Climate Impacts Programme 2002 (UKCIP02) scenarios (Hulme et al., 2002). These used the more recently developed HadRM3H RCM.

In the first part of this two-part paper (Fowler et al., 2004), two methods were used to assess the performance of HadRM3H in the simulation of UK extreme rainfall; regional frequency analysis (RFA) and individual grid box analysis (GBA). Both methods used L-moments (Hosking and Wallis, 1997) to produce rainfall growth curves with an extreme value distribution for 1-, 2-, 5- and 10-day events. It was found that HadRM3H provided a good estimate of event magnitude at a given return period for most parts of the UK. In this paper, the same methods are used to examine results from HadRM3H for a future scenario ensemble of enhanced greenhouse conditions. This provides an assessment of projected changes in extreme rainfall and an estimation of the related uncertainty. Additional information is then given on how these estimates can be used to alter design storm intensities to examine the impacts of climate change on various structures such as flood defences, etc. The overall aim of this paper is to provide an approach that may be used for impact assessments related to future changes in extreme rainfall in the UK.

2. Data

2.1. Model data

This analysis uses the future rainfall, as predicted from two RCMs from the UK Met Office Hadley Centre; HadRM2 and HadRM3H (see Fig. 1). These are the same models used in the companion paper, Fowler et al. (2004), and further descriptions of the models can be found in their Section 2.2.

The future rainfall projections based on these two RCMs are not entirely comparable for four reasons: (i) HadRM2 gives a future projection for the time period 2080–2100 whilst HadRM3H gives a projection for the period 2070–2100, (ii) the HadRM2 results are based on just one experiment whilst HadRM3H has a three member ensemble for both future and control integrations, (iii) HadRM2 is nested directly within the HadCM2 GCM (Johns et al., 1997), whilst HadRM3H is double nested within both the HadCM3 GCM (Gordon et al., 2000; Johns et al., 2003) and the higher resolution HadAM3H atmospheric model (Pope et al., 2000), and (iv) the emissions scenarios for the two RCMs are different.

The climate characteristics of the GCM simulations are based on a set of emission scenarios, or story lines, created by the Inter-governmental Panel

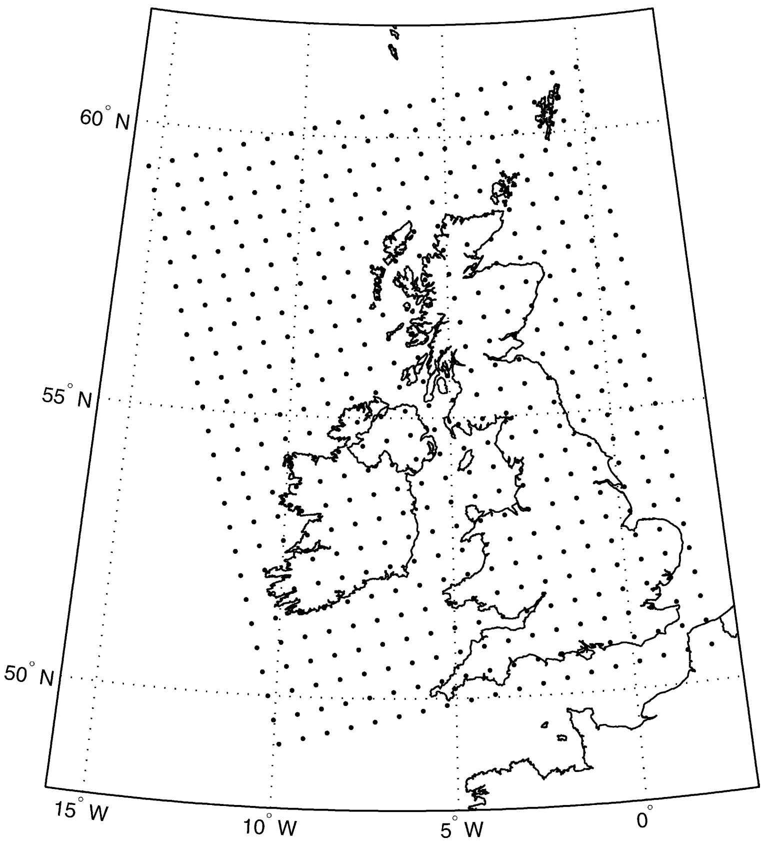

Fig. 1. HadRM3H model dataset over the UK where points denote grid box centres.

on Climate Change (IPCC). A scenario may be viewed as a coherent, internally consistent and plausible description of a future state of the world (IPCC, 1994). These scenarios are explicitly linked to the UKCIP scenarios, on which the experimental designs of HadRM2/3H are based. The HadRM2 model uses the old UKCIP98 scenarios (Hulme and Jenkins, 1998) based on the IPCC IS92a scenario (Leggett et al., 1992), whilst HadRM3H uses the UKCIP02 scenarios (Hulme et al., 2002) based on the four IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000). Compared to the earlier UKCIP98 scenarios, the UKCIP02 medium-high emission scenario (IPCC SRES scenario A2) shows a slightly greater warming rate over the UK, due to the use of a model with higher effective climate sensitivity and also from considering the effects of changing sulphate concentrations (Hulme et al., 2002). Furthermore, the new scenarios have a higher carbon dioxide concentration for the medium-high and high emissions scenarios, reflecting the projected higher levels of global carbon dioxide emissions during the 21-century in SRES (IPCC, 2000). Despite these differences the global warming during the period 2080–2100 in HadCM2 is very similar to that of the 2070–2100 period in the HadCM3 experiments; 3.1 °C for HadCM2 (the driving model of HadRM2) compared with 3.3 °C for HadCM3 (the driving model of HadRM3H) when using the A2 (medium-high emissions) scenario.

In terms of rainfall, the new 2002 scenarios (UKCIP02) suggest that future summers will be drier over the entire UK and by a larger amount (Hulme et al., 2002) than UKCIP98. For spring and autumn, the UKCIP98 scenarios projected wetter conditions; UKCIP02 now suggests that these seasons will be mostly drier in the future. The new scenarios also suggest a significantly different future pattern of rainfall for Scotland compared to the UKCIP98 scenarios.

2.2. Intra-ensemble variability

There are several sources of uncertainty associated with climate models, particularly for those aspects associated with projections. We have chosen not to address uncertainties that are associated with scenario development or model parameterisation, as these lie outside the scope of this paper. By using the three HadRM3H ensemble members, however, the analysis does include a component of uncertainty in terms of natural climate variability. This intra-ensemble variability can be shown as the range between the lowest and highest ensemble return period estimate for each grid box, divided by the corresponding total ensemble return period estimate (i.e. the return period estimate based on all 93 years). The result may be seen as the proportion of uncertainty relative to each return period estimate. This ratio produces a dimensionless measure of uncertainty.

Maps of uncertainty were produced for daily and multi-day annual maxima (AM). Here, we show maps of the 1- and 10-day totals for 10 and 50 year return periods to illustrate the differences amongst the HadRM3H model ensembles (Fig. 2). On average, there is little difference between events of different durations. The only marked difference is the larger percentages in southeast England where values are about 10–20% higher for the shorter duration events (Fig. 2a and b) compared to the longer duration events (Fig. 2c and d). The intra-ensemble variability becomes larger with higher return periods, this being particularly evident for the shorter duration events. Besides having somewhat larger values, the shorter duration events also show more spatial variability compared to the longer duration events. This is best shown by the increase in values for much of Scotland; an increase that is not found to the same extent for the longer duration events.

3. Analysis methods

As this study uses the same analysis methods as Fowler et al. (2004), only a brief description is given here. Two complementary sets of analyses were undertaken to provide an assessment of future projected changes in extreme rainfall on an annual basis: RFA and GBA. In both approaches, the analysis was performed using AM of 1-, 2-, 5-, and 10-day rainfall totals. Furthermore, both approaches estimate extreme rainfall using the Generalized Extreme Value (GEV) distribution fitted using the method of L-moments (Hosking and Wallis, 1997) to define extremes with given return periods. In this paper, we estimate the rainfall amounts associated with 5-, 10-, 25-, and 50-year return periods for the RCM future integrations (2080–2100 for HadRM2 and 2070–2100 for HadRM3H) and compare these to those estimated for the control integrations (1960–1990).

The RFA builds on the regionalisation of UK rainfall, first developed by Wigley et al. (1984), and later improved and updated by Wigley and Jones (1987), Gregory et al. (1991) and Jones and Conway, (1997). This regionalisation identified five spatially coherent regions for England and Wales, three for Scotland and one for Northern Ireland. For each of these regions, the RFA approach was used to generate rainfall growth curves for RCM AM data. For each grid box, the AMs were standardised using the grid box median AM event (Rmed) for the relevant period (i.e. either the control or future AM time series). L-moment ratios derived from single grid box analyses within a region were then combined by regional averaging and weighted according to record length (after Hosking and Wallis (1997)). A GEV distribution or 'growth curve' was then fitted for each region and aggregation level (1-, 2-, 5- and 10-days) for the RCM data by matching the sample L-moments to the distribution L-moments. Using these growth curves, the event magnitude for 5-, 10-, 25- and 50-year return periods were then estimated for each data set and region.

For the GBA on HadRM3H data, the event magnitude at a given return period were estimated individually per grid box, based on the same L-moment approach as the RFA.

To provide uncertainty bounds for the return period estimates a non-parametric bootstrap simulation method or 'resampling' (Efron, 1979) was used to estimate confidence intervals. If each dataset of AMs is based on n data points then, as defined by Efron and Tibshirani (1993), bootstrap simulation samples the original dataset with replacement multiple times to produce multiple independent samples of size n. For each dataset, 100 bootstrap samples were generated, the GEV distribution fitted and the 5-, 10-, 25-, and 50-year return periods estimated. The distribution of these 100 estimates of the 5-, 10-, 25- and 50-year return period event allows the construction of the 5th and 95th percentiles for the GEV distribution fitted to each original dataset or grid box.

4. Results

4.1. Estimating the event magnitude of given return periods using regional frequency analysis

The projected change in the event magnitude of a given return period in the future integrations of the HadRM2 and HadRM3H using the regional analysis are shown in Figs. 3–6 and detailed in Table 1. Figs. 3 and 4 present the change in magnitude for future 1- and 10-day extreme rainfall events as an anomaly (in mm) from the control value, whereas Figs. 5 and 6 present the future change in magnitude as a percentage change from the control value. These can be considered complementary, the first looking at the future as an anomaly from the present magnitudes, with the second estimating the change in magnitude as climate changes.

The HadRM3H future integration shows a very different pattern of change in extreme rainfall than the HadRM2 model, which is much more akin to trends noted in observations during the 1990s (see Fowler and Kilsby (2003b)). Although both show increases in extreme rainfall event magnitude for the same return period event, it is clear that the future changes projected by HadRM3H are of a much lower magnitude compared to those of HadRM2. For the 10-year return period event, magnitudes increase by a small amount across most of the UK; a maximum of 5 and 15 mm for the 1- and 10-day event, respectively (Figs. 3 and 4). This compares to projected increases of 20 and 55 mm from the HadRM2 model. Fig. 5 shows that for 1-day events there is little difference, in terms of either the spatial pattern of change or the relative change, between higher and lower return periods. This is again different to HadRM2, which shows greater relative change at higher return periods.

For longer duration events (e.g. 10-days) (Fig. 6), there is a variable spatial pattern of change across the UK. At lower return periods, there is a small percentage increase in magnitude in all regions (up to ~10%) excepting central and east England. However, at higher return periods, the relative increase in northern and western regions is greater than that at lower return periods. The largest changes are found in Scotland, with an

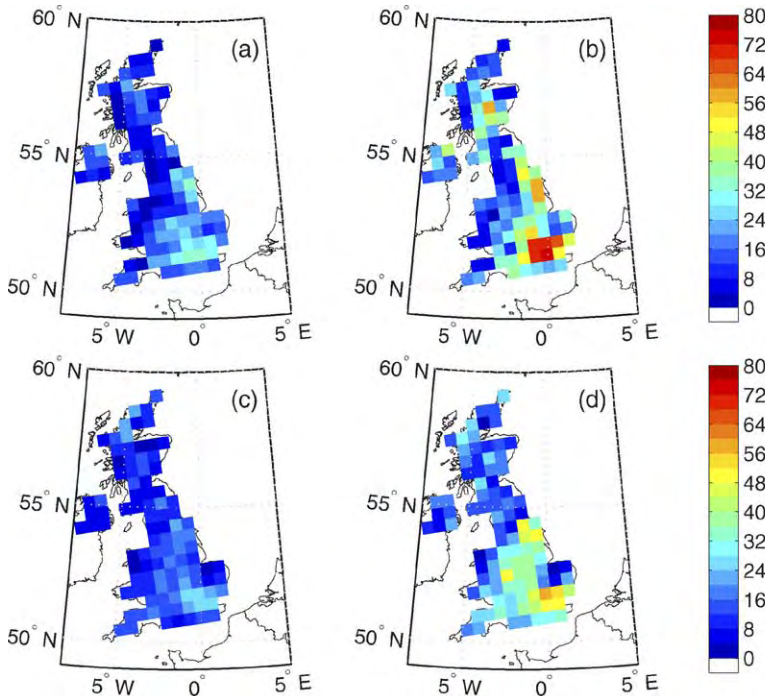

Fig. 2. HadRM3H intra-ensemble variability: graphs show the range between lowest and highest ensemble return period estimate for each grid box divided by the corresponding total ensemble return period estimate (based on all 93 years). (a) 1-day totals, 10-year return period, (b) 1-day totals, 50-year return period, (c) 10-day totals, 10-year return period and (d) 10-day totals, 50-year return period.

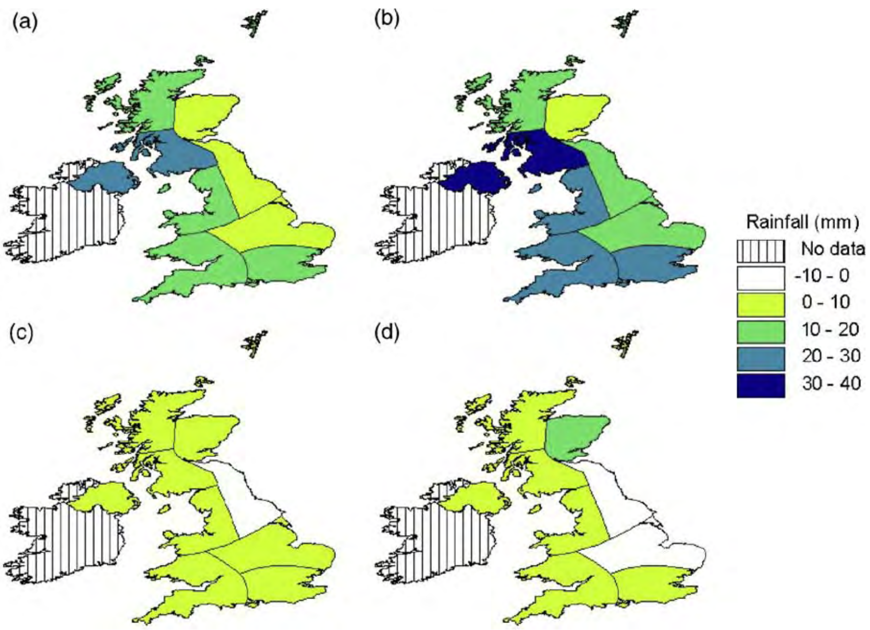

Fig. 3. Comparison of absolute difference (mm) in 1-day rainfall event magnitudes between control and future simulations for (a) HadRM2, 10-year return period, (b) HadRM2, 50-year return period, (c) HadRM3H, 10-year return period, and (d) HadRM3H, 50-year return period. Note that as no data is available for Ireland it has been given a value of zero change.

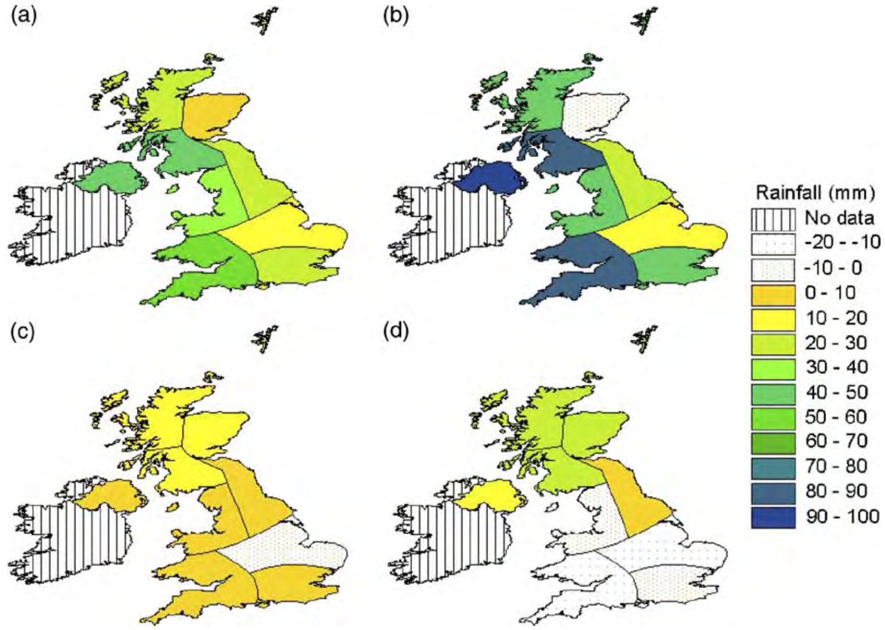

Fig. 4. Comparison of absolute difference (mm) in 10-day rainfall event magnitudes between control and future simulations for (a) HadRM2, 10-year return period, (b) HadRM2, 50-year return period, (c) HadRM3H, 10-year return period and (d) HadRM3H, 50-year return period. Note that as no data is available for Ireland it has been given a value of zero change.

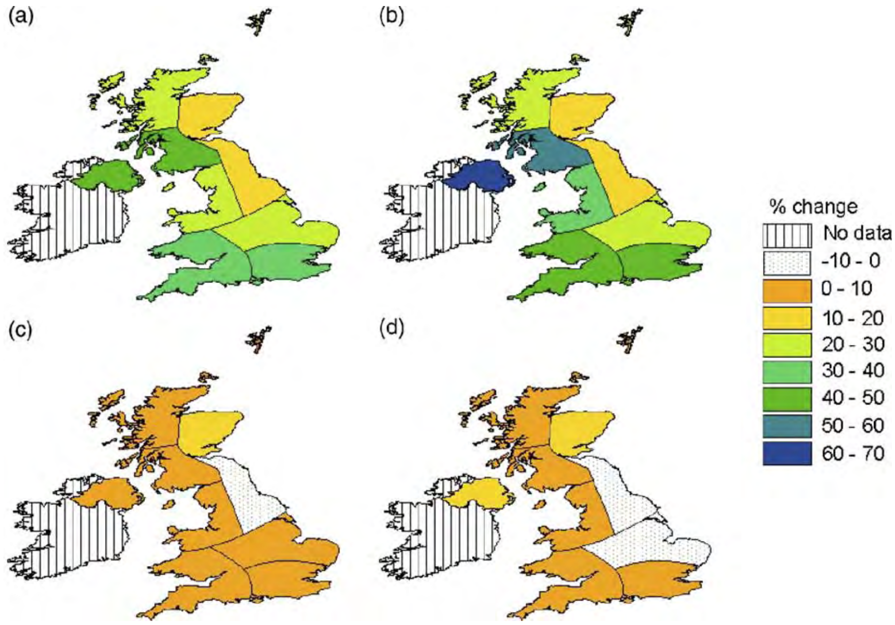

Fig. 5. Percentage change in 1-day rainfall event magnitudes between control and future simulations for (a) HadRM2, 10-year return period, (b) HadRM2, 50-year return period, (c) HadRM3H, 10-year return period, and (d) HadRM3H, 50-year return period. Note that as no data is available for Ireland it has been given a value of zero change.

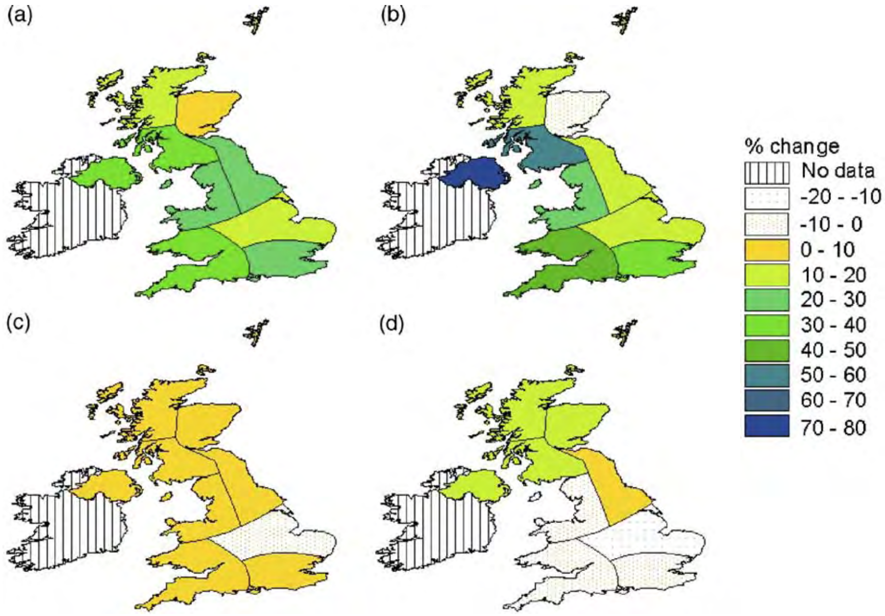

Fig. 6. Percentage change in 10-day rainfall event magnitudes between control and future simulations for (a) HadRM2, 10-year return period, (b) HadRM2, 50-year return period, (c) HadRM3H, 10-year return period, and (d) HadRM3H, 50-year return period. Note that as no data is available for Ireland it has been given a value of zero change.

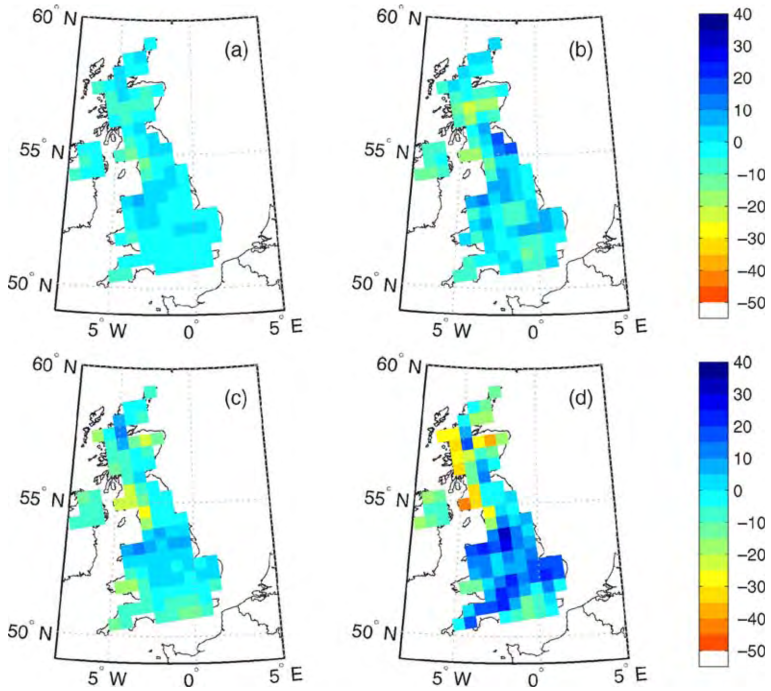

Fig. 7. Comparison of absolute difference (mm) in 1-day rainfall event magnitudes between control and future simulations for (a) HadRM3H, 10-year return period, (b) HadRM3H, 50-year return period, and for 10-day rainfall event magnitudes, (c) HadRM3H, 10-year return period and (d) HadRM3H, 50-year return period.

Table 1
Estimated changes in extreme rainfall event magnitude for the period 2070–2100 relative to 1960–1990 from HadRM3H using RFA in the 9 UK rainfall regions: North Scotland (NS), East Scotland (ES), South Scotland (SS), Northern Ireland (NI), Northwest England (NWE), Northeast England (NEE), Central and Eastern England (CEE), Southeast England (SEE) and Southwest England (SWE)

Region	Return period	1-day event	2-day event	5-day event	10-day event
NS	5	1.06	1.03	1.01	1.01
	10	1.07	1.06	1.01	1.03
	25	1.08	1.11	1.03	1.05
	50	1.09	1.15	1.04	1.07
SS	5	1.07	1.07	1.06	1.08
	10	1.06	1.08	1.06	1.09
	25	1.05	1.10	1.07	1.10
	50	1.04	1.11	1.07	1.12
ES	5	1.10	1.08	1.09	1.06
	10	1.16	1.13	1.12	1.10
	25	1.24	1.20	1.16	1.15
	50	1.30	1.25	1.20	1.20
NI	5	1.08	1.09	1.03	1.03
	10	1.08	1.10	1.05	1.05
	25	1.07	1.11	1.11	1.09
	50	1.07	1.12	1.16	1.12
NEW	5	1.02	1.03	1.01	1.03
	10	1.01	1.02	0.98	1.00
	25	0.99	1.01	0.94	0.96
	50	0.98	1.01	0.92	0.93
NEE	5	1.01	1.00	1.04	1.04
	10	0.99	0.99	1.02	1.04
	25	0.95	0.98	1.00	1.02
	50	0.92	0.97	0.98	1.00
CEE	5	1.05	1.06	1.03	1.03
	10	1.02	1.03	0.96	0.97
	25	0.97	0.99	0.87	0.89
	50	0.92	0.96	0.81	0.83
SEE	5	1.04	1.04	1.03	1.08
	10	1.04	1.05	1.00	1.05
	25	1.06	1.06	0.98	1.01
	50	1.09	1.08	0.96	0.98
SWE	5	1.06	1.02	1.03	1.07
	10	1.04	0.99	0.99	1.03
	25	1.02	0.96	0.93	0.97
	50	1.01	0.94	0.88	0.92

increase of 20% in east Scotland for the 10-day, 50-year event. This increase concurs with observed trends in extreme longer duration rainfall (Fowler and Kilsby, 2003a,b), which found that the east Scotland region has shown the greatest increase in event magnitude for a given return period over the 1990s. In southern and eastern regions, however, the relative change is much lower and is actually negative for higher return period events.

4.2. Estimating the event magnitude of given return periods using grid box analysis

The GBA provides more spatial detail on changes projected in the future RCM integrations, as the analysis is performed individually for each HadRM3H grid box. The absolute (mm) and relative (%) changes in return period estimates for the 10- and 50-year return periods, using the 1- and 10-day totals, are shown in Figs. 7 and 8, respectively. In absolute magnitude, small (±10 mm) and mainly negative changes are found in the majority of the UK for lower return period 1-day events (Fig. 7a). Regions with increases are found foremost in north Wales, north Scotland and northeast England. Decreases are more widespread, but tend to be somewhat larger in grid boxes located in northwest England and central Scotland. A similar spatial pattern but with more pronounced changes (±20 mm) is found for longer duration events (Fig. 7c). At higher return periods, a large number of grid boxes in the UK still show decreases for the 1-day event (Fig. 7b). Relative to the lower return period events, however, the number of grid boxes with increases has multiplied, with increases encroaching further into East Anglia and also in western England. The magnitude of longer duration events also show large increases (>20 mm) at higher return periods in England and Wales, whilst Northern Ireland (>10 mm) and particularly western Scotland (20–35 mm) and northwest England (35–45 mm) experience decreases.

The relative change in the event magnitudes of given return periods between the control and future integrations of HadRM3H are displayed in Fig. 8. For both 1- and 10-day duration events small changes generally dominate in the 10-year return period estimate (Fig. 8a and c), whilst patterns become more distinct for 50-year return periods (Fig. 8b and d). For the estimates based on 1-day totals, using a 10-year return period, the largest increases are found for grid boxes over northern Wales (>10%) followed by northeast England and central England (Fig. 8a). At higher return periods, the increases become more widespread and larger in magnitude (Fig. 8b). These increases are found primarily over East Anglia and western England (Fig. 8b). At all return periods, decreasing estimates are found mainly in northwest England and eastern Scotland. Generally, the decreases are larger and more widespread at higher return periods. For longer duration (10-day) events (Fig. 8c and d), the spatial pattern of change is more coherent than for 1-day events. Decreases in magnitude are largely confined to northwest England and eastern Scotland, followed by Northern Ireland and southeast England. Most other regions exhibit increases in magnitude, particularly for the 50-year return period when the majority of grid boxes in the UK show increases of at least 10%.

At lower return periods (5- and 10-years), there is an overall decrease in event magnitude at all durations (not shown). At higher return periods (25-and 50-years), however, the distribution of grid box values shows a less negative trend for 1- and 2-day duration events, and changes to an overall positive trend for 5- and 10-day duration events (not shown).

Uncertainty intervals for the future estimates were produced using a bootstrapping technique as detailed in Section 3. The range of uncertainty (the range between the 5th and 95th percentile) relative to the return period estimate can be seen in Fig. 9 for the 1-and 10-day event (10- and 50-year return period). All event durations show small spatial variability in uncertainty for the 10-year return period (Fig. 9a and c). Typical uncertainty ranges are from 6 to 16% of estimated return period for most of the western and northern UK but somewhat larger in southeast England, particularly for the 1-day event (Fig. 9a). At higher return periods, there are much larger proportions of uncertainty relative to the estimates (Fig. 9b and d). A particularly large uncertainty range is seen in southeast England for the 1-day event where estimates are up to 50% of the estimated return period (Fig. 9b). Increased uncertainty at higher return periods is also found in eastern Scotland, with estimates of ~30–50% for the 1-day event and ~30% for the 10-day event.

Table 2 details the HadRM3H grid box minimum and maximum estimated future event magnitude for given return periods within each of the nine rainfall regions. These values provide an estimate of the regional variability generated in the HadRM3H data. In general, there is little spatial difference in patterns for different return periods but the differences become larger for longer duration events. The largest range in estimates is found in north and south Scotland, followed by southwest and northwest England, and east Scotland. Other regions show a relatively small range of values.

5. Discussion

The future integrations of HadRM3H produce a very different pattern and magnitude of change in extreme rainfall than HadRM2. These results should be viewed with caution due to the significant differences in future changes generated by the two

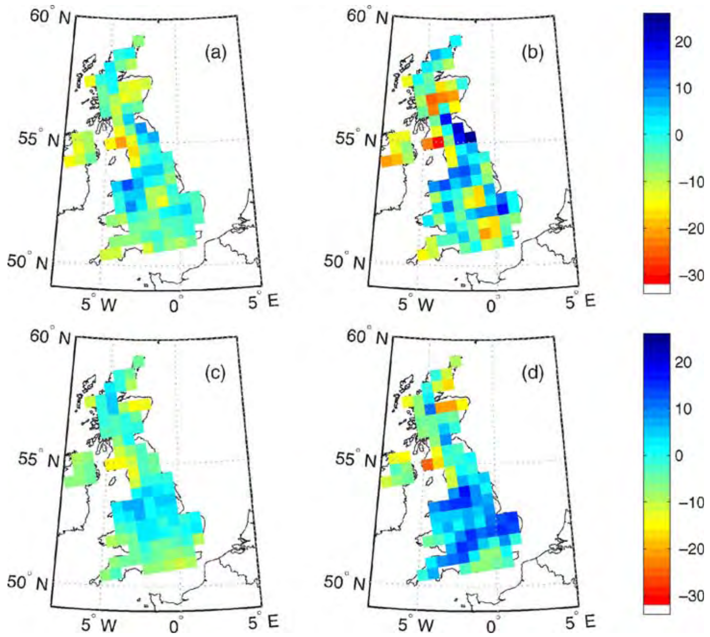

Fig. 8. Percentage change in 1-day rainfall event magnitudes between control and future simulations for (a) HadRM3H, 10-year return period, (b) HadRM3H, 50-year return period, and for 10-day rainfall event magnitudes, (c) HadRM3H, 10-year return period and (d) HadRM3H, 50-year return period.

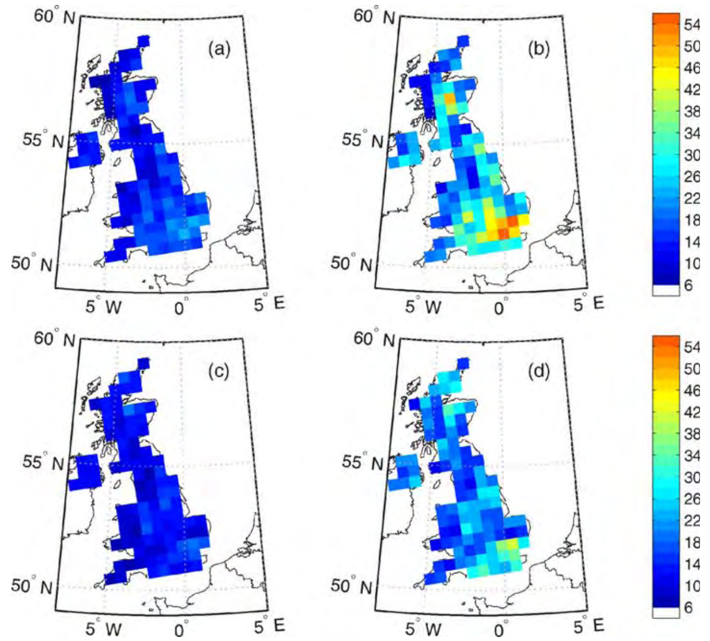

Fig. 9. Uncertainty ranges relative to the return period estimates in 1-day rainfall event magnitudes for the future simulations for (a) HadRM3H, 10-year return period, (b) HadRM3H, 50-year return period, and for 10-day rainfall event magnitudes, (c) HadRM3H, 10-year return period and (d) HadRM3H, 50-year return period.

models. It is also possible that future changes in scenario development and improvements of model parameterisation may produce different estimates to those presented here. However as, from a simple physical viewpoint, global warming will allow the atmosphere to hold more moisture then it is extremely unlikely that they will alter the sign of the change.

The future change in event magnitude for lower return periods for 1-day extreme rainfall is only small (±5 mm) for most grid boxes (Fig. 7a). Larger increases (10 mm) are found over north Wales, northwest England and north Scotland. Grid boxes with large decreases (10–15 mm) are found foremost in the Lake District, Scotland and Northern Ireland. The magnitude of change between present and future estimates becomes larger for both rarer (i.e. higher return periods) and longer duration events (Figs. 7 and 8). Although the spatial pattern of future change in extreme rainfall is fairly similar for both short and longer duration events, there are evident differences. These are particularly apparent in central England where there are decreases in magnitude for longer events rather than the increases found for shorter duration events, and southern Scotland, with pronounced increases in magnitude for longer events instead of the moderate increases found for shorter duration events.

The GBA approach highlights the large spatial variability in estimated future changes. This is particularly evident in central parts of England for shorter duration events (Fig. 8) and has important implications for how model data can be used in impact studies. Because neighbouring grid boxes can potentially show opposite future trends the user would benefit from investigating the trends over a number of grid boxes to better understand the regional trend. This potential problem is however avoided by using RFA, as this method does not rely on any single point/ grid box. The RFA does, however, rely on the assumption that the regional homogeneity of the UKs nine rainfall regions will not be altered by any future change in climate.

Using the RFA approach, the change in the event magnitude of given return periods as projected by the HadRM3H integrations were estimated for each of the nine rainfall regions of the UK (see Table 1). These 'new estimates' of the future (2070–2100) suggest increases of up to 30% in the magnitude of 1-day events across the UK. The greatest increases are over Scotland, Northern Ireland and southeast England and lowest over northeast England (see Figs. 5 and 6). This pattern of change is similar to that projected by Jones and Reid (2001) in their analysis of future changes using results from HadRM2; however, the magnitude of change is much lower than estimated using the HadRM2 model integration. For longer duration events, such as 10-day totals, there is a small increase (~10%) in event magnitude across the UK at lower return periods. However, for higher return period events, there is greater relative change with increases of up to 20% in Scotland for the 50-year event but reductions of 10% over most of England. These decreases in the event magnitude for higher return periods can be as great as 20% for a 50-year event in central and eastern England. This differs substantially from results from the HadRM2 model, which shows large increases across the whole UK, but concurs well with the spatial pattern of observed trends in extreme rainfall during the 1990s (Fowler and Kilsby, 2003a,b).

These new estimates have implications for the design of flood defence and drainage infrastructure. The increase in event magnitude for a given return period for shorter duration events across the UK has severe implications for systems affected by short duration intense rainfall, such as combined sewer systems and storm drainage. At the other end of the scale, an increase in longer duration event magnitude of a given return period will have implications for fluvial flood defence schemes.

As in Jones and Reid (2001), projected changes to a rainfall event of specific duration and recurrence can be calculated for impact studies by multiplying the present estimate, either taken from a site estimate or using the observed regional estimate given in Table 3, by the future change factor given in Table 1. It must be noted that these change factors are for the period 2070–2100 and for HadRM3H only. However, Santer et al. (1990) and Huntingford and Cox (2000) have confirmed that many changes associated with mean surface climatology projected by climate models may be scaled by changes in global mean temperature. Here, an assumption of linearity between changes in extreme rainfall and global temperature change is made (following Jones and Reid (2001)). This assumption is the simplest and may not be defensible;

Table 2
HadRM3H grid box minimum and maximum and estimated future event magnitudes for given return periods within each of the nine rainfall regions (shorthand notation explained in Table 1 caption), with difference as a proportion of the maximum given for comparison

Region	Return period	1-day event			2-day event			5-day event			10-day event		
		Min (mm)	Max (mm)	Diff. as prop. max	Min (mm)	Max (mm)	Diff. as prop. max	Min (mm)	Max (mm)	Diff. as prop. max	Min (mm)	Max (mm)	Diff. as prop. max
NS	5	34	118	0.71	44	172	0.74	59	268	0.78	78	392	0.80
	10	38	129	0.71	50	190	0.74	69	295	0.77	90	438	0.79
	25	44	143	0.69	58	212	0.73	82	333	0.75	104	497	0.79
	50	48	153	0.69	63	227	0.72	92	363	0.75	114	544	0.79
SS	5	39	105	0.63	51	154	0.67	69	232	0.70	90	344	0.74
	10	42	114	0.63	58	168	0.65	77	252	0.69	99	382	0.74
	25	47	124	0.62	66	184	0.64	87	274	0.68	109	431	0.75
	50	50	130	0.62	73	195	0.63	94	288	0.67	116	468	0.75
ES	5	36	63	0.43	45	94	0.52	60	137	0.56	76	177	0.57
	10	42	72	0.42	54	108	0.50	69	157	0.56	85	199	0.57
	25	52	84	0.38	65	125	0.48	82	182	0.55	98	226	0.57
	50	58	94	0.38	74	139	0.47	92	200	0.54	107	246	0.57
NI	5	36	52	0.31	47	70	0.33	62	100	0.38	81	136	0.40
	10	42	58	0.28	55	79	0.30	71	112	0.37	91	150	0.39
	25	50	67	0.25	67	88	0.24	84	129	0.35	105	166	0.37
	50	57	73	0.22	77	95	0.19	94	142	0.34	115	178	0.35
NWE	5	27	72	0.63	36	101	0.64	47	145	0.68	59	206	0.71
	10	32	79	0.59	44	114	0.61	56	161	0.65	69	227	0.70
	25	39	88	0.56	54	129	0.58	67	181	0.63	83	252	0.67
	50	45	94	0.52	63	140	0.55	75	195	0.62	94	270	0.65
NEE	5	32	50	0.36	42	69	0.39	53	96	0.45	67	127	0.47
	10	38	54	0.30	49	78	0.37	63	107	0.41	77	141	0.45
	25	45	60	0.25	59	88	0.33	75	121	0.38	91	158	0.42
	50	51	64	0.20	65	96	0.32	85	131	0.35	101	169	0.40
CEE	5	33	44	0.25	43	59	0.27	57	79	0.28	75	109	0.31
	10	38	50	0.24	49	67	0.27	66	89	0.26	85	123	0.31
	25	45	59	0.24	57	79	0.28	77	101	0.24	99	141	0.30
	50	49	65	0.25	63	89	0.29	86	111	0.23	109	155	0.30
SEE	5	33	42	0.21	43	56	0.23	57	81	0.30	77	112	0.31
	10	40	49	0.18	51	66	0.23	67	92	0.27	88	124	0.29
	25	49	61	0.20	64	81	0.21	80	109	0.27	102	141	0.28
	50	57	71	0.20	75	93	0.19	92	129	0.29	113	157	0.28
SWE	5	36	77	0.53	46	105	0.56	65	162	0.60	86	240	0.64
	10	41	84	0.51	53	115	0.54	74	175	0.58	96	262	0.63
	25	49	93	0.47	64	126	0.49	84	190	0.56	108	290	0.63
	50	54	99	0.45	73	134	0.46	91	200	0.55	116	309	0.62

however, Jones et al. (1997) found that 90% of the increase in intense rainfall over Europe in an earlier RCM integration could be explained by increasing the intensity of events in the control simulation by the percentage increase in mean rainfall. If estimated changes are required for dates between 2000 and 2070 therefore, as in Huntingford et al. (2003), data from the two RCM integrations (control and future) can be used to predict the incremental increase in extreme rainfall event magnitudes for years when RCM data is unavailable. Assuming a linear relationship between global temperature and extreme rainfall amount (as in Hulme et al., 2002), scaling factors (Table 4) can be combined with change factors (Table 1) to give extreme rainfall amounts for impact studies in the 2020s, 2050s and 2080s.

The uncertainty in these future projections can be ascertained by using the estimates presented in Table 5. These provide a lower and upper estimate of change between the control and future integrations of HadRM3H based on the bootstrap simulation method detailed in Section 3. It can be seen that in Scotland and Northern Ireland, both the lower and upper estimates of future change are positive. This suggests that increases in rainfall intensities at all return periods and all durations are likely in these regions. In England and Wales, however, the lower and upper estimates of change tend to span the 'zero change' line. For longer duration events, there is a tendency to more positive changes and this is similarly true for lower return periods.

6. Conclusions

Both the scientific community and policymakers are showing growing interest in the potential impacts of climate change on water resources and water management. Research into this topic is spurred by the recent large-scale flooding seen in Europe and the UK during the period 2000–2002 (Marsh, 2001; Lawrimore et al., 2001). To assess the extent of impact that climate change may have on the near surface environment, experts use impact models that rely on quantitative climate and non-climate scenarios as inputs. Such quantitative input is given in this study, which provides estimates of future change in

Table 3
Estimated event magnitude (in mm) for a given return period for observed extreme rainfall during the period 1961–1990 using RFA (shorthand notation explained in Table 1 caption)

Region	Return period	1-day event	2-day event	5-day event	10-day event
NS	5	54	75	115	167
	10	61	84	128	185
	25	71	96	144	206
	50	78	105	156	220
SS	5	53	70	107	156
	10	59	78	119	170
	25	68	89	134	188
	50	75	98	145	199
ES	5	47	62	87	116
	10	55	72	100	134
	25	65	84	118	156
	50	72	95	133	175
NI	5	46	62	85	112
	10	54	72	96	124
	25	66	86	110	139
	50	76	97	121	150
NEW	5	51	67	97	137
	10	58	77	109	152
	25	70	90	126	170
	50	78	100	138	183
NEE	5	43	56	73	96
	10	51	66	84	110
	25	61	78	99	128
	50	69	87	110	142
CEE	5	41	51	66	87
	10	49	59	75	97
	25	58	71	88	111
	50	66	80	97	120
SEE	5	43	53	72	100
	10	51	62	82	114
	25	62	76	96	132
	50	72	88	107	145
SWE	5	48	61	87	122
	10	56	70	97	135
	25	67	84	110	150
	50	76	93	118	159

Table 4
Scaling factors for future changes in extreme rainfall for three future 30-year periods centred on the decades of the 2020s, 2050s and 2080s (taken from Hulme et al. (2002))

Time period	ΔT (°C)	CO_2 (ppm)	Factor
2020s	0.88	435	0.27
2050s	1.87	551	0.57
2080s	3.29	715	1.00

Table 5
Uncertainty range for projected changes in extreme rainfall event magnitude for the period 2070–2100 relative to 1960–1990 from HadRM3H using RFA (shorthand notation explained in Table 1 caption)

Region	Return period (years)	1-day event		2-day event		5-day event		10-day event	
		Min	Max	Min	Max	Min	Max	Min	Max
NS	5	1.03	1.09	0.99	1.06	1.00	1.05	1.03	1.08
	10	1.02	1.09	1.00	1.07	1.00	1.07	1.04	1.10
	25	1.01	1.11	1.01	1.11	1.01	1.11	1.05	1.14
	50	0.99	1.12	1.01	1.14	1.01	1.15	1.06	1.18
SS	5	1.04	1.10	1.06	1.13	1.03	1.09	1.06	1.12
	10	1.02	1.11	1.06	1.14	1.03	1.10	1.06	1.14
	25	1.00	1.13	1.06	1.18	1.02	1.12	1.06	1.16
	50	0.98	1.15	1.05	1.20	1.01	1.14	1.05	1.19
ES	5	1.05	1.14	1.06	1.16	1.05	1.14	1.02	1.10
	10	1.06	1.18	1.06	1.20	1.06	1.18	1.03	1.12
	25	1.07	1.26	1.06	1.26	1.07	1.24	1.04	1.17
	50	1.07	1.32	1.05	1.31	1.07	1.30	1.04	1.22
NI	5	1.03	1.11	1.04	1.13	1.05	1.12	1.03	1.10
	10	1.03	1.13	1.04	1.14	1.06	1.13	1.03	1.11
	25	1.02	1.15	1.02	1.15	1.06	1.17	1.03	1.14
	50	1.02	1.17	1.00	1.16	1.05	1.20	1.02	1.16
NWE	5	0.98	1.04	0.98	1.04	0.98	1.04	1.01	1.07
	10	0.97	1.04	0.96	1.04	0.95	1.03	0.99	1.06
	25	0.95	1.05	0.93	1.03	0.91	1.02	0.94	1.05
	50	0.93	1.07	0.90	1.03	0.87	1.02	0.91	1.05
NEE	5	0.97	1.05	0.96	1.04	1.01	1.10	1.01	1.09
	10	0.94	1.05	0.94	1.04	1.00	1.11	0.99	1.09
	25	0.89	1.05	0.91	1.05	0.96	1.12	0.95	1.10
	50	0.84	1.05	0.88	1.05	0.93	1.12	0.91	1.12
CEE	5	0.99	1.06	0.98	1.05	0.95	1.02	0.98	1.04
	10	0.97	1.05	0.96	1.04	0.90	0.99	0.95	1.02
	25	0.93	1.05	0.92	1.03	0.84	0.95	0.90	1.00
	50	0.89	1.04	0.88	1.03	0.80	0.93	0.87	0.99
SEE	5	1.00	1.07	0.98	1.06	0.99	1.07	1.05	1.12
	10	0.99	1.09	0.97	1.09	0.95	1.06	1.01	1.10
	25	0.97	1.13	0.95	1.13	0.90	1.07	0.95	1.08
	50	0.96	1.18	0.93	1.17	0.85	1.08	0.90	1.06
SWE	5	1.03	1.09	0.99	1.05	1.01	1.06	1.05	1.10
	10	1.01	1.08	0.96	1.03	0.96	1.04	1.00	1.06
	25	0.97	1.07	0.90	1.02	0.88	1.00	0.94	1.01
	50	0.93	1.07	0.86	1.01	0.81	0.96	0.88	0.98

extreme rainfall across the UK that can be easily used in impact studies.

In Fowler et al. (2004), we suggested that the HadRM3H model may be used with some confidence to estimate extreme rainfall distributions, showing good predictive skill in estimating statistical properties of extreme rainfall during the baseline period, 1961–1990. This gives us confidence that the RCM will have some skill in predicting how these extremes might change under enhanced greenhouse conditions.

Using a RFA of the HadRM3H model integrations, in combination with a classification of rainfall regions of the UK, we suggest that by the end of the 21st century the return period magnitude for a 1-day event will have increased by approximately 10% across the UK, with values for 10-day events increasing more in Scotland (up to + 30%) than England (−20 to +10%). For longer duration events, there is greater relative change for higher return period events in Scotland. However, in England the situation is reversed, giving small increases in the magnitude of more frequent events but reductions in the magnitude of higher return period events. The large projected increases in the magnitude of longer duration extreme rainfall events in Scotland and parts of England have particular relevance, as much of the flooding in the UK during the autumn of 2000 was a result of long duration rainfalls. This implies that such flooding events may occur with increased frequency and severity under enhanced greenhouse conditions.

It is important to take account of the uncertainty in projected changes, particularly for impact studies. Here, we present results from a single climate change emissions scenario from only one model, HadRM3H. However, the uncertainty in climate change projections results from many different areas: uncertainty in future emissions, uncertainties in model parameterisation and from natural climate variability. The only existing high-resolution simulations of future UK climate for the new IPCC SRES emissions scenarios come from the HadRM3H model, therefore the present study does not reflect uncertainties associated with modelling the climate system response to climate change, or model parameterisation. Equally, as only one scenario is used, there is no quantification of the uncertainty associated with the chosen emissions scenario, A2. However, the A2 scenario applied in the HadRM3H integrations is near the centre of the range of the new IPCC estimates in terms of mean global temperature change (Johns et al., 2003). Here, the uncertainty resulting from natural climate variability is however assessed using a bootstrap simulation method in a similar way to Huntingford et al. (2003). This, together with the ensemble of simulations, allows uncertainty bounds to be estimated for future changes.

Whilst this study has focused on annual changes in extreme rainfall in the UK, future work will examine what changes are predicted by HadRM3H on a seasonal basis. Recent work on observed changes in seasonal extremes suggests that there are trends to increases in heavy rainfall events during winter and autumn months and reductions in summer (Fowler and Kilsby, 2003b), the changes being in line with what is expected with climate change (Jones and Reid, 2001). In flood generation, a change to the frequency and timing of extreme rainfall events may be as important as changes in magnitude and duration (Bayliss and Jones, 1993). Inappropriate seasonal changes in extreme rainfall may therefore further increase the frequency and severity of flood events under future enhanced greenhouse conditions.

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