Integrated Assessment **2:** 159–170, 2001.

Climatic implications of revised IPCC emissions scenarios, the Kyoto Protocol and quantification of uncertainties

Suraje Dessai [a] and Mike Hulme [b]

[a] *School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK*
E-mail: s.dessai@uea.ac.uk

[b] *Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK*

In December 1997, the United Nations Framework Convention on Climate Change (FCCC) adopted the Kyoto Protocol. This paper describes a framework that models the climatic implications of this international agreement, using Monte Carlo simulations and the preliminary Intergovernmental Panel on Climate Change emissions scenarios (SRES). Emissions scenarios (including intervention scenarios), climate sensitivity, and terrestrial carbon sink are the key sampled model parameters. This framework gives prior probability distributions to these parameters and, using a simple climate model, posterior distributions of global temperature change are determined for the future.

Our exercise showed that the Kyoto Protocol's effectiveness will be mostly dependent upon which SRES world evolves. In some worlds the Protocol decreases the warming considerably but in others it is almost irrelevant. We exemplified this approach with a current FCCC issue, namely "hot air". This modelling framework provides a probabilistic assessment of climate policies, which can be useful for decision-makers involved in global climate change management.

Keywords: climate change, climate policy, global modelling, greenhouse gas emissions scenarios, uncertainty analysis

1. Introduction

Global climate change is probably one of the most pressing environmental problems of our time. Results from the Second Assessment Report [5] of the Intergovernmental Panel on Climate Change (IPCC) predicted an increase of global-mean surface air temperature of between 1 and 3.5°C by 2100. These calculations used greenhouse gas (GHG) and aerosol precursor emissions scenarios published by the IPCC in 1992 (known in the literature as the IS92 scenarios) [10] and a simple climate model, MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) [25,28], that emulated the results of a number of ocean/atmosphere general circulation models. MAGICC is an upwelling-diffusion energy-balance climate model, driven by various forcing scenarios (e.g., IS92) to obtain future global mean temperature and sea level rise.

Much has changed since the creation of the IS92 emissions scenarios. The importance of sulphate aerosols and other non-CO_2 GHGs has been further recognised. The economic consequences of the breakdown of the former Soviet Union were larger than expected. Perhaps even more important was the advancement of integrated assessment modelling, which made it possible to construct emissions scenarios which jointly consider the interactions between energy, economy, and land use changes. Alcamo et al. [1] concluded that more work had to be done to compare the driving forces, particularly the economic assumptions, behind the IS92, their sensitivities, and the validity of the assumptions used. As a result, a new set of reference emissions scenarios was put together as an IPCC Special Report [13]. In this paper, we use preliminary results from the 1998 SRES open process [19]. These emissions scenarios did not include the effects of specific climate policies.

In December 1997, a historic landmark for international climate policy was achieved with the adoption of the Kyoto Protocol (KP) to the FCCC. If ratified by 55 Parties (containing 55% of 1990 GHG emissions), this multilateral environmental agreement requires the so-called Annex B countries (developed countries and those with economies in transition) to reduce their overall emissions of a "basket" of six-GHGs by an average of 5% below 1990 levels between 2008 and 2012. The unprecedented nature and complexity of such an agreement is the possible reason why so few studies [15,16,26] have thus far taken into account the KP and its environmental impacts. Wigley [26] considered the Protocol's implications for CO_2, temperature and sea level, using three post-Kyoto emissions scenarios. He found that in all cases, the long-term consequences were small. Parry et al. [15] suggested that the Kyoto targets would only reduce global warming by about 0.05°C, by 2050. Reilly et al. [16] used an integrated global-systems model, to show that a multi-gas control strategy could greatly reduce the costs of fulfilling the Kyoto Protocol compared with a CO_2-only strategy. One of the major caveats of all of these studies is the measurement of uncertainty.

Uncertainty is a constant companion of scientists and decision-makers involved in global climate change research and management [6]. It is an issue of crucial importance which has not yet been properly dealt with. There are multiple sources of uncertainty in climate science, some of which are endemic. Quantification of uncertainties have been performed using techniques such as model validation and intercomparison, sensitivity analysis, scenario analysis, etc. Yet, according to Katz [9] anything less than a fully probabilistic approach to uncertainty is inadequate. Uncertainties need a full and systematic treatment if the results are to be truly useful in policy-making [6].

This study assesses climate policies using Monte Carlo simulations (MCSs) with prior probability distributions for key variables. First we describe the methodology of our probabilistic framework of future climate change and explain the construction of intervention scenarios. Section 3 describes our results followed by an example of the application of this framework to a current FCCC debate, "hot air". We conclude by looking at some caveats, limitations, and implications of this framework.

2. Methodology

MCS analysis is a powerful tool for assessing the uncertainty in a forecast of future events, such as global climate predictions. Instead of using a single value for each variable, say climate sensitivity, in a model, it uses many values. These values are selected at random each time the model runs (called an iteration or trial). After a large number of iterations, the forecast is shown not as a single value, but as a range of values. In other words, the uncertainty is explicit.

We use MCSs to represent a stream of uncertainties from emissions scenarios, climate sensitivity and terrestrial carbon sink, that affect global climate change outcomes. Using results from a physically-based, deterministic model (MAGICC), and assuming that some of its input parameters, being characterised by probability density functions (pdfs), are inherently uncertain, 25,000 iterations were performed. Our approach takes advantage of the subjective expert judgement, provided in the literature, in order to define the pdfs. We follow the Morgan and Keith [12] survey for the climate sensitivity parameter and Wigley [24] for the terrestrial carbon sink, as prior distributions. The emissions scenarios used were considered equally sound, as suggested by Nakićenović et al. [13]. We also assume the pdfs for the parameters are Gaussian in nature and independent of each other. At first sight emissions scenarios, climate sensitivity, and terrestrial carbon sink seem to be fairly independent. However, as Shackley et al. [17] have noted, if the parameters are not statistically independent, then this assumption may lead to higher estimates of uncertainty in the model responses.

Rather similar approaches have been recently applied in modelling the global carbon cycle [17] and representing uncertainty in regional climate change scenarios [14]. However, part of the innovative aspect of this study is that intervention scenarios, which take into account the Kyoto Protocol and subsequent commitment periods post-2010, are fully considered. To our knowledge, this has not been attempted before in a probabilistic assessment. A description of our key input parameters: emissions scenarios, climate sensitivity and terrestrial carbon sink, follows.

2.1. Emissions scenarios

A scenario provides a description of how the future may develop based on a coherent and internally consistent set of assumptions about key social, economic and technological relationships and driving forces (e.g., rate of technology change, demography, prices, etc.). This should be the starting point of most climate predictions.

The four SRES "families" (here also called worlds), based on four qualitative storylines, are: A1, A2, B1 and B2. A1 describes a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. A2 is a very heterogeneous world with an emphasis on family values and local traditions, high population growth, and regionally oriented economic development. B1 describes a convergent world with rapid change in economic structures, "dematerialization" and the introduction of clean technologies, while B2 is a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. Table 1 summarises their main characteristics.

Four illustrative marker scenarios, one for each family (considered to be representative of each storyline), were used from the draft form of the 1998 SRES open process. We used non-harmonised marker scenarios due to the necessity of aggregating emissions into different regions, mainly developed and developing countries, which was consistent with the FCCC division into Annex I and non-Annex I. Annex B countries of the KP are composed of roughly the same countries as Annex I of the FCCC, and are here considered identical. Using non-harmonised scenarios also reflects the underlying uncertainty of current and past emissions, which harmonisation criteria somewhat artificially compresses.

In terms of emissions, the preliminary results released by the SRES team, can be very different for each world (figure 1). With respect to CO_2, B1 returns to 1990 levels in 2100 whereas A2 quadruples its emissions. A marked difference, from the IS92 scenarios, is the decrease in SO_2 emissions over the next century. This has important climatic implications because SO_2 emissions produce sulphate aerosols, which are believed to have a modest cooling effect on regional climate. The components of each SRES world are also very different (figure 2). A1 and B1 have a similar population to 1990 by 2100, whereas in A2 population nearly triples.

The SRES scenarios do not take into account direct climate policies aimed at GHG mitigation or climate change adaptation policies. Instead, they consider government policies, which have obvious implications for GHG emissions (i.e., population growth, economic and social development, technological change, resource exploitation, and pollution management). Although these policies are not motivated by climate concerns, some degree of overlap will inevitably occur (e.g., with "non-climate" policies that actually reduce GHG emissions, but were not initially intended to do so). Due to the qualitative nature of the SRES scenario storylines it would be impossible to make a precise link between gov-

Table 1
Main characteristics of SRES marker scenarios.

	A1	A2	B1	B2
Population growth	Moderate	High	Moderate	Moderate
Economic development	Fast	Slow	Fast	Moderate
Technological development	Fast	Slow	Fast	Moderate
Investment	High	Low	High	Medium
Cultural development (through:)	Education	Family values	Social & environmental awareness	Education
Institutionalisation	National and international	Local and regional	Local, national and international	Local
Environmental awareness	Medium	Low	High	High

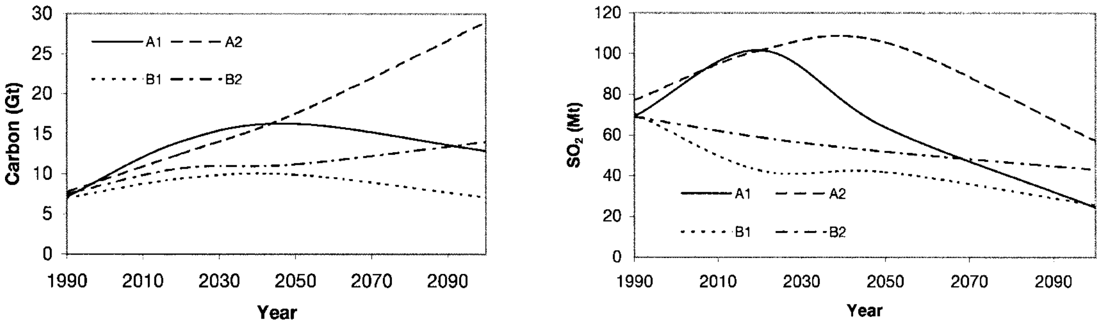

Figure 1. CO_2 and SO_2 emissions for each SRES marker scenario.

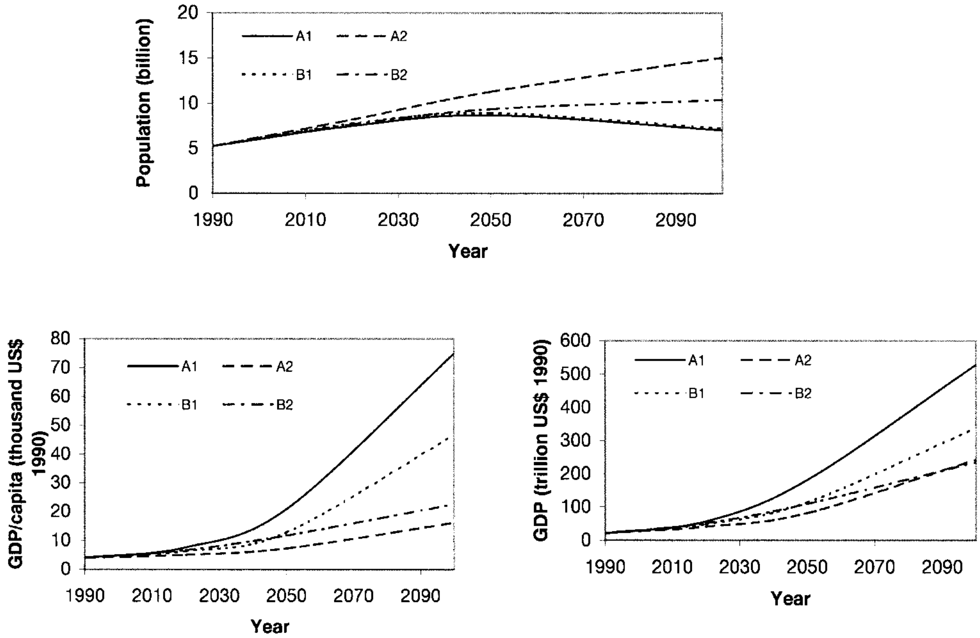

Figure 2. SRES marker scenarios population, gross domestic product (GDP) and GDP per capita.

ernment's application of specific policies and the outcome in various scenarios. Thus, we do not attempt to remove "potential" climate policies from the SRES emissions scenarios in order to prevent double counting with the intervention policies that we introduce next.

2.1.1. Building intervention scenarios

In an attempt to quantify the impact of climate policies on the climate system, intervention scenarios were constructed based on the four preliminary SRES marker scenarios. By intervention scenarios we mean scenarios which include explicit policies to limit GHG emissions (climate change adaptation policies are not accounted for). Climate policies are here seen in their broadest sense (globally), leaving national implementation aside.

The Kyoto Protocol does not explicitly forward policies to be implemented by Parties, so for all intervention scenarios we assume a 5% reduction of emissions (as in Article 3 of the KP) by Annex I countries up to 2010 (relative to 1990 levels). Regarding the different GHGs that the KP contemplates we take Wigley's [26] approach, assuming that CO_2 alone is used to achieve the target, consistent with Article 3

Table 2
Annex I and non-Annex I emission reductions for the K3 family of intervention scenarios.

	Annex I	Non-Annex I		
	K3a, K3b, K3c	K3a	K3b	K3c
1990	Baseline	0	0	0
2010	5	0	0	0
2020	10	0	0	Baseline
2025	12	0	0	0
2050	20	0	Baseline	5
2075	40	0	10	10
2100	60	0	20	20

of the KP, which states that some CO_2-equivalent should be used. Hence within any commitment period of GHG limitation (such as that of the KP and subsequent commitment periods), only CO_2 is limited. The other GHGs are brought down (or up) to their baseline year (1990) emission level and then remain constant. A range of post-Kyoto cases (i.e., commitments after 2010) are also considered, and described next.

From 1990 to 2000 all intervention scenarios follow the original non-harmonised SRES marker scenarios, reflecting the uncertainty of current emissions and the poor success to date in curbing emissions. After 2000, developed countries start reducing emissions up to 5% below 1990 in 2010 (as in the KP). From this date onwards, all scenarios differ because of different post-2010 assumptions. Intervention scenario K1 assumes no further emissions reductions for Annex I countries after Kyoto (thus, after 2010, it follows the SRES emissions). K2 considers that Annex I emissions remain constant at 2010 levels (this scenario will hence be very dependent on which SRES world is selected). K3a sees bigger increments on Annex I reduction commitments, reaching a 60% reduction below 1990 levels by 2100. These three scenarios have left non-Annex I countries emissions untouched (i.e., they follow the respective SRES pathways for their regions).

However, effective climate stabilisation will only occur if developing countries start reducing emissions sometime in the future. Recently, Argentina took a voluntary commitment to reduce its GHG emissions and Kazakhstan decided to join Annex I. Thus, it seems reasonable to construct scenarios where developing countries also reduce emissions. K3b and K3c have the same assumptions as K3a for Annex I emissions reductions, but also consider non-Annex I reductions. K3b assumes a baseline year of 2050 for non-Annex I countries, where these countries reduce emissions by as much as 20% below 2050 by 2100. K3c has the same reduction target (i.e., 20% reduction by 2100) but assumes a baseline year of 2020. Table 2 provides a more detailed description of these assumptions (which are not linear in all cases).

We make use of both the original draft SRES marker scenarios, here called non-intervention (NI) scenarios, and the described intervention scenarios (K1, K2, K3a, K3b, K3c), totalling 24 emissions scenarios (four worlds, six variants in each world), in our analysis. In all our emissions scenarios we include sulphate aerosols emissions as in the SRES 1998 preliminary results. For our initial MCS exercise we assume all 24 scenarios to be equally likely, but we later look at individual SRES worlds and non-intervention/intervention groups of scenarios.

Table 3
Probability density function of the climate sensitivity parameter used as priors of the Monte Carlo simulation.

Climate sensitivity (°C)	Probability
0.5	0.01
1.5	0.16
2.5	0.33
3.5	0.33
4.5	0.16
5.5	0.01

2.2. Climate sensitivity

The climate sensitivity is the equilibrium response, in terms of global mean surface temperature, to an instantaneous doubling of atmospheric CO_2 or CO_2-equivalent concentration. This variable remains poorly defined by climatologists as Morgan and Keith [12] have shown. The IPCC mid-range estimate of this parameter is 2.5°C, ranging from 1.5 to 4.5°C. To span a bigger distribution of this important unknown parameter we assume a range between 0.5 and 5.5°C. In this way we take into account non-climate model estimates, such as that of Richard Lindzen (0.5°C) and the upper-level of the UK Met. Office model estimate (a little below 5.5°C) [18]. Table 3 shows the triangular-shaped pdfs we use for this parameter. We later sampled each value in turn to assess the magnitude of uncertainty derived from this variable.

2.3. Terrestrial carbon sink

The last component of uncertainty handled in our approach deals with part of the global carbon cycle. The carbon cycle is an integral part of the climate system, and governs the build-up of atmospheric CO_2 in response to human emissions [4]. For this poorly understood process we use a pdf based on Wigley [24]. The carbon cycle has a number of key sub-processes, but here we focus on the 1980s-mean value of the net land-use change CO_2 emissions, i.e., we are only concerned with the terrestrial carbon sink. Table 4 presents the pdfs we assume for this variable. The IPCC's middle range value for this variable is 1.1 GtC per year. However, because of the substantial uncertainty about the true values of these land use change emissions, we use the IPCC range from 0.4 to 1.8 GtC per year. Afterwards we sample each value separately. It is worth noting that land use change CO_2 emissions are included in the used preliminary 1998 SRES scenarios. They were, therefore, subject to reductions based on the intervention scenarios described in 2.1.1, which are in accordance with Articles 3.3 and 3.4 of the KP.

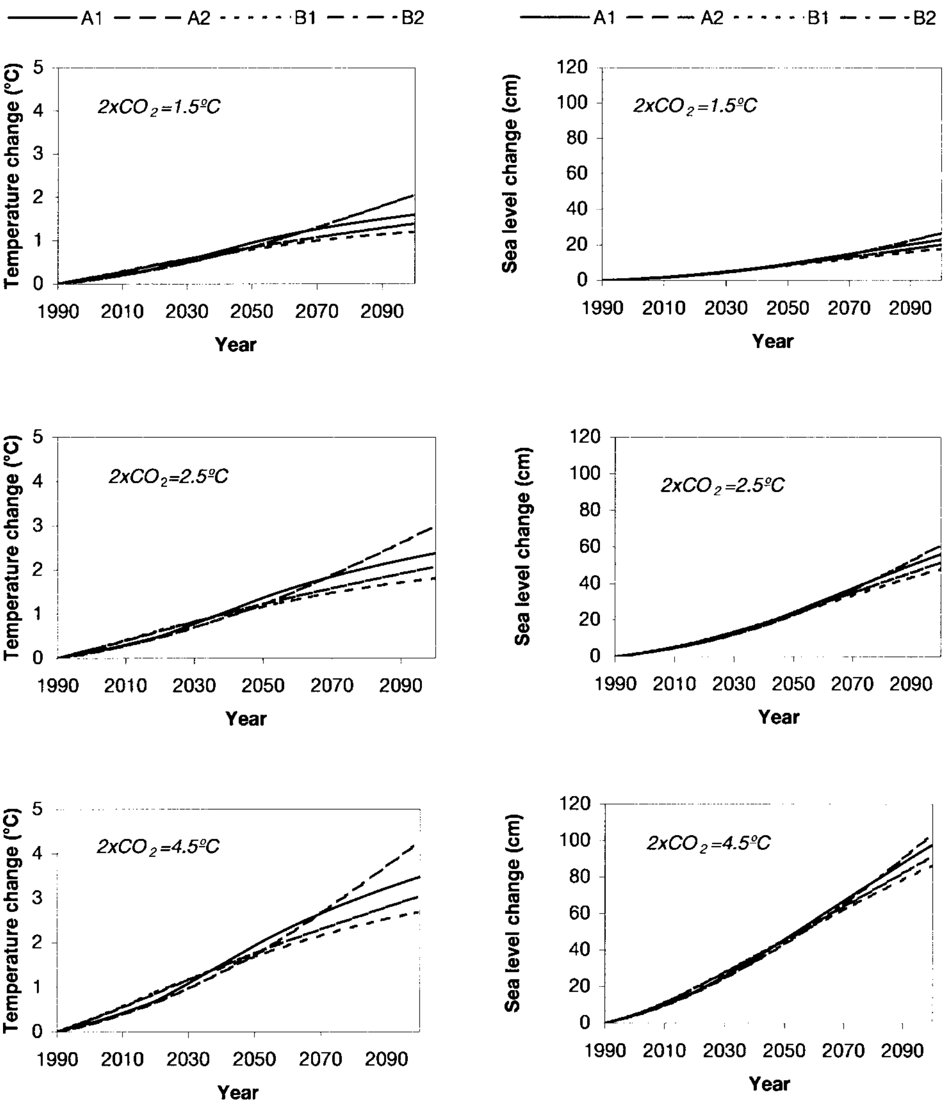

Figure 3. Global mean temperature and sea level change projections relative to 1990, using the SRES marker scenarios, for climate sensitivities of 1.5, 2.5 and 4.5°C (includes aerosols).

Table 4
Probability density function of the terrestrial carbon sink parameter used as priors of the Monte Carlo simulation.

C-cycle value (GtC)	Probability
0.4	0.25
1.1	0.50
1.8	0.25

In our initial simulation these three variables (emissions scenarios, climate sensitivity and terrestrial carbon sink) were sampled randomly 25,000 times, under the described pdfs.

3. Results

3.1. SRES discrete results

First we display and compare some of the discrete results of simply inputting the SRES emissions scenarios into the simple climate model. Using MAGICC the four SRES marker scenarios were converted into atmospheric concentration, then into radiative forcing and finally into temperature change and sea level rise (figure 3). This was performed under the IPCC's range of plausible climate sensitivities (i.e., 1.5, 2.5 and 4.5°C).

It is clear that the warming or the sea level rise will be dependent on which SRES family the world develops into (more obvious with temperature, especially as we increase the climate sensitivity parameter). Yet, as Schlesinger [18] pointed out, until the middle of the next century these projections are virtually indistinguishable, i.e., we won't know in which trajectory we are on until the second half of the next century. The surface warming, by 2100, ranges from 4.3°C for A2 with a high climate sensitivity to 1.2°C for B1 with a low climate sensitivity. There is a range of more than 3°C, which corresponds to 86 cm for sea level (from more than one metre in A2 to approximately 18 cm in B1).

These results are consistent with Wigley's [27] estimates,

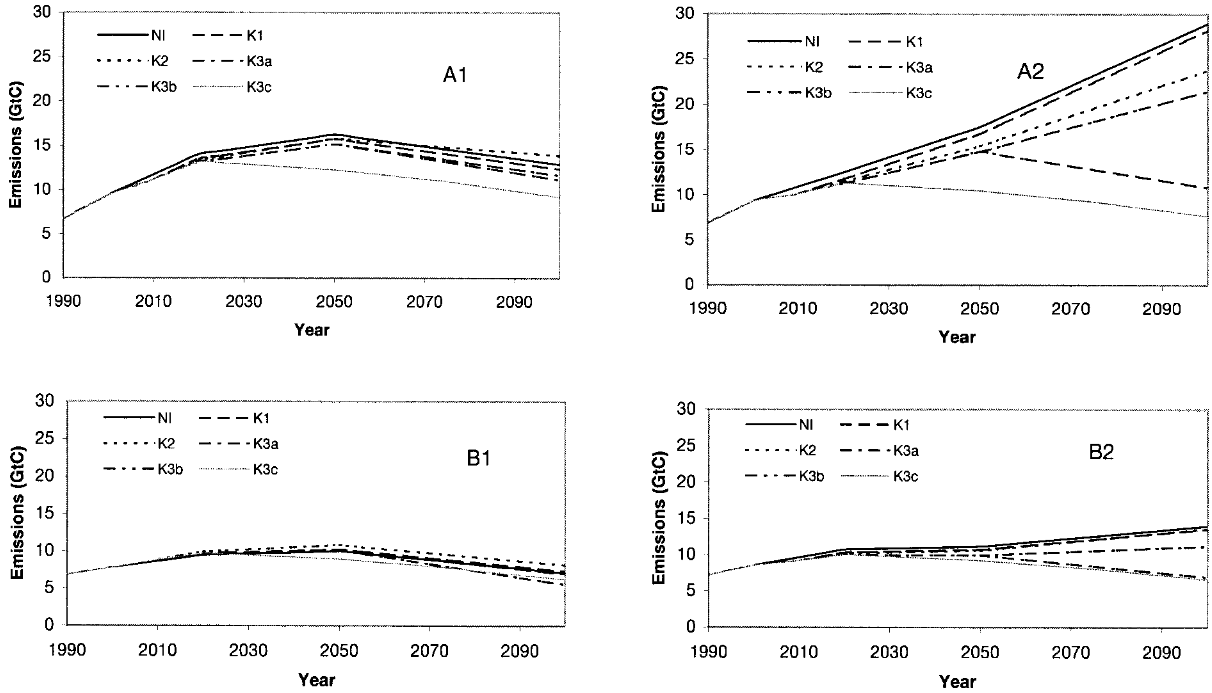

Figure 4. CO_2 emissions for each SRES world (A1, A2, B1, B2) under a non-intervention scenario (NI) and five intervention scenarios (K1, K2, K3a, K3b, K3c).

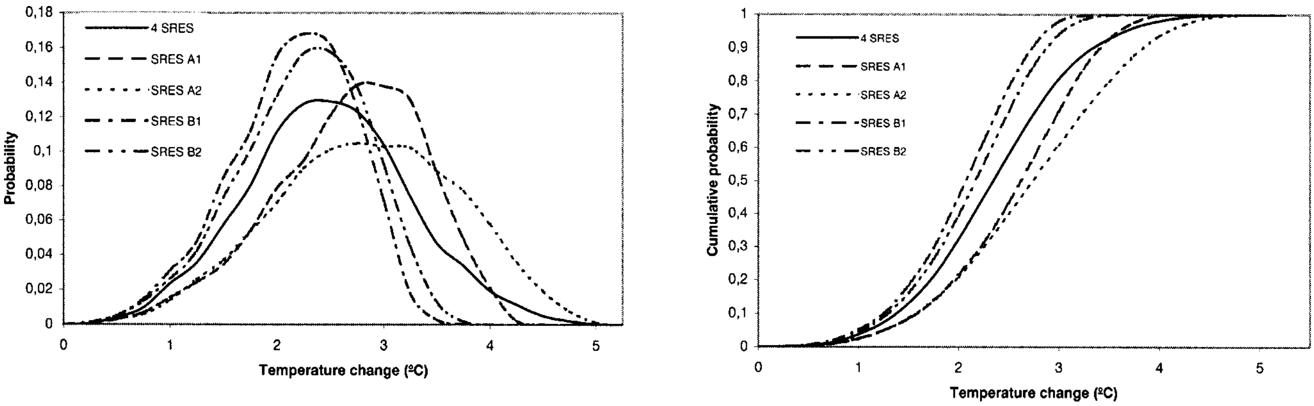

Figure 5. Monte Carlo simulation of the most comprehensive run (4 SRES) and each SRES world separately for temperature change in 2100. Left panel represents the probability and the right panel cumulative probability. In both panels values are presented in 0.25°C intervals.

±0.2°C because of the different radiative forcing parameters. Schlesinger [18] estimates a range from approximately 1–5°C (for 2100). Our results are somewhat lower than the forthcoming IPCC Third Assessment Report (TAR) findings, because we used an earlier version (2.4) of MAGICC and because we did not use the A1FI marker emissions scenario, only adopted by the SRES after the open process was concluded.

3.2. Intervention scenarios

CO_2 emissions in the intervention scenarios vary considerably depending on which SRES world they are applied to (figure 4). The effects of intervention policies are clearly more visible in SRES A2 and B2. This is due mainly to their future high carbon emissions. In SRES A1, intervention scenario K2 actually yields higher emissions than the non-intervention scenario by 2100. This occurs because of the assumptions taken by K2, that Annex I emissions will remain constant at 2010 levels from 2010–2100. In the non-intervention scenario, they rise until a certain point in time, and then start decreasing, hence this peculiarity which we will discuss further in section 5.1. This also occurs for K1 and K2 in SRES world B1.

3.3. Monte Carlo simulations

Our initial and most comprehensive simulation ran under the described pdfs (4 SRES in left panel of figure 5). The outcome, global temperature change in the 2100, is a function of random sampling of emissions scenarios, climate sensitivity and terrestrial sink strength. It becomes apparent

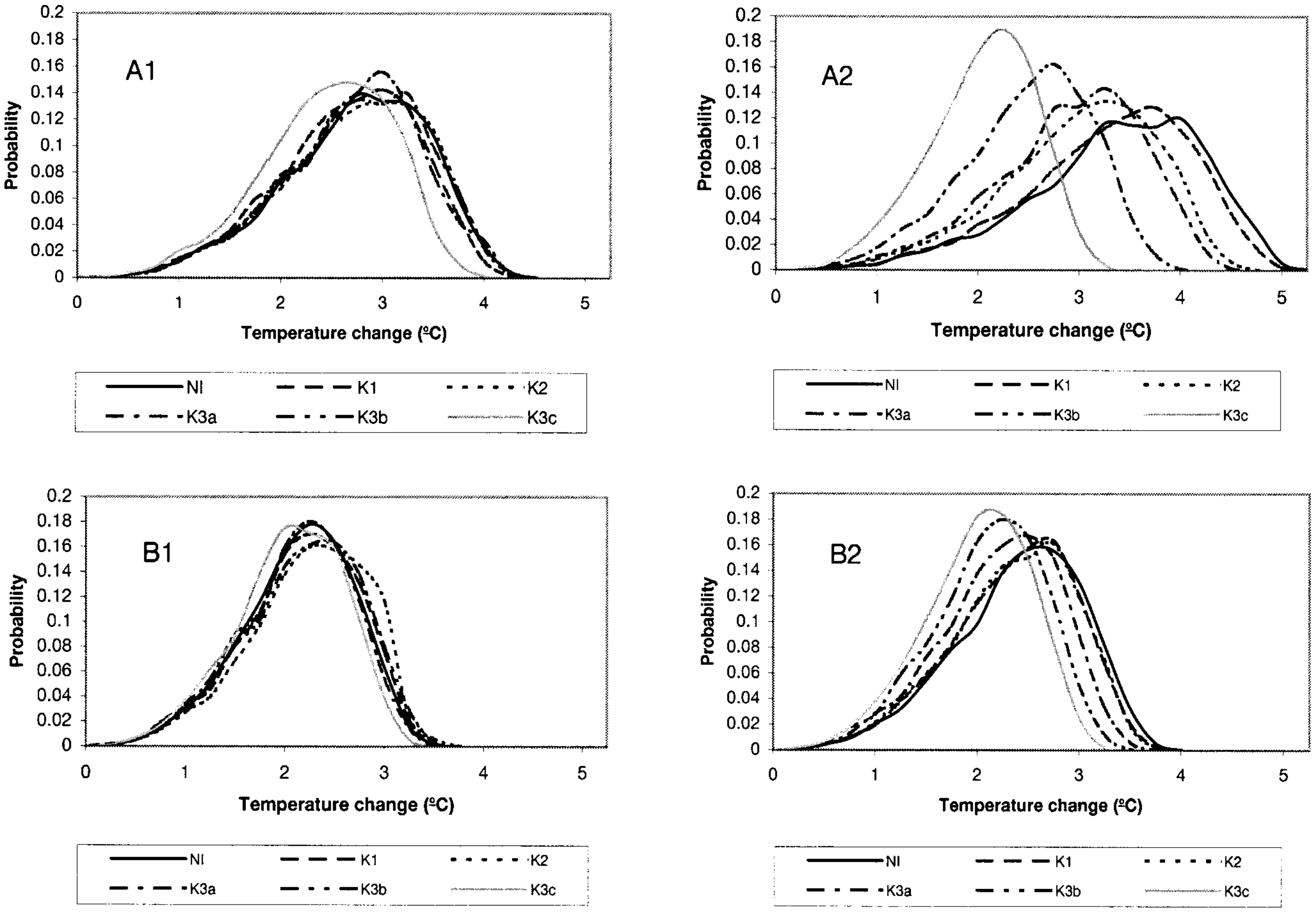

Figure 6. Sampled distribution of each scenario (NI, K1, K2, K3a, K3b and K3c) within each SRES world (A1, A2, B1 and B2) for temperature change by 2100, in 0.25°C intervals.

that the SRES B worlds are likely to experience smaller temperature changes compared to the A worlds. For example, from figure 5 (right panel) we can show that an increase in temperature of at least 2.75°C by 2100 is 0.91 probable in SRES B1, but only 0.51 probable in SRES A2.

We then sampled each of the six scenarios (NI, K1, K2, K3a, K3b, K3c), within each SRES world, in isolation, the other variables pdfs remaining constant (figure 6). It becomes clear how important Kyoto and future GHG reduction commitments are in a world such as A2. Any of the intervention scenarios seem to have substantial environmental benefits (i.e., a shift of almost 2°C could, hypothetically, prevent "dangerous" climate change, for example) over NI. In B2, intervention scenarios seem to have a more modest effect in reducing temperature change. As for A1, only K3c seems to stand out as an effective intervention scenario within the remaining group of scenarios. In a world such as B1, Kyoto will have little, if any, effect in slowing global warming.

We then ran simulations for each group of scenario (NI, K1, K2, K3a, K3b, K3c) considering all four SRES worlds equally likely (figure 7). Overall, as expected, any of the considered intervention scenarios will be better than non-intervention. Yet, their difference is not overwhelming, illustrating that Kyoto and subsequent commitments depend substantially on the world that develops. Considerable temperature reductions are only apparent under the K3 family of scenarios, especially in the K3c variant where a shift of one degree Celsius is attained in the upper end of the distribution.

In order to observe how these distributions vary through time, another MCS, under the most comprehensive approach, was performed for 2025, 2050 and 2100 (figure 8). From figure 8 we can show that an increase in global temperature of 2.4°C or more is highly unlikely by 2050, but moderately likely by 2100.

Two more MCS experiments were performed in order to assess the range of uncertainty solely due to the climate sensitivity and to the global carbon cycle parameters. We sampled each terrestrial carbon sink value (from table 4) in isolation, keeping the other variables pdfs as before (figure 9). The degree of uncertainty that this parameter carries is quite small when compared to the other variables. When we sampled each climate sensitivity value (from table 3) separately, giving the value a probability of one, we found this parameter to produce large uncertainties in the posterior distributions (figure 10). Even if we only consider the IPCC range for climate sensitivity, 1.5–4.5°C, this parameter uncertainty (measured by the biggest temperature change difference between cumulative probability curves) is 1.6 times larger than the SRES world extremes (B1 and A2), and 2 times larger than the scenario extremes (NI and K3c). Uncertainty in the

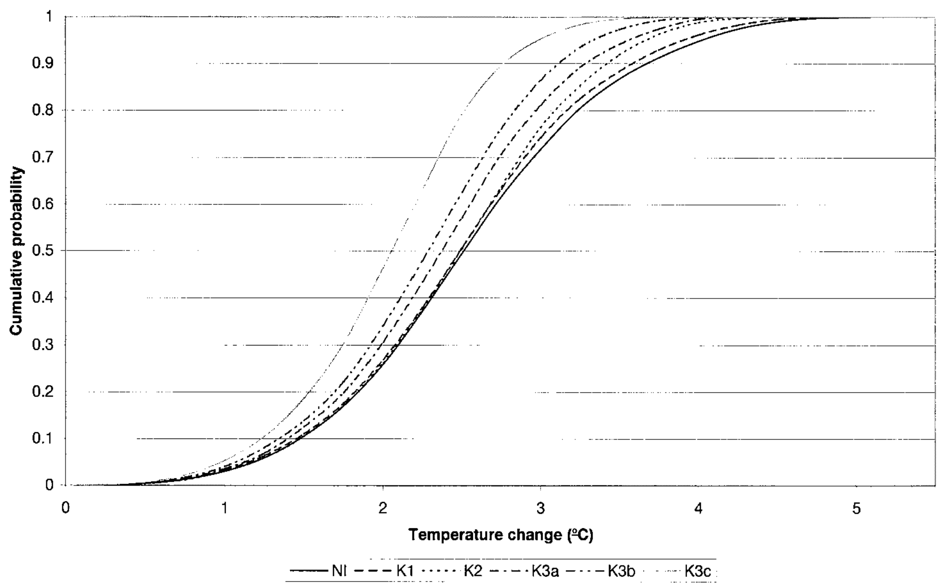

Figure 7. Cumulative probability distribution of each scenario (NI, K1, K2, K3a, K3b and K3c) for temperature change in 2100, considering all four SRES worlds equally likely.

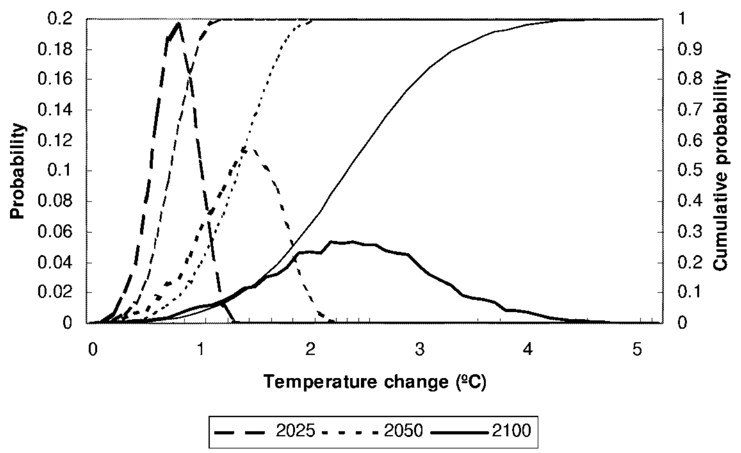

Figure 8. Monte Carlo simulation of the most comprehensive approach (includes all 24 scenarios for each realisation) for temperature change at different time periods (2025, 2050 and 2100) in 0.01°C intervals.

climate sensitivity clearly has the largest effect in our analysis on future temperature, while uncertainty in the terrestrial carbon sink has the least effect.

4. “Hot air” and emissions trading: an example

In this example we demonstrate how this MCS framework can be applied to current climate policy decision-making. At the time of writing, the FCCC is struggling to prepare principles, rules, and guidelines for emissions trading, the buying and selling of emission allowances between Annex-I Parties (Article 17 of the KP). Emissions trading brings about a problem known as “hot air”. Considered to be a big loophole within the Kyoto Protocol, “hot air” occurs if any Parties are allocated assigned amounts that exceed what their emissions would be even in the absence of any emissions limitation and transfer this surplus to other Parties that use it to lessen their degree of abatement. This could happen

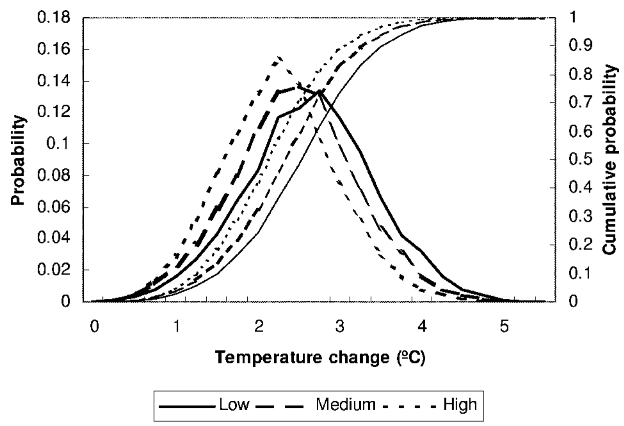

Figure 9. Monte Carlo simulation of global surface warming in 2100 using different carbon cycle parameter values (low, medium and high), in 0.25°C intervals.

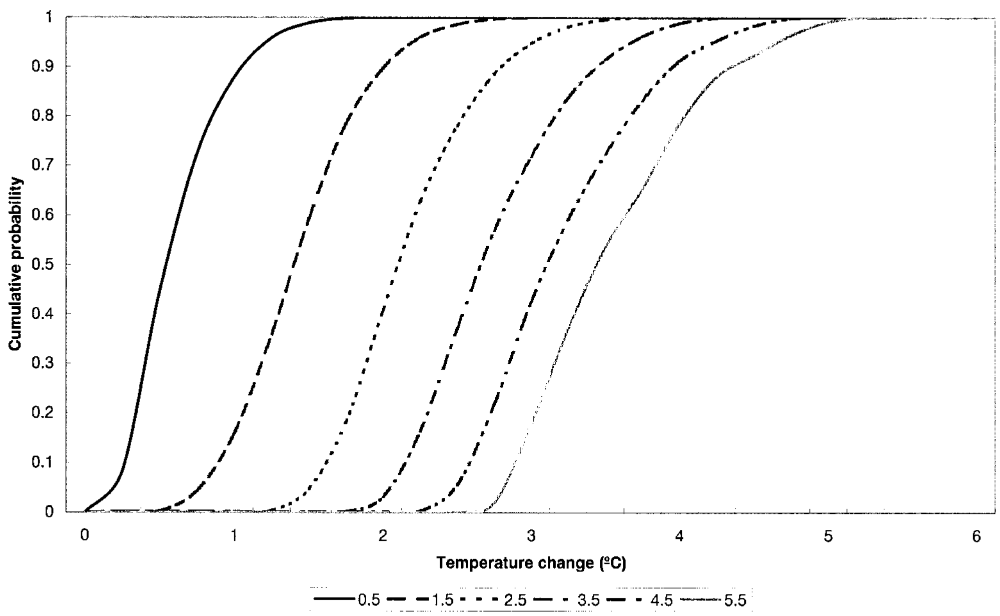

Figure 10. Monte Carlo simulation for temperature change in 2100, using different climate sensitivity parameter values.

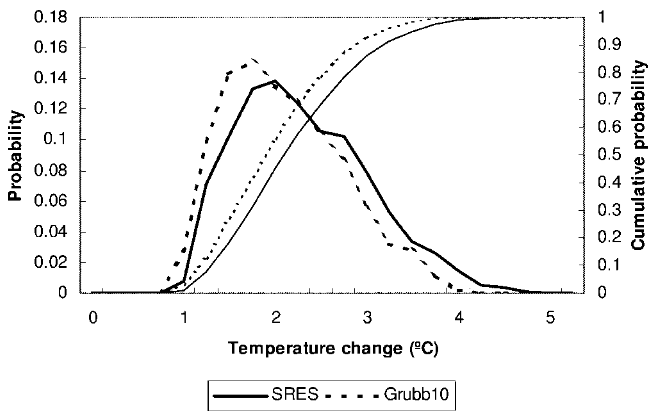

Figure 11. Comparison of Monte Carlo simulations for temperature change in 2100 without "hot air" (Grubb 10) and one with "hot air" (SRES), in 0.25°C intervals.

between Russia and other Parties, for example. Using results from Grubb's [2,3] International Trading of Emissions Allowances (ITEA) model we assume two hypotheses.

First, there will be no restrictions to emissions trading. Using the ITEA model Grubb has shown that unfettered trading of emissions allowances will result in a 5.3% reduction of emissions (relative to 1990), almost exactly the level required by the KP. In this case we use all 20 intervention scenarios which take into account the KP and were described in the section 2.1.1.

The second hypothesis assumes there will be no "hot air", bringing aggregate emissions down to 10% below 1990, so we call them "Grubb 10". For this hypothesis we created another set of 20 intervention scenarios which, instead of reducing emissions by 5%, like the KP, reduce emissions by 10% (these extra 5% of emissions reductions are added to all subsequent commitment periods in all intervention scenarios). Using the MCS framework we compared these two hypotheses (figure 11). For simplicity we only used the middle carbon cycle value (with a probability of one) and 1.5, 2.5 and 4.5°C values for climate sensitivity (with a probability of 0.25, 0.5 and 0.25, respectively). All 20 scenarios were considered equally likely.

Figure 11 shows a shift of 1°C in one end of the distribution, which is still considerable. The posterior distribution is skewed to the left, because the prior distribution of the climate sensitivity was also skewed. As in the earlier analysis, the effects of different policies are more distinct in SRES A2 than others (not shown).

It is clear that this "hot air" example inherits the uncertainty from the ITEA model. Nonetheless, it illustrates how policy options currently in debate at the international negotiations of climate change could ultimately impact upon the environment.

5. Discussion and concluding remarks

A framework, which assesses climate policies in a probabilistic manner, has been presented. This modelling exercise was found to be of importance in order to: (1) assess the impacts of climate policies on the climate system; (2) provide policy-makers with some of the implications of decisions taken during sessions at Conference of the Parties to the FCCC.

5.1. Caveats of building intervention scenarios

Building intervention scenarios is not straightforward. There are many conceptual problems inherent in producing such scenarios. The SRES team refer to three types of uncertainty: (1) uncertainties in quantities (of emissions); (2) uncertainties about model structure; and (3) uncertainties arising from disagreements among experts about the value of quantities or the functional form of the model. All these uncertainties are immediately propagated into our intervention scenarios. Furthermore, the four marker scenarios used here do not span the entire possible range of emissions scenarios in the wider literature, but about 80–90% of this range [14].

The first caveat is the overlap of policies, which could be exaggerating emissions reductions. The fact that the SRES scenarios are all "no-climate-policy", but include government policies, which have implications for GHG emissions, can produce double counting. This problem seems to be intractable due to the largely qualitative nature of the SRES storylines.

Second, besides the interdependence of climate impacts and scenarios (for the purpose of adaptation policies), climate policies also interact with the scenario itself. For example, in some worlds, intervention scenario K2 has negative emissions reductions (i.e., it starts to increase emissions). This occurs because scenario K2 assumes constant emissions after 2010 for Annex I countries, which under SRES A1 scenario creates an *increase* in emissions by around 2060. The same happens for B1 but not for A2 and B2 because of higher emissions. This problem arises because we constructed intervention scenarios in relation to 1990 levels (as adopted in the Kyoto Protocol) and not in relation to what was happening in the underlying SRES scenario. It proved impossible to take the latter approach because of the qualitative nature of the SRES storylines. We therefore encourage the IPCC to develop a classification scheme for classifying scenarios as either intervention or non-intervention [13].

The third caveat is the complexity of the Kyoto Protocol. Virtually no one involved in the negotiations is capable of grasping the overall picture of the entire process. For example, at present most of the so-called flexibility mechanisms have no rules or guidelines. If improperly implemented these mechanisms could offset real emissions reductions, "hot air" being an example. The uncertainty in all these issues is substantial, and has not been taken into account in the "hot air" example. Therefore, the results from figure 11 should be interpreted with caution.

Since 1999, when this study was conducted, the preliminary SRES marker scenarios have been marginally revised and complemented by two additional illustrative scenarios (A1FI and A1T). We believe the method described in this paper is still valid since it can be used with any combination of emissions scenario, climate model and climate policy. Had A1FI (30.3 GtC) and A1T (4.3 GtC) been included in our MCS they would have probably flattened the posterior distribution further, since these scenarios are extremes cases of GHG emissions (maximum and minimum respectively) within the SRES band of illustrative scenarios.

5.2. Limitations of the MCS framework

Expert judgement based climate predictions have been heavily criticised in the past [20], mainly due to the methods used. However, by using a different methodology, which takes expert judgement only as an *a priori* probability distribution, and not as the end result, we see it as an advantage. We do recognise that this Bayesian characterisation of probability is still subjective, and hence responsive to methodology.

With respect to the climate model, MAGICC, the fact that it does not consider natural and solar forcings, nor natural climate variability poses some drawbacks. However, when we added estimates of internal variability (from the HadCM2 control run) to the analysis, we found that it had an insignificant effect on the distribution, mainly because internal climate variability on 50–100 year time-scales have close to zero-mean and a small variance.

We sampled three parameters with this framework (emissions scenarios, climate sensitivity and terrestrial carbon sink), but a fully-fledged uncertainty analysis would require many more parameters (e.g., upwelling rate, Global Warming Potentials, etc.) to be sampled. A multi-gas assessment (such as Reilly et al. [16]) would be more appropriate and realistic, but considerably more complex and uncertain because of the dubious nature of global warming potentials of GHGs. This approach also does not take into account "surprises", i.e., rapid, non-linear responses of the climate system to anthropogenic forcing, but could do so, by assigning very low probabilities to such events (e.g., breakdown of the thermohaline circulation or collapse of the west Antarctica ice sheet [23]).

5.3. Implications

This study has shown that the Kyoto Protocol, our current mitigation agreement to combat climate change, will do modestly in its task, at least in the next 100 years. Its effectiveness will mostly depend on which of the SRES (or other) world develops, but also (if not primarily) on which post-Kyoto emission limitations will be agreed upon. Furthermore, until the second half of the next century, in terms of global temperature changes, it will be impossible to differentiate between which SRES world we are inhabiting.

Overall, and considering all SRES worlds equally likely, we must conclude that intervention is better than non-intervention. "How much better?" is a difficult question which this sensitivity study only starts to answer. The inclusion of developing countries commitments in subsequent commitment periods (K3b and K3c) greatly boosts its effectiveness. The timing is also quite important (as demonstrated by the differences between K3b and K3c), early action being preferred. However, most important is the Kyoto Protocol's dependence upon the SRES worlds. In the B1 world it is clear that Kyoto will do very little to mitigate climate change. In this world intervention is almost the same as non-intervention, although one could ask if it is possible to reach a world like B1 without intervention. If one were to believe this was possible, as the SRES literature suggests, then one would conclude that achieving a B1 world is far more important than reaching our Kyoto commitments. Further investigation on intervention scenarios and the Kyoto Protocol is needed to progress in this matter, as has been achieved in the forthcoming IPCC TAR Working Group III report.

Another important question raised by this study concerns adaptation. If Kyoto will do little to slow global warming, why have the international negotiations on climate change (FCCC process) to date been almost entirely focused on mitigation? In every SRES world we are committed to some degree of climate change. Even if we invested only in mitigation strategies, in a world such as A2 we would still be committed to some climate change which would probably require systems to adapt at a faster rate than their natural pace. In B1 it may even be undesirable to invest specifically in *climate* mitigation because it may not be cost-effective *vis-à-vis* adaptation. This study substantiates other claims [15] that adaptation also needs to be dealt with if we are to increase resilience to future climatic conditions.

We think this approach could be useful for policy-makers to visualise the environmental impacts, in terms of global temperature change, of their decisions at the international negotiations. We used the Kyoto Protocol and one of its sub-themes, "hot air", as examples, but there is wider application. We believe this approach could complement what was named the "Brazilian proposal" [22]. Briefly, this proposal suggested a "policy-maker" model as a simple means to translate emissions into temperature increases, for purposes of assigning emission ceilings to individual industrialised countries (within the Kyoto Protocol). In this way, historical emissions are included in sharing the burden of emission control, based on the polluter pays principle. The method described here could provide the measurement of uncertainty that would allow this methodology to become more practical/accurate.

Another case where such a method could be applied is Integrated Assessment-Focus Groups [8,11,21]. For example, Focus Groups participants could assign probabilities to SRES worlds, based on their world views of the future, which would output a different outcome for each person in terms of global temperature change, or even a more specific impact, such as crop yield or heat mortality, if an impact model was "added on". The real strength of this approach, however, lies in impact and adaptation assessments, as noted by New and Hulme [14]. The "4 SRES" line in figure 5 (or figure 8 through time), which represents the most comprehensive run of this study, potentially enables the identification of critical thresholds or "dangerous climate change" in a probabilistic fashion. This will be particularly useful for managers dealing with adaptation to climate change by enabling probabilistic information to be incorporated into decision-support systems. This approach is therefore only an intermediate step towards a more formal risk assessment and management framework for climate change management [7].

Acknowledgements

This research was supported by the Nuffield Foundation under the Undergraduate Research Bursary scheme (Award AT/10/99/0056). Two anonymous referees are thanked for helpful suggestions. We are grateful to Mark New and Tim Osborn for all their help with the numerical techniques used. We would also like to thank Tom Wigley and Sarah Raper for allowing the use of their model, MAGICC. The preliminary SRES emissions scenarios were obtained through the SRES website in May 1999 (their versions dated between October and December of 1998).

References

[1] J. Alcamo, A. Bouwman, J. Edmonds, A. Gruebler, T. Morita and A. Sugandhy, in: *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, eds. J.T. Houghton et al. (Cambridge University Press, Cambridge, 1995) pp. 247–304.

[2] M. Grubb, Implementing the 'Kyoto Mechanisms': principles and rules for emissions trading (paper presented at Concluding Workshop for the Project to Enhance Capacity under the Framework Convention on Climate Change and the Kyoto Protocol, London, 17–18 March 1999) (draft) (1999).

[3] M. Grubb, C. Vrolijk, D. Brack, T. Forsyth, J. Lanchbery and F. Missfeldt, *The Kyoto Protocol: A Guide and Assessment* (Royal Institute of International Affairs & Earthscan, London, 1999).

[4] D. Harvey, J. Gregory, M. Hoffert, A. Jain, M. Lal, R. Leemans, S. Raper, T. Wigley and J. de Wolde, *An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report: IPCC Technical Paper II* (IPCC, Geneva, 1997).

[5] J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, *Climate Change 1995: The Science of Climate Change*, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, 1996).

[6] M. Hulme and T. Carter, in: *Representing Uncertainty in Climate Change Scenarios and Impact Studies – ECLAT-2 Workshop Report*, eds. T. Carter, M. Hulme and D. Viner (Climatic Research Unit, Norwich, 1999).

[7] R.N. Jones, Analysing the risk of climate change using an irrigation demand model, Climate Research 14 (2000) 89–100.

[8] B. Kasemir, U. Dahinden, A.G. Swartling, R. Schüle, D. Tabara and C.C. Jaeger, Citizens' perspectives on climate change and energy use, Global Environmental Change 10 (2000) 169–184.

[9] R.W. Katz, in: *Representing Uncertainty in Climate Change Scenarios and Impact Studies – ECLAT-2 Workshop Report*, eds. T. Carter, M. Hulme and D. Viner (Climatic Research Unit, Norwich, 1999).

[10] J. Leggett, W.J. Pepper, and R.J. Swart, in: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, eds. J.T. Houghton, B.A. Callander and S.K. Varney (Cambridge University Press, Cambridge, 1992), pp. 75–95.

[11] I. Lorenzoni, A. Jordan, M. Hulme, R.K. Turner and T. O'Riordan, A co-evolutionary approach to climate change impact assessment: Part I. Integrating socio-economic and climate change scenarios, Global Environmental Change 10 (2000) 57–68.

[12] M.G. Morgan and D. Keith, Subjective judgements by climate experts, Env. Science and Technology 29 (1995) 468–476.

[13] N. Nakićenović, J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Papper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor and Z. Dadi, *Special Report on Emission Scenarios* (Cambridge University Press, Cambridge, 2000).

[14] M. New and M. Hulme, Representing uncertainty in climate change scenarios: a Monte-Carlo approach, Integrated Assessment 1 (2000) 203–213.

[15] M.L. Parry, N. Arnell, M. Hulme, R.J. Nicholls and M. Livermore, Adapting to the inevitable, Nature 395 (1998) 741.
[16] J. Reilly, R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kickligther, J. Melillo, P. Stone, A. Sokolov and C. Wang, Multi-gas assessment of the Kyoto Protocol, Nature 401 (1999) 549–555.
[17] S. Shackley, P. Young, S. Parkinson and B. Wynne, Uncertainty, complexity and concepts of good science in climate change modelling: are GCMs the best tools?, Climatic Change 38 (1998) 159–205.
[18] M. Schlesinger Global warming: a scientific panel to discuss the state of climate science since the 1995 IPCC, RFF Conference Center, Washington, DC (1999) http://www.weathervane.rff.org/refdocs/CSF%20Transcript.html.
[19] Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change – Working Group III: Mitigation of Climate Change (1999), http://sres.ciesin.org/.
[20] T.R. Stewart and M.H. Glantz, Expert judgement and climate forecasting: a methodological critique of "Climate Change to the Year 2000", Climatic Change 7 (1985) 159–183.
[21] S. Stoll-Kleemann, T. O'Riordan and C.C. Jaeger, The psychology of denial concerning climate mitigation measures: evidence from Swiss focus groups, Global Environmental Change 11 (2001) 107–117.
[22] UNFCCC, Proposed elements of a protocol to the United Nations Framework Convention on Climate Change, presented by Brazil in response to the Berlin mandate, 3-57, FCCC/AGBM/1997/MISC.1/Add.3.
[23] D.G. Vaughan and J.R. Spouge, Risk estimation of collapse of the West Antarctic Ice Sheet, Climatic Change (2001), in press.
[24] T.M.L. Wigley, Balancing the carbon budget: implications for projections of future carbon dioxide concentrations changes, Tellus 45B (1993) 409–425.
[25] T.M.L. Wigley, Global-mean temperature and sea level consequences of greenhouse gas concentration stabilization, Geophysical Research Letters 22 (1995) 45–48.
[26] T.M.L. Wigley, The Kyoto Protocol: CO_2, CH_4 and climate implications, Geophysical Research Letters 25 (1998) 2285–2288.
[27] T.M.L. Wigley, The science of climate change: global and U.S. perspectives, Pew Center on Global Climate Change (1999).
[28] T.M.L. Wigley and S.C.B. Raper, Implications of revised IPCC emission scenarios, Nature 357 (1992) 293–300.