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Recent climate variability and future climate change scenarios for Great Britain

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Abstract: This article reviews recent climatically extreme periods in Great Britain and presents results from the latest general circulation model (GCM) experiments showing the possible spatial patterns and magnitude of future climate change for this region. During the last decade the British Isles has seen record-breaking periods of above-average temperatures, alongside periods with above and below-average precipitation, combined with an increase in winter precipitation and a decrease in summer precipitation. The impacts of these anomalies, coupled with the possibility that future climate change may increase their frequency and/or severity, have prompted the UK Department of the Environment, Transport and Regions and other organizations involved in environmental management, such as the Environment Agency, to commission a number of studies into their impacts. These have highlighted wide-ranging impacts on the natural environment of Great Britain and on human activities to the extent of affecting the national economy.

The use of GCMs for the development of future climate change scenarios is reviewed. Results from recent ensemble GCM experiments with and without the effects of sulphate aerosols are presented. These show broadly similar changes in temperature and precipitation to previous climate change scenarios prepared for Great Britain. In summary, the scenarios suggest the following: a warming of about 3 °C (3.5 °C) over the region by 2100 with (without) the effects of sulphate aerosols; slight increases in annual precipitation over northern England and Scotland, more pronounced increases over the whole of the region in winter; and slight decreases in precipitation over Wales and central England in summer. These changes are synchronous with decreases in the number of wet-days and increases in the intensity of precipitation on wet-days. The high level of uncertainty associated with regional scenarios of temperature and precipitation is discussed and emphasized.

Key words: climate change; climate variability; general circulation models; scenarios; Great Britain.

I Introduction

Any changes in the radiative balance of the earth, whether due to human-induced increased concentrations of greenhouse gases, or naturally occurring fluctuations due to

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solar output or the frequency of explosive volcanic eruptions, will tend to alter atmospheric and oceanic temperatures and their associated circulation and weather patterns. These changes will be accompanied by changes in the distribution and amount of clouds, precipitation and evaporation. Current estimates from the Intergovernmental Panel on Climate Change (IPCC) of future climate change due to increasing concentrations of greenhouse gases in the atmosphere are in the region of a 2 °C increase in global-mean temperature and a 50 cm increase in sea level by the year 2100 (Houghton *et al*., 1996). Associated with this increase in temperature will be changes in other aspects of climate such as precipitation, evaporation, seasonal regimes and, possibly, the frequency of extreme events.

Although the average air temperature at the earth's surface has risen by about 0.6 °C since the mid-nineteenth century, it can be argued that such a change is natural in origin. Attempts to relate part of the recent change in global climate to anthropogenic influences are referred to as climate change detection. Detection studies have sought to show that the observed spatial and vertical patterns of temperature rise are in accord with those produced by computer model simulations. From the first attempts (Barnett and Schlesinger, 1987) to more recent ones (Santer *et al*., 1993), there was little success. The situation changed with the latest GCM integrations which included both the warming effects of increasing greenhouse gases and the more regionally specific cooling effects resulting from the release of additional pollutants from fossil fuel burning which produce atmospheric sulphate aerosols (Cubasch *et al*., 1992; Mitchell *et al*., 1995). Tropospheric aerosols (small particles) derived mainly from the emission of sulphur dioxide from fossil fuel burning can absorb and reflect solar radiation. They generally produce a negative radiative forcing and contribute to a relative lowering of surface temperature. Detection exercises using these new model integrations do show an increasing convergence between model changes in temperature and those observed, both at the surface (Santer *et al*., 1995) and in the free atmosphere (Santer *et al*., 1996). The increases have been shown to be statistically significant when compared with model-based estimation of natural variability on the decadal-to-century timescale. These results led the IPCC in 1995 to state '… the balance of evidence suggests that there is a discernible human influence on global climate' (Houghton *et al*., 1996: 4).

Assessments of the science of climate change are contained in the two main IPCC reports (Houghton *et al*., 1990; 1996) and developments in the science often appear in high-profile international journals such as *Science* and *Nature*. Reviews of progress can be found in Hulme (1996a; 1997a). There is also a large literature dealing with the potential impacts of climate change on the natural and human environment, for instance, on water resources by the former UK National Rivers Authority (Arnell *et al*., 1994) and the Environment Agency (Arnell *et al*., 1997), agriculture (Parry *et al*., 1996) and regional impacts such as southern Africa (Hulme, 1996b). Reviews of such work appear periodically in IPCC reports such as Watson *et al*. (1996) and regional assessments in Watson *et al*. (1998) and review articles such as Perry (1996) and Wilby (1995). The objectives of this article are two-fold. First, to review some of the impacts of recent climatically extreme periods in the Great Britain. Secondly, to present results from recent GCM experiments showing the possible spatial pattern and magnitude of future climate change in the Great Britain. The article ends with a discussion of the uncertainty associated with climate change scenarios and some of the various government-funded projects set up to consider climate change impacts in the UK.

II Recent climate variability in Great Britain

The past decade has provided ample opportunity to consider the impacts of pronounced climate variability upon the natural environment and human activities within Great Britain. Recent observed changes in climate highlight the complexity of climatic variability and the challenge inherent in its prediction: whilst the world experienced a fairly consistent gradual increase in temperatures during the last century, in line with what we might expect to occur as a result of global warming, Great Britain has seen record-breaking periods of above-average temperatures, alongside periods with above and below-average precipitation, combined with an increase in winter precipitation and a decrease in summer precipitation. During the period between 1901 and 1995, annual Central England Temperature increased by 0.47 °C, with the increase greatest in southern areas and in autumn (+0.93 °C) although with a slight decrease in winter (−0.11 °C) (Jones and Hulme, 1997). Four of the five warmest years in the record (starting in 1659) have occurred in the last decade (1990, 1995, 1997 and 1989). For annual precipitation totals, there has been little overall trend over England and Wales since 1766, although Scotland has recorded a 15% increase since about 1986 (due entirely to increased winter precipitation; Smith, 1995). Over the last two decades over Great Britain, however, there has been a decline in summer precipitation and an increase in winter precipitation and a marked exaggeration in the normal northwest to southeast precipitation gradient across the region (Jones and Conway, 1997). This is highlighted in Figure 1 which shows the ratio of winter to summer precipitation in England and Wales. These changes in

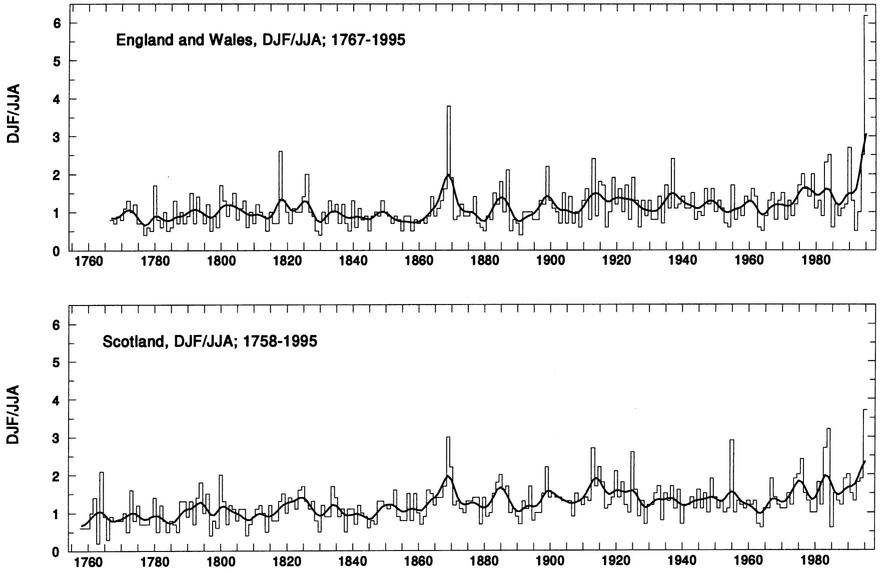

Figure 1 Time series of the ratio of winter (DJF) to the following summer (JJA) precipitation total for England and Wales (1767–1995) and Scotland (1758–1995)

Source: Data from Jones and Conway (1997). Reproduced with permission of *International Journal of Climatology* and the Royal Meteorological Society temperature and precipitation have had important implications for river flows and water resource management.

Over the last decade, there has been very little snow (Jones *et al.*, 1997), a marked upward trend in the frequency of severe gales since 1970 (Palutikof *et al.*, 1997a) and a decline in the frequency of westerly weather types since the 1960s (Kelly *et al.*, 1997). An extensive and up-to-date study of climate and climate variability in the British Isles is contained in Hulme and Barrow (1997). Table 1 lists the characteristics of the three largest climatically anomalous periods in the British Isles during the last decade. Table 2 summarizes the impacts of two of these periods, the warm winters and hot summers of 1988–90 (Cannell and Pitcairn, 1993).

Subak *et al*. (in press) present the results of a more recent study commissioned by the former UK Department of the Environment into the economic impacts of the third period, the warm year and hot summer of 1995, covering a wide range of sectors (see Table 3). Both positive and negative impacts occurred: positive for energy (lower consumption) and health (fewer deaths); negative for agriculture, water supply and buildings insurance. Interestingly, the study identified changes in sensitivity to climate extremes over time. Some changes had occurred inadvertently, but some were the result of deliberate adaptation, particularly in the water, insurance and transport sectors. The

Table 1 Temperature and precipitation characteristics of three climatically anomalous periods during the last decade

Mild winters, 1988–90	Hot summers, 1988–90	Hot summer and warm year, 1995
Change in temperatures		
December to February 1988–89 2.2 °C and December to February 1989–90 2.5 °C above the 1961–80 average (2nd and 6th mildest on record, respectively)	May to October 1989 1.3 °C and May to October 1990 0.9 °C above the 1961–80 average (equal 4th and equal 17th on record)	July and August were the warmest on record, 3 °C above the 1961–90 central England average
November to April 1988–89 had no days when daily mean temperature dropped below 0 °C. November to April 1989–90 had one day (only four such periods since 1845 have had no days below 0 °C)	Summer 1989 had 10 days with average temperature above 20 °C, 9 in 1990 (only 12 summers have had 10 or more days above 20 °C since 1845)	Temperatures for the period November 1994 to October 1995 were the warmest such period on record, since 1659
Change in precipitation		
November to mid-February 1989 was exceptionally dry (9th driest this century)	April to August 1989 was second driest in the England and Wales precipitation series (starting in 1766)	A strong seasonal precipitation contrast, with a very wet winter, a dry spring and a very dry summer (July and August were the driest on record, since 1766)
November to January 1989–90 was very dry but followed by a very wet February to April	May to October 1990 was 70% of the long-term average	

Adapted from: Hulme, 1997b; Jones and Hulme, 1997.

Table 2 Summary of the impacts of the warm winters and hot summers, 1988–90

Sector	Mild winters, 1988–90	Hot summers, 1988–90
River flows and groundwater	Low from November to February 1989, by February many reservoirs and aquifers not filled to usual levels. Wet winter 1990 produced rapid rise in river flows and groundwater. Precipitation, however, fell too rapidly to enable storage of all surplus water	Low river flows and groundwater levels, although not as low as 1976, continued until December 1989, large soil moisture deficits; 1990 river flows and groundwater levels below 1989 levels by early summer and fell below 1976 levels by August
Flora	Phenology – early flowering in many species that normally flower before April. Phenology of late-flowering plants less affected. Germination of many species that require chilling was reduced. Increase capacity of insect pests to overwinter led to increased tree damage, e.g., green spruce aphid outbreak in spring 1989	Despite exhibiting severe drought symptoms during both summers, most vegetation appeared to recover in the autumn or following spring. Broad-leaved types wilted, exhibited leaf discoloration and premature defoliation. Species of moist habitats experienced shoot death. High incidence of fires. High temperatures and sunshine directly affected some species. The combination of high temperatures, increased sunshine and drought affected the flowering of many species
Fauna	Phenology – increased activity of animals, particularly cold-blooded species (insects). Many other effects were observed but it is difficult to establish the effects of climate from many other factors that determine the abundance of fauna. Increase in prey numbers may be offset by increase in predators	Hot dry summers encouraged multiplication and spread of many insects. Adversely affected some habitat types such as wetlands. Some habitats also suffered fire damage. Improved breeding success of some birds
Freshwater	Water temperatures 2 °C above average in both winters, many lakes and rivers that normally freeze over remained ice free. Reduced inputs of salt from roads. Earlier hatching and emergence of fish such as brown trout. Increased winter survival of some river birds	River and lake water temperatures above average but not exceptional. Blooms of blue green algae occurred on 25% of all lakes and reservoirs surveyed by the National Rivers Authority, many were toxic. In 1989, the calm and warm early summer following a mild winter was conducive to the build-up of blue green algae in some lakes. No major effect on freshwater fish numbers

Source: Adapted from Cannell and Pitcairn, 1993.

overall results and some of the recommended adaptive strategies from the 'hot summer' study are summarized in Table 3.

A number of other studies have dealt exclusively with the hydrological aspects of this latter event (Foster *et al*., 1997). Marsh and Turton (1996) review the climatology of the drought and its impacts upon water resources. During early summer 1995 the impacts were mainly related to supply struggling to meet demand because of unprecedented levels of demand that were often associated with surges in garden watering. By August, however, even maintaining supplies became a problem as reservoir stocks had fallen below those of the 1989 and 1990 drought years. Heavy precipitation in the winter of 1994–95 helped maintain groundwater levels in important chalk aquifers; nevertheless, up to 18 million people were still affected by hose-pipe/sprinkler bans. Marsh and Turton (1996) emphasize the need for greater flexibility in the design and application of water strategies aimed at mitigating the effects of severe precipitation deficiencies in the light of what they described as the recent climate 'volatility'.

What can these climatically extreme periods tell us about the impacts of climate change in the future? In order to assess the implications of potential future climate change for society, we need to study and quantify, as far as possible, the sensitivity of environmental and societal systems to present-day climate and its variability. Studies of the impacts of anomalous climatic events reviewed here have highlighted wide-ranging impacts and presented an opportunity to assess the climatic sensitivity of the natural and human environment. There are, however, limitations to the use of past climate anomalies as proxies for the impacts of climate change in the future. First, changing climate is expected to be a continuous process (unlike isolated periods of extreme climate) during which natural and societal systems are also changing and responding regardless of climate change, but also to some extent adapting to it. Secondly, the direction, magnitude and spatial patterns of past climate anomalies may be quite different from those expected to occur in the future. Thirdly, it is necessary to distinguish between climate anomalies that result from natural climate variability from those related to anthropogenic climate change.

III Modelling future climate change

1 General circulation models (GCMs)

GCMs represent the most sophisticated method currently available for estimating the future effects of increasing greenhouse gas concentrations on climate. Coupled ocean–atmosphere GCMs are mathematical representations of the time evolution of the global climate system. Model calculations are based on the laws of physics and executed at widely spaced points of a three-dimensional grid at a resolution of approximately 5° by 5° latitude and longitude (the versions of the Hadley Centre GCM referred to in this study operate at 2.5° by 3.75° resolution). *Control* experiments are run to simulate current climate ($1 \times CO_2$) and two methods can be used to estimate the response of future climate to greenhouse gas forcing: *equilibrium* response and *transient* response.

In equilibrium mode, the GCM is run with an abrupt increase in CO_2 concentrations, usually a doubling from 300 ppm to 600 ppm, referred to as $2 \times CO_2$ equivalent ('$2 \times CO_2$'). The difference between the $1 \times CO_2$ and the $2 \times CO_2$ climate at each grid point is then used to represent the equilibrium climate change due to a doubling of atmospheric CO_2. Up until the early 1990s all GCM simulations had been equilibrium experiments, providing a representation of climate at a time when the climate system had reached a steady-state response to the given increase in greenhouse gas concentrations. The increase in computing power in recent years has led to a dramatic improvement in the scope and ability to simulate the climate system. This improvement is documented in

Table 3 Estimated losses and gains from the anomalous climate of 1995 (£ million gains) and summary of impacts

Sector	Financial/economic	Con./org. expenditure	Net producer revenues	Impacts
Water quality	Negative destabilizing conditions, algae blooms			Algal blooms more frequent than average, but less than expected due to atmospheric circulation, reduced phosphate concentrations and changed management practices
Air quality	Negative, ozone increase; positive, SO_2 decrease			Ozone concentrations did not increase as much as expected, due to certain characteristics of the atmospheric circulation
Forestry Yield improvement	Positive	Unchanged	e.g., double profits for sitka spruce harvest	One warm year will have negligible impact on coniferous forest productivity, prolonged/sustained higher temperatures will increase productivity
Crown condition	Negative, not valued			Health of lowland deciduous trees, particularly beech, suffered in 1995
Fires	− £0.35	Increased	Increased	
Agriculture				
Arable crops	+£29	Increased	Increased to a lesser extent because of higher costs	Some gains to arable crops, losses due to increased need for purchased feed and deterioration in overall animal health. Adaptive responses required for sustained warmer temperatures include increased irrigation for arable crops, sprinkling and dousing equipment for livestock, and water oxygenation for freshwater agriculture
Livestock	− £207	Increased	Decreased (?)	
Aquaculture	− £4	Decreased (?)		

Water	−£96	−£96 added water supply costs		Significant regional differences in impact due to reliance on groundwater (less sensitive) and surface water (more sensitive). Planned adaptation includes regional co-operation agreements and plans to drill permanent boreholes for use during drought conditions
Building insurance	Net negative: −£90			Unusually high losses due to increased subsidence-related damage. Reduced claims for burst pipes. Possible adaptation includes improving the knowledge base on potentially vulnerable properties. In the long term, changes in construction methods and underpinning will mitigate this problem
Subsidence	Negative	Unchanged	−£150–200	
Burst pipes	Positive	Unchanged	+£50–125	
Tourism	Lower spending	−£239	−£239	Annual summer breaks tend to be independent of the weather, breaks at other times of the year are more weather dependent
Fires[1]	Negative, not valued	Increased	Increased	Clear positive (negative) relationship identified between number of outdoor fires and temperature (precipitation)
GDP	*Not valued*	*£170*[2]	*£170*[2]	*Overall economic impact shows that the UK economy is sensitive to climatic variations, particularly periods of extreme weather such as 1995*

Notes:
1) Expenditures for fire control not quantified.
2) Sunny conditions in December linked to output increase in the fourth quarter.
Con./org. expenditure = Consumer/organization expenditure.
Source: Adapted from Palutikof *et al*., 1997b; Subak, 1997.

the two IPCC reports (Houghton *et al.*, 1990; 1996). These changes have resulted in higher-resolution capability in the GCMs, the production of improved simulations of the present climate, and the ability to model a transient future climate using coupled atmospheric–ocean GCMs.

Transient experiments involve coupled ocean–atmosphere GCMs which are run over a control period to simulate the climate without enhanced greenhouse gas forcing (and to ensure the ocean and atmosphere reach a steady state) and then forced with gradually increasing radiative forcing (representing increased concentrations of greenhouse gases and sulphate aerosols) over time to provide a time-dependent transient response of the climate system – more realistic than a '$2 \times CO_2$' experiment. It is results from recent transient experiments performed by the Hadley Centre for Climate Prediction and Research that are used here.

2 How much change globally?

Estimates of global mean increases in surface air temperature and sea level out to 2100 based on the latest IPCC estimates and incorporating the effects of sulphate aerosols are around 2 °C and 50 cm, respectively. Both estimates have a range of uncertainty associated with them due to the value of *climate sensitivity* and to the future rate of emissions of greenhouse gases. Climate sensitivity refers to the steady-state increase in global annual mean surface air temperature associated with a given global mean radiative forcing. This has been quantified by calculating the change in global mean temperature resulting from a doubling of CO_2 and ranges from 1.5° to 4.5 °C with a mid-value of 2.5 °C used by the IPCC as a 'best-guess'.

To account for the uncertainty of future emissions of greenhouse gases IPCC developed six scenarios, IS92a–f, based on different assumptions concerning population and economic growth, land use, technological changes, energy availability and fuel mix over the period 1990–2100 (Leggett *et al.*, 1992). Taking into account the uncertainty due to the magnitude of the climate sensitivity and the range of emission scenarios produces the following range of increase in global annual mean surface air temperature: a lower limit of 0.8 °C by 2100 with climate sensitivity of 1.5 °C and IS92c (lowest emissions); and an upper limit of 4.5 °C with climate sensitivity of 4.5 °C and IS92e (highest emissions). In spite of the wide range of warming rates in all the cases the average *rate* of global warming would probably be greater than any seen in the last 10 000 years. Uncertainty in rates of sea-level rise range from 15 cm by 2100 with IS92c emissions (low) and low climate and ice-melt sensitivity up to 95 cm by 2100 with IS92e emissions (high) and high climate and ice-melt sensitivities.

Along with increases in annual global mean temperature and sea level all GCM experiments with increased concentrations of greenhouse gases (with and without sulphate aerosols) produce the following set of changes (based on Houghton *et al.*, 1996). All experiments show greater surface warming of the land than of the sea in winter, a maximum surface warming in high northern latitudes in winter, an enhanced global mean hydrological cycle and increased precipitation and soil moisture in high latitudes in winter. Most experiments show a reduction in the strength of the North Atlantic thermohaline circulation and a widespread reduction in diurnal range of temperature. Aerosols tend to reduce the magnitude of temperature and precipitation changes; however, the effect is not a simple offset of the effects of increased greenhouse gases. The spatial distribution of aerosols has a strong influence on regional patterns of climate change. Higher temperatures will lead to a more vigorous hydrological cycle. Knowledge is currently insufficient to determine whether there will be any changes in the frequency and spatial distribution of severe storms. In spite of the agreement between GCM results, however, large uncertainties remain in the estimation of future emissions and concentrations of greenhouse gases, rates of biogeochemical cycling and the representation of climate processes in models (particularly feedbacks associated with clouds, oceans, sea ice and vegetation).

3 How much change regionally?

There is much greater uncertainty in constructing scenarios at regional scales because of the following uncertainties (from Houghton *et al.*, 1996):

- Coarse resolution of GCMs prevents realistic representation of many geographic features, vegetation and interactions between the atmosphere and land surfaces which may be important on regional scales.
- Greater natural variation in local climate than in climate averaged over continental or larger scales.
- Regional impacts of aerosols on climate.
- Changes in land use and land cover as a result of climate change may influence temperature and precipitation, especially in lower altitudes.

It is because of these uncertainties that the regional changes in climate derived from GCM experiments are termed *scenarios* or projections and cannot be considered predictions. At best, these scenarios are plausible and physically consistent descriptions of a future climate. Scenarios serve to provide a framework from which the potential magnitude and nature of future climate change can be assessed and which provide input to process models and integrated assessments to try to quantify the potential impacts of future climate change on the natural environment and human society.

IV Future climate scenarios for Great Britain

1 Previous scenarios

The methods of deriving climate scenarios from GCMs have been reviewed comprehensively in the literature. For Great Britain there have been a series of climate change scenarios put forward since the early 1980s. Table 4 lists the details of four such scenarios of future climate change. The first of these, the Climate Change Impacts Review Group (CCIRG, 1991) scenarios, was really the first published UK government-initiated assessment of the issue and it provided the basis for many impacts studies, such as the National Rivers Authority Research and Development Report 12 impacts assessment (Arnell *et al.*, 1994). The CCIRG was based on the IPCC 1990 scientific assessment of climate change and the results from equilibrium GCM experiments. Following developments in the science of climate change, in particular the second IPCC scientific assessment (Houghton *et al.*, 1996), a second CCIRG scenario was published in 1996 (CCIRG, 1996). This was based on the first transient GCM experiment (UKTR) undertaken in 1991–92 by the Hadley Centre and has also been widely used in climate impact studies.

Table 4 Details of four scenarios of future climate change prepared for the UK from GCM experiments

No.	Scenario	Year published	Models used	Emissions	Future periods
1	CCIRG	1991	Five equilibrium GCM experiments	IPCC BAU	2010, 2030, 2050
2	CCIRG	1996	UKTR	IS92a	2020, 2050
3	Raper *et al.*	1997	HADCM2 GHG + SUL	IS92a	2050
4	Arnell *et al.*	1997	Various	IS92a	2020

Note:
BAU = Business as usual.

2 Recent results from the Hadley Centre for Climate Prediction

Over the last couple of years, results have become available from a number of experiments performed by the Hadley Centre using the new Meteorological Office Unified Model (known as the HADCM2), itself derived from earlier model versions (Mitchell *et al.*, 1995). These results supersede those of previous scenarios produced for Great Britain and they form the basis for a new UK Climate Impacts Programme scenario (Hulme *et al.*, 1998). HADCM2 was used to perform a number of experiments to investigate future climate change, as follows:

1) A 1400 year control run (CON) with no changes in external forcing (with CO_2 fixed at the preindustrial level of 280 ppmv) in order to simulate climate without enhanced greenhouse forcing.
2) Greenhouse gas only experiments (GHG) in which the GCM is forced with historic (1860–1990) and future (1990–2100) concentrations of greenhouse gases similar to, but slightly higher than, IPCC scenario IS92a.
3) Greenhouse gas plus sulphate aerosols (GHG + SUL) in which the GCM is forced with historic and future concentrations of greenhouse gases similar to, but slightly higher than, IPCC scenario IS92a and with estimates of sulphate aerosol emissions also based on IS92a up to the year 2100.

Four experiments have been performed with the GHG forcing conditions and four with the GHG + SUL forcing conditions. These multiple experiments (known as *ensembles*) have the same external forcing (i.e., increasing levels of greenhouse gases and/or sulphate aerosols) but are started with slightly different initial conditions. The purpose of undertaking ensemble simulations is to estimate the change in climate due to increased greenhouse gas forcing (the greenhouse signal) from the natural climate variability generated within the GCM. More ensembles with different emissions scenarios have now been performed (e.g., a scenario similar to IS92d). For the purpose of this article, however, only the GHG and GHG + SUL with a forcing similar to IS92a emissions (Mitchell *et al.*, 1995; Mitchell and Johns, 1997) will be considered.

The following sections describe some of the changes in climate that may occur over Great Britain. Results from the GCM experiments are shown up to 2100 for the CON, the

GHG and GHG + SUL ensembles for four GCM grid boxes designated as land overlying Great Britain.

3 Change in temperature

In the GHG experiments warming compared to the control is slightly greater over central England (3.3 °C by 2100) than northern Scotland (3 °C by 2100, see Figure 2). The dashed line shows the mean of the four ensemble runs which generally lie within 1 °C of each other. Seasonal changes in the GHG are greatest in winter, roughly 4 °C in central England and 3.5 °C over northern Scotland by 2100 (Figure 4) – whereas all summer temperatures increase by roughly 3 °C and 2.2 °C, respectively (Figure 3). The range between the seasonal values of the ensemble members is much greater than the range in

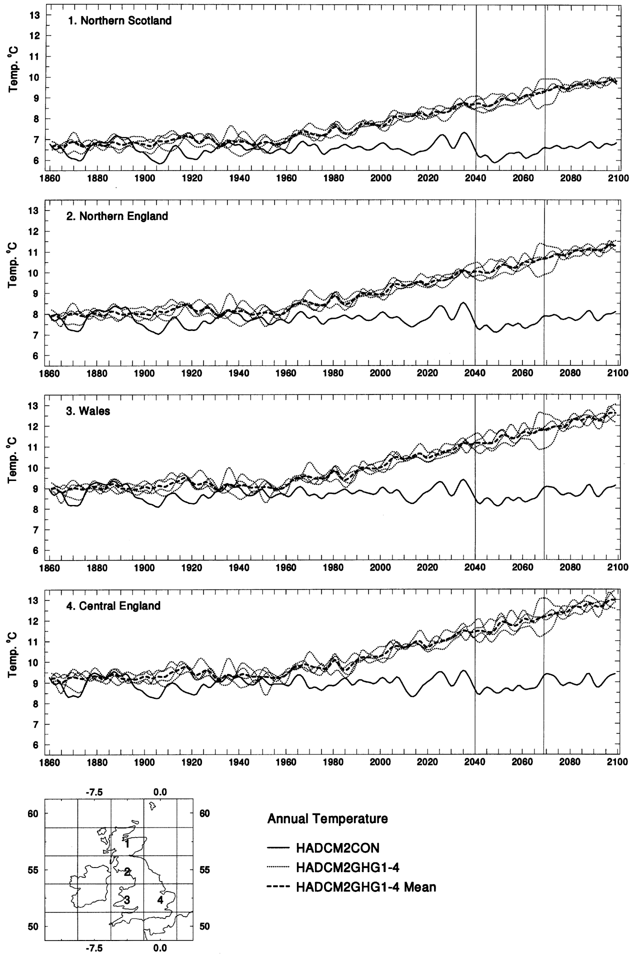

Figure 2 Ten-year moving average of mean annual temperature change (°C) in the four HADCM2 GCM land grid boxes overlying Great Britain (see map insert). Results are shown for the CON (bold), GHG ensemble (dotted) and GHG ensemble mean (dashed) experiments, from 1861 to 2099

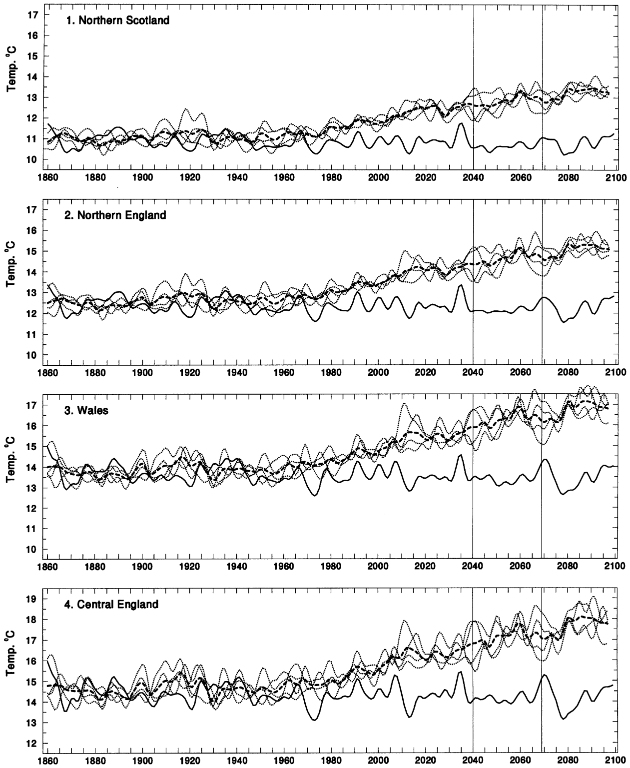

Figure 3 Ten-year moving average of mean summer (JJA) temperature change (°C) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG ensemble (dotted) and GHG ensemble mean (dashed) experiments, from 1861 to 2099

the annual values – roughly 2 °C in winter and 1.5 °C to 2 °C in summer, compared to 1 °C on annual time steps. Annual temperatures in the GHG + SUL ensemble are roughly 0.5 °C lower than the GHG ensemble by 2100 (Figure 5, seasonal changes are not shown). In Figures 2 and 5 the GHG and GHG + SUL results show temperature increases more rapidly and to a greater extent in the GHG compared to the GHG + SUL. The GHG + SUL rises faster than GHG in the second half of the next century as the sulphate forcing lessens as a fraction related to the forcing due to greenhouse gases. The natural variability of the control run means that the GHG + SUL ensemble in these regions only rises out of the background noise by 2020 at the earliest (if at all for precipitation) whereas in the GHG ensemble this occurs by about 1960 (although bearing in mind that the control experiment has no historic greenhouse gas or sulphate aerosol forcing).

4 Change in precipitation

The precipitation signal is much less pronounced than the temperature signal in both the GHG and GHG + SUL ensembles. There is no major change in annual precipitation over Wales and central England by 2100 in the GHG ensemble mean (Figure 6). Annual

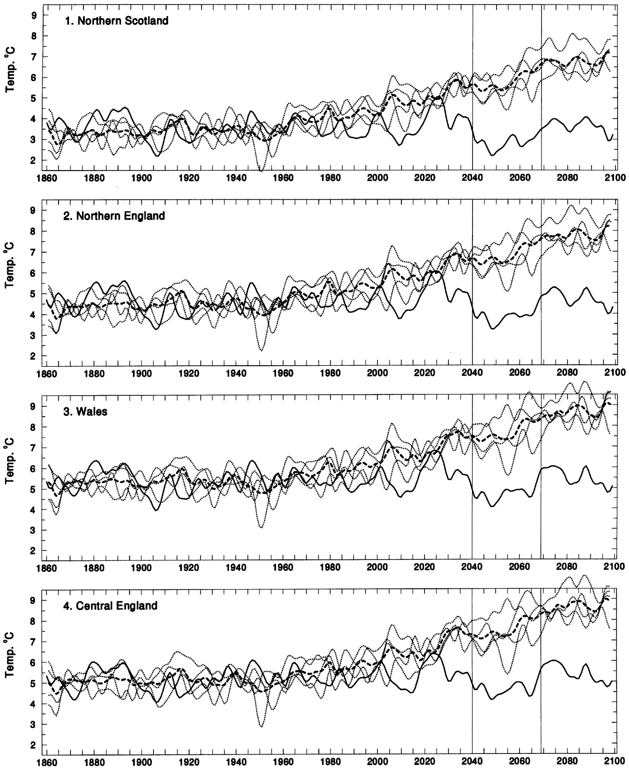

Figure 4 Ten-year moving average of mean winter (DJF) temperature change (°C) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG ensemble (dotted) and GHG ensemble mean (dashed) experiments, from 1861 to 2099

precipitation increases over northern England (roughly 0.5 mm/day by 2100) and northern Scotland (roughly 0.7 mm/day) with changes becoming apparent around the 1990s. The annual changes mask more pronounced seasonal changes: increases occur in winter (around 0.5 mm/day) over all four grid boxes whereas very slight decreases occur in summer (around 0.25 mm/day) over Wales and central England and slight increases (0.1 mm/day) over northern Scotland and northern England (Figures 8 and 7, respectively). In the GHG + SUL ensemble the spatial patterns of precipitation change on annual (Figure 9) and seasonal (not shown) time steps are similar to those with the GHG ensemble (increase in the north, slight decrease in the south); however, the magnitude of the change is lower (cf. Figures 6 with 9).

The scatter due to variability between the ensemble runs is much greater with precipitation than with temperature, so much so that in many cases (particularly summer) the range of ensemble values still encompasses the control value even by 2100. This makes it much more difficult to disentangle the ‘true’ greenhouse gas-induced change in precipitation from the natural variability – which may indeed be the case in the real world.

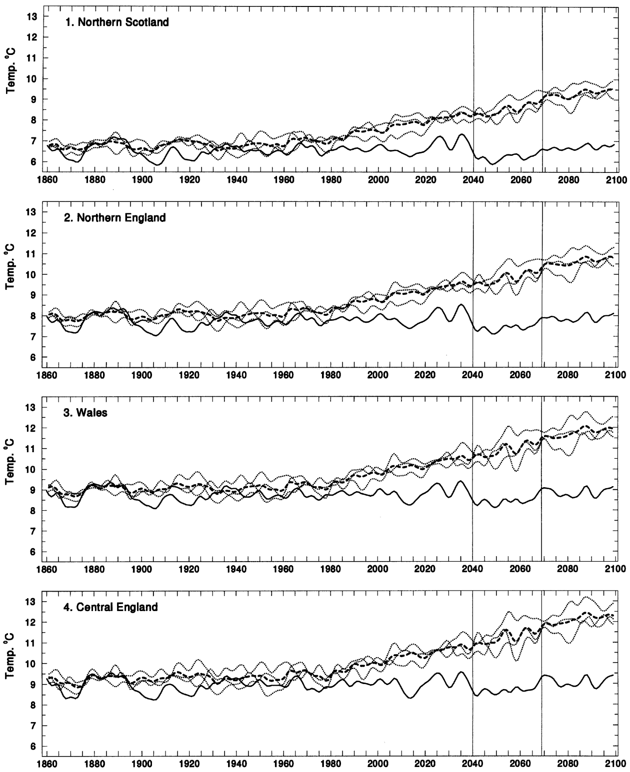

Figure 5 Ten-year moving average of mean annual temperature change (°C) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG + SUL ensemble (dotted) and GHG + SUL ensemble mean (dashed) experiments, from 1861 to 2099

5 Change in other variables

Along with changes in temperature and precipitation regimes, other aspects of climate are also expected to change but, as discussed earlier, there is less confidence in projections of many climate variables other than temperature. Potential evapotranspiration is likely to increase due to increases in temperature, although the nature of changes in the other factors which affect it may offset or enhance the effects of higher temperatures. Arnell *et al*. (1997) found changes in potential evapotranspiration for the UK, calculated using the Penman equation ranging from −3% to +7% with GHG + SUL and GHG experiments for the 2020s.

Conway and Jones (1996) looked at changes in the frequency of weather types that affect the British Isles. Figure 10 shows the monthly frequency of weather types for one member of the GHG + SUL ensemble over the period best representing the present day (1961–90) and for two 30-year periods in the future: 2040–69 and 2070–99. There are some slight differences between the three periods, such as a slight increase in the number of westerlies during spring and a decrease in easterlies during spring, but on the whole the differences are rather small. From this example there is no real indication of any major changes in the frequency of circulation patterns affecting Great Britain.

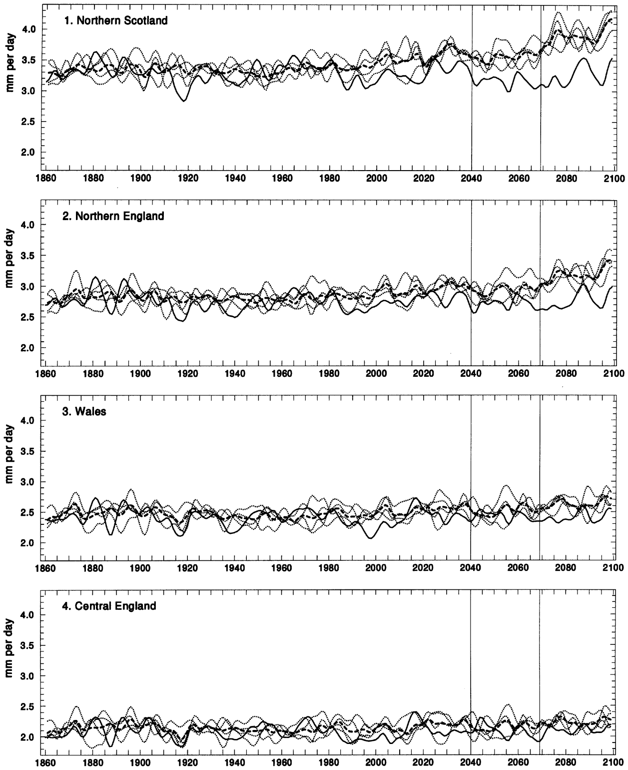

Figure 6 Ten-year moving average of mean annual precipitation change (mm/day) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG ensemble (dotted) and GHG ensemble mean (dashed) experiments, from 1861 to 2099

6 Changes in the frequency of extreme events

Although it is not really clear from GCM results whether or not the frequency of extreme events will change, a change in the mean temperature or precipitation without changing the variability will lead to a change in the magnitude of extreme values, simply by shifting the distribution. For instance, Barrow and Hulme (1996) looked at changes in probabilities of daily temperature extremes in the UK due to global warming. Table 5 lists some recent temperature anomalies and their return periods for the 1961–90 climate and for one of the SUL + GHG ensemble situations (centred on the year 2050) given a 1.5 °C change in global mean temperature and no difference between the observed and future frequency distribution of events. The results indicate that an event such as the 1995 'hot summer' may be expected to occur one in every 90 years in the current (1961–90) climate whereas by 2050 such events may increase in frequency to one in every three years.

Recent GCM integrations reviewed in the last two IPCC reports (Houghton *et al.*, 1990; 1996) have indicated increases in precipitation intensity and hence the magnitude and frequency of extreme precipitation events. Hennessy *et al.* (1997) found an increase in

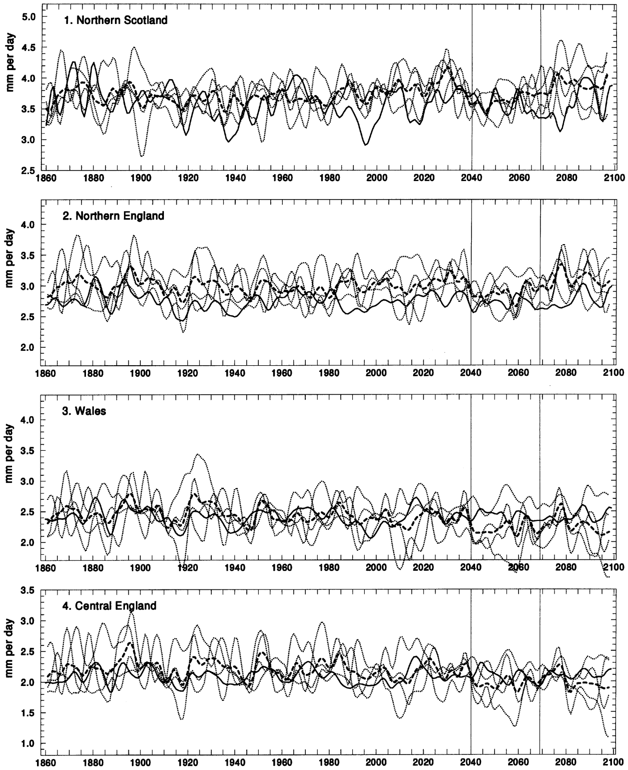

Figure 7 Ten-year moving average of mean summer (JJA) precipitation change (mm/day) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG ensemble (dotted) and GHG ensemble mean (dashed) experiments, from 1861 to 2099

Table 5 Some recent extreme annual and seasonal temperature anomalies from the 1961 to 1990 average and their approximate estimated return periods under current (1961–90) climate and under one of the SUL + GHG ensembles for the years centred around 2050 (from grid box 4, Figure 2). The global warming by this date is about 1.5 °C. Estimates derive from statistical analysis of the Central England Temperature record

	Seasonal anomaly (°C)		Return period (years)	
	Temperature	Anomaly	1961–90	2050
Annual 1990	10.6	+1.1	65	1.6
Summer 1976	17.8	+2.5	310	5.5
Summer 1995	17.4	+2.1	90	3.0
Winter 1988–89	6.5	+2.4	30	4.0
Winter 1962–63	−0.3	−4.4	230	∞

Source: From Raper, S.C., Viner, D., Hulme, M. and Barrow, E. 1997: Global warming and the British Isles. In Hulme, M. and Barrow, E., editors, *Climates of the British Isles, present, past and future,* London: Routledge, 326–39. Reprinted by kind permission of Routledge.

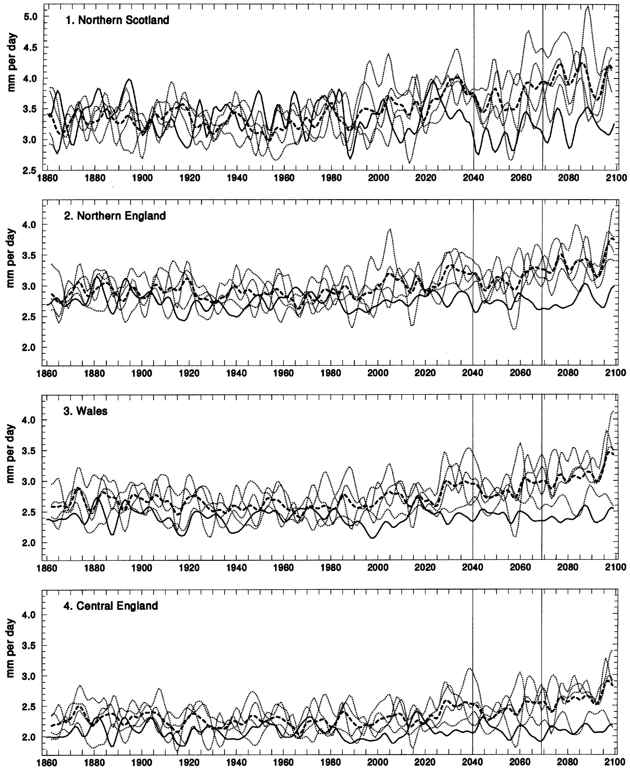

Figure 8 Ten-year moving average of mean winter (DJF) precipitation change (mm/day) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG ensemble (dotted) and GHG ensemble mean (dashed) experiments, from 1861 to 2099

precipitation intensity simulated in high latitudes in two '$2 \times CO_2$' equilibrium GCM experiments. For a given return period of at least one year, precipitation intensity in Europe increased by 10 to 25%. Conway and Jones (1996) analysed changes in daily precipitation produced by one ensemble member from the GHG and SUL + GHG experiments for the 30-year period, 2040–69 (highlighted by vertical lines in Figure 2). Interestingly, there are contrasting changes in the frequency of wet-days (defined as days with greater than 0.1 mm of precipitation) and the mean wet-day amount (see Table 6). There are decreases in the frequency of wet-days over Great Britain in most seasons (increases only occur during summer in GHG). In contrast to wet-day frequency, however, there are substantial increases in the mean wet-day amount in all grid boxes and seasons. This is indicative of a more intense hydrological cycle with fewer actual wet-days but much greater rain amounts on wet-days. The combined effects of decreased numbers of wet-days and increased wet-day amounts produce an increase in annual precipitation. How such changes in grid-box area average precipitation relate to finer scale changes (such as point intensity) in the real world is difficult to assess and may be affected by changing precipitation type (synoptic or convective; Osborn, 1997).

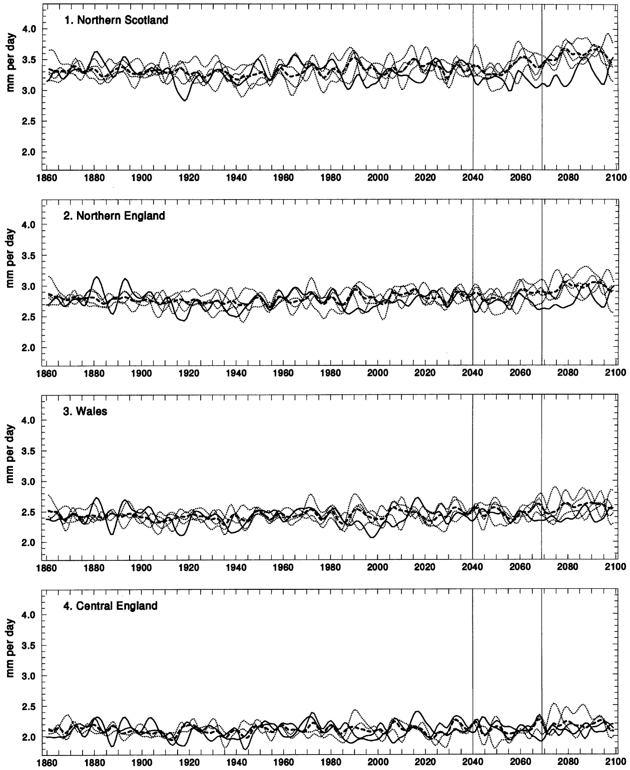

Figure 9 Ten-year moving average of mean annual precipitation change (mm/day) in the four HADCM2 GCM land grid boxes overlying Great Britain. Results are shown for the CON (bold), GHG + SUL ensemble (dotted) and GHG + SUL ensemble mean (dashed) experiments, from 1861 to 2099

7 Rates of change

The *rate* of future climate change is very important. The IPCC scenarios suggest rates of global-mean temperature change up to 0.2 °C per decade which appear unprecedented in the historical record. Parry *et al.* (1996) identify three types of critical levels of climate change:

1) Critical changes of climatic averages.
2) Critical changes of climatic variability.
3) Critical rates of climatic change.

Obviously, these critical levels will be heavily case dependent and Parry *et al.* (1996) suggest a stepwise method for defining critical climate change based on region and sector. The rate of future change may not necessarily be constant, and there is a possibility of fairly rapid and perhaps unexpected changes occurring. For instance, Klein Tank and Können (1997) assessed the impact of a sudden weakening in the Gulf Stream/North Atlantic Drift on temperatures in The Netherlands. Although it is beyond the capability of current GCMs to simulate fully such detailed features, many do suggest a weakening of

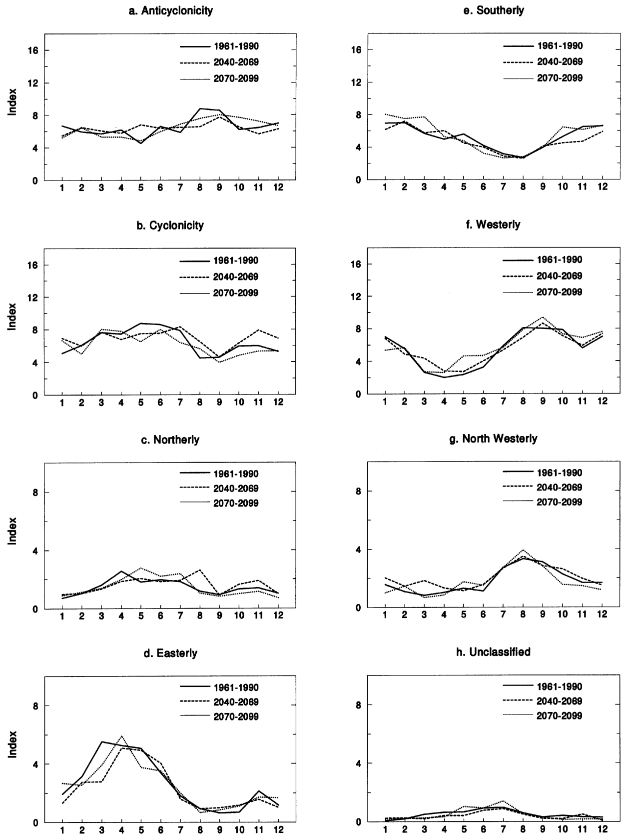

Figure 10 Monthly frequencies of the seven basic Lamb weather types and unclassified types. Results are shown for one member of the GHG + SUL ensemble: 1961–90 (bold), GHG + SUL 2040–69 (dotted) and GHG + SUL 2070–99 (long dash)

the thermohaline circulation in the oceans with enhanced greenhouse gas warming. Therefore, a pronounced change in the North Atlantic circulation in the future should not be discounted. In the study of Klein Tank and Können (1997) for The Netherlands, days with advection of air masses of maritime origin had their observed temperatures lowered by a fixed value to represent the influence of a cooler Atlantic Ocean. Temperatures were left unchanged on days with nonmaritime air masses. Such changes lead to a decrease in mean temperature throughout the year and an increase in the relative frequency of cold winters and cool summers. A similar result might be anticipated for Great Britain although the GCM experiments presented here do not indicate such an outcome.

V Uncertainties in scenarios of future climate change

1 Emissions scenarios

There is great uncertainty associated with scenarios of future emissions of greenhouse gases and further uncertainty involved in converting emissions to actual atmospheric

Table 6 Percentage changes in daily characteristics of temperature and precipitation in four GCM grid boxes taken from one member of each of the GHG and SUL + GHG integrations for the period 2040–69 minus the period 1961–90

	SUL + GHG, 2040–69			GHG, 2040–69		
	Precipitation	Precipitation intensity[1]	No. of days with precipitation[2]	Precipitation	Precipitation intensity[1]	No. of days with precipitation[2]
1) Northern Scotland						
Annual	4.1	6.5	−1.8	11.9	14.7	−1.5
Winter	3.0	10.1	−3.7	16.9	15.2	1.0
Summer	8.5	8.3	0.3	2.6	7.5	−3.1
2) Southern Scotland						
Annual	3.3	5.9	−1.1	15.2	17.6	−0.7
Winter	1.5	6.0	−2.1	21.0	17.9	1.4
Summer	2.0	4.6	−1.1	4.2	12.9	−4.4
3) Wales						
Annual	3.4	6.7	−1.1	15.2	16.0	0.3
Winter	7.6	10.9	−1.7	26.1	17.4	3.8
Summer	−4.0	3.6	−3.6	2.9	14.6	−4.4
4) Central England						
Annual	2.4	8.4	−2.2	13.0	16.0	−0.6
Winter	6.7	9.4	−1.4	24.1	20.8	1.5
Summer	−0.7	5.7	−2.5	−2.1	11.8	−5.2

Notes:
1) Percentage change in mean precipitation on wet-days.
2) Percentage change in number of days with 0.1 mm precipitation.

concentrations. Future emissions controls, such as those agreed at the recent Kyoto meeting, will also affect the rates of change (the recent agreement will produce a reduction in global mean temperature rise of 0.27 °C by 2100 from the IS92a IPCC emissions scenario, given no change in sulphate aerosols; Wigley, 1998). It should be noted that the adopted sulphate emission scenario used for the GHG + SUL scenario presented here overestimates present-day SO_2 emissions and, almost certainly, future SO_2 emissions. This overestimate, combined with the very simplistic treatment of aerosol chemistry and its radiative forcing effects, suggests the scenario will soon be superseded by an improved greenhouse gas plus sulphate aerosol scenario (Mitchell *et al.*, in press; Hulme, pers. comm.).

2 Climate modelling

Many aspects of the climate system remain imperfectly understood and GCMs are being constantly redesigned. To a certain extent, the rates of future change are dependent on the characteristics of the Hadley Centre GCM (HADCM2). Future model improvements or different GCMs may well affect the rate and spatial patterns of future climate change presented here. For instance the results presented here do not take into account the uncertainty in the range of values for the climate sensitivity to a given increase in radiative forcing. This varies between GCMs and is usually taken to range from 1.5 °C to 4.5 °C (in the HADCM2 GCM it is roughly 2.5 °C).

3 Spatial and temporal scales

It is likely that changes in the frequency of extremes will have a greater impact upon the environment and human activities than changes in mean climate. Unfortunately, however, at the present time GCMs cannot produce reliable estimates of localized extreme weather events such as storms. Indeed there is much greater uncertainty with GCM scenarios at the spatial and temporal scales required for impact assessment. Techniques such as 'downscaling' may be used to improve the resolution of GCM scenarios but they will always be constrained by the quality of the input data from the GCM (Wilby and Wigley, 1997).

4 Disentangling the anthropogenic climate change or trend from natural variability

From the review of recent climate variability in Great Britain it is clear that significant levels of variability lie within the bounds of what has traditionally been considered to be our stable climate. Anthropogenically induced climate change will be superimposed upon this natural variability, or noise. How it manifests itself is an issue for detection and modelling studies to determine. What is clear from the scenarios presented here is that for variables such as precipitation it may be some time before this is possible. In the GHG + SUL ensemble, for example, the forcing gradually increases temperatures but each future decade need not be warmer than the previous, as for a decade or two the natural variability of the model could act to counter the anthropogenic influence. Indeed, for an area as small as Great Britain it may still be possible for an extremely cool year to occur in the 2040s which would be no different in mean value from an average year occurring today. Taking into account the natural internal GCM variability through the use of ensemble experiments makes this even harder – although the practice will aid in distinguishing the 'natural' variability from the anthropogenic signal on a regional scale.

VI Conclusions

The impacts of three periods of extreme climate during the last decade clearly highlight the sensitivity of the natural environment and human activities to climate fluctuations. In the first study of its kind, Subak *et al*'s (in press) assessment of the economic impacts of the hot summer and warm year of 1995 shows the UK economy is affected by such events. It is too early to say whether any of the climate volatility within Great Britain during the last decade can be attributed to anthropogenically induced climate change. Nevertheless, similar changes in seasonal precipitation have occurred during the last decade to those suggested in the climate change scenarios presented here. What is clear from Subak *et al.*'s study, however, is that different sectors of the UK have already begun to take adaptive and mitigative measures to reduce the impact of such events. The Department of the Environment, Transport and Regions (DETR, the former Department of the Environment), put a duty on water companies to take into consideration climate change and the UK Environment Agency has a commitment to addressing the causes and effects of climate change. The Environment Agency, with its wide range of environmental management duties, is also currently carrying out research on the impacts of climate change in its areas of responsibility, which will give rise to a range of responses – both adaptation and mitigation. In response to the threat of future climate change the UK government has set up a number of facilities to promote climate impacts research in the UK: the Hadley Centre for Climate Prediction and Research (http://www.meteo. gov.uk/sec5/sec5pg1.html), which concentrates on climate modelling and observations; the Climate Impacts LINK project (http://www.cru.uea.ac.uk/link), concerned with the development and provision of climate change scenarios for impact assessment; and the UK Climate Impacts Programme (http://www.ecu.ox.ac.uk/ukcip.html), set up to provide a stakeholder-led assessment of climate change impacts on the UK. This has recently initiated, with the Ministry of Agriculture, Fisheries and Food and the DETR, an integrated study of the effects of climate change in the north west and East Anglia regions.

The future climate scenarios presented here show broadly similar changes in temperature and precipitation to the scenario in the CCIRG (1996) which came from an earlier version of the GCM used by the Hadley Centre. In summary, the changes suggest the following:

- A warming with respect to 1961–90 of about 3.5 °C by 2100 over Great Britain without taking into account the effects of sulphate aerosols, and about 3 °C with them accounted for.
- Slight increases in precipitation over northern England and Scotland, more pronounced increases over the whole of Scotland, England and Wales in winter and very slight decreases over Wales and central England in summer. This will cause a slight steepening in the north–south precipitation gradient and an enhancement of the winter–summer precipitation contrast over Great Britain.
- A decrease in the number of wet-days but an increase in the intensity of precipitation on wet-days.
- No major change in circulation patterns over the region.

There is a high level of uncertainty associated with regional scenarios of temperature and precipitation and the results presented here should be treated as one possible outcome of future climate. Future developments in climate modelling and 'downscaling' techniques will reduce the uncertainty of climate scenarios.

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References

Arnell, N.W., Jenkins, A. and **George, D.G.** 1994: *The implications of climate change for the National Rivers Authority. Final report (R&D report 12) to National Rivers Authority*. London: HMSO.

Arnell, N., Reynard, N., King, R., Prudhommme, C. and **Branson, J.** 1997: *Effects of climate change on river flows and groundwater recharge; guidelines for resource assessment. Environment Agency Technical Report* W82. London: UK Water Industry Research Ltd.

Barnett, T.P. and **Schlesinger, M.E.** 1987: Detecting changes in global climate induced by greenhouse gases. *Journal of Geophysical Research* 92, 14772–80.

Barrow, E.M. and **Hulme, M.** 1996: Changing probabilities of daily temperature extremes in the UK related to future global warming and changes in climate variability. *Climate Research* 6, 21–31.

Cannell, M.G.R. and **Pitcairn, C.E.R.** 1993: *Impacts of the mild winters and hot summers in the United Kingdom in 1988–1990*. London: HMSO.

CCIRG (Climate Change Impacts Review Group) 1991: *The potential effects of climate change in the United Kingdom*. London: Department of the Environment/HMSO.

—— 1996: *Review of the potential effects of climate change in the United Kingdom*. London: Department of the Environment/HMSO.

Conway, D. and **Jones, P.D.** 1996: *POPSICLE – Production of Precipitation Scenarios for Climate Impacts in Europe. Final report* (European Community Environment Research Programme, contract: EV5V-CT-94-0510). Norwich: Climatic Research Unit.

Cubasch, U., Hasselmann, K., Höck, H., Maier-Reimer, E., Mikola-Jewicz, U., Santer, B.D. and **Sausen, R.** 1992: Time-dependent greenhouse warming computations with a coupled ocean–atmosphere model. *Climate Dynamics* 8, 55–69.

Foster, M., Werrity, A. and **Smith, K.** 1997: The nature, causes and impacts of recent hydroclimatic variability in Scotland and Northern Ireland. In *Proceedings of the 6th BHS National Hydrology Symposium*, Salford.

Hennessy, K.J., Gregory, J.M. and **Mitchell, J.F.B.** 1997: Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dynamics* 13, 667–80.

Houghton, J.R., Jenkins, G.J. and **Ephraums, J.J.**, editors, 1990: *Climate change: the IPCC scientific assessment*. Cambridge: Cambridge University Press.

Houghton, J.R., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and **Maskell, K.**, editors, 1996: *Climate change 1996: the science of climate change*. Cambridge: Cambridge University Press.

Hulme, M. 1996a: Global warming. *Progress in Physical Geography* 20, 216–23.

—— 1996b: *Climate change and southern Africa: an exploration of some potential impacts and implications in the SADC region*. Norwich: Climatic Research Unit and WWF International.

—— 1997a: Global warming. *Progress in Physical Geography* 21, 446–53.

—— 1997b: The climate in the UK from November 1994 to October 1995. *Weather* 53, 242–57.

Hulme, M. and **Barrow, E.**, editors, 1997: *Climates of the British Isles, present, past and future*. London: Routledge.

Hulme, M., Barrow, E.M., Jenkins, G.J., New, M., Osborn, T.J and **Viner, D.** 1998: *Climate change scenarios for the UK Climate Impacts Programme. UKCIP Technical Report*. Norwich: Climatic Research Unit.

Jones, P.D. and **Conway, D.** 1997: Precipitation in the British Isles: an analysis of area-average data updated to 1995. *International Journal of Climatology* 17, 427–38.

Jones, P.D., Conway, D. and **Briffa, K.R.** 1997: Precipitation variability and drought. In Hulme, M. and Barrow, E., editors, *Climates of the British Isles, present, past and future*, London: Routledge, 197–219.

Jones, P.D. and **Hulme, M.** 1997: The changing temperature of 'central England'. In Hulme, M. and Barrow, E., editors, *Climates of the British Isles, present, past and future*, London: Routledge, 173–98.

Kelly, P.M.K., Jones, P.D. and **Briffa, K.R.** 1997: Classifying the winds and weather. In Hulme, M. and Barrow, E., editors, *Climates of the British Isles, present, past and future*, London: Routledge, 153–72.

Klein Tank, A.M.G. and **Können, G.P.** 1997: Simple temperature scenario for a Gulf Stream induced climate change. *Climatic Change* 37, 505–12.

Leggett, J., Pepper, W.J. and **Swart, R.J.** 1992: Emissions scenarios for the IPCC: an update. In Houghton, J.T., Callander, B.A. and Varney, S.K., editors, *Climate change 1992: the supplementary report to the IPCC scientific assessment*, Cambridge: Cambridge University Press, 75–95.

Marsh, T.J. and **Turton, P.S.** 1996: The 1995 drought – a water resources perspective. *Weather* 51, 46–53.

Mitchell, J.F.B. and **Johns, T.C.** 1997: On the modification of global warming by sulphate aerosols. *Journal of Climate* 10, 245–67.

Mitchell, J.F.B., Johns, T.C. and **Davis, R.A.** 1998: Towards the construction of climate change scenarios. *Climatic Change* (in press).

Mitchell, J.F.B., Johns, T.C., Gregory, J.M. and **Tett, S.F.B.** 1995: Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature* 376, 501–4.

Osborn, J.T. 1997: Areal and point precipitation changes: implications for the application of climate models. *Geophysical Research Letters* 24, 2829–32.

Palutikof, J., Holt, T. and **Skellern, A.** 1997a: Wind: resource and hazard. In Hulme, M. and Barrow, E., editors, *Climates of the British Isles, present, past and future*, London: Routledge, 220–42.

Palutikof, J.P., Subak, S. and **Agnew, M.D.**, editors, 1997b: *Economic impacts of the hot summer and unusually warm year of 1995. Report for the Department of the Environment*. Norwich: University of East Anglia.

Parry, M.L., Carter, T.R. and **Hulme, M.** 1996: What is a dangerous climate change? *Global Environmental Change* 6, 1–6.

Parry, M.L., Hossell, J.E., Jones, P.J., Rehman, T., Tranter, R.B., Marsh, J.S., Rosenzweig, C., Fischer, G., Carson, I.G. and **Bunce, R.G.H.** 1996: Integrating global and regional analyses of the effects of climate change: a case study of land use in England and Wales. *Climatic Change* 32, 185–98.

Perry, A. 1996: IPCC second assessment and beyond. *Progress in Physical Geography* 20, 477–81.

Raper, S.C., Viner, D., Hulme, M. and **Barrow, E.** 1997: Global warming and the British Isles. In Hulme, M. and Barrow, E., editors, *Climates of the British Isles, present, past and future*, London: Routledge, 326–39.

Santer, B.D., Taylor, K.E., Penner, J.E., Wigley, T.M.L., Jones, P.D. and **Cubasch, U.** 1995: Towards the detection and attribution of an anthropogenic effect on climate. *Climate Dynamics* 12, 77–100.

Santer, B.D., Taylor, K.E., Wigley, T.M.L., Johns, T.C., Jones, P.D., Karoly, D.J., Mitchell, J.F.B., Oort, A.H., Penner, J.E., Ramaswamy, V., Schwarzkopf, M.D., Stouffer, R.J. and **Tetts, S.** 1996: A search for human influences on the thermal structure of the atmosphere. *Nature* 382, 39–46.

Santer, B.D., Wigley, T.M.L. and **Jones, P.D.** 1993: Correlation methods in fingerprint detection studies. *Climate Dynamics* 9, 267–85.

Smith, K. 1995: Precipitation over Scotland, 1757–1992: some aspects of variability. *Journal of Climatology* 15, 543–56.

Subak, S. 1997: Conclusions. In Palutikof, J.P., Subak, S. and Agnew, M.D., editors, *Economic impacts of the hot summer and unusually warm year of 1995. Report for the Department of the Environment*, Norwich: University of East Anglia, 171–78.

Subak, S., Palutikof, J.P., Agnew, M.D., Watson, S.J., Bentham, C.G., Cannell, M.G.R., Crowards, T., Hulme, M., McNally, S., Sparks, T.H., Thomes, J.F., Turner, R.K., Waughray, D. and **Woods, J.C.** 1998: The impact of the anomalous weather of 1995 on the UK economy. *Climatic Change* (in press).

Watson, R.T., Zinyowera, M.C. and **Moss, R.H.**, editors, 1996: *Climate change 1995: impacts, adaptations and mitigation of climate change. Scientific and technical analyses. Contribution of Working Group II to the second assessment report of the IPCC.* Cambridge: Cambridge University Press.

Watson, R.T., Zinyowera, M.C., Moss, R.H. and **Dokken, D.J.**, editors, 1998: *The regional impacts of climate change: an assessment of vulnerability. A special report of Working Group II of the IPCC.* Cambridge: Cambridge University Press.

Wigley, T.M.L. 1998: The Kyoto Protocol: CO_2, CH_4 and climate. *Geophysical Research Letters* (in press).

Wilby, R.L. 1995: Greenhouse hydrology. *Progress in Physical Geography* 19, 351–69.

Wilby, R.L. and **Wigley, T.M.L.** 1997: Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21, 530–48.