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Downscaling of global climate models for flood frequency analysis: where are we now?

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Abstract:

The issues of downscaling the results from global climate models (GCMs) to a scale relevant for hydrological impact studies are examined. GCM outputs, typically at a spatial resolution of around 3° latitude and 4° longitude, are currently not considered reliable at time scales shorter than 1 month. Continuous rainfall-runoff modelling for flood regime assessment requires input at the daily or even hourly time-step. A review of the different methodologies suggested in the literature to downscale GCM results at smaller spatial and temporal resolutions is presented. The methods, from simple interpolation to more sophisticated dynamical modelling, through multiple regression and weather generators, are, however, mostly based directly on GCM outputs, sometimes at daily time-step. The approach adopted is a simple, empirical methodology based on modelled monthly changes from the HadCM2 greenhouse gases experiment for the time horizon 2050s. Three daily rainfall scenarios are derived from the same set of monthly changes, representing different possible changes in the rainfall regime. The first scenario represents an increase of the occurrence of frontal systems, corresponding to a decrease in the rainfall intensity; the second corresponds to an increase in convective storm-type rainfall, characterized by extreme events with higher intensity; the third one assumes an increase in the monthly rainfall without any change in rainfall variability. A continuous daily rainfall-runoff model, calibrated for the Severn catchment, was used to generate daily flow series for the 1961–90 baseline period and the 2050s, and a peaks-over-threshold analysis was undertaken to produce flood frequency distributions for the two time horizons. Though the three scenarios lead to an increase in the magnitude and the frequency of the extreme flood events, the impact is strongly influenced by the type of daily rainfall scenario applied. We conclude that if the next generation of GCMs produce more reliable rainfall variance estimates, then more appropriate ways of deriving rainfall scenarios could be developed using weather generators rather than empirical methods. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS GCMs; downscaling; flood; climate change; UK; impact study; Severn

INTRODUCTION

With the scientific understanding that the mankind-induced global warming of the atmosphere may have an effect on the climate of the Earth (Intergovernmental Panel on Climate Change, 1996; Climate Change Impacts Review Group, 1996), concern about the impact of the change of climate on the water cycle is growing amongst the population and various governmental or non-governmental authorities in the UK, such as the Environment Agency, the various water companies, the former Department of the Environment, Transport and the Regions (DETR) and the former Ministry of Agriculture, Fisheries and Food (MAFF).† The DETR, for example, funded the LINK project, which provides the scientific community with the most up-to-date climate-change scenarios from the Meteorological Office Hadley Centre. Recently, the UK Climate Impacts Programme was set up by the DETR. The first technical report presented a set of national-level climate-change

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scenarios for the UK, to provide a consistent set of data for climate-change impact studies in the UK (Hulme and Jenkins, 1998).

Many climate-change impact studies have, in the past, focused on assessing the potential implication of global warming in terms of water resources at a national or regional level (e.g. Arnell *et al*., 1997). Despite their undeniable importance for long-term planning, changes in annual or monthly runoff may give very little information on the changes in the flow regime, especially extremes. Assessing annual runoff can be done using simple monthly models. However, continuous rainfall-runoff simulation at daily, hourly or even sub-hourly time steps is necessary to model the flood regime of a catchment correctly. The outputs of current global climate models (GCMs) are not considered reliable at these temporal scales (Kilsby *et al*., 1999). Therefore, most current climate impacts studies on floods use monthly GCM outputs, and rely on simple techniques to derive daily rainfall scenarios from GCM monthly changes (Panagoulia and Dimou, 1997; Gellens and Roulin, 1998; Loukas and Quick, 1999). When monthly climate-change scenarios are converted for use with stochastic hourly rainfall series as an alternative for estimation of flood frequencies in small- or medium-sized catchments, variations on modelled flood regimes depend on the precise assumptions made in the conversion (Calver *et al*., 1999).

This paper describes the problem faced by hydrologists undertaking impact studies on flooding due to the inappropriate scales of the climatic output provided by current GCMs. After briefly reviewing some of the characteristics of current GCMs, the approaches developed to express the GCM outputs at finer spatial and temporal scales are listed. Empirical downscaling techniques to produce daily rainfall scenarios for the Severn catchment are described, and the results concerning the impact of these scenarios on the flood regime of the catchment are analysed.

CLIMATE-CHANGE MODELLING: STATE-OF-THE-ART

In recent years, some of the problems associated with GCMs in the early 1990s have been solved, improving significantly the reliability of modelling the climate under global warming. Specifically, the first generation of GCMs assumed that the concentration of CO_2-equivalent gases in the atmosphere had reached an equilibrium before the experiments were run. In addition, coupling between the climate modelled over the land and that over the ocean was hardly present, leading to potential differences in land cells adjacent to ocean cells. Since then, the adoption of transient methods of forcing and the development of fully coupled atmosphere–ocean GCMs have brought considerable improvements in the climate model results (Mitchell and Hulme, 1999).

Despite the significant progress made in modelling future climate, uncertainties still exist (Mitchell and Hulme, 1999). Second-generation GCMs are not fully consistent with each other at the regional scale, and these differences could call their reliability into question (Chiew *et al*., 1995; Cubash *et al*., 1996; Joubert and Hewitson, 1997; Kalvová and Nemešová, 1997; Pilifosova *et al*., 1997; Smith and Pitts, 1997; Jones, 1999; McGuffie *et al*., 1999). Moreover, reliable results are not yet available at the spatial and temporal resolutions required for many impact studies. One reason for this is that GCMs were not primarily designed for climate-change impact studies, and therefore are not well suited for answering questions of primary interest to hydrologists concerning regional hydrologic variability (e.g. Xu, 1999). A second reason is due to the high complexity of the atmospheric processes modelled by GCMs. Refining the spatial resolution would incur extremely heavy computational costs. However, GCMs are the only available tools for the detailed modelling of the future climate, and a key challenge to hydrologists is thus to express the GCM results at a scale more relevant to hydrological studies, i.e. to downscale GCM experiment outputs.

DOWNSCALING METHODOLOGIES: A REVIEW

Spatial downscaling

The spatial resolution of GCMs remains quite coarse: typically, the cells are about 3° or 4° in latitude and from 4° to 10° in longitude. At that scale, the regional and local detail of the climate is lost. GCMs are inherently unable to represent local subgrid-scale features and dynamics, such as convective cloud processes (Joubert and Hewitson, 1997). Spatial downscaling methods have been developed to overcome this problem.

The simplest method adopted by hydrologists is to interpolate the GCM outputs on to a finer grid, more appropriate for the study (Barrow *et al*., 1996; Conway and Hulme, 1996; Smith and Pitts, 1997; Strzepek and Yates, 1997; Hulme and Jenkins, 1998). This retains the spatial pattern of the GCM without any correction to the absolute predictions. Disaggregation of the GCM rainfall pattern on a catchment can also be achieved using an empirical exponential model to distribute the rainfall intensity within the catchment (Wheater *et al*., 1999).

More complex are the statistical downscaling approaches. These use statistical relationships between atmospheric variables given by the GCM (such as the modelled sea-level pressure) and locally measured climate variables (e.g. rainfall). Robust estimates are strongly dependent on the quality and the length of the data series used for the calibration (Wilby and Wigley, 1997) and on the performance of the regression models in capturing the variability of the observed data (Barrow *et al*., 1996). Statistical downscaling includes multiple-regression methods (Barrow *et al*., 1996; Easterling, 1999; Sailor and Li, 1999; Solman and Nuñez, 1999), artificial neural networks (ANN) techniques (Hewitson and Crane, 1996), and empirical orthogonal function (EOF) analysis, such as the analogue method (Zorita and von Storch, 1999). The underlying assumption of the methodology is that there are certain physical relationships underlying the statistical relationships developed, and that these physical relationships hold regardless of whether the model simulation is a control (stationary) experiment or an experiment incorporating a changed climate (Easterling, 1999). In the context of climate change, it is difficult to guarantee this assumption, and it remains a main weakness of the methodology (Hewitson and Crane, 1996; Schulze, 1997; Joubert and Hewitson, 1997; Solman and Nuñez, 1999).

A third option is the dynamical downscaling approach. Regional-scale limited-area models (LAMs) use GCM outputs as the boundary conditions to calculate estimates at a detailed scale, but these so-called 'regional nested models' are computationally expensive (Hewitson and Crane, 1996). Moreover, LAMs are dependent upon the veracity of the GCM grid-point data that are used to drive the boundary conditions of the region (Wilby and Wigley, 1997). Compared with statistical downscaling, the spatial patterns produced are more homogeneous, but not necessarily more realistic (Cubash *et al*., 1996; Mearns *et al*., 1999). 'Time-slice' experiments are also considered as dynamical models. These are similar to GCMs, but run only regionally (e.g. Europe) and at a much smaller space-scale (e.g. $0{\cdot}5^\circ \times 0{\cdot}5^\circ$) and their outputs may be combined with a statistical downscaling approach (Busuioc *et al*., 1999). They are also computationally expensive and may not simulate precipitation well (Cubash *et al*., 1996).

However sophisticated the downscaling method is, simulations of regional climate change are strongly dependent on the simulation of present conditions (Joubert and Hewitson, 1997). If the large-scale changes in the GCMs are inaccurate, then the derived local changes merely add misleading precision to the GCM results, and the downscaling techniques fail to add any predictive skill: downscaling cannot correct for model inaccuracies (Mitchell and Hulme, 1999). At the moment, there exists no universal downscaling method for all situations, and all are still at the stage of development and testing (Xu, 1999).

The quality of the absolute estimates of GCMs calls into question the direct use of GCM outputs for hydrological modelling. Climate scenarios from GCMs are *not* predictions, and some control run simulations fail to reproduce accurately various features of the current climate, particularly at regional scales and particularly with some precipitation regimes (Conway and Hulme, 1996). The uncertainty of the GCM outputs could be reduced using an ensemble of simulations, rather than one single experiment result (Mitchell and Hulme, 1999). Combining GCM estimates with the observed data also partially helps to correct the failure in the climate modelling accuracy. The *changes* predicted by the GCMs are favoured to the absolute values (Smith and Pitts, 1997). These changes may be used directly at the GCM spatial resolution or be interpolated to a finer spatial resolution (Arnell and Reynard, 1996; Barrow *et al*., 1996; Conway and Hulme, 1996; Strzepek and Yates, 1997; Hulme and Jenkins, 1998). The present conditions are then altered according to the modelled changes in the so-called perturbation method (Arnell, 1992; Chiew *et al*., 1995; Arnell and Reynard, 1996; Conway and Hulme, 1996; Kalvová and Nemešová, 1997; Panagoulia and Dimou, 1997; Seidel *et al.*, 1998; Buchtele *et al.*, 1999; Reynard *et al.*, 2001). Despite the fact that the statistical characteristics of the historical record (such as the sequences of storms and dry periods) are unchanged (Wood *et al.*, 1997), this last technique is widely used by hydrologists (Xu, 1999). One of the reasons is that it is extremely simple and easy to apply. Moreover, sophisticated downscaling methods, despite the physically based concepts, are not yet completely satisfactory and they do not appear to be a good practical alternative to the perturbation method (Wood *et al.*, 1997).

Temporal downscaling

Although GCMs run at a time scale as short as 15 min, there is little confidence in the predictions for time scales shorter than 1 month, especially for variables such as rainfall. A comparison between daily estimates of rainfall and the averaged measured rainfall for one GCM cell over Wales (extending from 5·635°W to 1·875°W and from 51°N to 53·5°N) was done for the baseline period 1961–90. For the given cell, a peaks-over-threshold (POT) series was sampled from daily rainfall series provided by the control run of the Hadley Centre second-generation GCM, HadCM2, and a rainfall frequency distribution fitted. For the same area, a daily rainfall time series was constructed for the 1961–90 baseline using over 3500 raingauges. The 'triangle method' (Jones, 1983) was used. A fine mesh was superimposed over the network, the resolution of the mesh depending on the gauge density. Within each cell of this mesh, the average rainfall of each day was calculated using a weighted-average method based on the inter-gauge distance. The areal rainfall was then calculated from the results for each of the cells in the fine mesh. A rainfall frequency distribution was fitted to the POT sample derived from the area-average daily rainfall series.

For all return periods, 1 day peak rainfall depths are lower when modelled by the GCM (dotted line) compared with the observed series (solid line), the difference increasing with the return period (Figure 1). The GCM rainfall frequency distribution is relatively flat, showing low variability in the extreme rainfall. In particular, the difference between a 2 year return period event and a 50 year return period event as modelled by the GCM is of the same magnitude as that observed between a 1 year event and a 3 year return period event. This illustrates the failure of the GCM to model the extremal properties of the daily rainfall regime adequately.

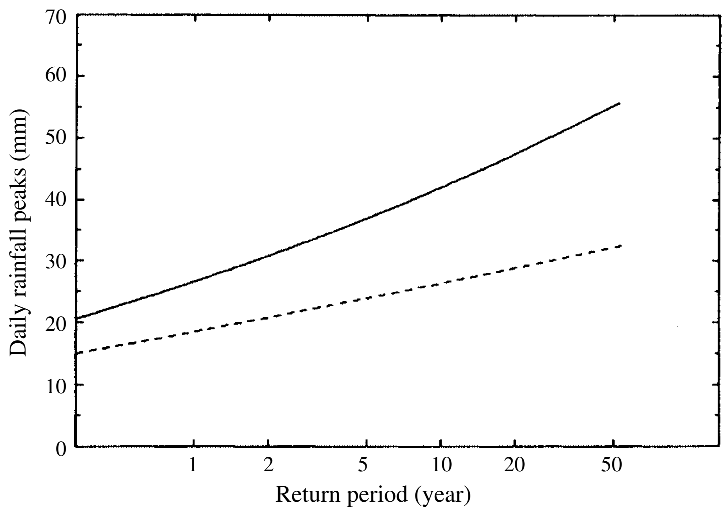

Figure 1. Daily rainfall frequency curves for the baseline period 1961–90 with average measured rainfall (solid line) and HadCM2 control run (dotted line) for the same cell

Whereas assessing the impact of climate change on water resources might only necessitate annual or monthly time steps, impact studies on flooding require data at least at the daily scale, and climatic changes need to be expressed at this resolution. Given that GCMs' daily outputs are unreliable for rainfall, producing daily rainfall series representative of the future time horizon is of crucial importance.

Dynamic temporal downscaling is a technique suggested by climatologists to predict daily rainfall from GCM outputs. It makes the assumption that atmospheric patterns, whose synoptic scales are comparable to the GCM resolution, are statistically linked to rainfall patterns. If such relationships exist, daily estimates of rainfall can be derived from GCM daily atmospheric variables, such as the sea-level pressure, thought to be more reliable at a daily time step than rainfall GCM outputs. Similar to spatial downscaling methodologies, the major underlying assumption is that the relationships found locally will be unchanged in the future (Goodess and Palutikof, 1998). Using weather classifications defined from past and current conditions, conditional statistics of rainfall and temperature can be derived (Conway and Jones, 1998) and combined with a weather generator to predict rain-day changes (Conway and Jones, 1998; Goodess and Palutikof, 1998). Multiple-regression models using airflow indices (Kilsby *et al*., 1997), ANN methods (Wilby *et al*., 1998) and the analogue method can also derive local rainfall estimates (Zorita and von Storch, 1999). These relationships are used to estimate rainfall from the GCM pressure field at each GCM point. The new local rainfall can be interpolated to provide maps of daily rainfall (Bárdossy *et al*., 1999), used regionally (Conway and Jones, 1998) or locally (Goodess and Palutikof, 1998; Wilby *et al*., 1998). However, GCMs have limited ability to simulate the correct frequencies of weather types and can fail to simulate some of the observed relationships between particular circulation patterns and temperature and precipitation [see Hulme *et al*., (1993), in Barrow *et al*. (1996)]. Moreover, methods purely based on atmospheric circulation can never capture the effects due to all relevant physical processes, resulting in changes of lower magnitude than expected (Wilby *et al*., 1998). Although monthly mean rainfall, wet and dry periods and interannual variability are reasonably well simulated, the models often fail to estimate daily rainfall depth correctly (Conway and Jones, 1998).

Weather generator techniques, using GCM output at a monthly time step to estimate daily rainfall, are also used (Wilby and Wigley, 1997; Goodess and Palutikof, 1998; Wilby *et al*., 1998). They are designed to produce daily rainfall estimates by stochastic models from data such as mean monthly rain and number of wet days in the month, and may be calibrated at the site of interest.

Despite providing climatic estimates at a time step relevant for hydrological studies, all the methods mentioned previously have assumed that the variability underlying the extreme events does not change, mainly because of the absence of reliable estimates from GCMs. However, changes in variability and intensity may well be more important than the changes in mean values in climate-change impact studies, especially when dealing with extremes (McGuffie *et al*., 1999). Incorporating changes in variability in the downscaling procedures may help to compensate for this weakness. This may be done using stochastic rainfall generator techniques, where the parameters of the model are changed according to the changes in the mean and intensity of rainfall (Barrow *et al*., 1996; Semenov and Barrow, 1997; Wilks, 1999). Again, this procedure depends on the ability of the GCM to model correctly the changes in mean rainfall, rainfall intensity and number of wet–dry days, which is not satisfactorily achieved by current GCMs (e.g. Figure 1). If the parameters of the rainfall generator are linked to air indices (Conway and Jones, 1998; Kilsby *et al*., 1998), the approach also heavily depends on the assumption that the observed relationship between precipitation and air flow indices will remain the same in the future, which is questionable (Wilby, 1997; Kilsby *et al*., 1999).

It is not clear which method provides the most reliable estimates of daily rainfall. Most of them use *daily* estimates of climatic variables. Despite the belief that GCMs model atmospheric variables (such as the sea-level pressure) better at a daily time step than they model rainfall, there is still no consensus about their reliability at that time scale. Alternatively, weather generators can potentially improve the daily rainfall estimates, by adding more inter-daily variability in the daily series. But the data they require are still not available from current GCMs, and it is not sure that they give satisfactory results. Improvement in the modelling of the inter-daily variability by GCMs will undoubtedly be of crucial importance for deriving more realistic scenarios. The simple empirical approach described here is designed to assess impacts on flooding from a range of future rainfall scenarios, all derived from the same GCM monthly changes but of different temporal structures. The results are compared with the traditional perturbation technique used in most impact studies.

SCENARIO DEFINITION

Amongst the numerous GCMs available, there are fundamental differences in the modelling theories and concepts. For that reason, the Intergovernmental Panel on Climate Change (IPCC) developed a Data Distribution Centre (DDC) aiming to provide relevant information to researchers in the climate-change impacts community. The IPCC-DDC distributes climate scenarios and related information, ensuring that all the researchers have the possibility of working with a consistent set of scenarios. In particular, the same emission forcing scenario is used, and a core set of variables needed for hydrological impact studies provided, all at the same temporal resolution (30 years monthly averages). Several baseline climatologies at smaller space resolutions, along with brief summaries of the modelling features of each GCM, are also available.

The GCM used here is amongst those provided by the IPCC-DDC. It is the Hadley Centre second generation GCM, named HadCM2, combined with a 1% per annum increase in the concentration of the equivalent CO_2 in the atmosphere, with associated projections of population rise and economic growth (similar to the IS92a emission scenario; Leggett *et al.*, 1992). The additional effect of sulphate aerosols is not considered. HadCM2 has a spatial resolution of 2·5° latitude by 3·75° longitude, and has a climate sensitivity of 2·5 °C (an anomaly of the global temperature after a doubling of the effective CO_2 concentration). The time horizon chosen for our study corresponds to the 30 year period 2041–70 (or the '2050s'). Averaged outputs from an ensemble of four simulations of the same GCM experiment were used here (the HadCM2 GGx run). The set of factors produced express the absolute changes between the baseline period (1961–90) and the future time horizon (2050s). They are calculated from the absolute changes between the baseline and the 2080s, scaled back according to a temperature signal (known to be modelled better by GCMs than rainfall) to reflect the climate of the 2050s. This 'scaling back' technique has been chosen because the signal due to global warming is the strongest for the 2080s. For a less-distant time horizon, the inter-annual variability of the output (or noise) may hide the climate change signal (Arnell *et al.*, 1997). This approach is broken into the following four stages.

(i) Extract the changes in monthly climate variables at the end of the model experiment (2080s).
(ii) Divide these changes by the change in global average temperature as simulated by the model at this time. This produces an estimate of the change per degree of global warming. For the HadCM2 greenhouse gas experiment, the global temperature increase by the 2080s is 3·1 °C.
(iii) Use a one-dimensional energy balance model, such as MAGICC (Wigley and Raper, 1992) to estimate the global temperature change for a given time horizon, under a given emission scenario. IS92a yields a warming of 1·56 °C for the 2050s.
(iv) Multiply the scaled monthly changes by these global temperature changes to produce the rescaled factors of monthly changes.

The choice of the baseline period as representative of the current climate is a critical part of a climate-change impact study (Kalvová and Nemešová, 1997). The baseline 1961–90 is the standard World Meteorological Organization period (Hulme *et al.*, 1995). It has been selected because it incorporates some of the natural variability of the climate, including both dry (1970s) and wet (1980s) periods (Wigley and Jones, 1987). A shorter period for the baseline may reflect a particular feature of the climate, and be non-representative of current conditions (Robson *et al*., 1998). Good-quality measurements and a wide network of climate stations were also key factors in building the 1961–90 climatology.

No complex spatial downscaling was undertaken in this study, because most of the methods suggested in the literature are dependent on the absolute values of the GCM outputs for the baseline period, and none of them appeared to give satisfactory results. The perturbation technique has the advantage of being extremely simple, and uses the changes rather than absolute values, and was preferred for this study. No interpolation procedure was added, but the average monthly changes (at the GCM scale, i.e. 2·75° latitude, 3·5° longitude) were expressed as percentage changes compared with the Climate Research Unit (CRU) global mean monthly climatology at 0·5° resolution (New *et al*., 1999). This final resolution is of similar scale to that used by the rainfall-runoff model.

Results of this spatial downscaling technique are shown in Figure 2 for the Severn catchment. The 'blocky' nature of the results is due to the absence of interpolation of the absolute changes. Interpolation of GCM results is an option sometimes adopted in climate-change impact studies, but has the disadvantage of introducing an artificial smoothness that 'looks realistic'. When no interpolation is done, step variations are introduced within the catchment as a reminder of the poor spatial resolution of the existing data (Figure 2 indicates that just two GCM values describe the Severn catchment). Increases in rainfall by the 2050s are predicted for the winter, spring and autumn, whereas summer rainfall is predicted to decrease. The highest increase is in January, with monthly rainfall going up by more than 15% in the eastern part of the catchment. In April and October, smaller changes are expected. July shows the reverse, with a decrease in rainfall over the whole catchment, by more than 15% in eastern parts, whereas the uplands show less of a decrease. This is consistent with the overall pattern of precipitation changes in the UK, where in the south the summers will become drier and in the north the summer rainfall increases (Hulme and Jenkins, 1998). These changes will be associated with an increase in the inter-annual rainfall variability for all seasons (Hulme and Jenkins, 1998).

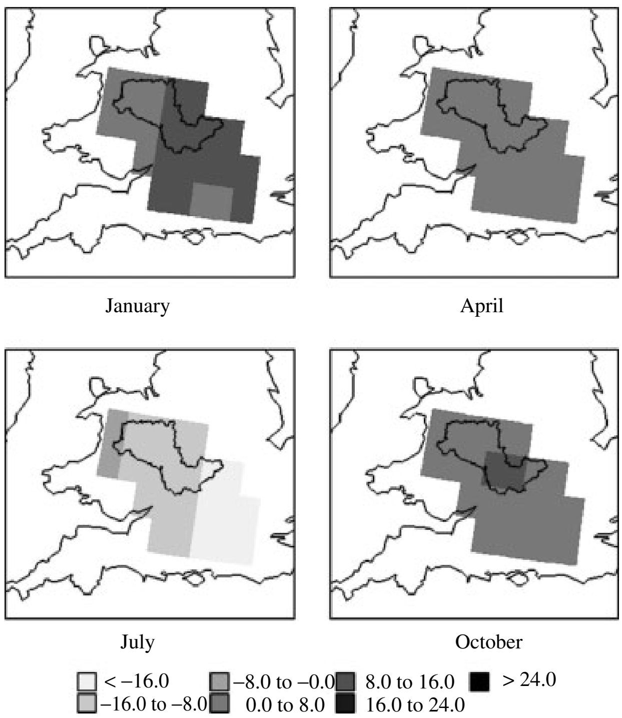

Figure 2. Spatial downscaling of the monthly rainfall for the 2050s as modelled by the HadCM2 model over the severn catchment, expressed in percentage changes

The factors of monthly rainfall changes derived from the GCM changes were then downscaled to daily time-step using three different empirical methods, representative of the spectrum of possible changes in the temporal structure of rainfall series (Figure 3). Let Figure 3a be the observed baseline daily rainfall series. The first method corresponds to a 'proportional' method (Figure 3b), where the same percentage change was applied to each rain day of the observed data used for the rainfall-runoff modelling. No change in the daily variability of the rainfall is assumed compared with that of the baseline series. This is the simplest method, widely applied in impact studies.

The second method changed the number of wet days in each month, as well as changing the monthly totals—the 'change in rain days' method. The increase in the monthly total during the winter (October to March) was modelled as an increase of the number of wet days in which every third dry day was made wet (Figure 3c). The percentage increase was divided equally between the 'new' wet days, giving typically between one and five extra wet days during each winter month. Proportional changes were applied to wet summer days when an increase was predicted. For a decrease in summer monthly totals, the change was initially applied proportionally and then any day with less than 2 mm of rainfall was deemed to be dry. The total rainfall removed by reducing the number of wet days was then redistributed amongst the remaining wet days to maintain the correct monthly total. This method essentially created wetter winters with more wet days and drier summers with more dry days. Such a change is typical of milder winters, with westerly type airflow with a succession of frontal systems, and of warmer and drier summers, punctuated by more intense, short-duration convective storms.

The third method, termed 'enhanced storm', sought to change the intensity of daily rainfall while maintaining the average monthly changes as prescribed by the GCM. This method held the number of wet days constant but added the percentage increase in rainfall equally onto those days with the three highest recorded totals, creating an enhanced storm profile (Figure 3d), thereby increasing the intensity of the most extreme events only.

Scenarios of potential evaporation (PE) were also needed for the rainfall-runoff modelling at a daily time-step. These were created using monthly changes of PE calculated according to the Penman–Montieth

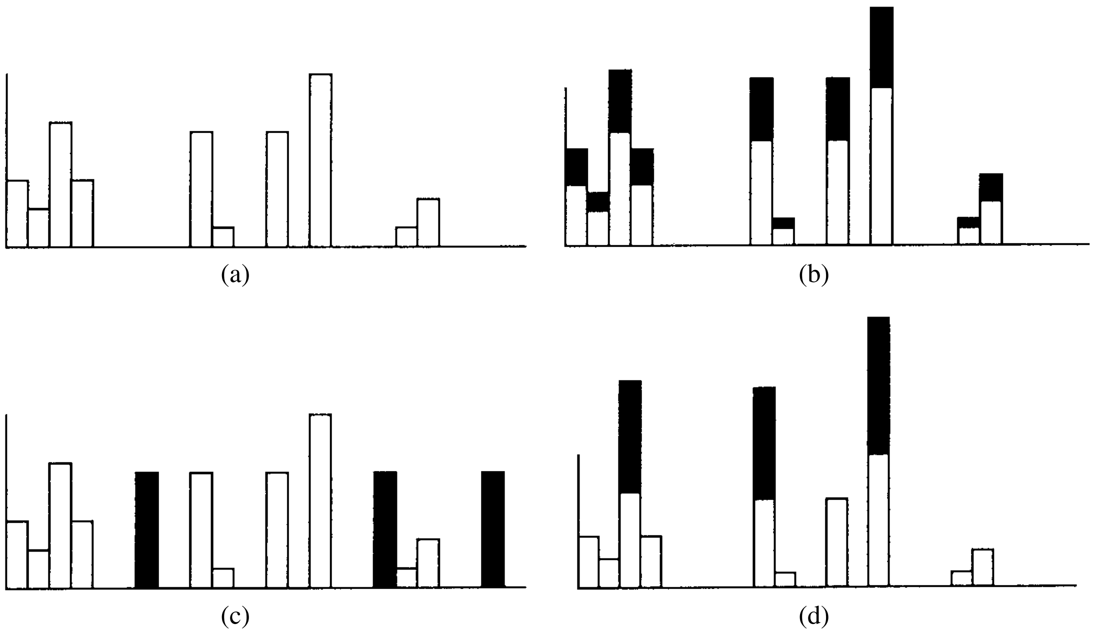

Figure 3. Temporal downscaling: daily rainfall series under current condition (a) and derived climate scenarios using the proportional change (b), the change in rain days (c) and the enhanced strom (d) methods

formula (Montieth, 1965) and applied proportionally to the daily time-series representative of the current conditions (for a given month, every day is allocated the same percentage change). Temperature series were produced similarly.

These daily scenarios are designed to reproduce two distinct patterns in the rainfall changes: a decrease of the average intensity of the daily rainfall or an increase of the intensity of the extreme daily events. It is currently not possible to know which scenario is the more probable in a context of climate change, due to the inability of the GCMs to model rainfall variability. However, it seems important to model their possible consequences in terms of flooding.

APPLICATION TO RAINFALL-RUNOFF MODELLING AND FLOOD FREQUENCY ANALYSIS

Rainfall-runoff model

A semi-distributed daily runoff-rainfall model named CLASSIC (Climate and LAnduse Scenario SImulation on Catchments), specifically designed for modelling the impacts of environmental change in large catchments, was used in the study (Crooks *et al.*, 1996; Naden *et al.*, 1996). The model is set within a geographical information system framework, incorporating soils, land use and digital terrain model databases in the calibration and running of the model. It has three components, corresponding to a soil water balance model, a drainage model and a basin-wide routing model. CLASSIC is applied to a catchment on a grid-square basis: in this study the 40 km MORECS grid (Meteorological Office Rainfall and Evaporation Calculation System; Thompson *et al.*, 1981). The soil water balance model incorporates a separate evaluation of effective rainfall (rainfall less evaporation) depending on the land use. Six land-cover types are considered: grassland, deciduous woodland, coniferous woodland, upland, tilled land (cereals) and urban/impermeable surfaces. The vegetation cover is derived from the Institute of Terrestrial Ecology land-cover data set (Fuller, 1993) and expressed as a percentage of each of the six land-cover types for each of the grid cells.

The effective rainfall for each grid square, calculated from the percentage of each land-cover type in the square, then becomes the input to the drainage model. This element is based on the unit hydrograph method and has two types, a one-component linear store for permeable, groundwater-dominated, response areas, and a two-component store representing quick and slow responses for semi-permeable soils. These two components operate in parallel, and both can operate within a grid square depending on the distribution of soils, with the effective rainfall being determined separately for each type.

The output from the drainage model for each grid square is routed to the catchment outlet by convolving the flow with the network response function, which combines a routing function with a representation of the spatial configuration of drainage paths within the catchment (Naden, 1992). This procedure provides a physically based, but simple function for routing flows through the river network. It assumes that the same parameters in the routing function apply for all discharge levels, and does not take explicit account of detailed hydraulic features (e.g. making allowances for overbank storage) (Crooks *et al.*, 1996).

Catchment description and data

The rainfall-runoff model was applied to simulate the runoff of the Severn at Haw Bridge, a catchment of 9895 km^2 situated in Wales and western England (Figure 4). It has a mean annual rainfall of 792 mm and a mean annual runoff of 336 mm. Flood discharges are predominantly the result of frontal rainfall during the winter, coming from westerly airflow from the Atlantic Ocean. Within the period of record (1971–94), the total volume of runoff was not significantly altered by snow (Crooks *et al.*, 1996). The likely warmer conditions suggested by the GCMs for the 2050s are unlikely to change these characteristics significantly. The catchment is modelled using 19 cells, each with a double-store drainage model.

A daily rainfall series for each cell was calculated for the baseline period 1961–90 using a modified version of the triangle method (Gannon, 1995). For each day in the 30 year series, rainfall was estimated based on all the raingauges working within the MORECS cell on that day.

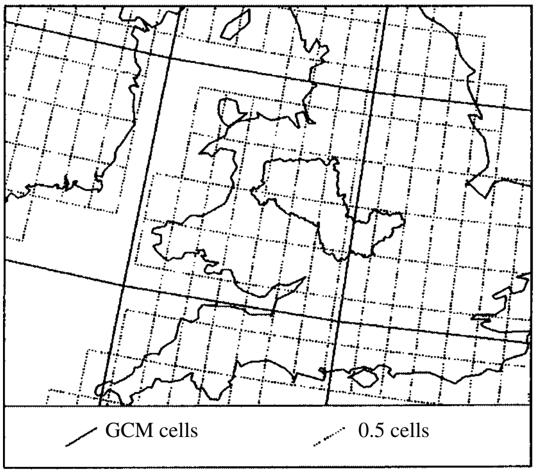

Figure 4. The Severn at Haw Bridge along with the GCM cells (solid lines) and the 0·5° cell of the mean monthly climatology (dashed lines). MORECS boxes have a resolution comparable to the 0·5° cells

Monthly PE data assuming a grassland cover are available from 1961 for each MORECS grid square. These data were used to give monthly totals for the other vegetation types in the model using a suite of regression equations previously developed (Crooks *et al.*, 1996). The monthly totals were downscaled into daily values assuming that the evaporation rate was constant over 10 day periods. PE from urban and other impermeable surfaces was taken as equal to the daily rainfall with an upper limit of 0·5 mm.

Model calibration

The model calibration for each grid square was based on sub-catchment calibration, relating model parameters to catchment characteristics, particularly soils. Calibration catchment areas ranged from 17 to 234 km^2. The Nash and Sutcliffe (1970) efficiency criterion was used, as given by:

$$E = 1 - \frac{\sum(O_i - M_i)^2}{\sum(O_i - \overline{O}_i)^2} \quad (1)$$

with observed value O_i and modelled value M_i. The efficiency of the fit for the daily time series of observed and modelled flows is 0·91 for the whole catchment for the period 1971–94.

The use of the parameters of a rainfall-runoff model calibrated during the current climatic conditions for climate-change studies is open to debate. Hydrological models are generally designed for stationary conditions. However, in climate-change studies, the hydrological models employed will be applied to changing conditions (Xu, 1999). Some authors recommend a 'split-sample test' methodology to ensure that the model has a general validity in predicting runoff for different climatic conditions (Xu, 1999). Some others adopt empirical methods to modify the fitting parameters depending on the new climatic conditions (Seidel *et al.*, 1998). Finally, most of the impact studies assume the parameters to be independent of climate, and that the model remains valid under climate-change conditions. Because the baseline period used for the calibration/validation of the model comprises dry (the 1970s) and wet (1980s) periods, there is a degree of confidence in the ability of the parameters of CLASSIC to simulate runoff satisfactorily under global warming.

Flood regime of the Severn as currently observed and under climate change

The flood regime of the Severn at Haw Bridge is summarized by its flood frequency distribution. Continuous daily runoff simulation by CLASSIC produces 30 year daily series of runoffs for the baseline period (1961–90) and the 2050s. For each of these periods, POT sampling of the mean daily flows is undertaken to select the 90 most-extreme floods (an average of three events per year) and flood frequency curves derived. Testing is included in the sampling method to ensure that the extracted peak flows are from independent events. It is assumed that the occurrence of the flood peaks follows a Poisson distribution, characterized by a single parameter λ (or the average number of peaks per year above the threshold). The magnitude of the peaks is fitted by a generalized Pareto distribution (GPD). A GPD is characterized by three parameters: a threshold (or location) parameter μ, a scale parameter σ, and a shape parameter κ. Flood frequency curves derived from observed and modelled flows show good correlation (Crooks *et al.*, 1996).

Whatever downscaling methodology used to derive the daily rainfall scenarios, the flood regime in the Severn is shown to be affected by global warming both in terms of magnitude and frequency (Figure 5). There is a significant shift of the flood frequency distributions, towards higher flood peaks occurring more often. A 10 year event may become a 5 year or 2 year event, depending on the rainfall scenario. For more extreme events, a flood of around 650 m^3 s^{-1}, corresponding to a 50 year return period flood, may occur as often as every 5 years under the enhanced storm profile scenario. Expressed in other words, a decadal flood, occurring on average once every 10 years, will see its magnitude rising by between 6·6% (scenario increasing the number of rainy days) and 23% (enhanced storm scenario).

Both the magnitude and the frequency of the floods are increased under climate-change conditions as modelled by the HadCM2 GGx experiment. On a catchment as large as the Severn at Haw Bridge, the highest flows are generally due to prolonged rainfall during the winter rather than flash floods in the summer. This means that the increase in winter rainfall in the HadCM2 climate scenarios dominates over the decrease in summer rainfall shown for England and Wales (Hulme and Jenkins, 1998). However, depending on how the increase in the winter rainfall will occur, the consequences for flooding could be significantly different. A milder winter, with a more regular rainfall regime (more days with rain, and less intense events) will, on average, increase the magnitude of the floods by about 6%. If the warmer weather conditions are reflected by an increase in the occurrence of convective storms, changes in the flood regime may be more dramatic, with a higher increase of the magnitude of the floods for rare events, of up to 30% for the 50 year event. Unfortunately, it is not possible at the moment to say which rainfall scenario is more likely.

CONCLUSION

Climate-change impact studies on flood regimes have been relatively rare until recently, mainly because GCMs do not provide results reliable enough at the time scale required for flood event, or continuous simulation

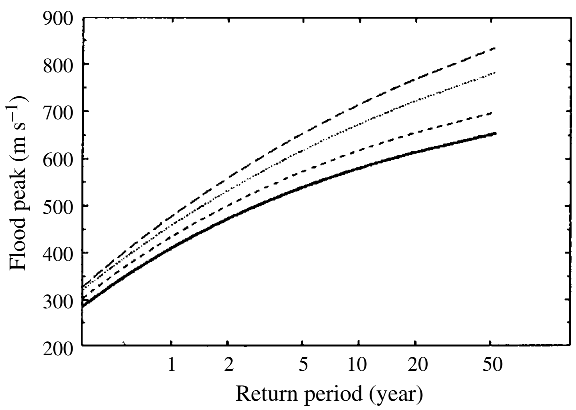

Figure 5. Flood frequency distribution modelled by CLASSIC for the baseline period (solid line) and as modelled by the HadCM2 GGx experiment for the 2050s under the proportional change scenario (dotted line), the change in number of rain days (small dash line) and enhanced strom (long dash line)

modelling. To overcome this problem, downscaling techniques have been developed to express GCM outputs on scales more appropriate for hydrological modelling. However, most of these methodologies are based directly on GCMs, outputs, which are known to be somewhat unreliable. A compromise is to concentrate on *changes* modelled by the GCMs rather than on the absolute values, but this involves maintaining the inter-daily variability of the rainfall, which is an unlikely scenario of climate change. Simple empirical methods have been developed to create daily rainfall scenarios for the Severn catchment in Wales, assuming changes in the intensity of the extreme rainfall events. Applied to baseline climatic series, these scenarios show an overall change of the flood regime both in terms of increase of magnitude and frequency of the extreme events. However, significant differences in the impacts exist, depending on how the monthly changes have been interpreted: a scenario of wetter, milder winters corresponding to a more uniform rainfall will have only a minor impact on the floods of the Severn, whereas an increase in the occurrence of convective weather systems, characterized by intense extreme rainfall, will generate a flood regime with magnitudes up to 30% higher than observed during the 1961–90 baseline. It is therefore very important to be able to develop realistic scenarios, incorporating the changes in the inter-daily variability of the rainfall regime. The current generation of GCMs still does not provide reliable estimates of rainfall variance, and it is currently difficult to develop appropriate downscaling methodologies. It is hoped that the next generation of GCMs will improve the modelling of the daily rainfall regime, or at least the changes in the mean and variance. If this is the case, the use of an appropriate weather generator, such as that developed by Goodsell and Lamb (1999), with GCM outputs should improve flood hydrological modelling in the context of climate change by creating more reliable and realistic rainfall scenarios.

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REFERENCES

Arnell NW. 1992. Factors controlling the effects of climate change on river flow regimes in a humid temperate environment. *Journal of Hydrology* **132**: 321–342.

Arnell NW, Reynard NS. 1996. The effects of climate change due to global warming on river flows of Great Britain. *Journal of Hydrology* **183**: 397–424.

Arnell NW, Reynard NS, King RS, Prudhomme C, Branson J. 1997. *Effects of climate change on river flows and groundwater recharge: guidelines for resource assessment*. Report to UKWIR/Environment Agency; 55 pp + annexes.

Bárdossy A, Giese H, Hartmann G, Nachtnebel HP, Diernhoffer W, Hebenstreit K. 1999. Impacts of climate change on mid-European river basin hydrology. In *Hydrological Extremes: Understanding, Predicting, Mitigating. Proceedings of IUGG 99 Symposium HS1*, Birmingham, July. IAHS Publication 255. IAHS: Wallingford; 11–18.

Barrow EM, Hulme M, Semenov M. 1996. Effect of using different methods in the construction of climate change scenarios: examples for Europe. *Climate Research* **7**: 195–211.

Buchtele J, Buchtelová M, Fortová M, Dubrovsky M. 1999. Runoff changes in Czech river basins—the outputs of rainfall-runoff simulations using different climate change scenarios. *Journal of Hydrology and Hydromechanics* **47**(3): 180–194.

Busuioc A, von Storch H, Schnur R. 1999. Verification of GCM-generated regional seasonal precipitation for current climate and of statistical downscaling estimates under changing climate conditions. *Journal of Climate* **12**: 258–272.

Calver A, Lamb R, Morris SE. 1999. Generalized river flood frequency estimation for Great Britain using continuous rainfall-runoff modelling: pilot study results. *Proceedings of the Institution of Civil Engineers—Water, Maritime and Energy* **136**: 225–234.

Chiew FHS, Whetton PH, McMahon TA, Pittock AB. 1995. Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. *Journal of Hydrology* **167**: 121–147.

Climate Change Impacts Review Group. 1996. *Review of the Potential Effects of Climate Change in the United Kingdom*. The Stationery Office: London.

Conway D, Hulme M. 1996. The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt. *Water Resources Development* **12**(3): 277–296.

Conway D, Jones PD. 1998. The use of weather types and air flow indices for GCM downscaling. *Journal of Hydrology* **212–213**: 348–361.

Crooks SM, Naden PS, Broadhurst P, Gannon B. 1996. *Modelling the flood response of large catchments: initial estimates of the impacts of climate and land use change*. Report to MAFF, project FD 412; 66 pp.
Cubash U, von Storch H, Waszkewitz J, Zorita E. 1996. Estimates of climate change in Southern Europe derived from dynamical climate model output. *Climate Research* **7**: 129–149.
Easterling DR. 1999. Development of regional climate scenarios using a downscaling approach. *Climatic Change* **41**: 615–634.
Fuller RM. 1993. The land cover map of Great Britain. *Earth Space Review* **2**: 13–18.
Gannon B. 1995. *Automating areal rainfall calculations for catchments*. Internal report, Institute of Hydrology: Wallingford; 44 pp.
Gellens D, Roulin E. 1998. Streamflow response of Belgian catchments to IPCC climate change scenarios. *Journal of Hydrology* **210**: 242–258.
Goodess CM, Palutikof JP. 1998. Development of daily rainfall scenarios for southeast Spain using a circulation-type approach to downscaling. *International Journal of Climatology* **10**: 1051–1083.
Goodsell G, Lamb R. 1999. *Estimating long return period floods by continuous simulation using a stochastic rainfall generator*. Report to MAFF, project FD 404; 31 pp.
Hewitson BC, Crane RG. 1996. Climate downscaling: techniques and application. *Climate Research* **7**: 85–95.
Hulme M, Jenkins GJ. 1998. *Climate change scenarios for the UK: scientific report*. Technical report No. 1. Climate Research Unit: Norwich; 80 pp.
Hulme M, Conway D, Jones PD, Jiang T, Barrow EM, Turney C. 1995. Construction of a 1961–1990 European climatology for climate change modelling and impact applications. *International Journal of Climatology* **15**: 1333–1363.
Intergovernmental Panel on Climate Change. 1996. *Climate Change 1995. The Science of Climate Change*. Houghton JT, Miera-Filho LG, Callander BA, Harris N, Kattenburg A, Maskell K (eds). Cambridge University Press: Cambridge; 572 pp.
Jones JAA. 1999. Climate change and sustainable water resources: placing the threat of global warming in perspective. *Hydrological Sciences Journal* **44**(4): 541–557.
Jones SB. 1983. *The estimation of catchment average point rainfall profiles*. Institute of Hydrology: Wallingford; Report 87.
Joubert AM, Hewitson BC. 1997. Simulating present and future climates of southern Africa using general circulation models. *Progress in Physical Geography* **21**(1): 51–78.
Kalvová J, Nemešová I. 1997. Projections of climate change for the Czech Republic. *Climatic Change* **36**: 41–64.
Kilsby CG, Fallows CS, O'Connel PE. 1997. Climate change impact assessment: an application to the Tyne basin. In *Proceedings of BHS 6th National Hydrology Symposium*, Salford, 15–18 September; 8.39–8.47.
Kilsby CG, Cowpertwait PSP, O'Connel PE, Jones PD. 1998. Predicting rainfall statistics in England and Wales using atmospheric circulation variables. *International Journal of Climatology* **18**: 523–539.
Kilsby CG, Buishand TA, Jones PD. 1999. *Production of precipitation scenarios for impact assessment of climate change in Europe (POPSCICLE)*. Final report to the EU, EU project EV5V-CT94-0510; 113 pp.
Leggett J, Pepper WJ, Swart RJ. 1992. Emissions scenarios for the IPCC: an update. In *Climate change 1992: the supplementary report to the IPCC scientific assessment*, Houghton JT, Callander BA, Varney SK (eds). 75–95.
Loukas A, Quick MC. 1999. The effect of climate change on floods in British Columbia. *Nordic Hydrology* **30**: 231–256.
McGuffie K, Henderson-Sellers A, Holbrook N, Kothavala Z, Balachova O, Hoekstra J. 1999. Assessing simulations of daily temperature and precipitation variability with global climate models for present and enhanced greenhouse climates. *International Journal of Climatology* **19**: 1–26.
Mearns LO, Bogardi I, Giorgi F, Matyasovzky I, Palecki M. 1999. Comparison of climate change scenarios generated from regional climate model experiments and statistical downscaling. *Journal of Geophysical Research* **104**(D6): 6603–6621.
Mitchell TD, Hulme M. 1999. Predicting regional climate change: living with uncertainty. *Progress in Physical Geography* **23**(1): 57–78.
Monteith JL. 1965. Evaporation and environment. In *State and Movement of Water in Living Organisms. 19th Symposium of the Society of Experimental Biology*. Cambridge University Press: Cambridge; 205–234.
Naden PS. 1992. Spatial variability in flood estimation for large catchments: the exploitation of channel network structure. *Hydrological Sciences Journal* **37**(1–2): 53–71.
Naden PS, Crooks SM, Broadhurst P. 1996. Impact of climate and land use change on the flood response of large catchments. In *Proceedings of 31st MAFF Conference of Rivers and Coastal Engineers*, Keele; 2.1.1–2.1.16.
Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models—part I: a discussion of principles. *Journal of Hydrology* **10**: 282–290.
New M, Hulme M, Jones PD. 1999. Representing twentieth-century space–time climate variability. Part I: development of a 1961–90 mean monthly terrestrial climatology. *Journal of Climate* **12**: 829–856.
Panagoulia D, Dimou G. 1997. Sensitivity of flood events to global climate change. *Journal of Hydrology* **191**: 208–222.
Pilifosova OV, Eserkepova IB, Dolghi SA. 1997. Regional climate change scenarios under global warming in Kazakhstan. *Climatic Change* **36**: 23–40.
Reynard NS, Prudhomme C, Crooks SM. 2001. The flood characteristics of large UK rivers: potential effects of changing climate and land use. *Climatic Change* **48**: 343–359.
Robson AJ, Jones TK, Reed DW, Bayliss AC. 1998. A study of national trend and variation in UK floods. *International Journal of Climatology* **18**: 165–182.
Sailor DJ, Li X. 1999. A semiempirical downscaling approach for predicting regional temperature impacts associated with climate change. *Journal of Climate* **12**: 103–114.
Schulze RE. 1997. Impacts of global climate change in a hydrologically vulnerable region: challenges to South African hydrologists. *Progress in Physical Geography* **21**(1): 113–136.
Seidel K, Ehrler C, Martinec J. 1998. Effects of climate change on water resources and runoff in an Alpine basin. *Hydrological Processes* **12**: 1659–1669.

Semenov MA, Barrow EM. 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* **35**(4): 397–414.

Smith JB, Pitts G. 1997. Regional climate change scenarios for vulnerability and adaptation assessments. *Climatic Change* **36**: 3–21.

Solman SA, Nuñez MN. 1999. Local estimates of global climate change: a statistical downscaling approach. *International Journal of Climatology* **19**: 835–861.

Strzepek KM, Yates DN. 1997. Climate change impacts on the hydrologic resources of Europe: a simplified continental scale analysis. *Climatic Change* **36**: 79–92.

Thompson N, Barrie IA, Ayles M. 1981. *The Meteorological Office Rainfall and Evaporation Calculation System (MORECS)*. Hydrological Memorandum 45, Met. Office: Bracknell.

Wheater HS, Jolley TJ, Onof C, Mackay N, Chandler RE. 1999. Analysis of aggregation and disaggregation effects for grid-based hydrological models and the development of improved precipitation disaggregation procedures for GCMs. *Hydrology and Earth System Sciences* **3**(1): 95–108.

Wigley TML, Jones PD. 1987. England and Wales precipitation: a discussion of recent changes in variability and an update to 1985. *Journal of Climatology* **7**: 231–246.

Wigley TML, Raper SC. 1992. Implications of revised IPCC emissions scenarios. *Nature* **357**: 293–300.

Wilby RL. 1997. Non-stationarity in daily precipitation series: implications for GCM downscaling using atmospheric circulation indices. *International Journal of Climatology* **17**: 439–454.

Wilby RL, Wigley TML. 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* **21**(4): 530–548.

Wilby RL, Wigley TML, Conway D, Jones PD, Hewitson BC, Main J, Wilks DS. 1998. Statistical downscaling of general circulation model output: a comparison of methods. *Water Resources Research* **34**(11): 2995–3008.

Wilks DS. 1999. Multisite downscaling of daily precipitation with a stochastic weather generator. *Climate Research* **11**: 125–136.

Wood AW, Lettenmaier DP, Palmer RN. 1997. Assessing climate change implications for water resources planning. *Climatic Change* **37**(1): 203–228.

Xu CY. 1999. From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. *Progress in Physical Geography* **23**(2): 229–249.

Zorita E, von Storch H. 1999. The analog method as a simple downscaling technique; comparison with more complicated methods. *Journal of Climate* **12**: 2474–2489.

