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Changes in drought frequency, severity and duration for the British Isles projected by the PRUDENCE regional climate models

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Summary Using multiple climate models for impact assessment allows the examination of uncertainty in projections of change, thus providing improved tools for the adaptation and mitigation of the impacts of future change. Here, the performance of integrations from six regional climate models (RCMs) driven by four different general circulation models (GCMs) have been assessed for British Isles mean precipitation and drought statistics for the 1961–1990 period, using two drought severity indices based on monthly precipitation anomalies. Spatially averaged statistics are examined in addition to spatial variations in model performance over water resource regions and compared with observations. Estimates of the range and sources of uncertainty in future changes are examined for the SRES A2 2071–2100 emissions scenario.

Results indicate that the RCMs are able to reproduce the spatially averaged annual precipitation cycle over the British Isles but the spatial anomalies suggest that they may have difficulty in capturing important physical processes responsible for precipitation. The RCMs are unable to simulate the observed frequency of drought events in their control climate, particularly for severe events, possibly due to a failure to simulate persistent low precipitation. Future projections suggest an increase in mean precipitation in winter and decrease in summer months. Short-term summer drought is projected to increase in most water resource regions except Scotland and Northern Ireland, although the uncertainty associated with such changes is large. Projected changes in longer droughts are influenced by the driving GCM and are highly uncertain, particularly for the south of England, although the longest droughts are projected to become shorter and less severe by most models. This suggests that many water supply companies may need to plan for more

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intense short-term droughts but may experience fewer longer duration events under future climate change.

Introduction

Climate models incorporate the effects of small-scale physics through the parameterization of unresolved processes. Consequently, a range of uncertainty exists in the value of such parameters. Models also contain uncertainties in the structures used to represent large-scale climate processes. Consequently, any one model simulation of future climate may represent only one of many possible future climate states. Improved parameterization of climate models is one way in which such uncertainty ranges may be narrowed. Alternatively, a large number of model simulations may be used to assess the uncertainty and estimate the most likely future climate. In practical terms this may be undertaken by running simulations in which parameters are varied within their range of uncertainty (e.g. Murphy et al., 2004), or using different models which may be compared in their ability to model historical climate and so their possible skill in predicting future climate. Methods using multi-model ensembles to provide probabilistic projections of future climate change have recently been developed (Allen et al., 2000; Palmer et al., 2005). However, this effort has been concentrated on assessing uncertainties in future temperature change and defining ''dangerous'' change (e.g. Mastrandrea and Schneider, 2004) at the global scale and there has been little analysis of other variables. Probabilistic methods have not been widely used in climate change impact studies, although they have been used for short- and long-term climate, weather and hydrological forecasting (e.g. Räisänen and Palmer, 2001; Grantz et al., 2005). However, in recent advances, some studies have begun to apply probabilistic methods to hydrological impacts projections (e.g. Wilby and Harris, 2006; Fowler et al., in press).

AquaTerra is a EU FP6 project which aims to address some of the deficiencies in impacts research by developing a framework for the construction of probabilistic climate change scenarios to assess climate change impacts at the regional (~100,000–250,000 km^2), river basin (~10,000 to ~100,000 km^2) and catchment (~1000 to 5000 km^2) scale. The project aims to produce probability density functions (pdfs) of future change by weighting the projections from each of a multi-model ensemble in a way that reflects their ability to reproduce observed climate statistics for the control integration (1961–1990), not only for the mean, but also for higher order statistics such as variability and extremes. These weightings will be derived from the ability of models to produce a range of climate statistics that are relevant to the desired impact application.

A potentially significant impact of climate change over many regions will be changes in the frequency and characteristics of droughts. Although historical drought events in the UK have been much studied (e.g. Bryant et al., 1992, 1994; Mawdsley et al., 1994; Jones et al., 1997; Goldsmith et al., 1997; Phillips and McGregor, 1998; Fowler and Kilsby, 2002, 2004), studies have tended to be based on either single drought events or single regions within the UK. Hisdal et al. (2001) indicated that for the UK there has been a mixed pattern of change in low river flows since the 1960s. A decrease in non-winter precipitation has resulted in an increase in drought severity in areas with limited groundwater storage capacity such as Wales, Scotland and southwest England. Hannaford and Marsh (2006) detected some spatial consistency in recent low-flow trends, with catchments in Wales and western England showing a decreasing frequency but increasing magnitude of low-flows. However, Jones and Lister (1998) indicated that low flows in the 1990s were not historically unusual as more severe events could be identified in the early 20th century.

During the late 1980s and early 1990s, summer droughts were a recurrent outcome of increased hydrologic seasonality (Marsh and Monkhouse, 1993). This culminated in the severe drought of 1995 which affected mainly the north and west of the country (Marsh, 1996). GCMs predict a prominent change in rainfall over the high latitudes of the Northern Hemisphere (Giorgi et al., 2001a,b), with wetter winters and drier summers over the UK (Hulme and Jenkins, 1998; Hulme et al., 2002). This, along with recent patterns of rainfall, evaporative losses and water demands, suggests that the type of water supply stress experienced in 1995–96 may now occur with greater frequency. An extension of these climatic variations and trends will have serious implications for the future management of water resource systems.

In this paper, a multi-model approach is adopted using six Regional Climate Model (RCM) simulations provided by the PRUDENCE project and previously examined on a European scale (Christensen et al., 2007). Here a regional impacts assessment is undertaken for the British Isles by firstly assessing the mean precipitation statistics from the control integration (1961–1990) of each model by comparison with an observed dataset for the same time period. Secondly, estimates of the range of uncertainty in future changes in the mean climate are examined for the SRES A2 emissions scenario for the period 2071–2100 and the role of RCM and GCM selection in that uncertainty discussed. Thirdly, two drought severity measures constructed from monthly precipitation anomalies are used to assess RCM ability to reproduce observed drought frequencies. Future changes in drought frequency, severity and duration are obtained and examined on a model grid cell and regional basis using regions defined by the UK water supply institutions that are responsible for managing water resources. Inter-model comparisons provide the means of assessing model uncertainties in projections of future drought that are essential in the provision of the best tools for policy-makers seeking to make long-term planning decisions.

Data and drought definition

Data

Two observed datasets have been used to examine the mean climate for the control period of 1961–1990. The primary series is the CRU TS 2.0 data set (Mitchell et al., 2004) which is a gridded global series of monthly climate means for the period 1901–2000. The data was constructed by the interpolation of station data onto a 0.5° grid and is an updated version of earlier datasets described in New et al. (1999, 2000). Here, the monthly mean precipitation for 209 grid cells comprising the British Isles (Fig. 1) were used for comparison. This examina-

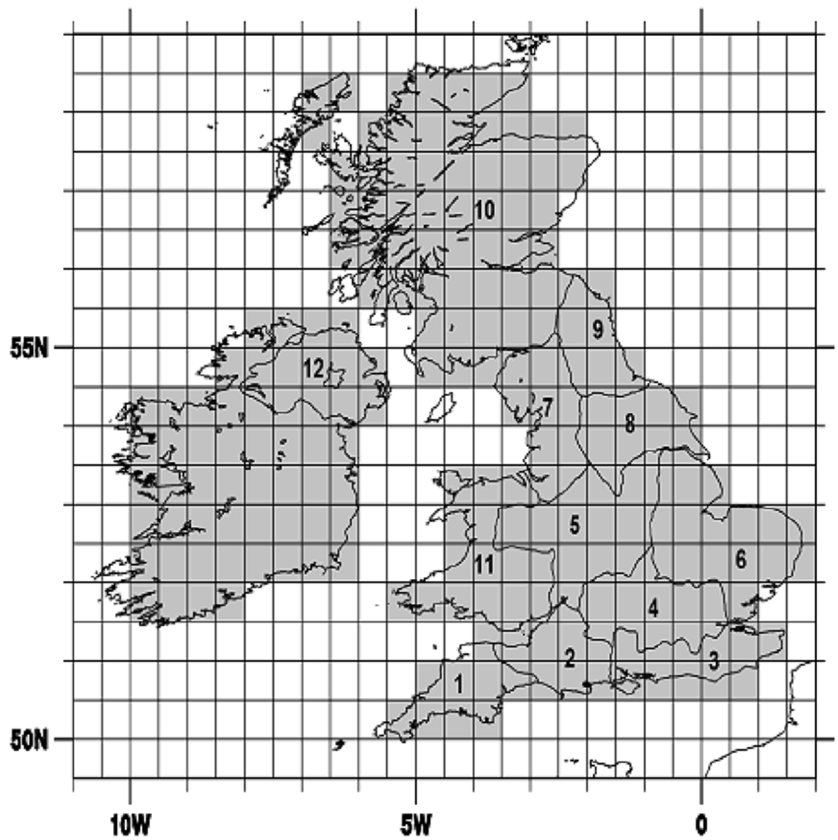

Figure 1 Grid cells and water supply regions used in this study. The regions referred to are: (1) South-West, (2) Wessex, (3) Southern, (4) Thames, (5) Severn Trent, (6) Anglian, (7) United Utilities, (8) Yorkshire, (9) Northumbrian, (10) Scottish, (11) Welsh and (12) Northern Ireland.

Table 1 Selection of PRUDENCE regional climate models used for this study

	RCM	Driving data	PRUDENCE acronym	AquaTerra acronym
Danish Meteorological Institute (DMI)	HIRHAM	HadAM3H	HC1	HIRHAM_H
			HS1	
		ECHAM4/OPYC	ecctrl	HIRHAM_E
			ecscA2	
Swedish Meteorological and Hydrological Institute (SMHI)	RCAO	HadAM3H	HCCTL	RCAO_H
			HCA2	
		ECHAM4/OPYC	MPICTL	RCAO_E
			MPIA2	
Hadley Centre – UK Met Office	HadRM3P	HadAM3P	adeha	HAD_P
			adhfa	
Météo-France, France	Arpège	Observed SST/HadCM3	DA9	ARPEGE_C
			DE6	

The AquaTerra acronyms are adopted here to provide an easier understanding of the format of each model run. The first part of each acronym refers to the RCM and the second to the GCM data used to provide the boundary conditions. The HadRM3P model is run for a total of 31 years (1960–1990 for control and 2070–2100 for the scenario).

tion of simulations of control and future changes in mean precipitation and drought frequency is relevant for a wide range of sectors but for water planning and management purposes it may be more useful to consider the impacts of climate change on drought on a regional scale. Changes in precipitation and related data for the UK are frequently presented in nine regions defined by Wigley et al. (1984) to represent homogenous characteristics of precipitation. However, these regions are not representative of many structures that exist in economic sectors within the UK, for example the water supply sector. Water and sewerage services in England and Wales are provided by 10 private companies, also shown in Fig. 1. Although a number of smaller companies providing water supply-only services operate within a number of regions, these have not been included for simplicity. Water-supply in Scotland is provided by one state-owned company and in Northern Ireland by a state run executive agency. For ease of reference however, these will be referred to collectively as ''companies''. In order to reflect the structure of the UK water industry the projected changes in drought indices have been regionally aggregated up to each of these water resource regions. Such an approach may assist in the incorporation of stakeholder perspectives in assessments of climate change (Kloprogge and van der Sluijs, 2006).

Finally, a daily gridded 5 km precipitation dataset produced by the UK Meteorological Office (Perry and Hollis, 2005a,b) has here been aggregated to the 50 km scale by taking a daily average across the 5km grid boxes contained in the 50 km grid cell. This has been used to enable a comparison with the RCM statistics of the proportion of dry days. These two series will be referred to as CRU and UKMO respectively.

Regional climate model data from the FP5 PRUDENCE project (Christensen et al., 2002) provides a series of high-resolution regional climate change scenarios for a large range of climatic variables for Europe for the period 2071—2100 using RCMs driven by boundary conditions derived from different GCMs. Although it may be infeasible to evaluate climate change impacts arising from every simulation made available by PRUDENCE, it is important to examine a range of models to evaluate the uncertainty of future predictions. Déqué et al. (2007) indicated that for the European domain different RCMs provide a greater range of temperature change than the difference between GCMs and RCMs. Therefore the model selection was made to examine the uncertainty in RCM output due to the bounding GCM versus that due to the choice of RCM. Inter-model differences in precipitation parameters have been shown to be at least as large as the differences between emissions scenarios for a single model (Haylock et al., 2006; Rowell, 2006). The contributions of RCM choice and bounding GCM to the uncertainty in the PRUDENCE simulations is therefore tested by using only the IPCC SRES A2 emissions scenario and using a selection of models which investigate the role of:

- same bounding GCM in combination with different RCMs (e.g. HIRHAM_H v RCAO_H; Table 1),
- same RCM in combination with different bounding GCMs (e.g. HIRHAM_H v HIRHAM_E; Table 1).

A full list of models and their acronyms used in this study is provided in Table 1. Model simulations are available for a control integration (1961—1990) and a future time-slice (2071—2100). Each of these simulations were re-gridded onto a common $0.5° \times 0.5°$ grid (Fig. 1) to allow direct comparison with the CRU series.

Two of the RCM integrations, using HIRHAM and RCAO, were conducted by nesting into the atmosphere-only high-resolution GCM HadAM3H of the UK Hadley Centre.

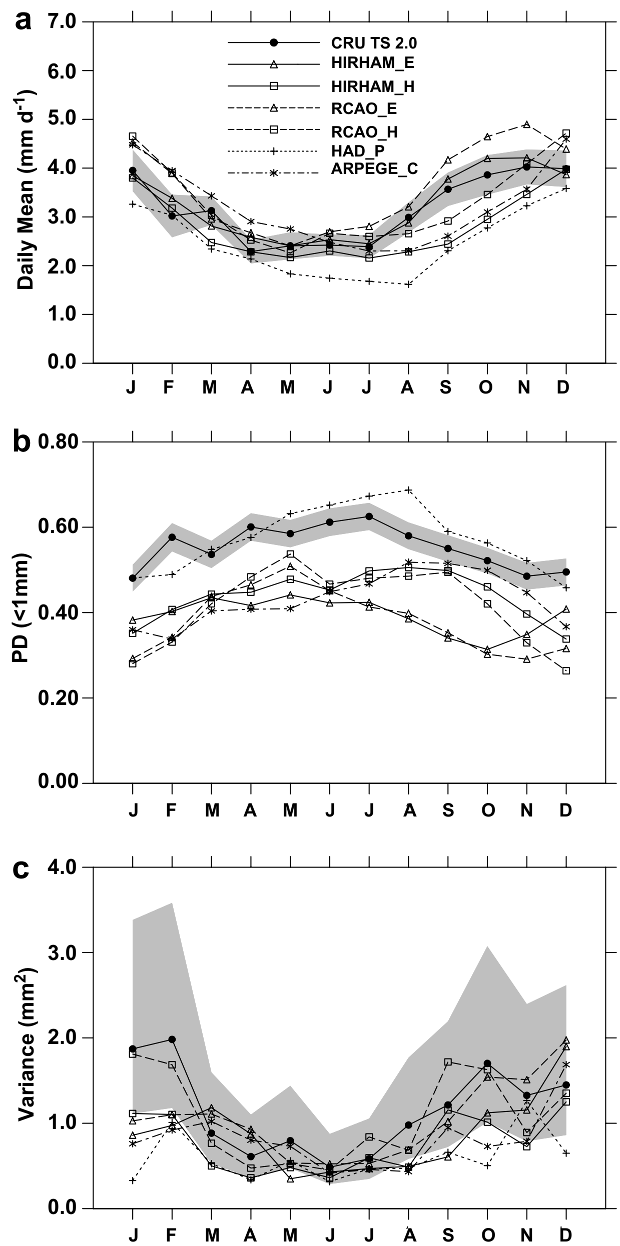

Figure 2 Observed and modelled precipitation statistics for UK grid cells for the control period 1961—90: (a) mean daily precipitation amount, (b) proportion of dry days (<1 mm), and (c) variance of monthly averages of daily precipitation intensity. Shaded areas represent the 95% confidence intervals for the CRU/UKMO statistics.

Additionally, two further RCM integrations, again HIRHAM and RCAO, are driven directly using lateral boundary conditions and sea surface conditions from the ECHAM4/OPYC3 coupled ocean–atmosphere GCM (Roeckner et al., 1996, 1999). These simulations enable the sampling of the dependence of results on the driving GCM. A further RCM simulation, HadRM3P, is nested into HadAM3P, a more recent version of the same atmosphere-only GCM. Finally, the variable resolution global atmospheric model, ARPEGE, with a resolution of 50–70 km over Europe (cf. Hagemann et al., 2004), is nested directly into HadCM3. HadCM3 (Gordon et al., 2000; Johns et al., 2003) is a coupled ocean–atmosphere GCM at a resolution of approximately 300 km from which both HadAM3H and HadAM3P take their boundary conditions. The HadAM3H (Pope et al., 2000) and HadAM3P (Jones et al., 2005) integrations have a resolution of about 150 km in the mid-latitudes. The newer HadAM3P model contains changes to the moisture parameterizations which affect biases observed in parts of the globe outside Europe; therefore HadRM3H and HadRM3P can be considered as essentially the same model for Europe (cf. Haylock et al., 2006).

It should also be noted that as most of the RCMs are run for annual cycles consisting of twelve 30-day months a direct comparison with observed monthly precipitation totals is not possible. The use of monthly totals would include an inherent bias in some months and so to enable a valid comparison between the observed and model data the mean daily precipitation amount averaged over all days was calculated for each month.

Drought definition

No universally accepted classification scheme has been developed to define drought, which may be classified in terms of meteorological, hydrological, agricultural and socio-economic conditions. Drought indices have been developed to reflect these different definitions and form a spectrum from simple indices based on the measurement of rainfall deficits, to more complex hydrological models (Heim, 2002). Two of the key factors in determining drought occurrence and severity are evapotranspiration and precipitation. However, difficulties in obtaining accurate measures of the former suggest that indices based solely on precipitation offer the most potential for a widely applicable, universal drought index. Oladipo (1985) demonstrated that over part of the US precipitation is the most important climatic input into meteorological drought whilst a good agreement between European precipitation changes and trends in droughts has been noted (Hisdal et al., 2001). Although precipitation indices may be inappropriate where temperature-driven meltwater from snow or glaciers provides a significant component of a region's water resources, this is not an important factor for the British Isles. Maracchi (2000) noted 17 drought indices based on only precipitation. The most commonly used of these are the standardised precipitation index (SPI) (McKee et al., 1993) which transforms monthly precipitation time series into a standardised normal distribution, and the drought severity index (DSI) which uses accumulated monthly precipitation anomalies (e.g. Phillips and McGregor, 1998). This index has been previously used to examine UK water resource drought (Fowler and Kilsby, 2002, 2004), and changes projected by the PRUDENCE models on a European scale (Blenkinsop and Fowler, in press).

This study uses two drought severity measures based on the DSI which are calculated using two ''termination rules'' (Goldsmith et al., 1997). The first is based on a 3–6 month drought, more appropriately describing a surface-water drought. The second describes a 6+ month drought, or a water resource drought likely to additionally affect groundwater resources. With recent precipitation deficits resulting in restrictions on the use of water in the UK during the summer of 2006, the companies responsible for the supply of water to domestic and commercial users will face an increasing challenge to maintain supplies; future changes will have important implications for how these companies manage the supply of water. Therefore, changes in the drought indices will be examined by calculating the indices for the areas supplied by each of the water companies shown in Fig. 1.

The monthly precipitation anomaly is defined relative to the 1961–1990 mean, and is used to define two drought indices: DSI3 and DSI6. To illustrate this, the calculation of the 3-month indices is described here. If the precipitation anomaly in month t is denoted as X_t and is negative and the precipitation in the preceding 3-month period i.e. $t-1$, $t-2$, $t-3$ is also lower than its mean, then a drought sequence is initiated. The value of DSI3 is assigned as the positive value proportional to the deficit in month t. Considering month $t+1$, if the precipitation deficit is $-Y$ mm, then DSI3 for month $t+1$ is $X+Y$ provided the mean monthly precipitation total for the preceding 3 months has not been exceeded. If the precipitation anomaly is positive in month $t+1$ then the drought can continue provided the three-monthly mean total has not been exceeded. The termination of a drought occurs when the three-monthly mean total is exceeded, whereupon DSI3 is assigned a value of zero. In order to allow comparisons between sites and regions the DSI values are standardised by dividing the absolute deficit by the site/grid cell mean-annual precipitation, which is then multiplied by -100. Thus the final index value expresses the accumulated precipitation deficit as a percentage of the annual mean total precipitation. DSI6 is calculated in an identical way except that the 6-month mean is used to determine drought termination.

For the UK, two types of drought events have been defined (as Fowler and Kilsby, 2004). DRO3 is a 3–6 month drought with an accumulated deficit exceeding 10% of mean annual rainfall. These events are likely to affect surface water resources and are based on DSI3. DRO6 is a longer drought, lasting at least 6 months, where the accumulated deficit exceeds 30% of mean annual precipitation. Such droughts are likely to affect groundwater resources and are based on DSI6.

Mean precipitation

Control climate

The models broadly simulate the observed annual cycle in the mean daily precipitation amount for the control period over the British Isles (Fig. 2a). The largest variation of monthly averages is during autumn, with a narrower range of results during the remainder of the year. In particular, from April to July most model means are within the 95% confidence limits of the CRU sample mean. HIRHAM_E captures the mean monthly precipitation amount most consistently; its average is within the observed uncertainty bound for most of the year. However, HAD_P significantly underestimates precipitation, particularly during summer and autumn. During most of the year model simulations seem to be influenced by the choice of RCM but during autumn, when precipitation tends to be greatest, the driving GCM provides significant differences; models driven by ECHAM4/OPYC3 GCM (hereafter referred to as ECHAM) overestimate precipitation and those driven by derivatives of the HadCM3 GCM (hereafter referred to as Hadley) underestimate precipitation This suggests a seasonal disparity in

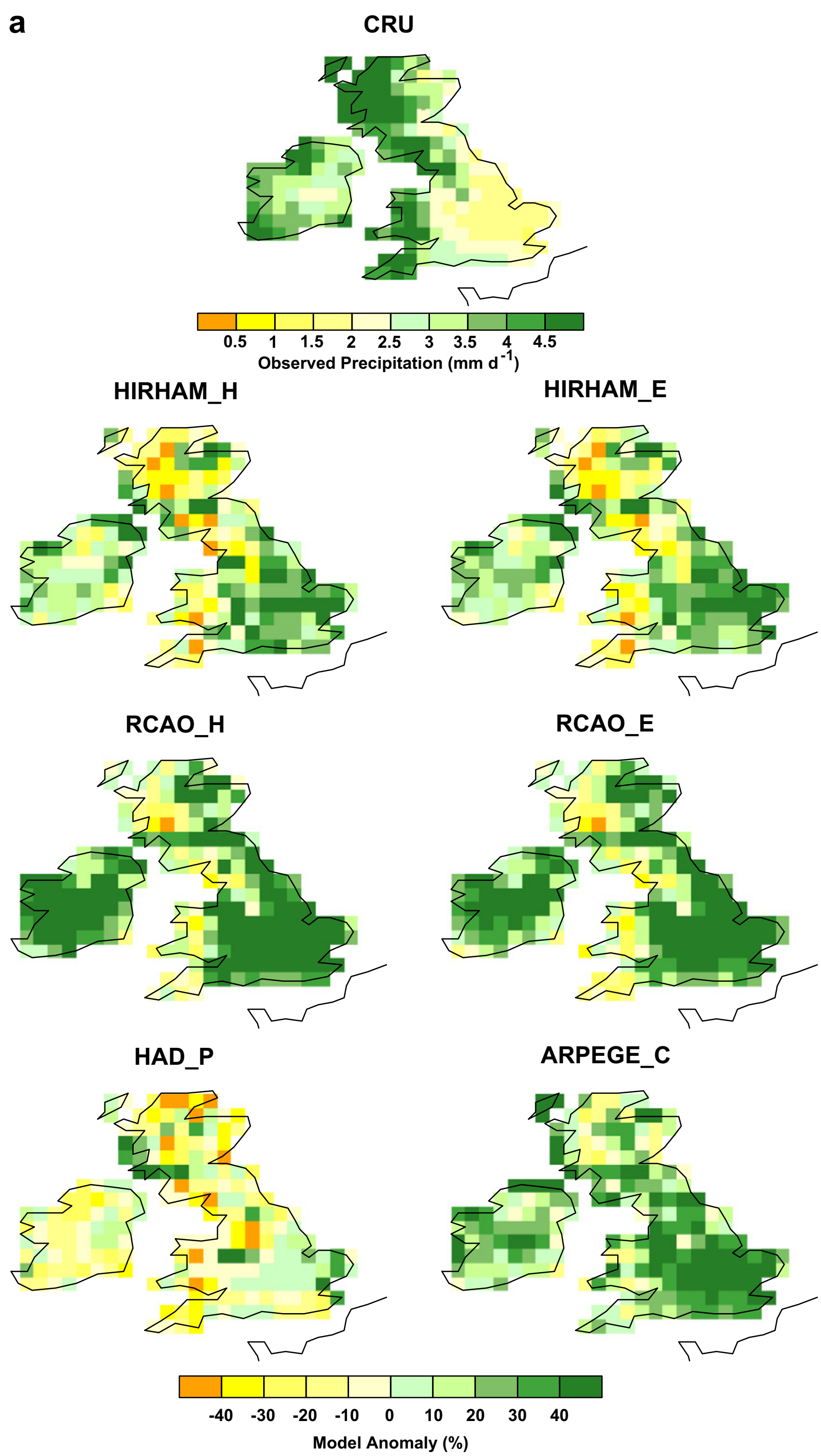

Figure 3 Observed mean (a) winter (DJF) and (b) summer (JJA) daily precipitation for the period 1961—1990 (1960—1990 for HAD_P). Model anomalies are expressed as a percentage deviation from the observed grid cell mean.

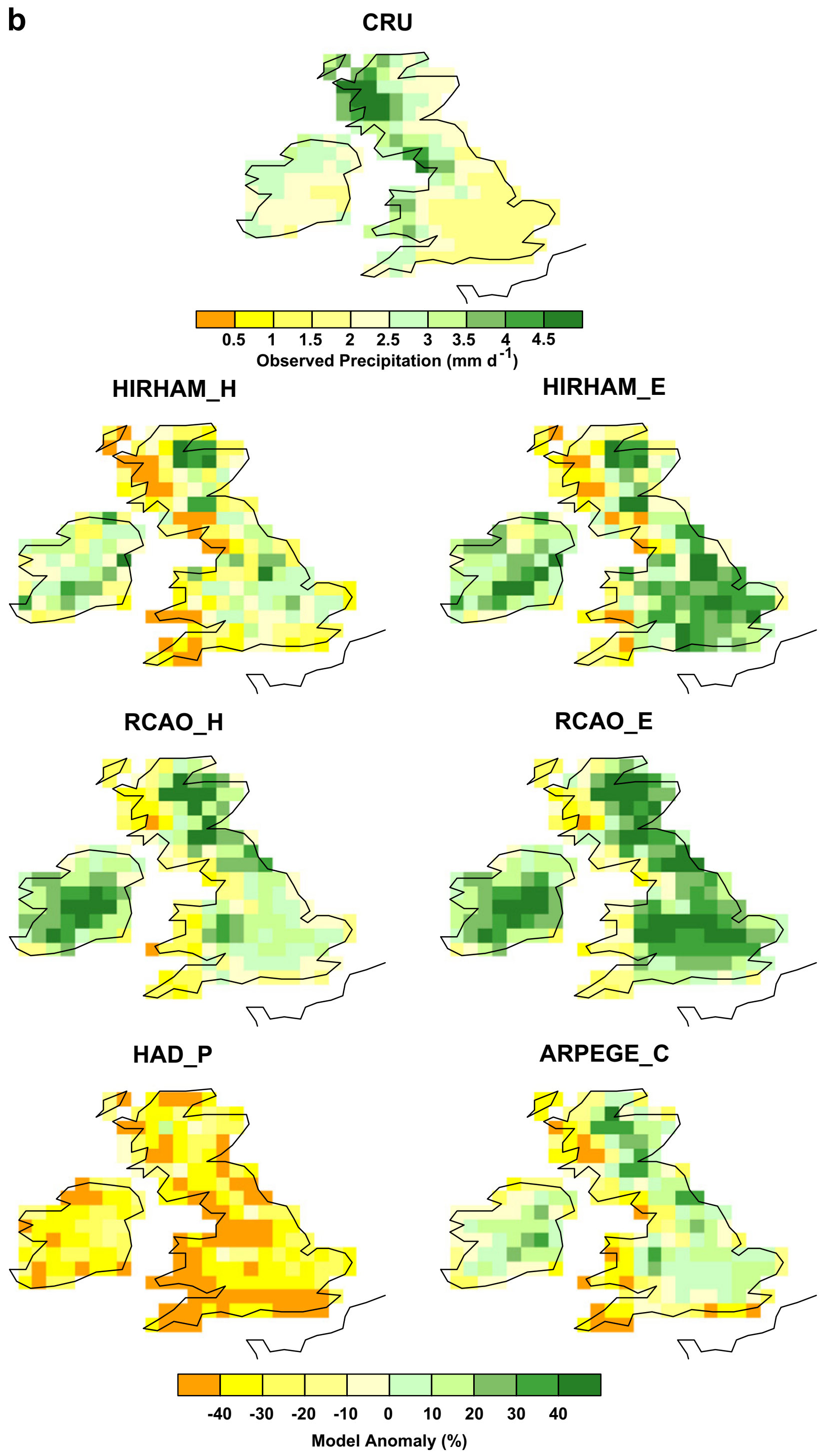

Figure 3 (*continued*)

the models' abilities to capture specific precipitation mechanisms. The proportion of dry days (PD, <1 mm), an indicator of how well models are able to simulate precipitation occurrence processes, was also calculated for each model and compared with those obtained from the UKMO series. The 1 mm threshold is used as lower thresholds may be sensitive to under-recording of low daily rainfall totals and to changes in the units of measurement (Haylock and Goodess, 2004). Fig. 2b shows that for PD the choice of GCM or RCM has a similar influence, with most models underestimating PD throughout the year. However, from July to October the choice of GCM becomes more influential with the ECHAM simulations producing lower estimates of PD. It is interesting to note however, that HAD_P captures precipitation occurrence processes reasonably well despite being poor at reproducing intensity processes.

Model precipitation anomalies are also demonstrated to be spatially variable. Fig. 2a indicates that in January both HIRHAM simulations are skilful in reproducing mean precipitation across the British Isles as a whole. However, Fig. 3a demonstrates that this hides important regional variations which compensate for each other. HIRHAM produces large underestimates over northern and western Britain and overestimates over central and eastern England during winter. RCAO produces similar spatial disparities, although the area of underestimation is smaller and larger positive anomalies are observed in central England, along the east coast and over Ireland. As expected, the HAD_P simulation significantly underestimates precipitation for most of the British Isles with very few grid cells overestimated. This analysis of the spatial distribution of model errors raises important questions as to how the performance of climate models should be assessed. For example, if ARPEGE_C is considered, Fig. 2a suggests that for the British Isles as a whole the model does not perform well in reproducing mean precipitation. However, when examined spatially, Fig. 3 indicates that this is not because errors are large in relation to the other models but because the errors are predominantly of the same sign and overestimates in some grid cells are not compensated for by underestimates in others. Indeed, although the HAD_P simulation considerably underestimates precipitation throughout the year, the lack of a clear spatial pattern to the model anomalies suggests that it may be better at representing the physical processes which produce the observed spatial pattern of rainfall compared with the other models which produce errors with a well-defined spatial structure (Fig. 3a and b).

As a relatively simple means of quantifying these errors, seasonal root mean square error (RMSE) statistics were calculated for each model (Table 2). These indicate that over the British Isles ARPEGE_C performs relatively well throughout the year, producing the lowest errors during winter and spring. HAD_P also performs relatively well over winter but has the largest errors during summer. In contrast, the two RCAO simulations perform best over summer but have the least skill in winter. Regional differences in errors for winter and summer precipitation for three of the UK water company regions are shown in Table 3. These regions have been selected as indicative of the different precipitation regimes that may be observed over the UK. Clear spatial differences in model performance may be observed. For example, over the Anglian Water region HAD_P produces the lowest RMSE statistics for both seasons but performs much less well in the other two regions, particularly that of the northwest England region of United Utilities. Over both the United Utilities and Scottish Water regions ARPEGE_C performs best but in contrast its performance is weaker over the Anglian Water region. The models that perform least well also differ between regions. The RCAO simulations for winter are relatively poor for Anglian Water whereas for Scottish Water, the HIRHAM simulations are the least skilful. During summer, HIRHAM_E is relatively poor for Anglian Water but HIRHAM_H and HAD_P perform less well over the other regions.

Fig. 2c indicates the large range in model skill in reproducing the inter-annual variability of monthly mean precipitation. Most models underestimate the variance in monthly precipitation throughout the year with this error derived from the choice of both RCM and driving GCM. In terms of the geographical distribution of the model errors, there is a degree of consistency between the models (not shown). During the wet months of autumn and winter models produce large underestimates of variance over western Britain and most of Ireland but during the drier summer months this area is confined to northwestern Scotland.

Table 2 Seasonal RMSE statistics for mean daily precipitation rate (mm/day) for the control integrations of each RCM

	HIRHAM_H	HIRHAM_E	RCAO_H	RCAO_E	HAD_P	ARPEGE_C
Winter (DJF)	1.23	1.21	1.37	1.31	1.13	1.13
Spring (MAM)	1.00	0.85	0.76	0.79	0.90	0.74
Summer (JJA)	0.95	0.84	0.76	0.80	1.16	0.84
Autumn (SON)	1.69	1.26	1.42	1.41	1.60	1.32

Table 3 Winter and summer RMSE statistics for mean daily precipitation rate (mm/day) for the control integrations of each RCM, calculated for the regions of three UK water companies

	HIRHAM_H	HIRHAM_E	RCAO_H	RCAO_E	HAD_P	ARPEGE_C
Anglian Water						
Winter (DJF)	0.52	0.91	0.97	1.28	0.30	0.64
Summer (JJA)	0.20	0.59	0.27	0.45	0.18	0.44
United Utilities						
Winter (DJF)	1.69	1.72	1.49	1.56	1.99	1.40
Summer (JJA)	1.88	1.55	1.42	1.48	1.88	1.09
Scottish Water						
Winter (DJF)	1.93	1.95	1.47	1.61	1.73	1.39
Summer (JJA)	2.19	1.78	1.55	1.65	1.97	0.93

Future scenario

Under the SRES A2 scenario, all models project precipitation increases in winter and most of autumn (Fig. 4a). The percentage increase peaks in December and January, with the smallest change in spring, and decreases from June to September. Evidence for similar change to the seasonal distribution of UK precipitation has already been detected in observed precipitation series (e.g. Osborn et al., 2000; Osborn and Hulme, 2002). There is no clear distinction between the choice of RCM or driving GCM for the source of uncertainty in future change. Fig. 4b shows that changes

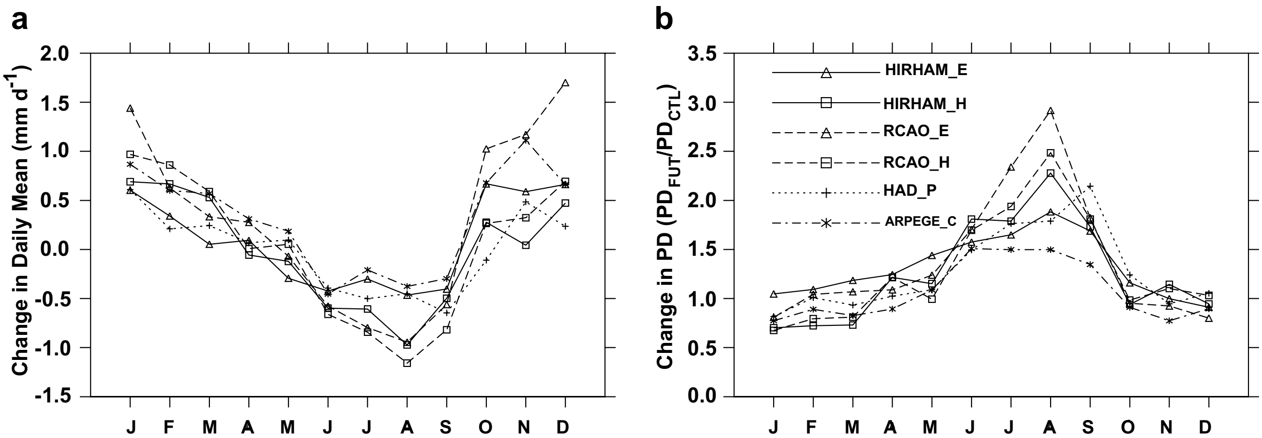

Figure 4 Modelled changes in (a) mean daily precipitation and (b) proportion of dry days for the British Isles for the period 2071—2100 (2070—2100 for HAD_P) from the control period 1961—1990. Change in the proportion of dry days is presented as a factor representing the scenario proportion as a multiple of the control proportion, values less than 1 denoting a decrease.

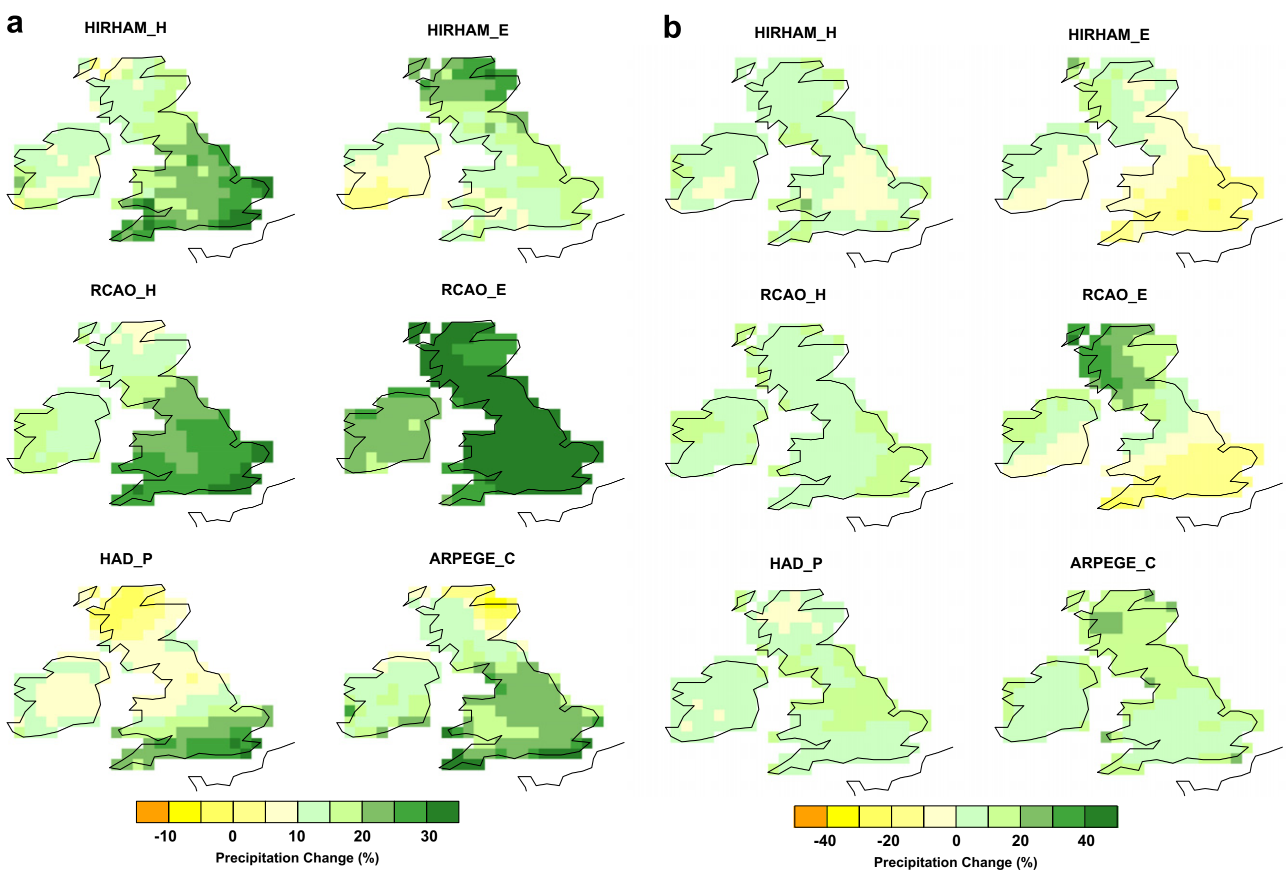

Figure 5 Projected change in mean (a) winter (DJF) and (b) spring (MAM) daily precipitation amount for the SRES A2 scenario expressed as a percentage change from the control period. Projected change in mean (c) summer (JJA) and (d) autumn (SON) daily precipitation amount for the SRES A2 scenario expressed as a percentage change from the control period. Note different seasonal scales are used.

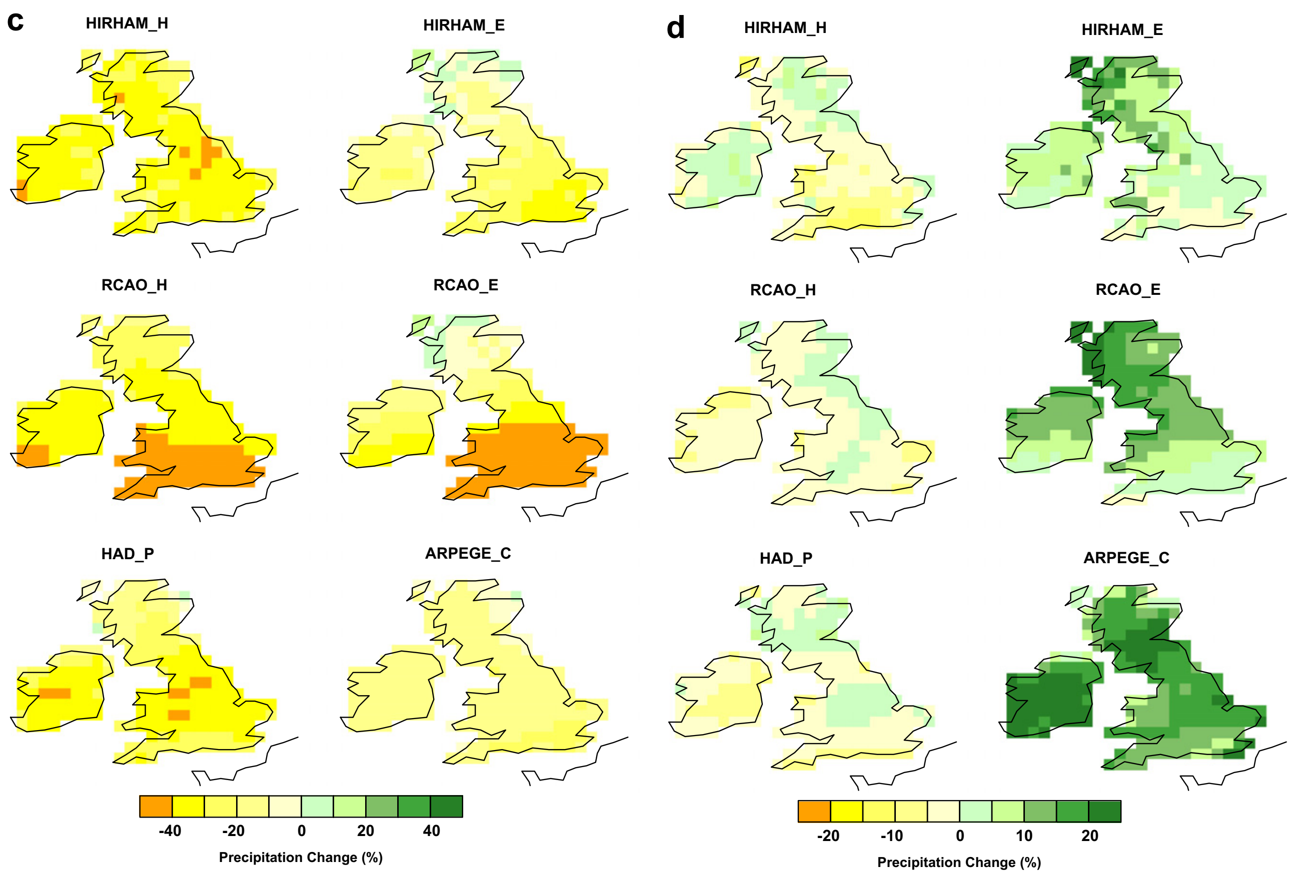

Figure 5 (*continued*)

in mean precipitation are at least in part explained by changes in PD, with summer decreases in precipitation coupled to increases in PD for all models. Increases in PD are largest in months showing the greatest decrease in mean precipitation and during the summer months are greatest for the RCAO simulations. For most models part of the increase in the mean precipitation during winter is explained by a decrease in PD, particularly for HIRHAM_H and RCAO_H.

Examining the spatial distribution of change reveals that in winter Hadley-driven models project a gradient of increased precipitation, largest over southern England and smallest over northern Scotland (Fig. 5a). This would reduce the current northwest—southeast gradient of winter precipitation. A very different pattern of change is predicted by the ECHAM-driven models. HIRHAM_E predicts a gradient of change that is the reverse of the Hadley-driven models with the largest percentage increases over northern Scotland, whilst RCAO_E suggests a uniform pattern of large increases across the British Isles. The ECHAM-driven models also project distinct patterns of change during spring (Fig. 5b) with increases over Scotland and northern England and decreases over southern regions.

As was observed for the control period, the regional average may mask important spatial differences. In summer, the driving GCM is an important source of uncertainty. For example, although the projected average change in precipitation over the British Isles for summer is similar for the two RCAO simulations, Fig. 5c indicates that the ECHAM-driven simulation produces a stronger north—south gradient of change. The Hadley-driven models project decreases of at least 30% across much of the British Isles with the largest decreases generally in the south though with a much weaker north—south gradient of change, whilst for autumn (Fig. 5d) the decreases are more moderate and contrast with the increases projected by the ECHAM-driven models and ARPEGE.

The predicted change in inter-annual variability is very complex with no model showing consistent seasonal patterns of change (not shown). This makes it impossible to establish likely changes in variability on a regional scale. Spatial patterns of change are variable from month to month. For example, ARPEGE_C predicts decreased variability in December rainfall over all grid cells except those for eastern Scotland but in January predicts increased variability for most regions. This represents a particular problem for managers in the water industry for whom variability in precipitation is important.

Drought

Control climate

The RCMs are unable to reproduce the observed patterns of DRO3 and DRO6 (Fig. 6a and b). For DRO3 in particular

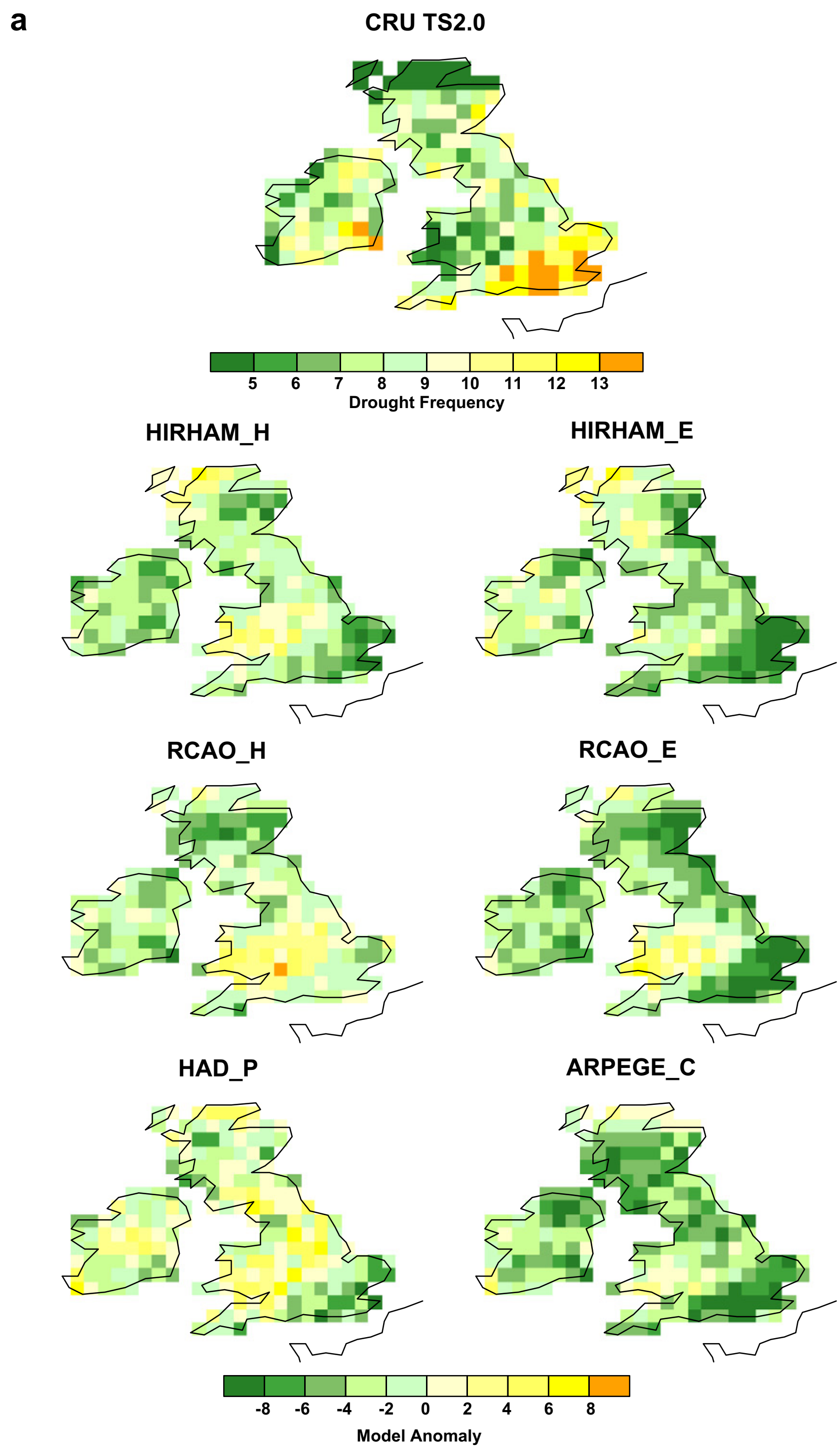

Figure 6 Observed frequency of (a) DRO3 and (b) DRO6 events (CRU) for the period 1961—1990 and absolute anomaly simulated by each RCM.

they fail to simulate the higher frequency of droughts in the southeast relative to western England, Scotland and Ireland (Fig. 6a). Most models underestimate drought occurrence by at least six events for a substantial part of south-east England, and some models produce similar anomalies for eastern England and Scotland. Positive anomalies, overestimation of drought occurrence by at least three events, are found most frequently in Wales and central England although ARPEGE_C underestimates drought frequency for all but a few grid cells. As all models underestimate the variability of precipitation, they are consequently unable to build up the accumulated deficits necessary to reproduce the observed frequency of DRO3 events for the British Isles.

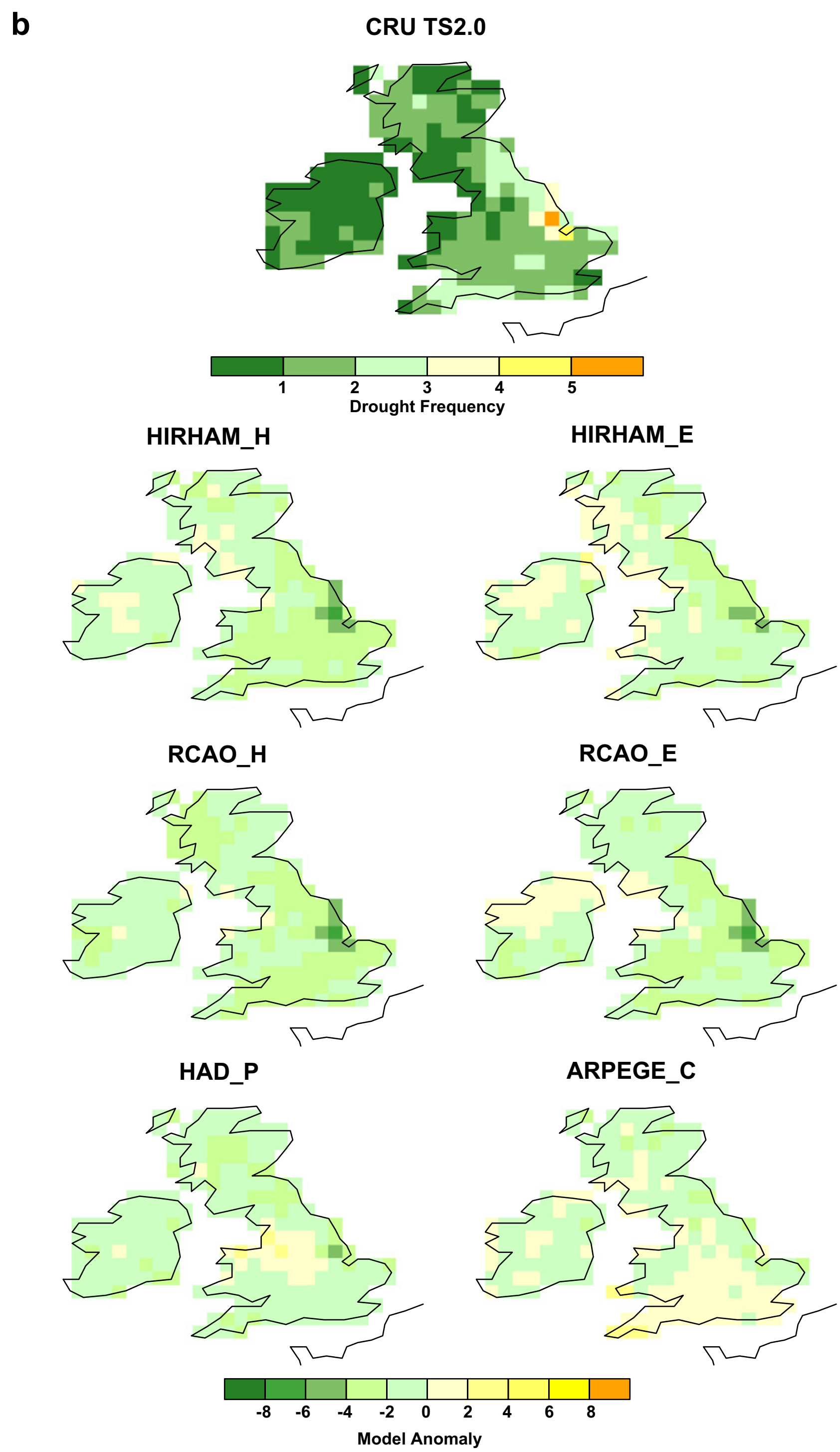

Figure 6 (*continued*)

RMSE statistics calculated for both DRO3 and DRO6 (Table 4) indicate that for the whole domain, simulations driven by HadAM3 (HIRHAM_H, RCAO_H and HAD_P) produce the lowest errors in DRO3 but not in DRO6 whilst ARPEGE_C, despite having relatively high skill in reproducing mean precipitation, produces relatively large errors in DRO3. For DRO6, the two RCAO simulations produce the largest errors, with relatively small differences between the other models. By region, the HadAM3-driven simulations clearly outperform the others in reproducing the frequency of DRO3 events over the Anglian and Scottish Water regions but there is less difference between the models over the United Utilities region. In contrast, for DRO6, ARPEGE_C produces the lowest errors over the Anglian and Scottish Water regions. Despite producing relatively good results for DRO3 over the Anglian Water region, HIRHAM_H and RCAO_H both

Table 4 RMSE statistics for DRO3 and DRO6 frequency for the control integrations of each RCM, calculated for the whole of the British Isles and for the regions of three UK water companies

	HIRHAM_H	HIRHAM_E	RCAO_H	RCAO_E	HAD_P	ARPEGE_C
British Isles						
DRO3	0.40	0.50	0.37	0.54	0.41	0.55
DRO6	0.18	0.15	0.20	0.19	0.14	0.14
Anglian Water						
DRO3	4.48	6.34	3.08	5.87	3.84	5.18
DRO6	3	2.15	2.84	2.92	1.81	1.46
United Utilities						
DRO3	2.71	2.94	2.65	2.56	3.04	3.83
DRO6	1.16	1.16	1.45	1.00	1.89	1.29
Scottish Water						
DRO3	3.47	4.20	3.79	5.01	3.08	4.99
DRO6	1.02	1.12	1.46	1.04	1.25	0.91

produce large errors in DRO6 over this area (see also Fig. 6b). Stated simply, the relative skill of the models is not only sensitive to the time of year and to the spatial domain but also to the climatic parameter being examined.

Future change

Drought indices DRO3 and DRO6 were recalculated using RCM simulations for the 2071—2100 SRES A2 scenario and indicate that three clear modes of change are projected for DRO3 droughts (Fig. 7a). Hadley-driven RCMs project increases in drought frequency over most of the British Isles, with the largest increases produced by HIRHAM_H and RCAO_H. The ECHAM-driven models, however, project a clear north—south gradient of change with a decrease in drought occurrence in Scotland, northwest England and Ireland, but increases over England and Wales. ARPEGE_C projects more modest changes, with decreases in drought frequency along the west coast of England and in Wales but large increases projected for southern England.

For DRO6 droughts, similar patterns of change to DRO3 are projected by the ECHAM-driven models but the other models project different patterns (Fig. 7b). HIRHAM_H projects small changes in longer duration droughts, with increases in central England and decreases in Scotland and southwest England. Both RCAO_H and HAD_P project increases in drought frequency in Scotland and decreases over England whilst ARPEGE_C projects decreases in DRO6 drought occurrence for all grid cells. Future projected decreases in the occurrence of longer duration droughts are likely to be related to the projected increase in mean winter precipitation which recharges water supplies, breaking the sequence of drought by exceeding the six-monthly mean precipitation. Since all models suggest an increase in winter precipitation across the British Isles under the SRES A2 scenario (Fig. 5a) it would be expected that all models might predict decreases in DRO6. However, in some models the projected winter increase in precipitation is more than offset by the summer decrease in precipitation which extends through spring and autumn in some regions. It is thus the seasonal balance of precipitation changes within individual simulations that determine whether drought frequency will increase or decrease in a particular region, most notably the divergent patterns of change projected by the simulations during spring and autumn.

Changes in the drought indices have also been examined after aggregation up to the regional level of the UK water companies (Figs. 8 and 9). Fig. 8a indicates that although there is uncertainty as to the magnitude of change, almost all water supply regions are likely to experience an increase in DRO3 frequency for RCAO_E of over 15 extra events in the case of Anglian Water. Only Scottish, Northern Ireland and South-West Water are projected to experience fewer events by any of the models. In water resource terms this will present a need for water companies to manage the change in the seasonal supply of water to ensure that supplies are adequate when surface water supplies are not being replenished. The use of a multi-model approach also gives an indication of the uncertainty associated with the use of individual climate models in impact studies; the range of projected change for the Scottish Water region, for example is from an additional six events (HIRHAM_H) to six fewer (HIRHAM_E) (Table 5) in the future scenario. Even where there is agreement to the direction of change there is uncertainty as to the magnitude, for instance within the Anglian Water region projected increases range from an additional 15 events (RCAO_E) to only two (HIRHAM_E).

Fig. 8b demonstrates that for DRO6 events projected changes are generally small in magnitude. For all regions except United Utilities there is uncertainty as to the sign of the change in these events and it is evident that the most uncertainty in future projections from the RCMs is for the south of England. The largest increases of more than three additional events are for South-West, Thames and Southern Water by the two ECHAM-driven models. This may be attributable to the projected increase in winter precipitation being more than offset by the summer decrease over southern Britain with decreases also projected during spring and autumn. Although in general winters will be wetter, occasional dry winters will still occur which will allow longer droughts to develop and produce the type of event experienced during 2006 in southern Britain. The uncertainty in the future occurrence of DRO6 events means that companies in the south of England are likely to face the most difficult challenges in the long-term planning of water

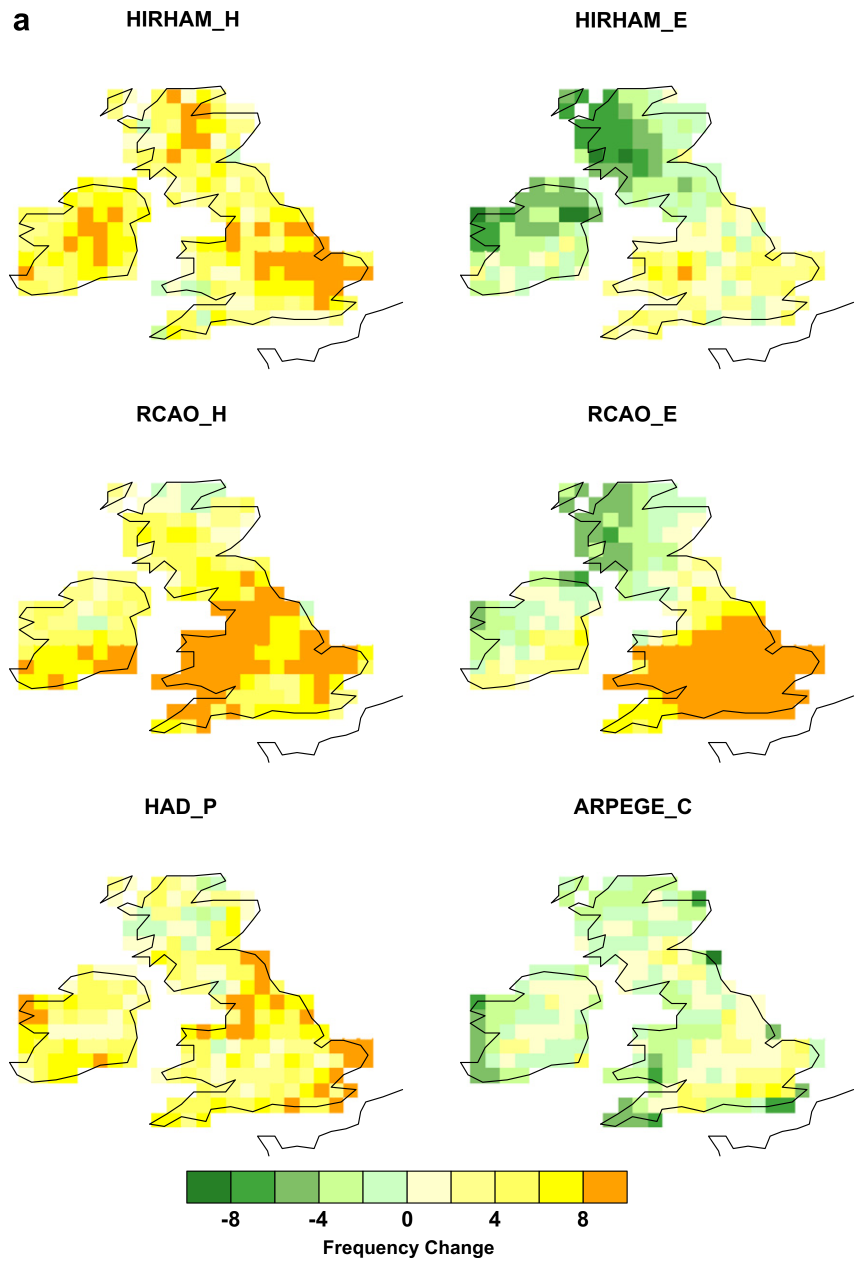

Figure 7 Change in the frequency of (a) DRO3 and (b) DRO6 events between the period 1961–1990 and 2071–2100 for the SRES A2 scenario.

resources. The development of a probabilistic climate change scenario which weights individual models on the basis of their skill in reproducing the observed climate may help to incorporate this uncertainty in a way which better aids decision-making.

The maximum severity of DRO6 events is likely to decrease in most regions (Fig. 9a) due to projected increases in winter precipitation although the largest possible increases in drought severity are projected for Anglian and Severn Trent Water, with Yorkshire Water also projected to experience more severe droughts by one model. Changes in the severity of both DRO3 and DRO6 events (Table 6) indicate that, notwithstanding the uncertainties already discussed, many UK water suppliers may need to plan for more intense short-term droughts but less severe longer duration events.

Decreases in the maximum duration of drought events are also projected by most models although there are uncertainties which encompass the direction of projected change. For example, RCAO_E and RCAO_H indicate large changes of opposite signs for Scottish Water (Fig. 9b) and at least one model projects an increase in the maximum drought length for each company. However, the unweighted model average (not shown) suggests that all regions are likely to experience a decrease in the maximum duration of DRO6 droughts.

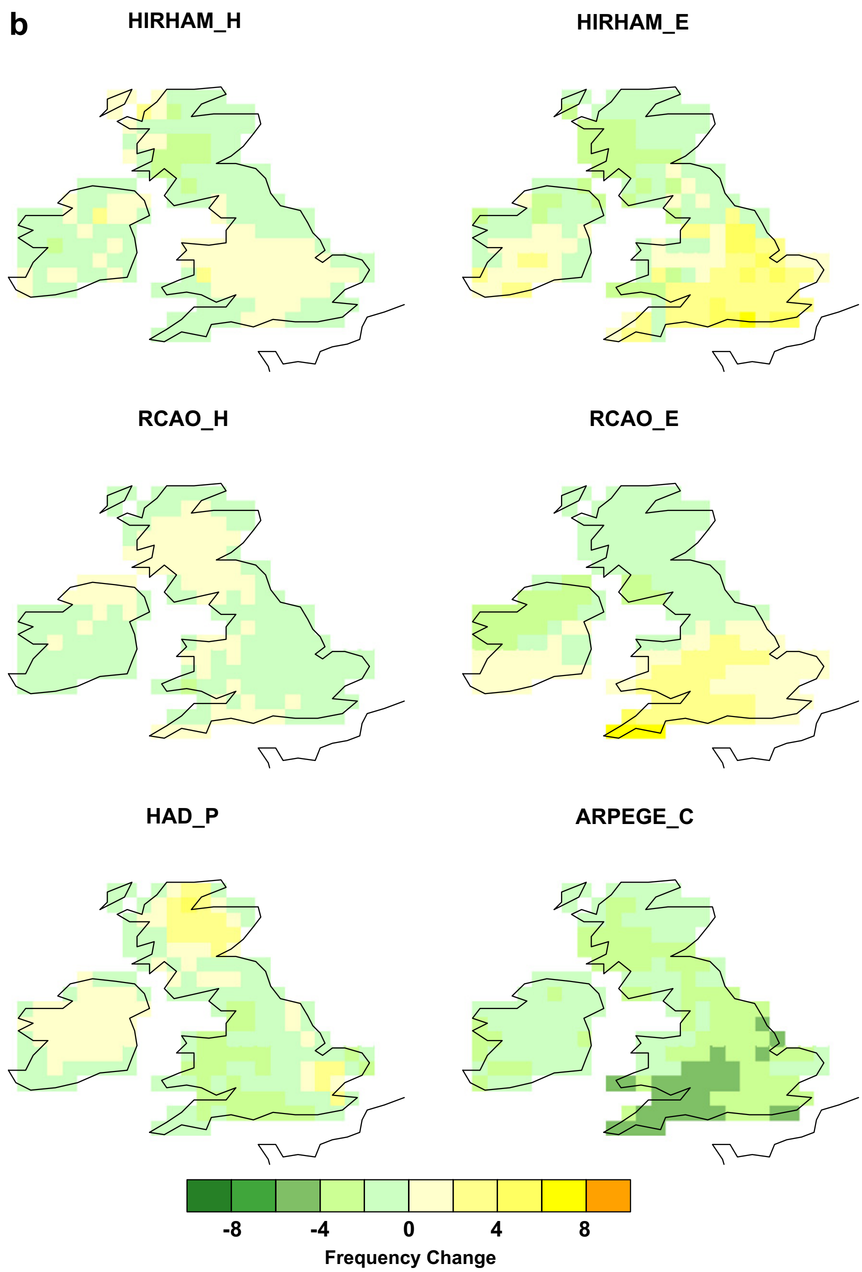

Figure 7 (*continued*)

Discussion and conclusions

A selection of six regional climate models from the set of PRUDENCE experiments were used to assess the ability of each model to accurately reproduce observed climate statistics for the 1961—1990 control period. All models reproduce the form of the annual cycle of precipitation when grid cells are averaged over the British Isles, with HIRHAM_E performing best and HAD_P notably underestimating precipitation totals throughout the year. However, the spatial distribution of model precipitation anomalies indicates that the models may have difficulty in capturing important physical processes that are responsible for precipitation. The choice of RCM is an important factor in contributing to this spatial component of model errors. This uncertainty is likely due to model parameterization within RCMs, particularly during summer when the climate is more strongly controlled by parameterized physics (Déqué et al., 2005) due to weaker flows from lateral boundary conditions (Rowell, 2006).

Future projections of change in mean precipitation indicate an increase during winter months with decreases during summer. However, during the summer in Scotland and northern England there is uncertainty as to the sign of change with three models indicating small increases in precipitation. The driving GCM may be an important influence

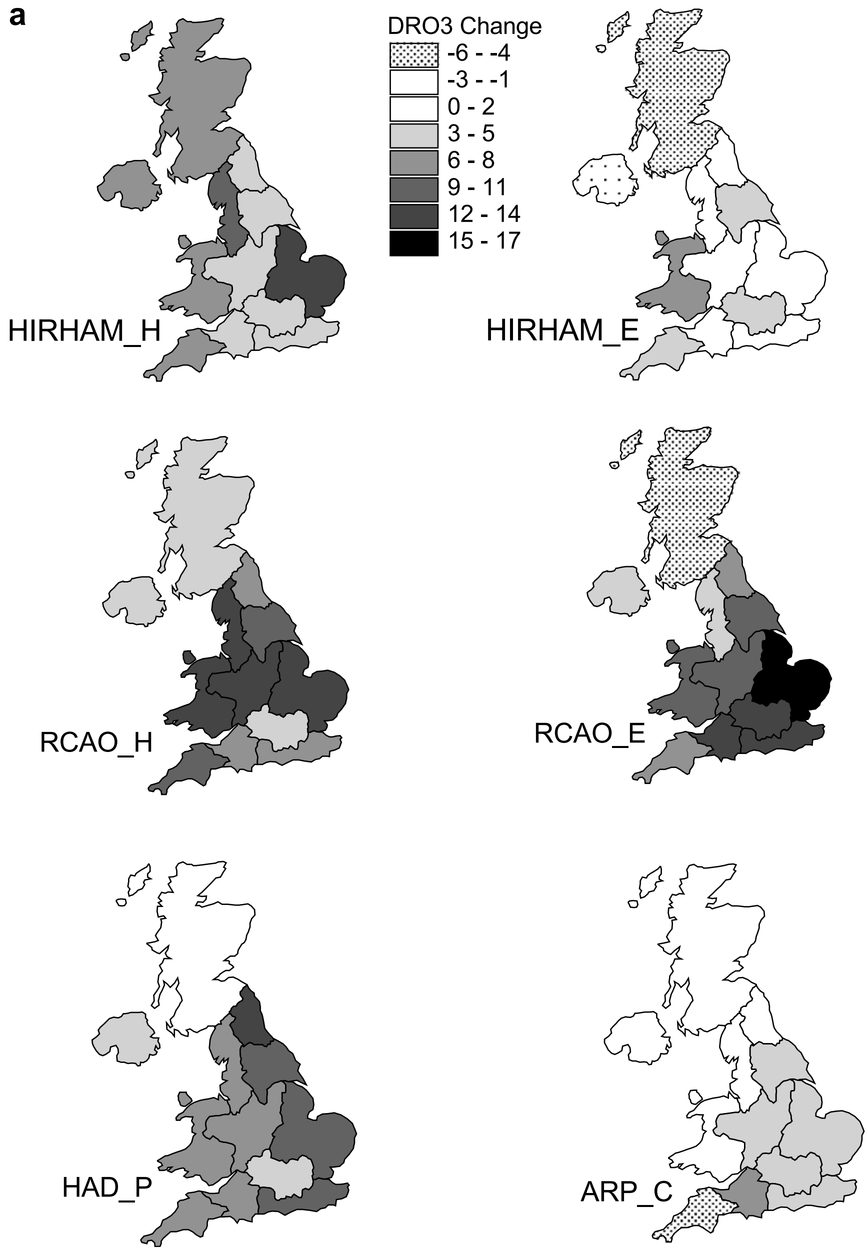

Figure 8 Change in the frequency of (a) DRO3 and (b) DRO6 events between the period 1961–1990 and 2071–2100 for the SRES A2 scenario for each of the UK water company regions.

on this with none of the Hadley-driven simulations predicting increases over these areas. Large positive anomalies have been found in wintertime precipitation in RCM control simulations driven by HadAM3H which is thought to be due to a positive bias in the north–south pressure gradient over Europe. This produces increased eastward advection of water vapour (Räisänen et al., 2004; van den Hurk et al., 2005). This indicates one possible source of uncertainty arising from GCM selection, however the partitioning of specific mechanisms within the models (e.g. Rowell and Jones, 2006) would be required to attribute specific deficiencies in model parameterization to errors in simulations.

This study has indicated that the uncertainty in future projections resulting from the choice of GCM or RCM varies with the variable being examined, the time of year and the spatial resolution. For precipitation, the RCM strongly influences the simulated average statistics across the British Isles in most seasons but during autumn it is the GCM driving the regional models that has the largest influence. However, if the spatial pattern of anomalies is also considered, the distribution of errors in summer precipitation can also be seen to be influenced by the driving GCM.

It is clear therefore that if models are to be quantitatively assessed and weighted for use in the production of probabilistic climate change scenarios, the choice of criteria on which to apply the weights is not a trivial one. Using a relatively simple statistic such as RMSE has highlighted that it is impossible to designate a ''best model'' as their

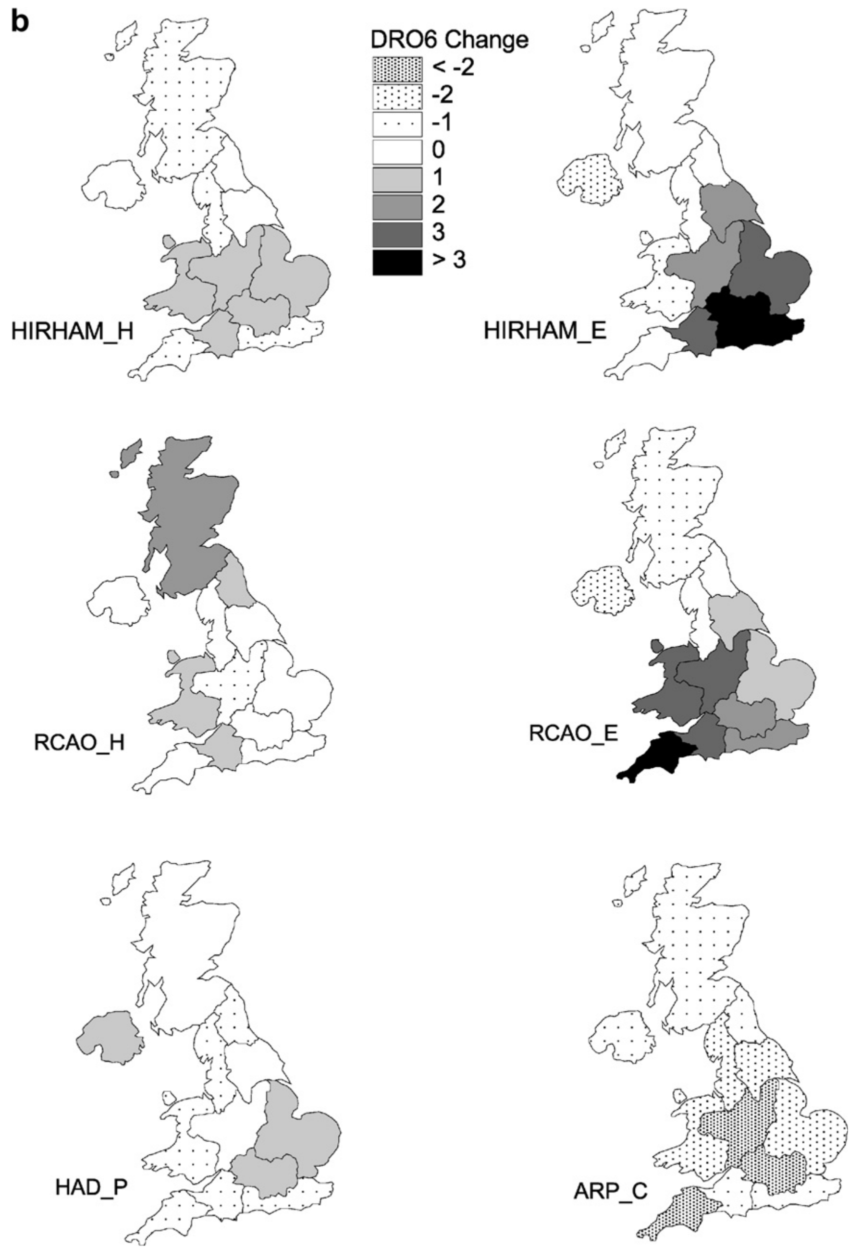

Figure 8 (*continued*)

simulation skill for even mean precipitation varies both temporally and spatially. Such a statistic might form the basis by which model skill can be quantitatively measured and used as a basis for weighting their relative contributions to probabilistic scenarios of change. However, models which perform relatively well for the mean do not necessarily perform well at reproducing the observed occurrence of related impacts such as drought. Important issues therefore remain unresolved as to how such models should be assessed.

A measure such as RMSE may not be appropriate for all impacts studies given that within-region differences are likely to be important for some impacts of climate change. It may be more appropriate to assess how well models reflect the spatial characteristics of climate. The examination of mean precipitation indicated that large opposing errors in different regions are apparent in some models, indicating potential weaknesses in capturing important precipitation processes for the British Isles. Statistical methods such as pattern correlation might offer potential for weighting schemes where the spatial distribution of model errors is important for the impact in question, for example, for hydrological modelling of a large catchment. These methods have been widely used in climate change detection and attribution studies (e.g. Santer et al., 1995). In this regard climate models should be ''fit for purpose''. For example, here it has been demonstrated that the spatial distribution of model errors for the drought indices is very different from that for the model simulation of mean precipitation. Any impacts study should therefore clearly select a climate model carefully or preferably adopt a multi-model approach which will allow the assess-

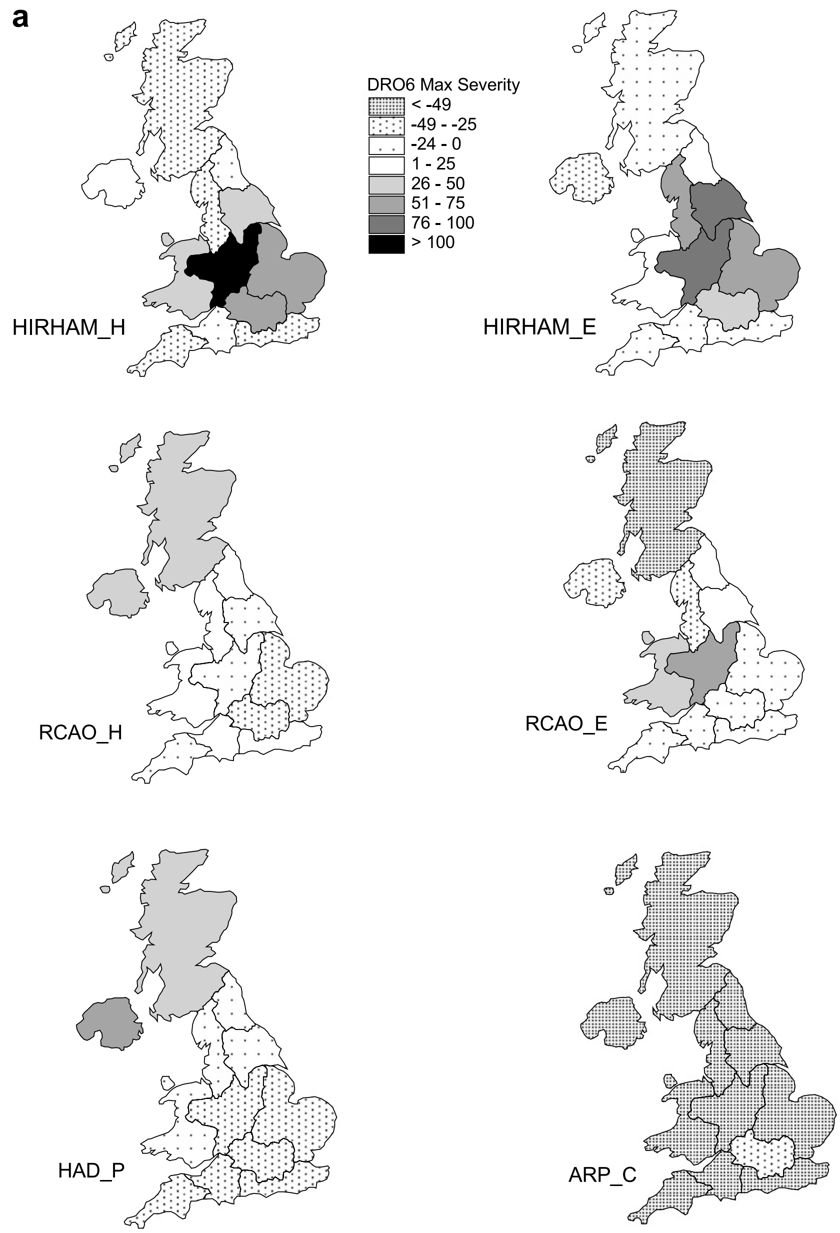

Figure 9 Change in the (a) maximum severity (expressed as a percentage change from control period) and (b) maximum duration of DRO6 events (expressed as an absolute change in months). Changes are between the period 1961—1990 and 2071—2100 for the SRES A2 scenario.

ment of uncertainty based upon the key climate parameters.

To reflect this need, changes in drought occurrence have been examined for each of the climate models. The use of a drought index based on monthly precipitation anomalies offers the advantage of relative simplicity of calculation and data requirements. Increased frequencies of short-duration droughts, likely to affect surface water resources are expected to increase over most of the UK, with some uncertainty as to the sign of change over Scotland and northern England. Longer events are likely to become less frequent over most of Britain although more frequent drought events are projected for southern Britain by the ECHAM-driven models. Consequently, when results are considered on a regional basis for the UK water supply companies some models project more than 3 additional long droughts over the period 2071—2100 for companies in the south of England and these could be more severe than current events. The fact that potential increases in long-duration droughts are projected by some models in the regions that are more reliant on groundwater resources represents potentially serious challenges for the companies concerned. However the study has emphasised that the range of uncertainty for most regions encompasses the direction of future change for these types of drought events.

As well as noting the uncertainty in future projections, the drought index employed here does not take into account

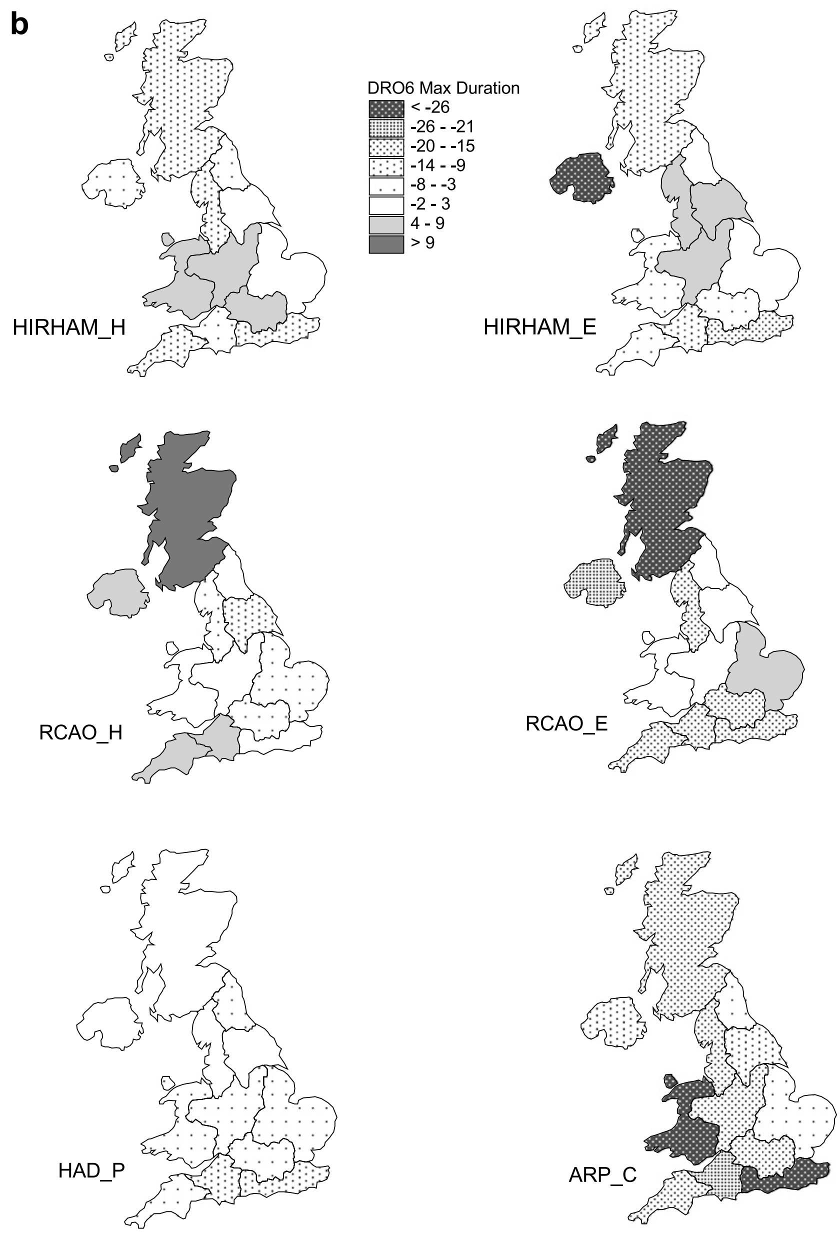

Figure 9 (*continued*)

other features of a changed climate which could impact on drought occurrence. In particular, the index does not reflect changes in evapotranspiration which would arise with temperature change. The projected change in mean temperatures from the control period for the SRES A2 emissions scenario for the period 2071—2100 (Fig. 10) indicate that the average increase in temperature across the British Isles ranges from 1.5 °C in February (HAD_P) to 4.9 °C in August (RCAO_H). For most models, the projected increase is largest in the months from July to September and smallest in winter and spring. With the exception of HIRHAM_E, all models predict the largest increases for south-east England, decreasing towards north-west Scotland, with this gradient of warming strongest in summer months. Such changes and their associated uncertainties would thus have an effect on evapotranspiration rates which are implicitly assumed to be stationary by the DSI.

The DSI also makes no account for potential changes in the temporal distribution of precipitation events. Under enhanced greenhouse conditions it is predicted that the frequency and magnitude of extreme precipitation events will increase (Ekström et al., 2005) and GCM integrations have indicated that convective/frontal precipitation ratios will increase (Hennessy et al., 1997). It is feasible therefore that some of the increase in precipitation or even an increased proportion of existing precipitation may be provided by events which result in overland flow of surface water and will not be effective in the recharge of groundwater aquifers. Therefore, the assumption of a stationary hydrometeorological process is questionable in the calculation of precipitation-based drought indices.

However, even using a simple drought index, all models produce large errors in simulating the frequency of drought events for the control climate. The continuation of a

Table 5 Change in the frequency of DRO3 and DRO6 droughts for each of the UK regional water institutions from the period 1961–1990 to 2071–2100

	HIRHAM_H		HIRHAM_E		RCAO_H		RCAO_E		HAD_P		ARPEGE_C	
	DRO3	DRO6	DRO3	DRO6	DRO3	DRO6	DRO3	DRO6	DRO3	DRO6	DRO3	DRO6
South West Water	6	−1	4	0	9	0	7	4	7	−1	−4	−4
Wessex Water	4	1	2	3	7	1	13	3	6	−1	8	−4
Southern Water	4	−1	1	5	7	0	13	2	9	−1	3	−3
Thames Water	5	1	3	4	3	0	13	2	4	1	4	−3
Severn Trent Water	5	1	0	2	12	−1	11	3	7	0	5	−3
Anglian Water	12	1	2	3	13	0	15	1	10	1	5	−2
United Utilities Water	11	−1	0	0	13	0	3	0	8	−1	0	−2
Yorkshire Water	5	0	3	2	10	0	11	1	11	0	3	−2
Northumbrian Water	4	0	0	0	7	1	6	0	14	−1	1	−1
Scottish Water	6	−1	−6	0	5	2	−4	−1	2	0	1	−1
Welsh Dwr Cymru Water	7	1	7	−1	12	1	9	3	6	−1	0	−2
Northern Ireland Water	7	0	−2	−2	4	0	4	−2	5	1	2	−1

Changes in are expressed as absolute changes in frequencies.

Table 6 Change in the maximum severity of DRO3 and DRO6 droughts for each of the UK regional water institutions from the period 1961–1990 to 2071–2100

	HIRHAM_H		HIRHAM_E		RCAO_H		RCAO_E		HAD_P		ARPEGE_C	
	DRO3 (Δ%)	DRO6 (Δ%)	DRO3 (Δ%)	DRO6 (Δ%)	DRO3 (Δ%)	DRO6 (Δ%)	DRO3 (Δ%)	DRO6 (Δ%)	DRO3 (Δ%)	DRO6 (Δ%)	DRO3 (Δ%)	DRO6 (Δ%)
South West Water	−32	−34	31	−9	−17	0	43	−18	−22	−44	−42	−56
Wessex Water	22	−8	−30	−4	−14	24	46	−16	−16	−34	−32	−57
Southern Water	−13	−36	119	−7	11	8	50	−21	−31	−38	−54	−65
Thames Water	75	62	120	26	−15	−26	68	−13	−2	−33	−36	−43
Severn Trent Water	118	110	188	92	−19	−5	83	60	15	−25	−31	−51
Anglian Water	67	56	99	62	−26	−30	77	−7	−24	−31	−45	−56
United Utilities Water	−1	−28	9	55	57	10	18	−40	45	−5	−46	−64
Yorkshire Water	94	42	8	76	−13	−24	44	16	−22	−12	−44	−53
Northumbrian Water	23	−5	−17	15	−11	14	−8	2	−7	−23	−47	−66
Scottish Water	−8	−31	−9	−24	16	50	−36	−74	46	28	−43	−58
Welsh Dwr Cymru Water	0	49	21	4	−25	8	48	42	2	−24	−22	−55
Northern Ireland Water	−3	1	4	−38	4	30	−42	−39	76	51	−27	−53

Changes are expressed as a percentage change from 1961 to 1990.

drought relies on model ability to simulate not only the mean precipitation throughout the annual cycle, but also the variability of precipitation necessary to maintain precipitation deficits over a sustained period. This study suggests that climate models may be unable to simulate persistently low rainfall and therefore are likely to be less able to simulate the longest and most severe of events which are the ones likely to be associated with the most significant impacts. Furthermore, by their nature such ''time-slice'' experiments are unable to simulate inter-decadal variability in precipitation. The availability of transient climate simulations in the future will enable the assessment and projection of other important features of the precipitation regime.

Changes to the seasonal distribution of precipitation and the occurrence of drought will have significant implications for the management of UK water resources and therefore

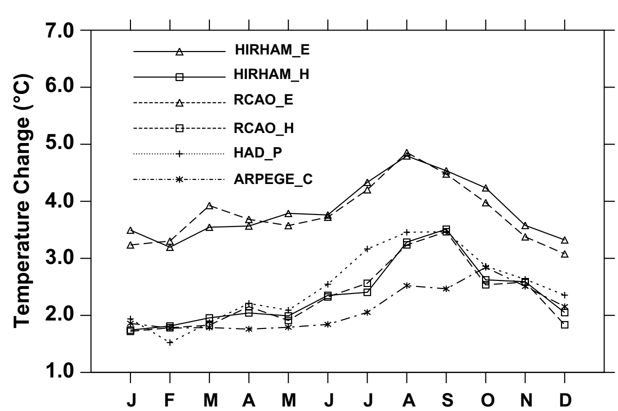

Figure 10 Projected increase in mean monthly temperature for the British Isles grid cells for the period 2071–2100 (2070–2100 for HAD_P) from the control period.

the companies which are responsible for water supply. The RCMs indicate that for UK water companies there is considerable uncertainty surrounding future change in drought occurrence and severity. Indeed, for some companies the projected change from different RCMs could be either positive or negative. This represents a significant challenge for the research community in extracting useful predictions of these events from climate models and in communicating the nature of this uncertainty to resource planners. It is clear that the future management of an important strategic resource should not be based on the use of just one climate model and the generation of probabilistic climate change scenarios to explore impacts offers considerable potential to achieve this.

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