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Negotiating future climates for public policy: a critical assessment of the development of climate scenarios for the UK

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ABSTRACT

Climate scenarios serve a number of functions in helping society manage climate change—pedagogic, motivational or practical (for example, in engineering design, spatial planning and policy development). A variety of methodologies for scenario construction have been experimented with, all of them to a greater or lesser extent depending on the use of climate models. Yet the development of climate scenarios involves much more than climate modelling. The process of scenario development is one of negotiation between relevant stakeholders—funding agencies, policy communities, scientists, social actors and decision-makers in a variety of sectors. This process of negotiation is illustrated through an analysis of four generations of UK climate scenarios—published in 1991, 1996, 1998 and 2002. Using ideas from science and technology studies and the sociology of scientific knowledge to guide our analysis, we reveal complex relationships between the interests of UK science, policy and society. Negotiating climate scenarios involves compromise between the needs of policy, science and decision-maker in relation to, for example, the selection of the development pathway(s) and emissions scenario(s), the choice of climate model(s), the assessment and communication of uncertainty and the presentational devices used. These insights have a significant bearing on the way in which climate scenarios should be viewed and used in public discourse, strategic planning and policy development.

1. Introduction

The last 20 years have seen a revolution in the way UK society perceives, relates to and plans for future climate. The origins of this revolution lie in the unfolding discovery (see Weart, 2003) that global climate is changing as a result of human emissions of greenhouse gases. This revolution has been abetted by a number of high profile, high impact extremes of weather in recent years (e.g. 2003 European heatwave) and international climate policy agreements (e.g. Kyoto Protocol) and the revolution has been fuelled by the emerging capability of science to offer quantitative assessments of the evolution of future climate (e.g. IPCC, 2007). These assessments extend well beyond the conventional timescales of numerical weather prediction (a few days) or of seasonal forecasting (a few months): Earth system models aim to simulate future climatic evolution over periods from several decades up to the next millennium or beyond (e.g. Lenton et al., 2006). For the first time science is claiming to be able to reveal the climate of future generations as a function of the actions of past, present and future generations. Climate change is a highly visible and contentious issue in public policy and in international relations, which some claim has greater saliency and urgency than any other global issue (King, 2004; Blair, 2006). Securing a

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stable climate as a 'public good' is a new grand project of humanity (Ashton, 2005).

One facet of this revolution has been the development of scenarios of future climate and their increasing visibility in debates around public policy and planning. The UK Government has cultivated a desire to subject far-reaching investment, management, planning and policy decisions to scrutiny with respect to their influence on both future climate and on society's ability to cope with future climate (Hedger et al., 2006). The 'scenario' terminology was borrowed by climate scientists from its original 1950s usage in military strategy and planning and its 1970s usage in the energy business (see, e.g., Van der Heijden, 1997). As viewed by climate researchers, a scenario is a coherent, internally consistent, and plausible description of a possible future state of the world (Carter et al., 1994). A 'climate scenario' may form one component of a broader scenario of the future, and yet is itself informed by broader descriptions of the future world, for example, demographic trends, energy prices or greenhouse gas emissions. This paper focuses specifically on UK climate scenarios, but recognises that such scenarios have to be embedded within wider sets of assumptions about the future. The first formal climate scenarios were published in 1980 (Wigley et al., 1980) and over the subsequent quarter century numerous scientific papers and reports (initially) and strategy, policy and management studies (latterly) have been devoted to the methodology, quantification and communication of climate scenarios.[1] In the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) an entire chapter in the Working Group 1 report was devoted to assessing the science of climate scenario construction (Mearns et al., 2001).

Most of the early climate scenarios were developed for use in scientific impacts assessments (e.g. Carter et al., 1994). These quantitative or semi-quantitative descriptions of possible future climates were used as input to research studies exploring what future climate change might mean for a range of ecosystem, and (sometimes) social system, services and functions. During the 1990s and early 2000s, however, some climate scenarios began to take on a rather more formal and significant role because they were commissioned by public bodies with responsibility for public policy and planning; for example, the UK Department of the Environment (CCIRG, 1991, 1996; Hulme and Jenkins, 1998; Hulme et al., 2002), the EU Directorate General-Environment (Rotmans et al., 1994), EU Directorate General-Research (Parry, 1999), the US Government (MacCracken et al., 2003) and the Australian Greenhouse Office (e.g. CSIRO, 2001). These scenarios, and their subsequent use in policy and planning, carried significant authority. Not only were they commissioned by public bodies and based upon peer-reviewed scientific models and assessments, but they started to be used to inform, or even to define, statutory public policy guidelines.

Despite this widespread development and uptake of climate scenarios there is another starting point for thinking about climate change adaptation which focuses on the nature of the decision to be made. From this standpoint it is not necessarily the case that climate scenario(s) will lead to better decision-making. This may be because information about future climate is marginal to the decision criteria or else because climate scenario(s) cannot offer the types of climate information (scale, resolution, accuracy) which the decision framework requires. We have explored these issues elsewhere (Dessai and Hulme, 2004, 2007) so this is not the focus of the present paper, but any evaluation of a climate scenario process should keep this perspective in mind.

Notwithstanding the above concern, national climate scenarios are increasingly prevalent (existing for, *inter alia*, The USA, Australia, UK, Sweden, Portugal, Finland, Spain, The Netherlands) and are often endowed with governmental authority to guide decision-making. It is important to understand the negotiated processes of climate scenario construction for a number of reasons. First, it helps to reveal what information is contained within the scenarios, what information is absent or suppressed and why these decisions were made. Failure to expose such limitations and contingency endows scenarios with an unwarranted aura of authority for downstream users (Lahsen, 2005). Second, an analysis of climate scenario construction processes is a specific case which illustrates the broader issue of how science is introduced into policy (e.g. Jasanoff and Wynne, 1998; Sarewitz and Pielke, 2006). Third, understanding the way in which scenarios have been constructed in the past may help in the design, operation and products of scenario construction processes in the future. The demand for climate scenarios is only likely to increase in the future and making best use of science for policy in this area is a priority shared across many governmental agencies.

The paper examines this process of climate scenario negotiation drawing upon the four generations of formal climate scenarios that have been published by the UK Government between the years 1991 and 2002. The UK is chosen as the case study since it has been longest in the business of climate scenarios (cf. Wigley et al., 1980), since it has been through four generations of scenario development, and since one of the authors (Hulme) was directly involved in all four generations. The UK is also a good case study to choose because it is about to launch a fifth generation set of climate scenarios during 2008 under the auspices of the UK Climate Impacts Programme—UKCIP08.[2] This critical assessment of the construction of past scenarios may well illuminate important facets of the next generation of UK climate scenarios about which users and producers should be aware. Our assessment draws upon published reports and papers relating to the scenarios, unpublished contractual agreements and the informal meeting notes of one of the authors (Hulme).

The paper is structured in five subsequent sections. In Section 2, we introduce four ideas from science and technology studies and the sociology of scientific knowledge which we use to frame our assessment. Section 3 provides a very brief chronology of the four generations of UK climate scenarios – 1991, 1996, 1998 and 2002 – commenting on their

[1] There is a formal distinction between a 'climate scenario' and a 'climate change scenario' depending on whether the scenario describes future *changes* in climate (from some assumed, unarticulated baseline), or whether the scenario describes an actual future climate (Mearns et al., 2001).

[2] Details of this on-going process can be found at http://www.ukcip.org.uk/scenarios/ukcip08.

origins and basic construction and characteristics. In Section 4, we assess these scenarios with respect to process, content and delivery. Section 4.1 examines the relationships between the stakeholders involved in the respective processes and how negotiations between these stakeholders resulted in important decisions being made about their design and communication. Section 4.2 reveals the different ways in which uncertainty about future climate has been characterised and articulated in the different climate scenarios. Uncertainty is perhaps the single most sensitive facet of a climate scenario and one that climate science has struggled to come to terms with (Shackley and Wynne, 1996; Moss and Schneider, 2000; Van der Sluijs, 1997; Van der Sluijs et al., 1998; Lahsen, 2005). In Section 4.3, we examine the ways in which the UK climate scenarios have been communicated and applied in wider public debate and policy planning. Using the three framing ideas introduced in Section 2, we then draw out some of our key insights from this critical assessment (Section 5), before concluding in Section 6 with some final thoughts that are relevant for the future construction, understanding, communication and application of climate scenarios.

2. Four framing ideas

Based on our reading of the sociology of science literature and our *a priori* understanding of the nature of climate scenarios, we consider the following ideas to be of potential use to us in our later interpretation of the four generations of UK climate scenarios.

In relation to science policy, we adopt the thinking of Sarewitz and Pielke (2006) in their recent assessment of the metaphor of 'reconciling supply and demand' for understanding the design of science policy. With the exception of what may be considered 'basic' science (a minority of the total science spend), most decisions to invest in science have some purposeful goal in mind. In pursuing a particular set of societal goals, how do we know if a given research portfolio is more potentially effective than another portfolio? In other words, how are decisions made which seek to reconcile the supply of scientific ideas and capabilities with the demand for specified types of scientific products or outcomes? These decisions not only, obviously, determine what science gets done, but they also have a large bearing on the eventual types of scientific information that may be available for decision-makers or, in our case, available for the construction of climate scenarios. This constraint has long been identified in science and technology studies (e.g. Gibbons et al., 1994), but its resolution remains contentious and brings into play questions around the nature of 'experts' (e.g. Jasanoff, 2003), of trans-disciplinarity (e.g. Pohl, 2007) and of peer review (e.g. Scott, 2007). While the metaphor of reconciling supply and demand is too linear a caricature of a complex interplay of social forces we use it here cautiously to subject our evolutionary history of UK climate scenarios to a critical screening.

Drawing upon the ideas of Cash et al. (2003) about how boundaries between knowledge and action can be managed when engaged in post-normal science, we also use the idea of 'saliency, credibility and legitimacy' as three criteria against which to evaluate the effectiveness of the UK climate scenarios. Salience is concerned with the relevance of the scenarios to the needs of decision-makers, credibility is concerned with the scientific adequacy of the technical component of the scenarios, and legitimacy is concerned with the process and transparency of the scenario design, construction and distribution.

'Boundary objects' (Star and Griesemer, 1989) and 'boundary organisations' (Guston, 1999) are also useful constructs for thinking about how climate scenarios may be evaluated against these three criteria. Boundary objects (for example, a climate scenario) act as an anchor or bridge between two social worlds (for example, climate modelling and climate policy) with a sufficiently shared understanding to gain legitimacy in each world, but where mismatches in the overlaps become problems to be negotiated (Star and Griesemer, 1989). Boundary organisations, existing at the boundary of science and politics, also receive legitimacy from both worlds and emerge as a way of preserving the cognitive authority of science whilst diluting its hegemonic tendencies.

The fourth framing idea we use is that of social constructivism as developed by the sociology of scientific knowledge (SSK) community (e.g. Golinksi, 1998; Hannigan, 2006). In particular, following Demeritt (1994, 2006) and drawing upon the ideas of Beck (e.g. 1992), Jasanoff and Wynne (e.g. 1998) and Latour (e.g. 2004), we consider that scientific tools for public policy – such as climate scenarios – have an essential and unavoidable constructionist dimension, i.e., they cannot emerge solely as a product of a conventional positivist science. The insights provided by such sociologists of science would suggest that such tools are products of an interactive process (or negotiation) between scientists and the interests of society in which a number of considerations extrinsic to a positivist methodology play an important part. How the interests of society are represented in this negotiation is by no means the least significant factor.

We therefore contend that climate scenarios are socially contingent products of a post-normal science; they are 'situated' in a particular time and place and carry the mark of a particular set of power relationships between a bounded set of social actors. We do not suggest that climate scenarios are 'nothing but' a social construction (nor indeed that climate change is simply constructed rather than observed and discovered, avoiding the destructive relativism of some constructionists), but we do recognise Latour's normative claim that 'there are good constructions and bad constructions' (Latour, 2004). There are other variants on this position (e.g. the idea of 'co-production' as explored by Jasanoff, 2004), but the central idea is recognising the social contingency of science and its products.

3. A chronology of UK climate scenarios

This account should be read in conjunction with Fig. 1 (which provides a simple timeline of the period concerned) and Table 1 (which summarises the key characteristics of the climate scenarios—emissions (forcing) scenarios, models used, variables presented, etc.). In providing these thumbnail sketches of the four generations of climate scenarios, we

UK Climate Scenarios		UK developments	International developments
	1989	Hadley Centre established	
	1990		IPCC FAR
CCIRG91 scenarios	1991	LINK Project established	
	1992		IPCC IS92 emissions scenarios UN FCCC agreed
	1993		
	1994		UN FCCC comes into force
	1995		
CCIRG96 scenarios	1996		IPCC SAR
	1997	UKCIP established	Kyoto Protocol agreed
UKCIP98 scenarios	1998		
	1999		
	2000	UK climate change programme	IPCC SRES emissions scenarios
	2001		IPCC TAR
UKCIP02 scenarios	2002		
	2003		
	2004		
	2005		Kyoto Protocol comes into force
	2006	UK climate change programme	
	2007		IPCC AR4
UKCIP08 scenarios	2008		

Fig. 1 – A timeline from 1989 to 2008 of the main developments internationally and within the UK relating to climate change science and politics.

include the emissions (forcing) scenarios used as well as the choice of model(s).

3.1. *CCIRG91*

The first climate scenarios for the UK which carried an 'official' government stamp were published in 1991 as part of the work of the Climate Change Impacts Review Group (CCIRG, 1991). CCIRG was a group of academic experts brought together by the Department of the Environment[3] (DoE) to make an assessment of the possible impacts of climate change for the UK. Their work was based primarily on published literature and was informed by the recently published First Assessment Report of the IPCC (IPCC, 1990) and by the CCIRG91 climate scenarios. The scenarios were based on previous work by Hulme and Jones (1989), further elaborated in Warrick and Barrow (1991).

By the end of the 1980s a number of climate modelling groups around the world had completed model experiments in which atmospheric General Circulation Models (GCMs) were used to simulate the response of the global climate to a doubling of carbon dioxide in the atmosphere. Hulme and Jones (1989) examined results from five such GCM experiments (Table 1) to construct regional scenarios of temperature and precipitation change for the UK. These results suggested a generally warmer and wetter UK, with the exception of summer where the model results diverged on the sign of the precipitation change. Warrick and Barrow (1991) elaborated these results by making them time-dependent (or transient) by combining the normalised spatial patterns of change from the equilibrium GCM experiments with results from a simple upwelling-diffusion energy-balance climate model (Wigley and Raper, 1987), an approach called pattern-scaling (Santer et al., 1990). This approach required one or more forcing scenarios to be adopted and CCIRG91 used just one such scenario: a growth in greenhouse gas concentrations of 1.5% per annum. This was an arbitrary scenario which fell roughly in the middle of the range published in IPCC (1990); no narrative about the world development path associated with such a forcing scenario was introduced. On the other hand, the concept of 'climate change commitment'[4] was introduced and was estimated to be between 0.6 and 1.7 °C over the decades ahead.

These results formed the basis of the CCIRG91 climate scenarios which in turn were used by the CCIRG expert group in writing their report. The CCIRG91 scenarios were not independently disseminated, other than through the scientific paper (Warrick and Barrow, 1991) and report cited above. There was no concerted effort by government to promote the use of these scenarios, although the DoE subsequently established the Climate Impacts LINK Project at the University of East Anglia (UEA) (Viner and Hulme, 1994) to make it easier for research scientists to gain access to modelling results from the UK Hadley Centre.

3.2. *CCIRG96*

The second set of 'official' UK climate scenarios (CCIRG96) was associated with the publication of the second CCIRG report in 1996 (CCIRG, 1996). As with CCIRG91, and again commissioned by the DoE, these new scenarios were

[3] The UK environment ministry changed shape and name twice during the period of this assessment, in 1997 from the Department of the Environment (DoE) to the Department of Environment, Transport and the Regions (DETR), and again in 2001 to the Department of Environment, Food and Rural Affairs (Defra). We use whichever acronym was appropriate to the time.

[4] The thermal inertia of the ocean means that climate will continue to warm even if greenhouse gas emissions were suddenly to cease (cf. Meehl et al., 2005; Wigley, 2005).

Table 1 – Summary characteristics of the four generations of UK climate scenarios

	CCIRG91	CCIRG96	UKCIP98	UKCIP02
Number of scenarios	1	1	4	4
Forcing	1.5% p.a. growth in GHG concentration	IPCC IS92a emissions scenario	0.5% and 1.0% p.a. growth in GHG concentration	IPCC SRES scenarios: B1, B2, A2, A1FI
Climate sensitivity	3 °C (although 2 °C and 4 °C used in report)	2.5 °C (IPCC 'best-guess')	2.5 °C, plus IPCC range of 1.5–4.5 °C	3 °C
Models used	Five atmospheric GCMs (including UKLO)	One atmosphere-ocean GCM, HadCM1 (plus a table with 11 other GCMs of various designations)	One atmosphere-ocean GCM, HadCM2 (plus some results from three coupled GCMs)	One regional climate model (HadRM3), conditioned by HadAM3H, conditioned by HadCM3 (simple maps from eight other coupled GCMs)
Spatial resolution	5° by 5° grid (c.500 km), plus interpolated maps	2.5° by 3.75° grid (c.300 km), plus interpolated maps	2.5° by 3.75 grid (c.300 km), plus interpolated maps	0.44 by 0.44 grid (c.50 km); no interpolation
Temporal resolution	Seasonal averages	Seasonal averages	Monthly/seasonal averages, plus some daily weather variables	Monthly/seasonal averages and interannual variability, plus some daily weather variables
Pattern-scaling	Yes	Yes	Yes	Yes (but without use of a simple model)
Climate variables	Temperature and precipitation (and degree-days)	Temperature and precipitation (and eight other variables)	Temperature and precipitation (and nine others)	Temperature and precipitation (and 13 others)
Sea level	Yes	Yes	Yes	Yes
Baseline observational data	No	No	Yes; and observed trends	Yes; and observed trends
Other attributes	Mentions 'climate change commitment'	Uses a statistical model for changes in temperature extremes	Mentions sulphate aerosol effects, the effect of the Kyoto Protocol, and the thermo-haline circulation	Mentions the thermo-haline circulation, discusses climate feedbacks not considered, and has a section on other uncertainties
Report pages	10	32	78	112
Data available?	No	Available, but not mentioned in the report	Yes, via UKCIP office/LINK Project	Yes, via UKCIP web-site

developed explicitly as part of the work of this expert group. The CCIRG96 scenarios were based almost entirely on the results of one GCM experiment, the first transient climate change experiment completed by the Hadley Centre in 1992 with their coupled ocean-atmosphere model (known as UKTR or HadCM1; Murphy, 1995; Murphy and Mitchell, 1995). This used just one forcing scenario which approximated the IS92a emissions scenario of the IPCC (1996), but again no attention was paid to world development paths consistent with this forcing. The scenarios were more detailed than CCIRG91 since they included estimates of changes in a number of climate variables other than average temperature and precipitation (e.g. wet day frequency, precipitation intensity, potential evapotranspiration, etc.). Daily data from the GCM were also used in addition to monthly data. As well as a narrative and tabulated numbers, the scenarios also presented contoured maps of these changes for the UK extrapolated from four GCM grid boxes representing the UK land area.

The pattern of warming across the UK in CCIRG96 – greater in the southeast, lesser in the northwest – was the opposite of that reported in CCIRG91, a consequence of the explicit representation of ocean dynamics in HadCM1. As with CCIRG91, the 1996 scenario showed wetter winters throughout the UK, but summer now saw a regional pattern with drying in the south and wetting in the north. While only one model was used to create the scenario – HadCM1 – the report discussed the different qualitative levels of confidence that were attached to different climate variables (e.g. temperature had greater certainty than wind speed) and a table supplied headline results from 11 other available climate models (Table 1).

3.3. UKCIP98

The UK Climate Impacts Programme (UKCIP) was established by the DoE in early 1997 to facilitate a national integrated climate change impacts assessment for the UK. One of the first major products of this initiative was the publication of a new set of climate scenarios for the UK, referred to as UKCIP98 (Hulme and Jenkins, 1998). In contrast to the 1991 and 1996 scenarios, the UKCIP98 scenarios were developed as a standalone product within this much larger co-ordinated government programme for engaging and facilitating stakeholder assessments of climate change impacts and adaptation (Hedger et al., 2000).

UKCIP98 was designed around two sets of climate change experiments completed in 1996 by the Hadley Centre using their new HadCM2 model, forced with greenhouse gas equivalent concentration increasing by 0.5% per annum for one set (approximating IPCC emissions scenario IS92d) and by 1.0% per annum for the other set (approximating IS92a). In contrast to 1991 and 1996, four climate scenarios were presented in UKCIP98 labelled ‘Low’ (low forcing with low climate sensitivity[5]), ‘Medium-Low’, ‘Medium-High’ and ‘High’ (high forcing with high climate sensitivity) (Table 1). The results for annual and seasonal average temperature were similar to those in CCIRG96: a UK warming rate similar to the global-mean with a gradient in the magnitude of warming decreasing from southeast to northwest. Precipitation changes were also similar to CCIRG96: annual and winter precipitation increased for all periods and scenarios and for summer a general tendency for drying in the south of the UK and wetting in the north. A wider range of variables was provided for the ‘Medium-High’ scenario (e.g. diurnal temperature range, relative humidity, potential evapotranspiration, etc.) and changes in interannual variability were also reported for this scenario. This was because these variables had only been saved for this particular model experiment by the Hadley Centre. Although based on results from just one climate model, UKCIP98 also presented results in map form from three other GCMs (one each from Canada, USA and Germany; Table 1). Some of the patterns of change across the UK, especially for precipitation, were different in these other models.

3.4. UKCIP02

The fourth generation of UK climate scenarios were published by UKCIP in 2002, following the Third Assessment Report (TAR) of the IPCC. The UKCIP02 scenarios (Hulme et al., 2002) again presented four scenarios, but each scenario was now explicitly tied to a different emissions profile derived from the four storylines published in the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000). The UKCIP02 scenarios were presented at a much higher spatial resolution than previously – 50 km cells compared to 300 km cells in 1996 and 1998 and 500 km in 1991 – based on a new regional climate model from the Hadley Centre (HadRM3). Due to the computational expense of this approach, only four regional model experiments for one future time period (2071–2100) were conducted (three with the SRES A2 forcing scenario and one with B2). Pattern-scaling techniques were used to derive climate change scenarios for other time periods (the 2020s and 2050s) and for the three other emissions scenarios (Table 1).

Since all results presented in UKCIP02 were again drawn from one climate model hierarchy – that built around HadCM3 – a range of headline results for temperature and precipitation from the other coupled GCM experiments reported in the IPCC TAR were mapped and tabulated. For UK summer precipitation, HadCM3 was amongst the driest of models, whereas for winter precipitation and overall temperature HadCM3 lay in the middle of the model range. Based on these results, expert-based uncertainty margins were included for seasonal temperature and precipitation changes for each emission scenario for the 2080s. As with the earlier scenarios, the UK warmed at a rate very similar to the world as a whole and the same southeast to northwest warming gradient existed as in UKCIP98. The warming in the southeast was particularly pronounced in summer. Winter precipitation increased for all periods and summer was expected to become drier, especially in the southeast. The UKCIP02 report presented results for a number of other climate variables (e.g. diurnal temperature range, cloud cover, relative humidity, etc.) and also for daily

[5] ‘Climate sensitivity’ is the estimated mean global surface warming that would eventually result were concentrations of greenhouse gases in the atmosphere to be doubled. The likely range for this value is currently estimated (IPCC, 2007) to be between 2 and 4.5 °C.

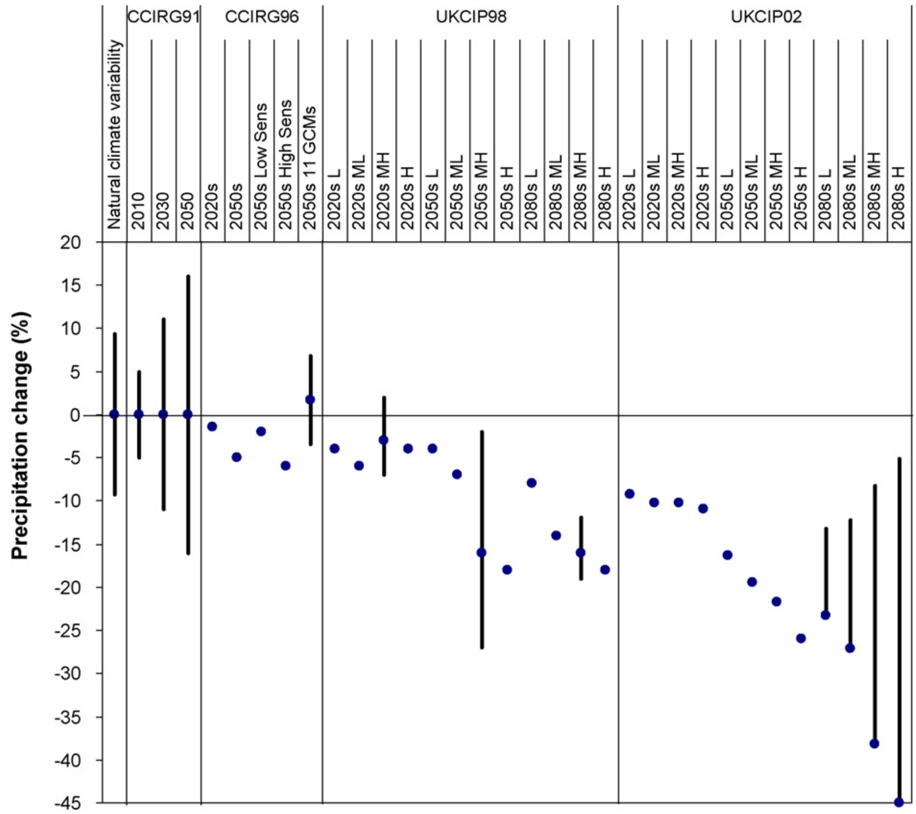

Fig. 2 – Chronology (earliest on the left; latest on the right) of estimates of summer precipitation change (%) for the southeast of England for different four sets of UK climate scenarios and for different future time horizons (2010s, 2020s, 2030s, 2050s and 2080s). The interval ranges are based on the judgment of the authors of the studies based on the GCM results (CCIRG91), other GCM results (CCIRG96 and UKCIP02 2080s) or ensemble runs (UKCIP98 MH).

climate variables which allowed the examination of changes in heating and cooling degree days, daily precipitation, etc.

To give a sense of how the estimates of future climate change evolved during these 11 years and between the four generations of scenario, Fig. 2 shows the results for one climate variable of some significance for UK impacts: the change in summer precipitation for eastern England, the driest region in the UK. The evolving estimates of this variable between 1991 and 2002 were not stable: in successive scenarios the estimate of summer drying for eastern England – whether for the 2020s, 2050s or 2080s – became more severe. In the 1998 and 2002 scenarios, no scenario (or scenario range) suggesting summers might become wetter, in contrast to the 1991 and 1996 scenarios.

4. Assessing the key issues

4.1. *Institutional relationships*

The changing UK institutional arrangements for climate change research and policy (e.g. Wynne and Simmons, 2001; Hulme and Turnpenny, 2004) influenced the processes of scenario specification, design and implementation. The primary funding for each generation of UK climate scenarios originated with the Department of Environment. In 1991 and 1996 the scenarios were constructed as part of the work of the Climate Change Impacts Review Group, an expert Group superseded after 1996 by the UK Climate Impacts Programme. Throughout this period, the Hadley Centre received funding from the DoE/DETR/Defra.

The CCIRG91 scenarios were designed and constructed almost entirely by a small group of climate scientists based at the University of East Anglia (UEA) who were invited by DoE to draft the scenarios. Drawing upon a very small number of published studies, and limited by access to results from the first generation suite of equilibrium GCM experiments, a scenario report was written and submitted to the CCIRG for use in their deliberations. There was no specific consultation process with a wider peer community and no formal process for allowing perspectives from outside the review group to influence the design and construction process. The key choices about the scenarios (see Table 1) were based on the scientific judgement of the UEA scientists alone, although influenced by the recent publication of the IPCC First Assessment Report (IPCC, 1990). The IPCC report provided a wider scientific context for the choices made—for example, 3 °C was the mid-point of the IPCC range for the climate sensitivity. The CCIRG91 scenarios were therefore a product of a privileged relationship between commissioning civil servants and a scientific elite, and the construction decisions were closed and unchallenged.

The CCIRG96 scenarios emerged as a result of a similar process, although with one important difference which further reinforced the existing institutional relationships. In 1991, the DoE established at UEA the Climate Impacts LINK Project,[6] a contracted activity to facilitate the dissemination and use of results from Hadley Centre climate change GCM experiments to the impacts research community (Viner and Hulme, 1994). By 1996, this Project had been operating for nearly 5 years and had established UEA scientists as having privileged (gatekeeper) access to Hadley Centre modelling results. The (untendered[7]) commission from DoE to UEA in 1996 to construct an updated climate scenario for the UK was explicitly associated with the LINK Project and with DoE's desire to further widen the visibility and use of results from its major climate change research investment, the Hadley Centre. The design of CCIRG96 around the first coupled ocean-atmosphere HadCM1 transient climate change experiment was therefore a direct consequence of these institutional relationships. The existence of HadCM1 results, together with the LINK Project, closed down options to consider results from a wider range of GCM experiments. On the other hand, the use of the pattern-scaling method did allow the results from HadCM1 to be presented for the IS92a emissions scenario – then widely regarded as the standard Business-as-Usual – and for the IPCC Second Assessment Report (SAR) best-estimate climate sensitivity of 2.5 °C (IPCC, 1996).

The existing contractual relationships between the DoE, the Hadley Centre and UEA, coupled with the recent publication of the IPCC SAR, shaped the design of the CCIRG96 scenarios. Nevertheless, as with CCIRG91, this was a predominantly top-down process with little involvement of scientific peers (other than the selected members of the CCIRG) and no formal consultation with potential users of the scenarios or decision-makers.

The decision to publish the next set of climate scenarios just 2 years later (November 1998) was driven by a different combination of factors. A new set of climate change experiments had been completed in 1996 by the Hadley Centre using a new generation of their model – HadCM2 – and there was a desire from DETR for their large investment in this model development and in the computational resources used for the experiments to be exploited. Furthermore, the newly established (and also DETR-funded) UK Climate Impacts Programme based at the University of Oxford was in its first year of operation. One of the most immediate ways of engaging the attention of public and private sector organisations to become partners in a national assessment of impacts and adaptation options was to have an engaging product. A new state-of-the-art set of national climate scenarios was recognised as one of the best ways to entrain stakeholders in the work of UKCIP (Hedger et al., 2000).

These two factors were sufficient to initiate the process in 1997 for the design of the UKCIP98 scenarios, despite the Third Assessment Report of the IPCC – providing the next international climate science benchmark – not being due until 2001. The existence of UKCIP now changed the institutional relationships between DETR, UEA and Hadley. Although the contract (through a single-action tender[8]) to develop and publish UKCIP98 was between DETR and UEA, the contract was to be completed under the auspices of the UKCIP and with a more explicit role in the design and construction process for scientists from the Hadley Centre.

A four-way relationship was now established between the key actors, each of whom had a different role and interest in the scenario construction. DETR remained the ultimate funders of the work (i.e., they were the client) and their primary concern was to see science, particularly Hadley Centre science, being used to support the policy goal of a well-adapted UK through the development of impacts and adaptation assessments. UKCIP was a DETR-funded programme with their own objectives of facilitating a stakeholder-led national impacts assessment, and they acted as a conduit for representing the interests and needs of an emerging constituency of stakeholder organisations (Hedger et al., 2000). The Hadley Centre, also largely-funded by the DETR, were the developers of the premiere UK climate model and were concerned to ensure appropriate, and highly visible, use of their model results. UEA were the contractors for delivering the UKCIP98 scenarios, comprising a small team of independent scientists who for many years had undertaken contract research for DETR, and several of whom were UK-nominated scientists heavily involved in the IPCC. As contract-based researchers their concern was to secure funding for their salaries and to secure kudos for their institution.

The publication of the Third Assessment Report of the IPCC in 2001 acted as the main influence on the timing of the fourth generation of UK scenarios, UKCIP02. The UK Climate Impacts Programme had now embarked on its second phase contract (2000–2005) with Defra and had established a much larger and more vociferous network of stakeholder organisations in the UK who were actively engaged in thinking about the implications of climate change for their business strategies (Hedger et al., 2006). The contract to design and publish the UKCIP02 scenarios was let by Defra to UEA (again through single-action tendering) in the first half of 2000, providing an almost 2-year design and development period, far longer than had existed in previous scenario rounds.

This extended time-frame allowed for the completion of new climate model experiments by the Hadley Centre, for example, using high-resolution atmosphere models and a 50 km-resolution regional climate model. It also allowed for an extended period of consultation with the UKCIP user com-

[6] The LINK Project contract was subject to an open competition between potential contractors. The initial 3-year contract once secured, however, was then re-negotiated bi-laterally every 3 years with the DoE/DETR/Defra and continued throughout the period of this assessment.

[7] This commission was appended as a supplement to another pre-existing research contract between DoE and UEA.

[8] 'Single-action tenders' were issued by a Government Department when only one contractor was invited to submit a bid to meet the specifications for a commissioned piece of work. Such tenders were competitive against benchmark criteria of quality and cost, but not competitive against rival contractors. The latter would result from 'multiple-action' or 'open tenders'.

munity about some of the more detailed aspects of the scenario construction methods. A UKCIP02 stakeholder panel was established consisting of about 15 individuals representing a range of governmental departments, non-departmental public bodies and private companies, and a number of consultation exercises were designed through the UKCIP.

The design and development process for the scenarios was again led by UEA, but was embedded in a larger, more complex set of interests and perspectives than had existed in earlier scenario rounds. Key decisions were again taken by a small informal group of Defra officials, Hadley Centre scientists, UKCIP representatives and UEA scientists, but with the wider views of users being filtered through UKCIP and a more iterative series of discussions about some of the key design components that took up to 12 months.

For example, extensive discussions took place within this group about the number and naming of the scenarios, their connection with non-climate scenarios (mediated via the IPCC SRES scenarios), their spatial resolution, the selection of a baseline period, the representation of results from modelling centres other than Hadley, what sub-set of weather extremes to be presented, the adoption and meaning of a precise uncertainty lexicon. Whilst the UKCIP consultation process had opened up the design activity to user viewpoints (for example, the user demand for higher resolution information strongly influenced some of the key decisions about uncertainty representation), there was no formal mechanism for a wider peer community of science experts (UK or international) to influence or comment on the design. There *was* a limited expert peer review exercise conducted using a late draft of the UKCIP02 document, but comments and subsequent adjustments were restricted mostly to presentational and linguistic issues. On the other hand, following IPCC procedures and conventions, the final text of the executive summary UKCIP02 was approved word-by-word by Defra officials with any changes made to the summary subsequently being reflected in the main body of the report.

4.2. *Representations of uncertainty*

Uncertainty is perhaps the most pervasive feature of climate scenarios. Its presence manifests itself in a number of different forms from uncertainty about future estimates of greenhouse gas emissions to uncertainty about the value of climate sensitivity or uncertainty surrounding initial model conditions and parameterisations (Schneider and Kuntz-Duriseti, 2002; Dessai and Hulme, 2004). It is important to examine uncertainty in climate scenarios because of the importance of uncertainty in shaping public policy.

The first set of UK climate scenarios (CCIRG, 1991) had a relatively explicit treatment of uncertainty because uncertainty ranges were provided, at least for precipitation change. The ranges were subjective, but they explained the contradictory results given by GCMs and showed that uncertainty expanded with distance into the future. While uncertainties in climate sensitivity were explored to estimate future global-mean temperature – a range of 2–4 °C was used – only one emission scenario was used (Business-as-Usual with greenhouse gas concentration growing at 1.5% per annum). The scenarios were constructed by scaling regional patterns from GCMs using projections of future changes in global-mean temperature. This technique, called 'pattern-scaling', was first developed by Santer et al. (1990). It allowed equilibrium GCM experiments (1× and 2× CO_2) to become time-dependent by scaling the change fields with results from a simple climate model. This technique assumes a linear relationship between the local (grid box) climate variable and global-mean temperature. While some studies have showed that the linear assumption of pattern-scaling is broadly valid for temperature and somewhat for precipitation (Mitchell et al., 1999; Mitchell, 2003) other studies have shown the opposite (Murphy et al., 2004; Kjellström and Bärring, submitted).

The CCIRG91 climate scenarios used information from five GCM experiments, one from the UK (UKMO) and four from the USA (Table 1). For temperature the average of five GCM equilibrium results was used, but not for precipitation. According to Warrick and Barrow (1991), ''*... this is because the regional patterns of precipitation changes predicted by GCMs are very unreliable, more so than for temperature changes*''. They corroborate this by stating that ''*most GCMs have serious difficulties in simulating the present precipitation patterns accurately at the regional scale*'' and ''*the qualitative and quantitative differences amongst GCMs for CO_2 doubling experiments are very large*''. The authors also express their lack of confidence in the results as predictions, emphasising that ''*they must be regarded useful only as scenarios*''. These comments suggest that the authors recognised the importance of communicating uncertainty.

The temperature projections in CCIRG91 assumed that the average of five GCM results was better than any single model simulation. Given the large uncertainties associated with precipitation change, in particular for summer (three models showed a decrease and two models showed an increase in rainfall), the authors expressed a subjective judgement (based on the five GCM results) for precipitation change by 2050: a change of $0 \pm 16\%$ for summer and $8 \pm 8\%$ for winter. CCIRG91 remained silent about other climate parameters because it argued that at the regional scale, ''*the uncertainty in climate modelling is very large indeed*''. Projections of sea-level rise were also given for the single Business-as-Usual scenario, including both climate sensitivity and sea level associated uncertainties. By the year 2050, sea level was estimated to be 35 ± 15 cm higher than 1990.

Section 3 explained the major differences between CCIRG96 and CCIRG91. While sophistication 'grew' – in the form of a transient simulation using a coupled model with many more climate variables presented in the scenario – uncertainty was 'lost'. There was a move from using multiple models in CCIRG91 (an ensemble mean or a subjective range) to using a single model (HadCM1) in CCIRG96. The effect this had was that the projections assumed more certainty than was warranted even though the report again classified them as scenarios and not predictions. A sub-section of the report (entitled 'Uncertainties') did mention headline results from 11 other GCM experiments (some equilibrium, some transient), so the reader was aware of inter-GCM uncertainty, but these results were not portrayed in the scenario itself.

This section of the report also elaborate the impact of climate sensitivity uncertainty (1.5–4.5 °C) on regional projections. Despite the existence of six IPCC emissions scenarios at the time (IS92a–f; Leggett et al., 1992), CCIRG96 only used one emissions scenario arguing that "*the IS92a scenario remains a sensible one to use at the present time given that the emissions fall roughly mid-way in the range of scenarios recently reviewed by the IPCC (Alcamo et al., 1995)*". From an uncertainty perspective this again reduces the plausible range of the regional projections. Finally, numerous assumptions were made throughout the report (e.g. linear pattern-scaling; changes in extremes without inclusion of changes in variability from the A/OGCM), but not much information was given about their associated uncertainties. For example, for linear pattern-scaling it was only stated that: "*this may be a poor assumption*". In summary, the amount of detailed information presented in the CCIRG96 scenarios increased (compared to CCIRG91) and with better model representation of the dynamics of the climate system (oceans plus atmosphere), but the characterisation of uncertainty regressed. The headline scenarios sampled only one climate model compared to five models in 1991.

The UKCIP98 scenarios grew further in complexity by using the latest version of the Hadley Centre AOGCM (HadCM2, which included an ensemble of four simulations) and by including detail about changes in a wider set of climate variables. UKCIP98 presented four alternative scenarios that mixed uncertainty about emissions of greenhouse gases with uncertainty about climate sensitivity. The 'Medium-Low' scenario was composed of the ensemble mean of the HadCM2 experiments forced by 0.5% per annum increase in carbon dioxide equivalent (this forcing scenario was not greatly different from IS92d). The 'Medium-High' scenario was forced by 1% per annum increase in carbon dioxide, which was similar to IS92a. The 'Low' and 'High' scenarios were derived, respectively, from the ensemble-mean patterns of the 'Medium-Low' and 'Medium-High' scenarios. Furthermore, the 'Low' and 'High' scenarios were derived by scaling these patterns using results from a simple climate model to explore, respectively, a 1.5°C and 4.5 °C climate sensitivity. The 'Medium-Low' and 'Medium-High' scenarios used the climate sensitivity from the original AOGCM (HadCM2), which was 2.5 °C.

By presenting four scenarios, the uncertainty range of UKCIP98 was considerably larger than for the CCIRG96 scenarios. However, these four scenarios confounded uncertainty from emissions of greenhouse gases with uncertainty from the climate sensitivity. For the number of sampled emissions scenarios (2) and climate sensitivities (3) the number of possible cases were six (2×3), but UKCIP98 only explored the combination of extremes (1.5 °C climate sensitivity with IS92d; 4.5 °C climate sensitivity with IS92a) to keep the number of scenarios (4) to a minimum. The uncertainty range would have been larger if all six IPCC IS92 scenarios had been used ($6 \times 3 = 18$ combinations) and even larger if other A/OGCMs had been sampled. Like the CCIRG96 scenarios, UKCIP98 only used results from one A/OGCM, thus only sampling a fraction of the plausible uncertainty space. However, results from three other A/OGCMs were discussed in the report.

Annual, winter and summer mean temperature and precipitation change results were presented for all four UKCIP98 scenarios, but only for the 'Medium-High' scenario did the report provide information for other climate variables,[9] for climate variability and for daily extremes. This approach understated the uncertainty involved in these estimates and implicitly favoured one scenario over the other three. Other climate-related variables (such as changes in seasonal gales and airflow characteristics) and the transient evolution of the climate over the 21st century were also reported. A chapter of the UKCIP98 report was devoted to discussing the downscaling of climate change information (e.g. unintelligent, statistical and dynamical), but no analysis was presented. A section of a chapter focused on uncertainty and levels of confidence. Here the authors ranked subjectively the level of confidence ('high', 'low', etc.) associated with climate variables from UKCIP98. For example, they had 'high confidence' in global-mean temperature, but 'low confidence' in change in climatic variability and even lower confidence on a potential collapse of the thermohaline circulation. In summary, while the complexity of the scenarios increased in UKCIP98, the characterisation of uncertainty was more thorough than in CCIRG96 because uncertainty about initial conditions was tackled (using ensembles), as was uncertainty in emissions of greenhouse gases and the climate sensitivity; at least to some extent.

As with previous scenarios, UKCIP02 grew in sophistication by using results from a high-resolution regional climate model (50 km grid), new emissions scenarios based on the IPCC SRES, and greater detail about daily climate and changes in extremes. The regional climate model was conditioned by an AGCM (HadAM3H), which itself was conditioned by an A/OGCM (HadCM3). This "double-nesting" approach improved the quality of the simulated European climate (see Appendix 2 in Hulme et al., 2002), but in terms of uncertainty it represented only one possible combination of emissions scenario and climate sensitivity. UKCIP02 therefore presented information at finer spatial and temporal scales than previous scenarios, but this highly resolved information lacked any quantitative characterisation of the associated uncertainties. On the other hand, a more consistent treatment of the levels of confidence ('high', 'medium' or 'low') surrounding the contributing science was given in UKCIP02 than in earlier scenarios. Levels of confidence were provided for qualitative statements using the judgements of the authors with respect to the following criteria:

- knowledge of the physical reasons for the changes;
- the degree of consistency between different climate models;
- an estimate of the statistical significance of the results.

In the report, the words "*will change*" were used where there was high confidence, whereas the words "*may change*" were used where there was less than high confidence. The report distinguished between emissions uncertainty and scientific uncertainty. There was some attempt at exploring scientific uncertainty by comparing the results of eight other A/OGCMs with the three ensemble members of HadCM3. However, no other features of the climate modelling hierarchy

[9] They are: diurnal temperature range, vapour pressure, relative humidity, incident short-wave radiation, total cloud cover, mean 10 m wind speed and potential evapotranspiration.

(different high-resolution atmospheric GCMs or regional climate models) were explored. On the basis of the A/OGCM comparison, the authors of the report provided semi-objective uncertainty margins to be applied to the UKCIP02 scenarios for the 2080s for changes in average winter and summer temperature and precipitation and for all four emissions scenarios. As in previous scenarios, pattern-scaling (this time using patterns from a regional model) was used to derive different emissions scenarios (A1FI, B1 and B2) and different time periods (2020s and 2050s) from the original three ensembles of 2071–2100 under SRES A2.

4.3. *Communication and application*

When considering the ways in which the UK climate scenarios have been presented to, and used by, British society there is a clear difference between the scenarios developed in the context of CCIRG and UKCIP. In 1991 and 1996, the scenarios had no independent existence or separate marketing; they were created for a specific purpose (to service the expert review group looking at climate impacts in the UK) and they were communicated by DoE solely in this context. In 1996, for example, the media release (2 July) quoted the then Environment Minister, John Gummer, under the headline 'Climate change will have an impact on the UK'. Most of the text of the media release referred to the impacts on Britain of climate change, with only very brief mention of 'the climate scenario adopted by the report' for the year 2050.

In contrast, the 1998 and 2002 scenarios produced under the auspices of UKCIP were both launched as new stand-alone scientific 'products'. In both cases a major media event in London was orchestrated by DETR/Defra and fronted with an opening statement from, in November 1998, the Environment Minster Michael Meacher, and in April 2002 from the Secretary of State for the Environment,[10] Margaret Beckett. The focus of the media launch was therefore the climate scenarios themselves—and the headline messages were about how much Britain's climate might change, what changes in weather extremes might occur and what effects might be felt by the 2020s, 2050s or 2080s. The scenarios were presented as 'new science' from the experts and operated both as pedagogic devices – this is what climate change means for Britain – and as quantitative tools for strategic long-term planning and design.

The institutional context of the respective scenarios, and the changing profile given to them by the DoE/DETR/Defra, heavily influenced their subsequent use. In 1991 and 1996, there were no guidelines issued alongside the scenarios either to encourage users to make use of the data or to help decision-makers interpret the scenarios for analytical or strategic purposes. Indeed, in 1991 it still remained very difficult for anyone outside the small technical research elite even to know how to access the data (in 1996 this could be done via the LINK Project, but this was not then a widely marketed public web portal). The use of the 1991 and 1996 scenarios in any quantitative sense was therefore very limited. One exception was the water industry. The UK drought of 1995 initiated an unprecedented planning exercise to include future climate change in water resources planning. A total of 12 climate scenarios for the 2020s – including CCIRG96 – were considered by the water industry to estimate changes in river flows and groundwater resources (Arnell et al., 1997). While some water companies made use of the scenario provided, many other organisations had reservations about their usefulness for planning (Subak, 2000). This showed mixed success in the 1990s for the application of climate scenarios to adaptation planning.

In 1998 and 2002, however, a more formal mechanism was provided to assist the passage of the scenarios from producers to users. On both occasions UKCIP acted both as the gateway for the data and as the *de facto* interpreter of the scenario applications for users who wanted the underlying data at whatever level of sophistication.[11] Nevertheless, in 1998 there was little formal indication about how DETR and UKCIP expected users to interpret the four scenarios—were all four equally likely and to be given equal weight in a risk assessment? Was the Government recommending use of the 'Medium-High' scenario in strategic planning since this scenario had the greatest amount of detail? Was the 'High' scenario presented as an inducement for organisations to consider 'worst-case' scenarios? Uncertainties also arose about how the four UKCIP98 climate scenarios should be mapped onto the four non-climate futures which UKCIP subsequently published in 2001 (UKCIP, 2001). Should users assume a one-to-one correspondence, even though the design process for the two sets of scenarios had been quite different? What happened in practise was that different assessments and organisations made their own *ad hoc* assumptions about how to combine climatic and non-climatic futures in integrated analyses (e.g. Shackley and Deanwood, 2003).

Some of these lessons were learned before the publication of the UKCIP02 scenarios, but formal guidelines for their use in strategic risk assessment and business planning were still not available at the launch. This in part was due to differences of opinion between the various actors involved in the scenario design about what recommendations should indeed be issued. A formal risk assessment framework for undertaking adaptation assessments was later published by UKCIP, but this did not appear until 2003 (Willows and Connell, 2003) and was a generic risk framework rather than specific to the UKCIP02 scenarios. An additional note about uncertainty in the UKCIP02 scenarios was also subsequently published – by the Hadley Centre in 2003 (Jenkins and Lowe, 2003) – in part a response to the number of questions and issues that had been raised by stakeholders after the April 2002 launch. On the other hand, UKCIP provided a well-staffed office through which enquiries about the use of the scenarios could be handled, and in subsequent months and years ran a series of hands-on workshops to which public and private sector analysts and decision-makers were invited (Hedger et al., 2006).

[10] This development itself is significant, elevating the perceived status of the scenarios in 2002 by associating their launch with the Secretary of State, a Cabinet-level post, as opposed to the more junior Environment Minister in 1998.

[11] In 1998, requests to UKCIP were forwarded to the LINK Project, but in 2002 users had to register with UKCIP to obtain access to the data through the UKCIP web site.

Nevertheless, different organisations subsequently used the UKCIP02 scenarios in different ways according to their own perspectives and priorities. For example, the UK water industry commissioned their own study to calculate the recommendation water resource guidelines for use by the industry regulator (UKWIR, 2005), in so doing deciding that the uncertainty range represented in UKCIP02 was insufficient for their purposes (they used a wider envelope of results from GCM experiments other than the Hadley Centre; Arnell and Delaney, 2006). The Chartered Institute of Building Survey Engineers also commissioned their own work, drawing upon UKCIP02, but used their own methodology in applying the scenario results to revise the heating and cooling building design standards to be recommended to their members (CIBSE, 2005). There are also examples of organisations that decided not to consider climate change in their planning (e.g. Hertin et al., 2005; Cabantous and Pearman, 2006).

5. Critical assessment

We now return to our framing ideas to help understand and interpret the evolution and characteristics of UK climate scenarios which we have summarised above. We start by considering the relationship between science and policy using the metaphor of supply and demand.

5.1. *Supply and demand*

The design and construction of each generation of UK climate scenarios has been predominantly science-led (i.e., supply-led) rather than decision-led (i.e., demand-led). While there were clearly elements of a negotiation between potential users, designers, funders and model suppliers in each scenario generation (most evident in UKCIP02), this negotiating started from a position in which the supply-side had greater power than the demand-side. Only the UKCIP02 scenarios had any formal mechanism to allow user (demand) perspectives to be heard, and even here such users were not elevated to co-negotiators in the design process. Thus the supply-side drivers were dominant: the IPCC assessments and the Hadley Centre models. The benchmark science reported in successive assessments of the IPCC (1990, 1996, 2001) exerted a strong influence on the design (and timing) of the UK scenarios (and on their representation of uncertainty, for example the emissions/forcing scenarios adopted). Even more important was the hegemony increasingly established over the UK scenarios by the climate modelling of the Hadley Centre. This influence was weakest in CCIRG91 and strongest in UKCIP02. In 1996, 1998 and 2002 new modelling experiments (using new models) from the Hadley Centre, acted as the primary driver for the scenario design: transient experiments (1996), ensemble experiments (1998), nested regional models (2002). In each case, any discussion about which emissions/forcing scenarios to use for the UK scenarios – and hence the associated pathways of world development – was virtually precluded by the prior choices made by the Hadley Centre of which emissions scenarios forced their climate models.

The difficulties of finding a suitable compromise between supply and demand are illustrated in UKCIP02, when there was an attempt to give users and decision-makers a voice. The strong demand expressed by many UKCIP stakeholders for higher-resolution information influenced the decision to use the 50 km regional model experiments from the Hadley Centre as the centrepiece for UKCIP02. But in meeting this particular user requirement, options for expressing a wider context of modelling uncertainties, for example as expressed in model results from other centres, were closed off. No other modelling centre had then run a suite of 50 km experiments, although if a coarser resolution for the scenarios had been adopted, for example 300 km, then a much wider range of modelling uncertainties could have been explicitly present in UKCIP02. The contradictory outcome of this was that one user demand had been met (higher spatial resolution) at the expense of another (broad representation of modelling uncertainty). Resolving this trade-off (for example by running multiple regional climate model simulations for many different emissions scenarios and driving A/OGCMs) would have required greater computational power than was available on the supply-side. The water industry subsequent had to commission independent work in order to capture the larger uncertainty range they believed was desirable and that was lacking in UKCIP02 (UKWIR, 2005). In this case, the alignment of interests between one user demand (spatial resolution) and the scientific desire for novelty (use of new 50 km models) marginalised another user demand (wide representation of uncertainty).

5.2. *Saliency*

In our interpretation of the history of UK climate scenarios we also refer to the ideas of Cash et al. (2003) about the management of knowledge at the interface between science and policy. They use the ideas of saliency, credibility and legitimacy. We have already commented above on one aspect of saliency—the suitability of the UK climate scenarios for user needs. Whilst we have exposed some limitations in respect of this criterion, we also make the observation that the creation of the UK Climate Impacts Programme in 1997 offered some possibilities for longer-term institutional learning about how best to deploy climate science in the construction of climate scenarios for the UK and in their application in decision-making. If the UK climate scenarios are seen as 'boundary objects' (cf. Star and Griesemer, 1989) – constructed by interaction between the worlds of science and policy and thus gaining authority in both worlds – then allowing their construction to take place in 1998 and 2002 under the auspices of UKCIP enhanced their saliency compared to the more *ad hoc* arrangements which led to CCIRG91 and CCIRG96. In this respect, we agree with Lorenzoni et al. (2006) that UKCIP has acted as a 'boundary organisation' (cf. Guston, 1999; Miller, 2001), drawing in experts from both worlds – science and policy – and allowing their interaction to be mediated by a further cohort of professionals.

There is nevertheless more learning that is needed here – about reconciling user needs and expectations with the supply-side of climate science and modelling – if future UK climate scenario products are to further improve their saliency. For example, can climate change modelling experiments genuinely be co-designed between scientists and users?

Can multiple, and sometimes conflicting, demands from users for certain scenario attributes be reconciled? Can different ways of framing uncertainty between scientists and decision-makers be captured in one set of scenario products?

If one looks across different sectors of UK society it is noticeable that there has been an uneven uptake of climate scenario information. This is not surprising since different individuals, organisations and sectors are sensitive to climate in different ways and to different degrees. Consequently, the saliency of climate scenarios will be unevenly distributed amongst sectors of society. It is also the case that downstream products (e.g. impact assessments) may be more useful to decision-makers than the scenarios themselves, although climate scenarios are generally used as an input into such assessments.

5.3. *Credibility and legitimacy*

The second criterion identified by Cash et al. (2003) is credibility—was the technical handling of the scientific issues involved in the scenarios credible to a wider peer community? In part this is bound up with the legitimacy criterion, although there are other benchmarks which could be used as well (cf. Clark and Majone, 1985). So, for example, one might view the successive reports of the IPCC as providing a reference point against which the technical handling of issues in the UK scenarios could be judged. We have noted that certain design aspects of CCIRG91, CCIRG96 and UKCIP02 all drew upon these IPCC reports (e.g. climate sensitivity, emissions scenarios, baselines), thus gaining a degree of credibility. On the other hand, subjective interpretations of IPCC products/statements were still needed such that CCIRG91 and CCIRG96 only used one value for the climate sensitivity rather than the IPCC range, and in UKCIP02 a sample of different GCMs (a specific recommendation of IPCC; Mearns et al., 2001) was used in a rather peripheral sense and was not central to the scenario design.

The representation of uncertainty in the UK climate scenarios therefore certainly played an important role with respect to their credibility. The role of the pattern-scaling technique is of interest in this regard. It was used – with slight variants – in all four generations of scenarios, functioning as an anchoring device to compensate for the limited sampling of uncertainties elsewhere in the scenario design – for example, of future emissions, of climate sensitivity or of different time periods. Yet pattern-scaling techniques are themselves contested within the specialist literature and are opposed by some climate modellers. They also lead to identical *patterns* of climate change being replicated across all scenarios which prompted questions from a number of more sophisticated users about why this should be. There was very little discussion in any of the scenario reports about the significance of using pattern-scaling as a technique, nor any account of the full traceability of its pedigree.

We have seen how the institutional relationships between important climate change actors in the UK, and the nature of available funding streams, had a powerful influence on different generations of the UK scenarios. These relationships had an important bearing on the legitimacy of the scenarios. The dominance of DoE/DETR/Defra funding of the Hadley Centre, UKCIP and of specific contracts to UEA acted to exclude other potential institutions, research groups, models or ideas from contributing to the scenario construction. This was most evident in the nature of DoE's contracts to UEA—either informal or else operating through single-action tenders. The special relationship between DoE and Hadley Centre throughout this period – even more so at the end than at the beginning – also acted to narrow scientific input into process. Thus other scientific capabilities in the UK, for example the University of Reading, University of Oxford, the NERC-funded UGAMP Consortium,[12] were never invited to tender for the work, were never formally involved in any peer-consultation, nor acted as peer reviewers of the final product (the light peer review of UKCIP02 was mostly by international experts).

The consequence of this deficit in legitimacy as seen by the wider UK peer community was that both the UKCIP98 and, especially, the UKCIP02 scenarios were subject to repressed criticism (it was rarely voiced in public or in written form) by other UK climate scientists.[13] This legitimacy deficit was also expressed in a different form through a House of Commons Science and Technology Select Committee Enquiry into the way in which the Government secured its scientific advice on climate change (House of Commons, 2000), claiming an 'over-reliance' on results from the Hadley Centre models.

As argued by Cash et al. (2003), saliency, credibility and legitimacy are three ways of looking at the effectiveness of 'boundary objects' – such as scenarios – in their role of linking knowledge with action. If UK climate scenarios are to retain their cohering function for assessments of climate change impacts and adaptation options – i.e., to earn their 'benchmark status' as desired by Government – then it is important that they score highly on these three criteria. We have suggested that the saliency, credibility and legitimacy of the UK climate scenarios have not been as great as they could be.

5.4. *Social construction*

Our final interpretative comment draws upon some of the insights of social constructivism from environmental sociology. Throughout the four generations of UK climate scenarios there were decisions made about the representation of uncertainty that were never made explicit and that were a reflection of certain attitudes, unstated assumptions or belief systems of the key actors in the construction process and influenced by the computational constraints on running climate model experiments. The decisions may well have been sympathetic, again implicitly, with the views of the wider scientific community with respect to climate change, but they tended to reflect a particular natural science attitude to uncertainty and the future. These are examples of the hidden interpretations of knowledge informing policy that Wynne and Simmons (2001) identified in their study of institutional cultures in the UK in relation to the management of global change risks.

[12] The Hadley Centre collaborated in a background research mode with these other UK climate modelling capabilities, but never specifically in the context of generating the UK scenarios.

[13] For example, one prominent climate modeller expressed concerns about the under-representation of uncertainty in the UKCIP02 scenarios in more than one UK research funders forum meeting.

For example, in 1991 and 1996 only one future growth rate in greenhouse gas concentrations was used for the UK scenarios. This occurred despite the IPCC in 1990 publishing three different future growth rates and then in 1992 publishing a range of six different emissions scenarios. In CCIRG96 the use of IS92a was defended on the grounds that it was 'in the middle' of the range of emissions curves. As subsequently shown, however, by the IPCC SRES report (Nakicenovic et al., 2000), a wide range of future emissions paths are possible depending on the choice of future world development and attaching relative likelihoods to these different pathways is a value-laden exercise (e.g. Schneider, 2001). Simply choosing the middle curve because it's the middle curve is a poor rationale.

Another example of hidden, yet potential significant, assumptions or decisions about the scenario design concerns the UKCIP98 scenarios. Four scenarios were described, based on two different emissions futures, and although no explicit weighting was given to any one of these, there was a clear subliminal message to users that the 'Medium-High' scenario was the one that carried greater weight. This occurred because it was only for this scenario that detail was provided about changes in a wide range of climate variables and about changes in daily and interannual variability. As with UKCIP02 – where the regional patterns were all derived from the SRES A2 (again, the 'Medium-High' scenario) – it was technical, scientific reasoning that led to this choice being made and, implicitly, weighting the future range of possible worlds according to the dictates of climate modellers. For climate modellers, it makes sense only to run a series of expensive climate model simulations when the greenhouse gas forcing is sufficiently large to induce a large ('detectable') signal in the climate response relative to natural variability. This reasoning always leans in favour of climate model experiments forced with high-end emissions scenarios, for example, IS92a, 1% per annum growth or SRES A2. Exploring a low emissions world – such as SRES B1 – in a climate model experiment is rarely as interesting for a climate modeller.

This sociological reading of the UK climate scenarios reveals that all such exercises at constructing future climates will carry with them specific attitudes towards the predictability of complex systems, the weight to be given to computer simulations (cf. Petersen, 2006) and the belief systems about how future society is 'likely' to develop. The influence of such proto-scientific beliefs on the way scientific knowledge is used and interpreted is perhaps inescapable (this after all is the insight offered by SSK studies), but the response to such insight is to argue for greater transparency (honesty) of such epistemological assumptions and for more care to be given to the legitimacy of the processes of negotiation and construction (see above). Attention to these dimensions of social construction will go some way towards securing what Latour (2004) suggests, in a precisely normative sense, 'good construction' over 'bad construction'.

6. Conclusions

We have surveyed the construction and application of four generations of UK climate scenarios over a decade and more. We have considered the institutional relationships within which these scenarios were negotiated, the ways in which they represented uncertainty and were communicated to a wider society. We have sought to interpret some of the characteristics and outcomes in terms of a number of different framing ideas drawn from wider thinking in science and technology studies and from the sociology of scientific knowledge. Our final reflections lead us to propose a number of conclusions.

There is an increasing move towards the construction of nationally-based climate scenarios. On the basis of the UK experience, the construction of such climate scenarios is a multi-layered process in which values, scientific capability and institutional capacity interact in complex ways. The emergence in the UK of a boundary organisation (UKCIP) to help orchestrate such negotiation has been significant. UK climate scenarios have emerged as exploratory and situated products in time and space, rather than as universal and definitive narratives (even less as absolute predictions) about the future.

Constant vigilance is needed to ensure that appropriate mechanisms and weights are given to the supply (science) and demand (decision-context) sides of the scenario negotiations. Consideration should be given in each instance as to what the appropriate voices and weights are, rather than leaving them to emerge by chance (which usually means acceding to the most powerful voices). There is a tendency, emerging from the epistemological hegemony of natural science-based climate models over other approaches to the portraying the future, that debates about scenario construction revolve around technical details – spatial downscaling, construction of probabilities, temporal resolution, more climate variables – rather than around different ways of seeing world futures or of articulating the particular decision-contexts in which scenarios will be used (e.g. the way uncertainty should be represented, the type of risk-management framework adopted, the relationship between seasonal-decadal forecasts and climate scenarios).

An essential component of the communication and dissemination process for such climate scenarios is to convey the range of assumptions, conflicts and compromises that have been made in their construction. This is not just a transparent account of the uncertainties that are represented (cf. Moss and Schneider, 2000), but should also encompass a description of the processes that led to one particular scenario design rather than any other. Given the reliance of climate scenarios on data from climate models, model quality assurance needs to be conducted in order to assess the robustness of the knowledge being produced (cf. Risbey et al., 2005). There is also a need to make clear the ways in which scenarios may be re-interpreted by different types of decision-makers and in different kinds of decision-making; for example, in strategic business planning, in policy regulation or in engineering design. Just as there are many ways to design and negotiate climate scenarios, there are many ways in which they can be used.

Climate scenarios are not simply the immutable product of a climate modelling laboratory; they do not emerge fully formed and articulated as the end result of a modelling experiment. Climate scenarios are the result of an increasingly intricate negotiation between scientists, policy-makers, communicators and numerous and diverse stakeholders in society, a process characteristic of 'post-normal science'. They are designed through negotiation, not discovered through research.

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REFERENCES

Arnell, N.W., Delaney, K., 2006. Adapting to climate change: public water supply in England and Wales. Climatic Change 78, 227–255.

Arnell, N.W., Reynard, N., King, R., Prudhomme, C., Branson, J., 1997. Effects of climate change on river flows and groundwater recharge: guidelines for resource assessment UKWIR/EA Report No. 97/CL/04/1, London, p. 55

Ashton, J., 2005. The European project is in crisis Speech to the Foundation for Sustainability, Bonn, 14 April 2005, http://www.e3g.org/index.php/programmes/europe-articles/the-european-project-is-in-crisis/.

Beck, U., 1992. Risk Society: Towards a new Modernity. Sage, London, UK.

Blair, T., 2006. Speech on Holocaust Memorial Day, 23 June 2006, Strasbourg, http://www.number10.gov.uk/output/Page9003.asp.

Cabantous, L., Pearman, A., 2006. Climate change information in search of decision-makers: why do managers (not) consider climate change in their long-term projects? Paper presented at the Conference of the Society of Risk Analysis Europe (SRA-E), Ljubljana, 11–13 September (now under review for Risk Analysis).

Carter, T.R., Parry, M.L., Harasawa, H., Nishioka, S., 1994. IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. UCL/CGER, London/Tsukuba, p. 59.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jaeger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. 100 (14), 8086–8091.

CCIRG, 1991. The Potential Effects of Climate Change in the United Kingdom, Department of the Environment. HMSO, London, p. 124.

CCIRG, 1996. Review of the Potential Effects of Climate Change in the United Kingdom. HMSO, London, p. 247.

CIBSE, 2005. Climate Change and the Indoor Environment: Impacts and Adaptation CIBSE Technical Memorandum No. 36. CIBSE, London, UK, p. 53.

Clark, W.C., Majone, G., 1985. The critical appraisal of scientific inquires with policy implications. Sci., Technol. Hum. Values 10 (3), 6–19.

CSIRO, 2001. Climate Change Projections for Australia. CSIRO, Melbourne, Australia, p. 8.

Demeritt, D., 1994. Ecology, objectivity and critique in writings on nature and human societies. J. Historical Geography 20 (1), 22–37.

Demeritt, D., 2006. Science studies, climate change and the prospects for constructivist critiques. Econ. Soc. 35, 453–479.

Dessai, S., Hulme, M., 2004. Does climate adaptation policy need probabilities? Climate Policy 4, 107–128.

Dessai, S., Hulme, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: a case-study on water resources management in the East of England. Global Environ. Change 17 (1), 59–72.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge. Sage Publications, London, UK.

Golinksi, J., 1998. Making Natural Knowledge: Constructivism and the History of Science. Cambridge University Press, Cambridge, p. 236.

Guston, D.H., 1999. Stabilizing the boundary between US politics and science: the role of the Office of Technology Transfer as a boundary organization. Soc. Stud. Sci. 29 (1), 87–111.

Hannigan, J., 2006. Environmental Sociology, second ed. Routledge, London, p. 194.

Hedger, M., Connell, R., Bramwell, P., 2006. Bridging the gap: empowering decision-making for adaptation through the UK Climate Impacts Programme. Climate Policy 6, 201–215.

Hedger, M., Gawith, M., Brown, I., Connell, R., Downing, T.E. (Eds.), 2000. Climate Change: Assessing the Impacts-Identifying the Responses. UKCIP, Oxford, UK, p. 168.

Hertin, J., Berkhout, F., Gann, D.M., Barlow, J., 2005. Climate change and the UK house building sector: perceptions, impacts and adaptive capacity. Building Res. Inf. 31, 278–290.

House of Commons, 2000. Scientific advisory system: scientific advice on climate change House of Commons Science and Technology Committee Report, HC 14, HMSO, London, UK, p. 89

Hulme, M., Jenkins, G.J., 1998. Climate change scenarios for the United Kingdom UKCIP Technical Note No.1, Climatic Research Unit, Norwich, UK, p. 80

Hulme, M., Jones, P.D., 1989. Climatic change scenarios for the UK Report prepared for the Institute of Hydrology (Contract No. F3CR05-C1-31-01), Climatic Research Unit, Norwich, UK, p. 51

Hulme, M., Turnpenny, J., 2004. Understanding and managing climate change: the UK experience. Geographical J. 170, 115–125.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate change scenarios for the UK: the UKCIP02 scientific report Tyndall Centre, UEA, Norwich, UK, p. 112

IPCC, 1990. In: Houghton, J.T., Jenkins, G.J., Ephraums, J.J. (Eds.), Climate Change: the IPCC Scientific Assessment. Cambridge University Press, Cambridge, p. 364.

IPCC, 1996. In: Meiro Filho, J.T., Callendar, L.G., Harris, B.A., Kattenburg, N., Maskell, K. (Eds.), Climate Change 1995: the Science of Climate Change. Cambridge University Press, Cambridge, UK, p. 572.

IPCC, 2001. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Johnson, C.A. (Eds.), Climate Change 2001: the Scientific Basis. Cambridge University Press, Cambridge, UK, p. 944.

IPCC, 2007. Climate Change 2007: the Physical Science Basis Summary for Policymakers. IPCC, Geneva, p. 21.

Jasanoff, S., 2003. Breaking the waves in science studies: comment on H M Collins and Robert Evans. 'The third wave of science studies' Soc. Stud. Sci. 33 (3), 389–400.
Jasanoff, S. (Ed.), 2004. States of Knowledge: the Co-production of Science and the Social Order. Routledge, London, p. 332.
Jasanoff, S., Wynne, B., 1998. In: Rayner, S., Malone, E.L. (Eds.), Science and decision-making pp. 1–87 in, Human choice and climate change, the societal framework, vol. 1. Batelle Press, Columbus, OH, USA.
Jenkins, G., Lowe, J.A., 2003. Handling uncertainties in the UKCIP02 scenarios of climate change Hadley Centre Technical Note No. 44, Met Office, Exeter, UK, p. 15
King, D., 2004. Climate change science: adapt, mitigate or ignore? Science 303, 176–177.
Kjellström, E., Bärring, L. Evaluating different methods of pattern-scaling in time. Inter. J. Climatol., submitted for publication.
Lahsen, M., 2005. Seductive simulations? Uncertainty distribution around climate models.. Soc. Stud. Sci. 35/6, 895–922.
Latour, B., 2004. Whose cosmos, which cosmopolitics? Comments on the peace terms of Ulrich Beck. Common Knowl. 10, 450–462.
Leggett, J., Pepper, W.J., Swart, R.J., 1992. In: Houghton, J.T., Callander, B.A., Varney, S.K., (Eds.), Emissions Scenarios for the IPCC: an Update pp.75–95 in, Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment. Cambridge University Press, Cambridge, p. 200
Lenton, T.M., Williamson, M.S., Edwards, N.R., Marsh, R., Price, A.R., Ridgwell, A.J., Shepherd, J.G., Cox, S.J., The GENIE team, 2006. Millennial timescale carbon cycle and climate change in an efficient Earth system model. Climate Dyn. 26, 687–711.
Lorenzoni, I., Jones, M., Turnpenny, J.R., 2006. Climate change, human genetics and post-normality in the UK. Futures 39, 65–82.
MacCracken, M.C., Barron, E.J., Easterling, D.R., Felzer, B.S., Karl, T.R., 2003. Climate change scenarios for the US national assessment. Bull. Am. Meteor. Soc. 84, 1711–1723.
Mearns, L.O., Hulme, M., Carter, T.R., Lal, M., Leemans, R., Whetton, P.H., 2001. Climate scenario development pp. 739–768 in, Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Contribution of WG1 to the IPCC Third Assessment. Cambridge University Press, Cambridge, UK, p. 944.
Meehl, G.A., Washington, W.M., Collins, W.D., Arblaster, J.M., Hu, A., Buja, L.E., Strand, W.G., Teng, H., 2005. How much more global warming and sea level rise? Science 307, 1769–1772.
Miller, C., 2001. Hybrid management: boundary organisations, science policy and environmental governance in the climate regime. Sci. Technol. Hum. Values 26 (4), 478–500.
Mitchell, J.F.B., Johns, T.C., Eagles, M., Ingram, W.J., Davis, R.A., 1999. Towards the construction of climate change scenarios. Climatic Change 41, 547–581.
Mitchell, T.D., 2003. Pattern-scaling: an examination of the accuracy of the technique for describing future climates. Climatic Change 60, 217–242.
Moss, R., Schneider, S., 2000. In: Pachauri, R., Taniguchi, T., Tanaka, K., (Eds.), Uncertainties pp. 33–52 in, Cross-cutting guidance papers: IPCC supporting material Geneva, Switzerland, p. 138
Murphy, J.M., 1995. Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part I, control climate and flux adjustment. J. Climate 8, 36–56.
Murphy, J.M., Mitchell, J.F.B., 1995. Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part II, spatial and temporal structure of the response. J. Climate 8, 57–80.
Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M., Stainforth, D.A., 2004. Quantifying uncertainties in climate change from a large ensemble of general circulation model predictions. Nature 430, 768–772.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000. Emissions scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, p. 599
Parry, M.L., (Ed.) (1999) Assessment of the potential effects of climate change in Europe, The draft report of the ACACIA Concerted Action, October, 1999, UEA, Norwich, p. 350
Petersen, A.C., 2006. Simulating Nature: a Philosophical Study of Computer-Simulation Uncertainties and Their Role in Climate Science and Policy Advice. Het Spinhuis, Amsterdam, p. 220.
Pohl, C., 2007. From science to policy through trans-disciplinary research Environmental Science and Policy, doi:10.1016/j.envsci.2007.06.001.
Risbey, J., van der Sluijs, J., Kloprogge, P., Ravetz, J., Funtowicz, S., Quintana, S.C., 2005. Application of a checklist for quality assistance in environmental modelling to an energy model. Environ. Model. Assessment 10, 63–79.
Rotmans, J., Hulme, M., Downing, T.E., 1994. Climate change implications for Europe: an application of the ESCAPE model. Global Environ. Change 4, 97–124.
Santer, B.D., Wigley, T.M.L., Schlesinger, M.E., Mitchell, J.F.B., 1990. Developing climate scenarios from equilibrium GCM results Max Planck Institute für Meteorologie, Report No.47, Hamburg.
Sarewitz, D., Pielke Jr., R.A., 2006. The neglected heart of science policy: reconciling supply of and demand for science. Environ. Sci. Policy 10, 5–16.
Schneider, S.H., 2001. What is 'dangerous' climate change? Nature 411, 17–19.
Schneider, S.H., Kuntz-Duriseti, K., 2002. In: Schneider, S.H., Rosencrantz, A., Niles, J.O. (Eds.), Uncertainty and Climate Change Policy pp. 53–87 in, Climate Change Policy: a Survey. Island Press, p. 368.
Scott, A., 2007. Peer review and the relevance of science. Futures 39, 827–845.
Shackley, S., Deanwood, R., 2003. Constructing social futures for climate-change impacts and response studies: building qualitative and quantitative scenarios with the participation of stakeholders. Climate Res. 24, 71–90.
Shackley, S., Wynne, B., 1996. Representing uncertainty in global climate change science and policy: boundary ordering devices and authority. Sci. Technol. Hum. Values 21, 275–302.
Star, S.L., Griesemer, J.R., 1989. Institutional ecology, translations and boundary objects - amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Soc. Stud. Sci. 19 (3), 387–420.
Subak, S., 2000. Climate change adaptation in the UK water industry: managers' perceptions of past variability and future scenarios. Water Resour. Manag. 14, 137–156.
UKCIP, 2001. Socio-Economic Scenarios for Climate Impact Assessment: a Guide to their use in the UK Climate Impacts Programme. UKCIP, Oxford, UK, p. 123.
UKWIR (2005) Climate change uncertainty in water resource planning Report 05/CL/04/4, UK Water Industry Research, London.

Van der Heijden, K., 1997. Scenarios: the art of Strategic Conversation. John Wiley & Sons, Chichester, UK, p. 305.
Van der Sluijs, J.P., 1997. Anchoring Amid Uncertainty: on the Management of Uncertainties in risk Assessment of Anthropogenic Climate Change. Utrecht University, Netherlands, p. 260.
Van der Sluijs, J.P., van Eijndhoven, J., Shackley, S., Wynne, B., 1998. Anchoring devices in science for policy: The case of consensus around climate sensitivity. Soc. Stud. Sci. 28, 291–323.
Viner, D., Hulme, M., 1994. The Climate Impacts LINK Project: Providing Climate Change Scenarios for Impacts Assessment in the UK. DoE/CRU, Norwich, UK, p. 24.
Warrick, R.A., Barrow, E.M., 1991. Climate change scenarios for the UK. Trans. Inst. Brit. Geogs. 16, 387–399.
Weart, S., 2003. The Discovery of Global Warming. Harvard University Press, Harvard, USA, p. 240.
Wigley, T.M.L., 2005. The climate change commitment. Science 307, 1766–1769.
Wigley, T.M.L., Raper, S.C.B., 1987. Thermal expansion of sea water associated with global warming. Nature 330, 127–131.
Wigley, T.M.L., Jones, P.D., Kelly, P.M., 1980. Scenario for a warm, high CO_2 world. Nature 283, 17–21.
Willows, R., Connell, R. (Eds.) (2003) Climate adaptation: risk, uncertainty and decision-making UKCIP Technical Report, UKCIP, Oxford, UK, p. 154
Wynne, B., Simmons, P., (Eds.) 2001. Institutional cultures and the management of global environmental risks in the United Kingdom pp. 93–113 in, Learning to manage global environmental risks: a comparative history of social responses to climate change, ozone depletion, and acid rain The Social Learning Group, MIT Press, Cambridge, MA, USA.

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