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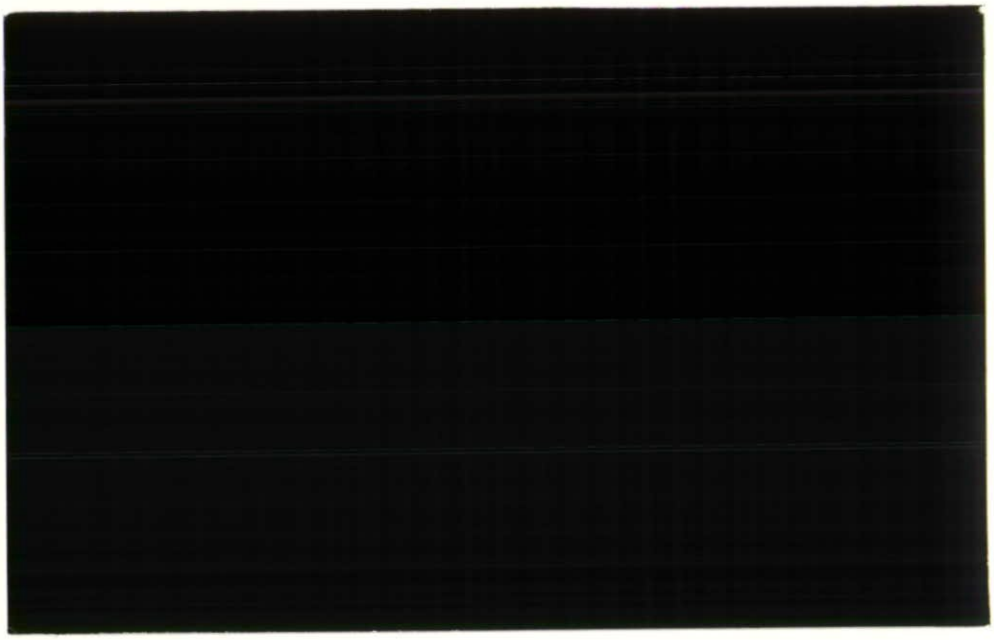

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Global warming and water resources: an update

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Report to the National Rivers Authority

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EXECUTIVE SUMMARY

This report provides an update on global warming and its implications for water resources to NRA R&D Report 12, published in March 1994.

It presents updated global temperature data, and reviews recent research into the factors affecting global temperature variability; the role of sulphate aerosols in counteracting, to a certain extent, the greenhouse effect is highlighted.

The report also summarises recent advances in the development of climate change scenarios for the UK, focusing on the Climate Impacts LINK project, the Hadley Centre transient change simulation, and methods for downscaling from climate model scale to catchment scale.

Finally, the report reviews briefly research on climate change and water resources undertaken in the UK since publication of NRA R&D Report 12.

1. INTRODUCTION

Global warming continues to attract scientific, public and political attention. The United Nations Intergovernmental Panel on Climate Change (IPCC) has estimated that global temperature may increase by 0.3°C per decade, unless urgent actions are taken to limit the increasing concentrations of so-called greenhouse gases (primarily carbon dioxide, methane and nitrous oxide) in the atmosphere (IPCC, 1990a;1992). Such an increase in temperature would have a significant effect on evaporation, which, coupled with changes in precipitation, may have very large effects on hydrological regimes and hence water resources.

In 1992 the National Rivers Authority (NRA) commissioned a review of the potential implications of global warming, which was published as NRA R&D Report 12 in March 1994 (Arnell *et al.*, 1994). The current report is intended to update Arnell *et al.* (1994), concentrating specifically on:

i. improvements in the understanding of global temperature changes and the significance of increased greenhouse gas concentrations;

ii. updated climate change scenarios for the UK, and improvements in methods for determining catchment-scale scenarios;

iii. reviews of published studies of potential climate change impacts relevant to the National Rivers Authority.

It is also appropriate to review the current status of the Intergovernmental Panel on Climate Change.

2. THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988. Three working groups were initially created, focusing on mechanisms of climate change (IPCC, 1990a; 1992), impacts of climate change (IPCC, 1990b) and strategies for responding to climate change (IPCC, 1991). The reports of these three working groups provided the foundation for the Framework Convention on Climate Change, introduced at the United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro in June 1992. Article 2 of the Framework Convention states:

> The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system.

The Framework Convention came into force on March 21 1994, after being ratified by the 50th nation: the European Union ratified the Framework Convention on December 16 1993. Countries are therefore now obliged, under international law, to limit greenhouse gas emissions so as to prevent "dangerous anthropogenic interference". The UK Government has committed the UK to reduce emissions to 1990 levels by 2005. In practice, it is not yet possible to define what is meant by dangerous interference, for several reasons. First, the effects on atmospheric radiative forcing of increasing emissions of greenhouse gases are uncertain (due largely to uncertainties about reactions in the atmosphere and the size of sources and sinks of greenhouse gases). Second, the effects on climate of a change in radiative forcing are unknown, because of uncertainties in the understanding and modelling of global atmospheric processes. Third, the impacts - in ecosystem or monetary terms - of a given climate change are unknown, reflecting both uncertainty in the magnitude of possible climate change and poor understanding of the links between climate and impact.

To address these uncertainties the IPCC is producing a Second Assessment Report, which is scheduled to be published in October 1995. There are again three working groups under this second phase of the IPCC, but the objectives of the three groups have been redefined. Working Group I is charged with updating the scientific understanding of the mechanisms of global warming, and with producing updated estimates of possible changes in climate. Working Group II is concerned with impacts, adaptation and mitigation, whilst Working Group III is considering both emission scenarios and socio-economic aspects of climate change. Each Working Group will produce a Second Assessment Report, with chapters devoted to specific issues. Each chapter is prepared by a group of Lead Authors and reviewed by scientific peers. The main Lead Author of the chapter in the Second Impacts Assessment on water resources is Professor Z. Kaczmarek of Poland; Dr Nigel Arnell of the Institute of Hydrology is one of the team of Lead Authors.

3. GLOBAL WARMING AND THE GREENHOUSE EFFECT

3.1 THE GLOBAL TEMPERATURE RECORD

Figure 3.1 shows the average global temperature, between 1861 and 1993. Nine of the ten warmest years in the record occurred during the 1980s. Global average temperatures in 1992 and 1993 were still above the long-term average, but were lower than in previous years due largely to the dust plume from Mount Pinatubo in the Philippines, which erupted in 1991. The eruption sent vast clouds of particulate material high into the atmosphere, increasing planetary albedo and resulting in a greater proportion of incoming solar radiation being reflected back out to space. Computer simulations using a global circulation model (Hansen *et al* 1992) suggest that the effect of the aerosols ejected by Mt Pinatubo might last for two to three years (until the winter of 1994/95): these simulations have so far been supported by observations.

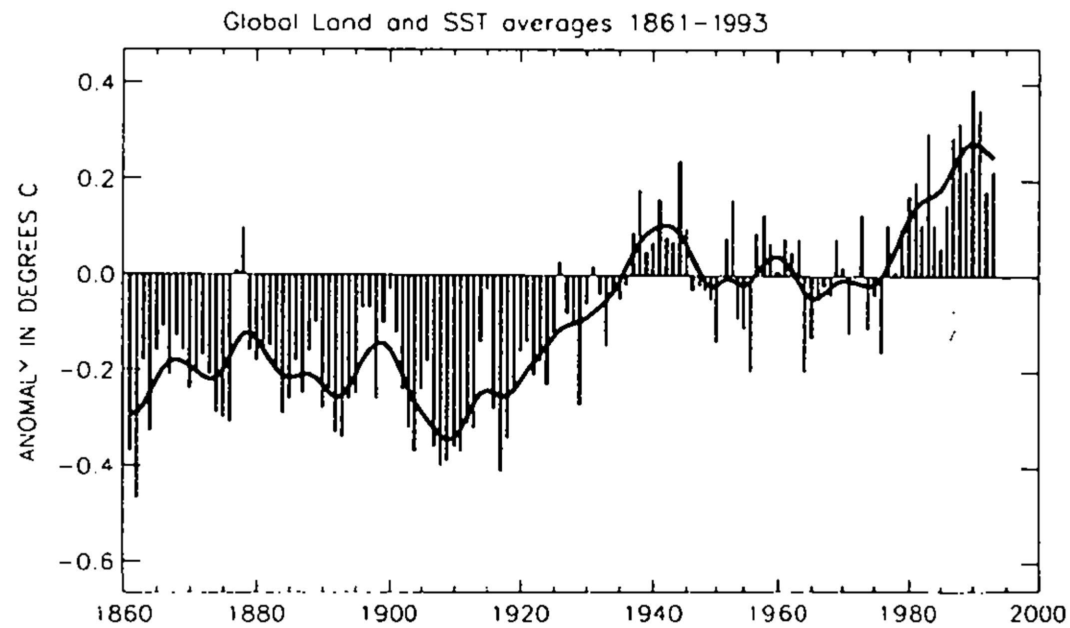

Figure 3.1 *Global temperature, 1861-1993. Figure supplied by the Hadley Centre*

Recent analysis of global temperature data has suggested that much of the increase in temperature over the last forty years has occurred during the night (Kukla & Karl, 1993). Minimum temperatures increased over large parts of the land surface of the northern hemisphere at three times the rate of the increase in maximum temperatures: this has important ecological implications (consequent on the reduction in diurnal range).

Although surface-based temperature observations show a clear increase in temperature, substantially smaller trends have been found from 15-year records derived from satellite microwave data (Spencer & Christy, 1992; Christy & McNider, 1994). Uncorrected global temperature data between the period 1979 and 1993 showed no significant trend, although once the effects of volcanic activity and the El Nino-Southern Oscillation signal were removed, the satellite data showed an increase of 0.09°C per decade. This increase is still smaller than that derived from surface-based measurements. However, there are some problems with satellite-based temperature estimates (Schneider, 1994). They are based on remotely-sensed radiances which must be converted to atmospheric temperature using empirical relationships which allow for water vapour, clouds and instrumental drift. Also, the microwave observations sample the entire troposphere and even a part of the stratosphere: according to the greenhouse gas theory, the upper parts of the atmosphere should cool as the lower parts warm.

3.2 UNDERSTANDING VARIABILITY IN GLOBAL TEMPERATURE

The trend in global temperature shown in Figure 3.1 has not been constant. Temperature rose between 1910 and 1940, and then stayed relatively constant until 1980 before rising again. Some large parts of the Northern Hemisphere showed a considerable *decrease* in temperature well into the 1980s. Such trends appear at first to be inconsistent with the hypothesis of increasing temperatures due to an increasing concentration of greenhouse gases in the atmosphere. However, improved understanding of reasons for variability in global temperature show there is no inconsistency. The effect of certain volcanic eruptions on global temperature was mentioned above, and the contribution of *sulphate aerosols* to global temperature is now being highlighted. Sulphate aerosols are essentially a product of atmospheric pollution, and have the effect of reflecting incoming solar radiation back out to space. They therefore counteract the greenhouse effect, to a certain extent. This counteracting effect varies geographically, and is greatest in the Northern Hemisphere where most of the sulphate aerosols are produced. Simulations of global temperature at the Hadley Centre using an energy balance model incorporating the effects of sulphate aerosols produce a much closer fit to the observed global temperature record over the last 100 years than simulations which do not consider aerosols: the stabilization of temperature after the 1940s can be explained in terms of the large increase in sulphate aerosol emissions triggered by the rapid expansion of the chemical industry. Sulphate aerosols have a very short lifetime in the atmosphere - of the order of days - and so any moves to curb atmospheric pollution will make greenhouse warming more obvious. The relatively greater increase in nighttime temperatures (Kukla & Karl, 1993) has also been attributed to sulphate aerosols: these affect daytime temperatures by cutting down the amount of sunlight reaching the ground, but have little effect on nighttime temperatures.

Variations in solar irradiance, and hence radiation recieved by the earth, have been proposed as possible explanations for discrepancies between observed and expected global temperatures. Friis-Christensen & Lassen (1991), for example, found a relationship between the length of the solar sunspot cycle (as a proxy for solar irradiance) and global temperature, over the period 1861 to 1990, and concluded that most of the variation in temperature was explained by variations in sunspot cycle length; more recently, variations in temperature at Armagh Observatory in Northern Ireland since the end of the 18th century were found to be closely correlated with the length of the solar cycle (Calder, 1994). However, both Kelly & Wigley (1992) and Schlesinger & Ramankutty (1992) concluded that *whilst variations in solar irradiance did explain some of the variability in global temperatures, the greenhouse forcing was dominant.* Kelly & Wigley (1992) essentially used the observed global temperature record to calibrate the parameters of an energy balance model which combined the effects of greenhouse (plus sulphate aerosols) and solar forcings. The calibrated parameters depended on the actual data series used, but implied that the greenhouse/aerosol forcing generally explained twice as much of the variance as variations in solar forcing: with one combination of greenhouse and solar forcing data sets, 41.2% of the variation in global temperature was explained by the greenhouse forcing, and 19.4% by solar forcing.

4. CLIMATE CHANGE SCENARIOS FOR THE UK

4.1 CLIMATE IMPACTS LINK PROJECT

The Climate Impacts LINK project, based at the Climatic Research Unit at the University of East Anglia, provides climate change scenarios to the UK climate change impacts research community (Viner & Hulme, 1994). More specifically, the Climate Impacts LINK project creates change scenarios from output from the Hadley Centre global climate models. Two approaches are used to create two change scenarios.

4.1.1 Hadley Centre high-resolution equilibrium model (UKHI), plus STUGE climate model

The UKHI global climate model represents the equilibrium climatic conditions with an atmospheric carbon dioxide concentrations stabilized at twice the pre-industrial value. In reality, of course, carbon dioxide concentrations are increasing gradually, and an equilibrium stable climate may never be reached. Also, equilibrium climate simulations do not represent conditions at a fixed time period. Scenarios for a given time - such as 2050 - can however be created by combining the equilibrium change with transient changes as simulated by a much less complicated one-dimensional global energy balance model. STUGE (Sea-level and Temperature Under the Greenhouse Effect) is such a "simple" model, which can simulate global temperature for a given year under different scenarios for the greenhouse gas emissions (Wigley *et al*, 1991).

The equilibrium climate model output is standardised by dividing estimated change at each point (percentage change in rainfall, for example), by the equilibrium global temperature change (the *climate sensitivity* of the model). The change for a given year can then be determined by rescaling the dimensionless change by the global temperature change as simulated using STUGE. The method is easy to apply, but has the major disadvantage that it is assumed that the spatial pattern of change does not vary over time.

The Climate Impacts LINK project is able to provide changes in the monthly means of all important meteorological variables - by grid square - and also 70-year time series of monthly mean temperature, precipitation, mean sea level pressure, windspeed and net solar radiation under current and double-CO_2 conditions, from UKHI. The monthly mean data have also been interpolated onto a 10x10km grid across the UK (see Section 4.3). The monthly mean changes are available from the Climatic Research Unit through the MAFF-funded SPECTRE software package (Barrow *et al.*, 1994).

4.1.2 Transient scenarios from the Hadley Centre transient climate model (UKTR)

Transient climate model experiments allow for the gradual increase in greenhouse gas concentrations over time. The climate evolves in response to this gradual increase, with due allowance for lags in the atmosphere and ocean systems. Far fewer transient global circulation model experiments have been run, and the one with the highest spatial resolution (2.5x3.75°) is that from the Hadley Centre (UKTR).

The Climate Impacts LINK project is able to provide 70-year transient time series of monthly temperature, precipitation, radiation, windspeed and humidity from UKTR.

4.2 IPCC SECOND ASSESSMENT SCENARIOS

A set of global climate change scenarios for specific years have been produced for the IPCC Second Assessment reports (Greco *et al*, 1994), although in practice very few of the impact assessments reported in the Second Assessment will use these scenarios. Scenarios are based on three different transient general circulation models: UKTR (resolution 2.5x3.75°), GFDL (from the U.S. Geophysical Fluid Dynamics Laboratory: resolution 7.5x7.5°) and ECHAM (from the Max Planck Institute for Meteorology, Germany: resolution 5.625x5.625°). Each experiment used a slightly different increase in greenhouse gas concentrations, so different periods have been selected from each to represent conditions in 2020 and 2050. The scenarios as provided by the IPCC define changes in *monthly* temperature, precipitation and incoming solar radiation for 2050, and changes in *seasonal* temperature, precipitation and soil moisture content for 2020 and 2050.

Figure 4.1 shows the percentage change in winter (December, January and February) precipitation by 2050 for the three transient IPCC scenarios, plus the UKHI equilibrium simulation rescaled using STUGE. Figure 4.2 shows the same for summer (June, July and August). Although there are differences between the different GCMs, all suggest an *increase in winter precipitation* across England and Wales (of over 20% with UKHI), and most show a *decrease in summer rainfall*. These scenarios need to be developed further (and applied at the correct spatial scale) before they can be used in impact assessments in the UK. It is also necessary to develop methods for separating a greenhouse-gas signal in a transient model simulation from year-to-year variability and gradual model drift.

4.3 DOWNSCALING TO THE CATCHMENT SCALE

General circulation models currently operate at a very coarse spatial resolution: Figure 4.1 shows how few grid cells cover the UK. This makes it very difficult to define directly climate change scenarios at the catchment scale, and several methods have been proposed to add higher-resolution spatial detail to GCM output. All, of course, assume that the coarse-scale GCM simulations are realistic: in practice, GCMs do not necessarily simulate the locations of important large-scale circulation features very accurately.

Most climate change impact assessments define a change in climate - temperature, precipitation, potential evaporation - and apply these changes to observed baseline climate data. The choice of baseline climate period is therefore critical. Arnell & Reynard (1993) used 1951 to 1980 as a baseline, as this represents a reasonably stable view of the "current" climate as simulated by GCMs (see also Figure 3.1). The current World Meteorological Organisation (WMO) climatic normal, however, is 1961 to 1990, and the UK Meteorological Office is currently calculating climatic averages for this period. The Climate Impacts LINK project is able to provide, to research groups, a gridded 1961-1990 baseline climatology at a resolution of 10x10km. The monthly mean baseline data are also available at a resolution of 10'x10' (or approximately 15x15km) from the Climatic Research Unit through the MAFF-funded SPECTRE software package (Barrow *et al.*, 1994). The disadvantage with the 1961-1990 baseline period is that it includes the warm years during the 1980s.

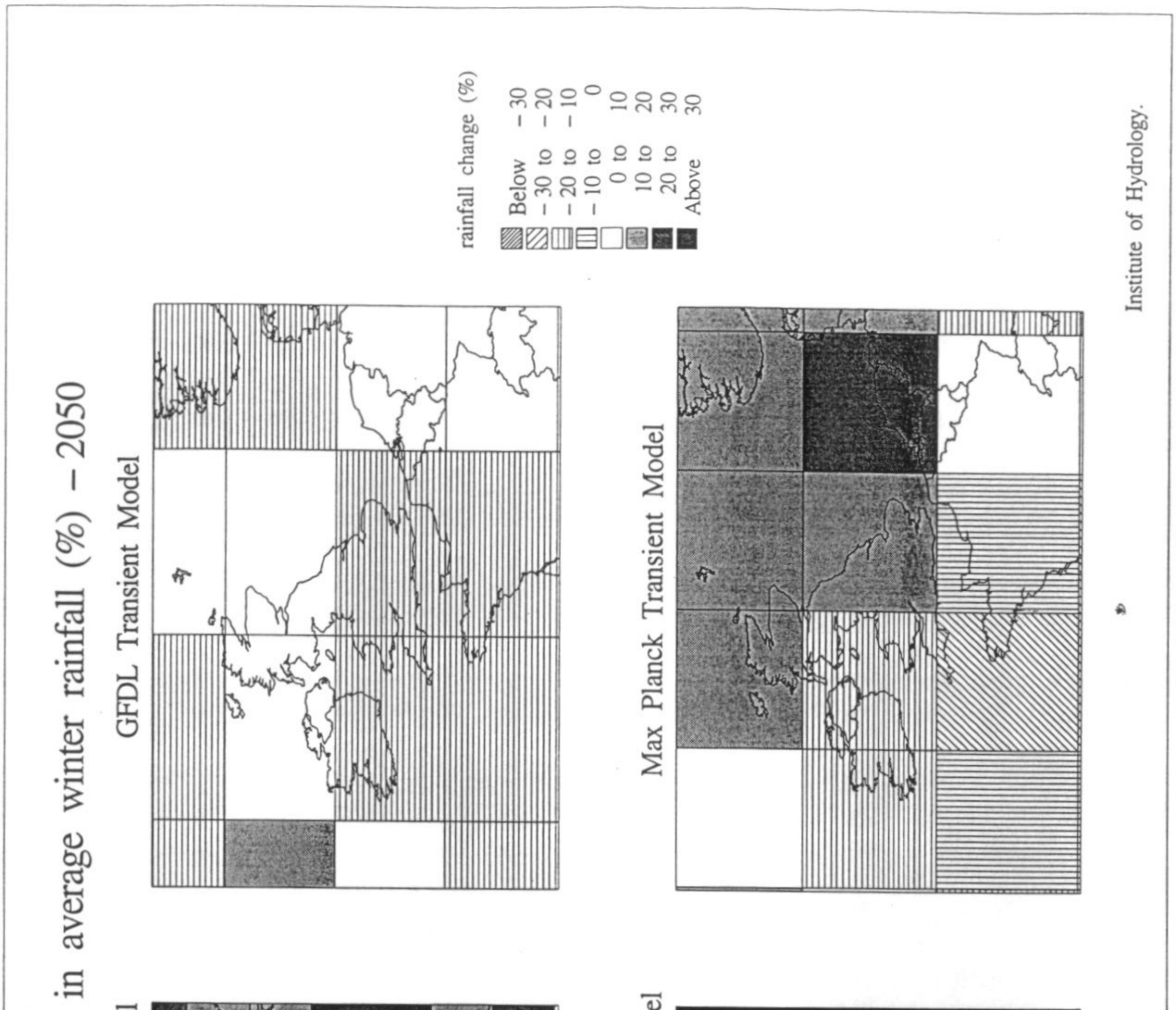

Figure 4.1 *Percentage change in winter rainfall by 2050, as simulated by four GCMs*

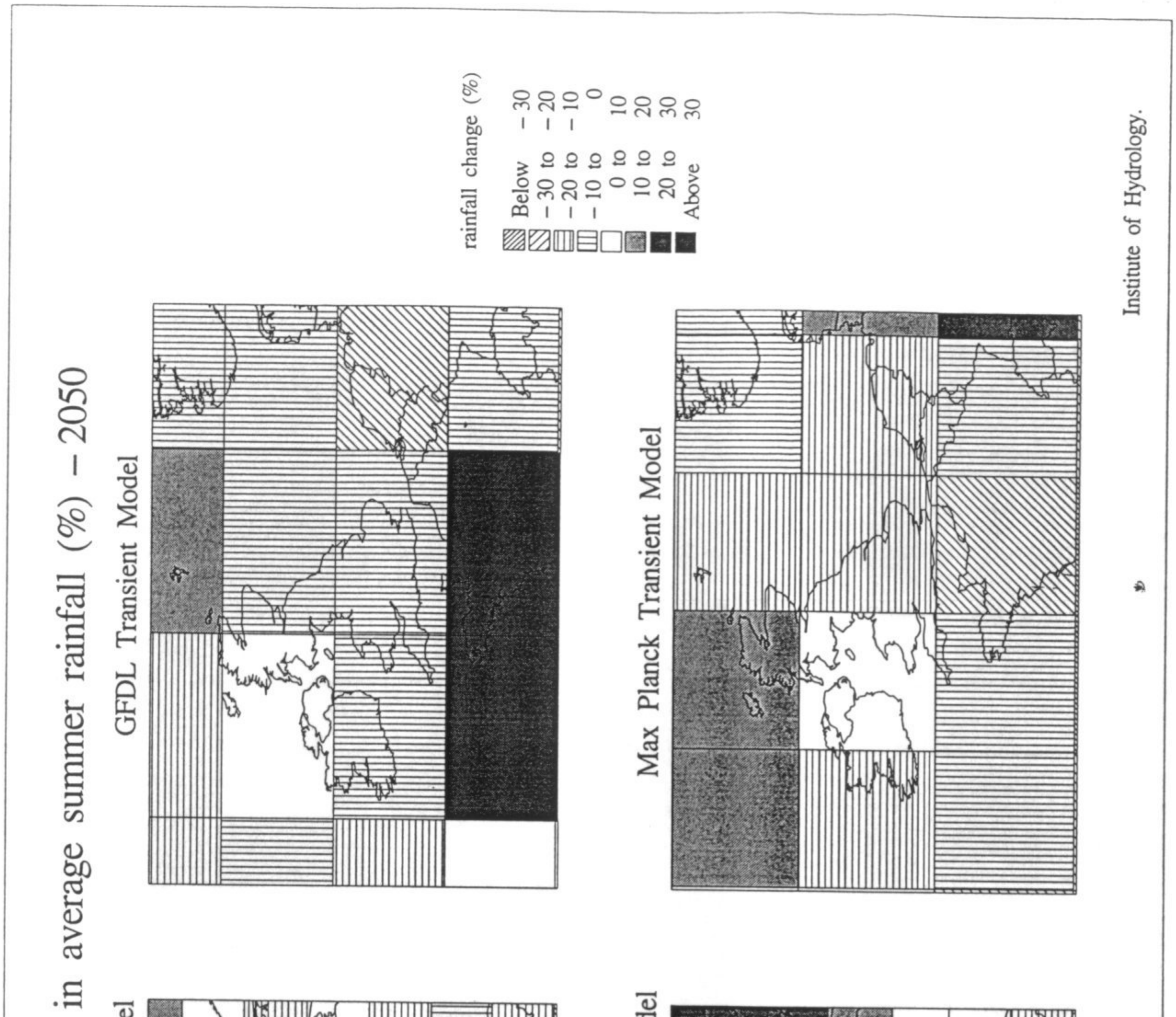

Figure 4.2 Percentage change in summer rainfall by 2050, as simulated by four GCMs

4.3.1 Simple interpolation

Under this approach, the coarse resolution estimates of change derived from a general circulation model are simply interpolated down to a finer resolution. Arnell & Reynard (1993) for example interpolated Climate Impact LINK scenarios based on the UKHI simulation down to the 40x40km MORECS resolution, whilst the LINK project itself can now provide the UKHI-based scenarios interpolated down to 10x10km or 10'x10'.

4.3.2 Guided interpolation

This approach uses meteorological expertise in interpolating GCM output. The method is subjective, and has not been widely used.

4.3.3 Empirical relationships between large-scale and point climate

This approach has attracted considerable research attention over the last few years. There are essentially three variants. The first uses empirical relationships between large-scale (GCM scale) average climate and point climate to add spatial detail to the GCM large-scale averages. This has not been applied in the UK. The second variant develops relationships between temperature and local rainfall. It has been applied in the Netherlands (Klein-Tank & Buishand, 1993), but not in the UK.

The third variant uses relationships between an index of large-scale atmospheric circulation and weather at a point, and has the following stages:

i. define a measure of atmospheric circulation type;

ii: for each type, determine the probability of rainfall and the characteristics of daily rainfall totals at a point;

iii. determine a daily time series of atmospheric circulation type from GCM output and use the empirical relationships between circulation type and local weather to calculate daily time series of point weather.

The method has been applied in the UK (Wilby, 1993; Wilby *et al*, 1994). Circulation patterns affecting the UK have been classified into a number of Lamb Weather Types, distinguishing for example between anticyclonic weather and patterns dominated by westerly air flows. Table 4.1 gives examples of daily rainfall characteristics for each weather type for two sites in central England (Wilby, 1993). Wilby (1993) applied the method to estimate time series of catchment rainfall by generating stochastically time series of weather types, rather than using directly weather types as determined from daily GCM output.

The attraction of this approach to downscaling is that it uses features that GCMs should simulate well (large-scale anticyclones and depressions). There are, however, two main problems. First, current GCMs do not necessarily simulate these large-scale features very well. It is possible in principle to use higher-resolution model output (Section 4.3.4) to define circulation features. Second, the empirical relationships between large-scale circulation and local weather may not be very stable, and may not apply under a warmer climate.

Table 4.1 Probability of rainfall and mean daily rainfall by Lamb Weather Type, at two locations (Wilby, 1993; Wilby et al, 1994)

	Loughborough		Cotswolds	
Lamb Weather Type	Probability of rainfall	Mean rainfall (mm/day)	Probability of rainfall	Mean rainfall (mm/day)
A-type	0.098	2.51	0.118	3.71
W-type	0.50	3.30	0.613	3.63
C-type	0.667	5.72	0.793	5.42
N-type	0.343	3.76	0.475	2.37
NW-type	0.36	1.53	0.399	2.15
S-type	0.429	2.93	0.637	4.56
E-type	0.448	4.74	0.435	5.57
O-type	0.379	4.33	0.453	4.57

4.3.4 Using a regional atmospheric model nested within a GCM

The final way of adding higher-resolution detail to the output of a coarse-scale GCM is to nest a higher-resolution regional atmospheric model, operating at a grid resolution of around 50x50km, within the GCM. There are two alternative approaches.

The first is to use the global GCM to provide the boundary conditions to a regional atmospheric model covering a defined region, which then essentially adds local detail according to topography and the position of the sea. In this case, the regional model can be run off-line from the GCM. The simulated detail, however, is dependent on the quality of the simulated boundary conditions, and the choice of the domain of the regional model is critical: it must be large enough to allow the generation of small-scale circulation features, but not so large that it interferes with the simulation of large-scale features. The Hadley Centre is currently experimenting with a 50x50km regional model for Europe, which is nested within the 2.5x3.75° resolution global circulation model. Preliminary results show that current rainfall patterns in Europe are simulated much more accurately using the nested meso-scale model - orographic effects, rain-shadows and small-scale circulation features are better simulated - and that the pattern of change in rainfall due to increased CO_2 is different to that interpolated from the global GCM data. The Hadley Centre is still examining these results in detail, and scenarios based on nested model output could be available during 1995. This nested approach to creating climate change scenarios is being actively explored at the National Center for Atmospheric Research, USA.

In the second approach, which is much more complicated, the meso-scale regional model would be integrated within the global GCM. As above, the GCM would provide boundary conditions to the regional model, but this time the atmospheric fluxes as simulated by the regional model would be passed back to the GCM. This should allow the global model to simulate large-scale climate much more accurately: the summed fluxes from a meso-scale regional model will not necessarily be the same as the summed fluxes for the same area from a coarse global model. The approach, however, whilst feasible in principle is presently infeasible in practice. The additional computational burden would be too high, and the approach may not lead to improvements in regional climate simulations whilst global

GCMs continue to simulate poorly very large-scale features (such as the position of the jetstream). Metéo-France is currently developing a "stretched" GCM, which has high resolution over the region of interest and lower resolution elsewhere (with the lowest resolution at the antipode of the region of interest). At present, however, the low resolution across the Southern Ocean forced by the higher resolution across Europe is too coarse to allow the model to simulate well global circulation features.

4.3.5 Creating daily-scale scenarios from GCM output

Most climate change scenarios are expressed in terms of change in monthly climate, and this is essentially because of the large spatial scale of current GCMs: rainfall from a GCM, for example, is averaged or summed over a very large area (of the order of 80,000 km^2). However, hydrological models ideally require *daily* (or sub-daily) input data. Whilst it might be possible in the future to use nested meso-scale models to provide catchment-scale daily input data (although a resolution of 50x50km is still too coarse), in the short and medium term other approaches must be used to apply monthly change scenarios at the daily scale.

The simplest approach is to apply the monthly changes to an observed daily baseline climate data set, and this is what has been done in most studies. Arnell & Reynard (1993), for example, used this approach to simulate changes in flows in UK catchments (see Section 5.2). The disadvantage with the approach is that it assumes no change in the temporal structure of daily weather.

A refinement is to add a random component to the existing daily time series, together with the monthly change. Arnell & Reynard (1993), for example, created scenarios which add or lost at random rain-days, in an attempt to explore the sensitivity of changes in flow regimes in the UK to changes in temporal structure.

A third approach is to use stochastic weather generation procedures. Several studies in the United States have used simple two-state first-order Markov models to simulate daily rainfall occurrence. In these models there are two states - wet and dry - and the probability of today being wet is dependent solely on whether yesterday was wet or dry. Unfortunately, such simple Markov models do not reproduce well the observed characteristics of daily rainfall in the UK: they tend to underestimate the length of dry spells. An alternative stochastic weather generation procedure is being developed by Semonov (Long Ashton Research Station, University of Bristol) for UK conditions, which basically simulates the *lengths* of dry and wet periods rather than simulate weather one day at a time.

4.3.6 Transient scenarios

Nearly all climate change impact assessments have used scenarios defining average conditions around a particular year (for example 2020, 2050 or "at a doubling of atmospheric CO_2"). These provide useful information on the change in flow regimes which may have occurred by that time, and allow assessment of a change in risk by a particular date. However, it might also be very useful to have information on the *rate* of change, and this can only be provided by transient change scenarios.

Transient scenarios can most easily be created by adding a gradually-varying change to a baseline climate data set, and this is the approach Arnell & Reynard (1993) used to create transient scenarios for UK catchments. It was found that a climate change trend would be small compared with year-to-year variability, but could be noticeable at the decadal time scale.

5. IMPACTS ON HYDROLOGICAL REGIMES AND THE WATER ENVIRONMENT

5.1 INTRODUCTION

There have been a great many studies of possible changes in hydrological regimes due to global warming, both in the UK and elsewhere. The estimated sensitivities depend to a large extent on the climate change scenarios used, and so far there has been little consistency. Hopefully the widespread use of IPCC scenarios (Section 4.2) should mean that different studies are more closely comparable.

The potential implications of global warming for UK hydrological regimes and water management were reviewed in some detail in Arnell *et al* (1994), and are not repeated here. Instead, it is appropriate to emphasise three general points:

i. the overall effect of global warming on an institution - the NRA, for example - is determined by the sensitivity of that organisation to change, the way that institution responds to change in each sector, and on how other organisations respond to climatic and other changes;

ii. there may be *critical thresholds* of change: a system might be able to cope with change up to a certain amount, beyond which it would fail, cease to be sustainable, or require substantial investment.

iii. global warming impacts on one aspect of the water environment, and responses to those impacts, affect other parts of the water environment: it is not possible to treat each sector in isolation.

Figure 5.1 (Arnell, 1994a) attempts to summarise the potential types of impact global warming might have upon the water environment: the magnitude (and often direction) of change depend on the climate change scenario. It is useful to attempt to estimate the impacts of global warming for two main reasons. First, impact assessments are necessary to determine the consequences of reducing the build-up of greenhouse gases in the atmosphere: they determine "dangerous" change. Second, impact assessments are necessary as part of the medium and long-term planning process. They can be used to determine the sensitivity of a proposed scheme or plan to alterations in climate.

5.2 THE DEPARTMENT OF THE ENVIRONMENT WATER DIRECTORATE STUDY

Between 1990 and 1993 the Water Directorate of the DoE funded a set of studies into the effect of global warming on water resources in Britain. The studies are listed in Table 5.1. An overview of each project is provided in the summary report by Arnell (1994b), so only brief highlights are summarised here.

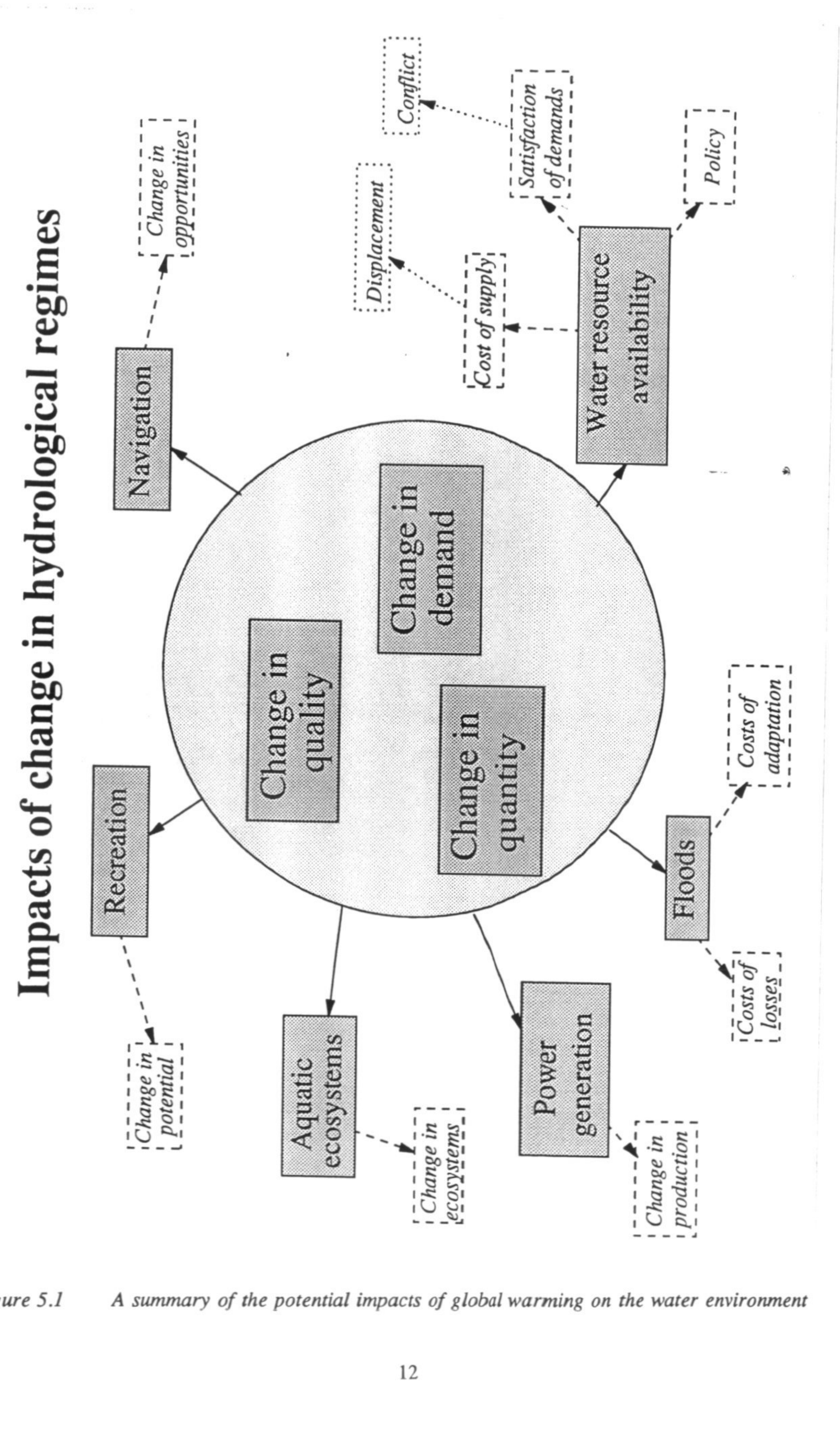

Figure 5.1 *A summary of the potential impacts of global warming on the water environment*

Table 5.1 Components of the DoE Water Directorate climate change impact project

Project title		Contractor	Reference to final report
Impacts of climate change on water quantity			
1.	Impact of climate change on river flow regimes	Institute of Hydrology	Arnell & Reynard (1993)
2.	Climate change and the demand for water	Department of Economics, University of Leicester	Herrington & Hoschatt (1993)
Impacts of climate change on water quality			
1.	Climate change and the thermal regimes of rivers	Department of Geography, University of Exeter	Webb (1992)
2.	Impacts of climate change on water quality in the United Kingdom	Institute of Hydrology	Jenkins *et al* (1993)
3.	Impact of climate change on estuarine water quality	HR Wallingford	Dearnaley & Waller (1993)

The river flow regimes project investigated changes in annual and monthly flow regimes in a several UK catchments, using a daily rainfall-runoff model and a range of climate change scenarios based on the UKHI simulation output as provided by the Climate Impacts LINK project, and the UK Climate Change Impacts Review Group (CCIRG, 1991). There was considerable variability between scenarios, but under the driest scenario annual runoff could be reduced in southern England by over 15% by 2050. The percentage reduction would be even greater in summer, whilst in winter flows might increase. Figure 5.2 shows the percentage change in monthly mean flows by 2050 for six of the study catchments, and also indicates that the effect of a given change scenario varies between catchments. The progressive effects of climate change on river flows would be small compared with year-to-year variability, but would be noticeable on a decade-to-decade basis. The study used a range of potential evaporation scenarios, with annual increases ranging between 9 and 30%, reflecting uncertainty in possible changes in some of the meteorological components determining evaporation. The newer, more detailed, LINK scenarios should allow this range to be reduced.

The demand study examined potential changes in public water supply and direct abstractions in southern and eastern England by 2021. A micro-component approach resulted in an increase in per capita demand of 4%, over and above the 21% increase assumed to arise from economic and lifestyle changes. Spray irrigation demand was predicted to increase by 75% without climate change and 125% with global warming, although predicted demands for irrigation are affected very much by the price of water and agricultural produce.

The river water temperature study suggested that by 2050 will be between 1 and 2.5°C higher than at present in most UK watercourses. The smallest increases will occur in groundwater-dominated catchments, whilst those with large, wide, open channels will experience the greatest increase. The probability of high water temperatures will increase significantly, and the probability of low temperatures will fall. The predicted change in river water temperature has large potential implications for water quality and the sustainability of some fish populations and aquatic ecosystems.

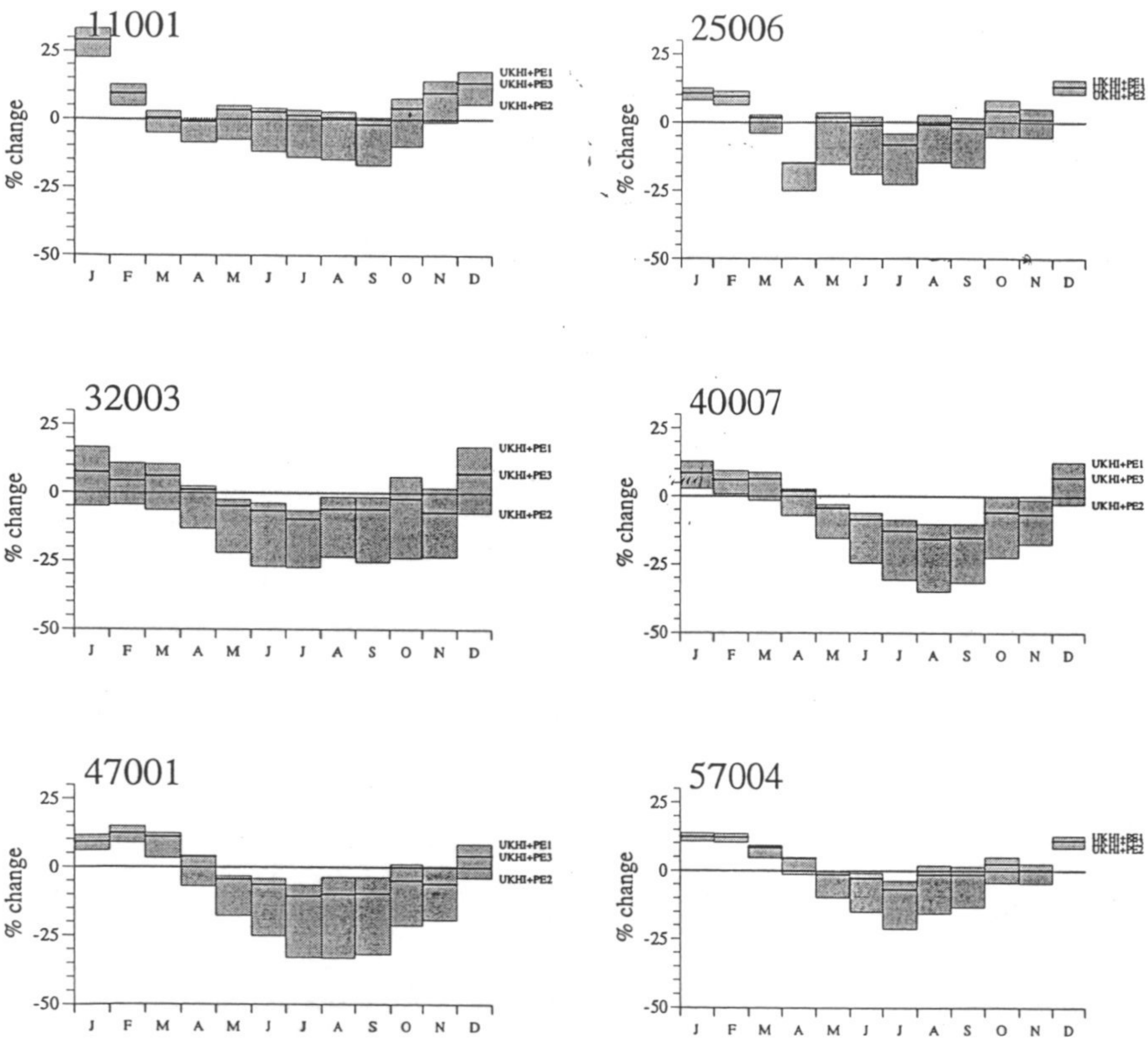

Figure 5.2 *Percentage change in monthly runoff, for six study catchments, under three climate change scenarios derived from the UKHI experiment by the Climate Impacts LINK project (Arnell & Reynard, 1993)*

The water quality effects of global warming are essentially site-specific. Simulation results, however, suggested that changes in water temperature and flow volumes may be less important for water quality than changes in land use and effluent inputs. Nitrate concentrations are simulated to *decrease* in lowland rivers with higher water temperature and lower flows (assuming no change in inputs), but there is the potential for increased flushing in autumn after a dry summer, and higher temperatures might result in increased mineralisation of organic nitrogen in the soil. Biochemical Oxygen Demand is simulated to increase in rivers currently heavily utilised for effluent disposal, largely due to an increase in the growth of algal blooms.

Finally, the estuarine water quality study investigated the sensitivity of the salt front in case study estuaries to rising sea level and changes in freshwater inflows. In the estuaries studied, a sea level rise gives greater tidal oscillations and higher levels of salinity, but the changes are well within the range of natural variability through the tidal cycle. Changes in river discharge are more significant than a rise in sea level: lower freshwater flows mean greater penetration of the salt front.

5.3 THE DEPARTMENT OF THE ENVIRONMENT GLOBAL ATMOSPHERE DIVISION CORE MODEL

The Global Atmosphere Division of the DoE is primarily concerned with the processes behind climate change, but has funded since 1991 a project aimed at developing methods for assessing the impacts of climate change on biogeochemical and ecological systems. The project is carried out by the Institute of Terrestrial Ecology (ITE) and the Institute of Hydrology (IH), each with a number of subcontractors.

The three main objectives of the project are; to provide core models for predicting the impacts of climate change on biogeochemical and ecological systems, to provide models which run for both equilibrium and transitional climates, and to couple models with a geographical information system to examine the impacts spatially across the UK.

Throughout the study many demonstration projects have been undertaken to assist in meeting the three aims of the project. One such demonstration study, at IH, looked into the methodology of linking a GIS with a hydrochemical model. The Agricultural Non-Point Source Pollution Model (AGNPS) was linked to a GIS, and applied to the Bedford Ouse catchment area. The impacts of nitrogen in the surface waters were assessed spatially, under various fertilizer and rainfall scenarios. The main product of the IH work, however, is a linked model which addresses all three aims of the project.

The IH linked model consists of four modules: a water balance model, a grassland model (developed in the Department of Animal and Plant Sciences at Sheffield University), a nitrate model and an evapotranspiration model. Feedbacks between the models are incorporated. For example, the grassland model is driven by a requirement for water and nitrate to simulate grassland productivity. The grassland model in turn provides dead organic matter back to the soil for input to the nitrate model and calculates transpiration for use in the water balance model. The water balance model calculates flow and soil water content which in turn drive the grassland model.

The ecological component of the project (at ITE) is essentially concerned with producing GIS-based models which can predict regional changes in habitat suitability and species occurrence given a climate change scenario.

The project has developed a methodology which will allow future specific climate change research much easier. It has highlighted many of the problems in climate change impact studies, and some of the possible solutions (for example temporal and spatial scaling problems, applying catchment models at the regional scale and difficulties in using and accessing large data sets). The project has also shown how mechanistic models of different parts of the ecosystem can be linked and how they can be coupled to a GIS. The use of GIS has also been demonstrated in the handling of very large spatial data sets, running models and the spatial analysis of the results.

5.4 OTHER RELEVANT UK WORK

The effects of global warming on the water environment have formed the basis of many Masters theses over the last few years, but none of these have yet been released into the public literature.

A PhD student at Aberystwyth is supported by Welsh Water to investigate potential effects of climate change on hydrological regimes in Wales and impacts on reservoir systems. Some of the work is reported in Holt & Jones (1993), which describes possible changes in the yield of a few Welsh reservoirs and changes in 5-year drought return periods. The study uses empirical regression relationships between precipitation, temperature, effective precipitation and actual evaporation.

More generally, studies of the impact of global warming will benefit from the continued development of physically-based models of different aspects of the water environment. For example, studies into potential changes in groundwater recharge will be helped by the development at IH of improved regional recharge models. Investigations into the sensitivity of aquatic ecosystems will be helped by the refinement of predictive models such as PHABSIM (Armitage, 1994; Stalnaker, 1994).

5.5 IMPACTS OF GLOBAL WARMING ON WATER RESOURCES IN THE EUROPEAN COMMUNITY

A project to assess the potential impacts of global warming on water resources in the European Community began in October 1993. The project is funded by the European Commission under the Third Framework Environment Programme (project EV5V-CT93-0293), and is being undertaken by a consortium led by the Institute of Hydrology: the consortium partners are the Commission for the Hydrology of the Rhine Basin (which has several subcontractors in Germany, the Netherlands, Switzerland and Belgium), the National Technical University of Athens and the Rühr-universität Bochum in Germany.

The aims of the project are

- to provide quantitative information to decision-makers in the European Commission and water managers in the European Community on the impacts of climate change on the water balance, through the use of climate change scenarios and mathematical hydrological models, and
- to provide guidance on the management of water resources in the EC in the face of climate change.

The major specific objectives of the project are to:

i. identify the potential impacts of climate change on annual water resource availability, river flow regimes and the frequency of droughts at the EC scale, on a spatial resolution of 0.5x0.5°;

ii. review the characteristics of variability in runoff regimes over time, to characterise the variability of EC water resources;

iii. identify the potential impacts of climatic change on river flow regimes, at a high spatial resolution, throughout the Rhine basin;

iv. examine possible changes in the effects of climate change at regional and catchment scales for selected water use systems across the EC;

v. develop procedures for adapting reservoir management to changing conditions;

vi. compare the effects of future climate change with past variability and future effects of non-climatic changes (specifically land use change).

The project operates on three scales: the EC (or European) scale, the regional scale (the Rhine basin) and the catchment scale. The links between the various elements are through a *consistent impact assessment methodology* and the use of *consistent climate change scenarios*. Climate change scenarios will be based on IPCC scenarios, and are being provided to the project by the Climatic Research Unit of the University of East Anglia.

The project provides the foundation for other studies into implications of global warming for water resources, both because it is providing a regional framework and because it has acquired a consistent baseline climatology (1961-1990) and state-of-the-art climate change scenarios.

6. CONCLUSIONS

This report has summarised developments over the last two years in the understanding of the potential impacts of global warming on water resources in the UK. The most important developments are:

i. progress with the IPCC Second Assessment report;

ii. preparation of more refined climate change scenarios by the Climate Impacts LINK project and the Hadley Centre;

iii. provision of climate change scenarios by the IPCC;

iv. completion of the DoE Water Directorate-funded investigation into potential changes in water quantity, demand and water quality.

There are still considerable uncertainties in the potential impacts of global warming, due largely to differences between climate change scenarios. However, *the possibility of costly impacts over the NRA planning horizon cannot be excluded*. It remains important to undertake sensitivity studies to investigate the potential consequences of global warming for a medium or long-term plan.

The amount of warning of change required varies between different parts of the NRA, largely because different sectors can respond at different rates. Also, some parts of the NRA will be able to react to change, whilst others - particularly the conservation and fisheries functions - will have to accept change.

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