



# Safe policies in an uncertain climate: an application of *FUND*

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## Abstract

Various aspects of the role of uncertainty in greenhouse gas emission reduction policy are analyzed with the integrated assessment model *FUND*. *FUND* couples simple models of economy, climate, climate impacts, and emission abatement. Probability distribution functions are assumed for all major parameters in the model. Monte Carlo analyses are used to study the effects of parametric uncertainties. Uncertainties are found to be large and grow over time. Uncertainties about climate change impacts are more serious than uncertainties about emission reduction costs, so that welfare-maximizing policies are stricter under uncertainty than under certainty. This is more pronounced without than with international cooperation. Whether or not countries cooperate with one another is more important than whether or not uncertainty is considered. Meeting exogenously defined emission targets may be more or less difficult under uncertainty than under certainty, depending on the asymmetry in the uncertainty and the central estimate of interest. The major uncertainty in meeting emissions targets in each of a range of possible future is the timing of starting (serious) reduction policies. In a scenario aiming at a stable CO<sub>2</sub> concentration of 550 ppm, the start date varies 20 years for Annex I countries, and much longer for non-Annex countries. Atmospheric stabilization at 550 ppm does not avoid serious risks with regard to climate change impacts. At the long term, it is possible to avoid such risks but only through very strict emission control at high economic costs. © 1999 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Uncertainty abounds in climate change. Part of it relates to imperfect understanding of the mechanisms at work. Another part relates to the stochastic nature of important systems. A third part relates to the long lead-times of cause and effect. In time, we may be able to tackle, to some extent, the first source of uncertainty, but that time may well be a far future. We have to learn to live with the other two sources of uncertainty. This paper attempts to further that learning process.

There are various ways of approaching climate change uncertainties, each with its merits. Below, I take four alternative approaches. These have been taken before, but never with one single model or, arguably, as rigorous as I do here. I leave other approaches aside. *Stochasticity*

is omitted because it relates to variability at various time-scales, most of which are different than the model's time-scale. The economic module, for instance, is a growth model, suitable for analyzing tendencies but not for recessions or adjustment processes. Dowlatabadi (1997) and Lempert et al. (1996) analyze stochasticity and adaptation. *Learning* is omitted partly because it is a very complex issue worthy of separate treatment (cf. Kolstad, 1994,1996; Nordhaus and Popp, 1997; Peck and Teisberg, 1993; Tol, 1998; Ulph and Maddison, 1997; Ulph and Ulph, 1996) and partly because its relevance for current decision-makers is not clear to me. It is uncertain what future decision-makers will learn or how they will react to it, so seen from the present the uncertainty is unresolved. Other approaches, such as *fuzzy logic* (Leimbach, 1996,1998), *cultural theory* (Van Asselt et al., 1996), *grey programming* (Bass et al., 1997), *ambiguity* (Eismont and Welsch, 1996; Welsch, 1995) *Dempster-Shafer theory* (Luo and Caselton, 1997), are omitted because these deviate too much from the Monte Carlo simulation techniques used here. The technique of *representative*

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scenarios (Nordhaus, 1994a; Yohe and Wallace, 1996) is a computationally efficient variant of Monte Carlo simulations.

The next section describes the model, the *Climate Framework for Uncertainty, Negotiation and Distribution*, version 1.6 (*FUND*). Cf. Tol (1997,1999) for further results. Section 3 continues with an analysis of the uncertainties about the business as usual scenario, the necessary first step. Section 4 analyzes optimal, i.e., welfare-maximizing, emission reduction trajectories, comparing cooperative and non-cooperative policies under certainty and uncertainty. Section 5 looks at 'safe' policies, for various definitions of safety. Emission targets may be agreed upon, and these can be met assuming under certainty, in expectation, or with a certain chance. Alternatively, one may seek a trajectory which avoids a 'high' probability of 'large' climate change impact, or 'high' emission reduction costs. Section 5 concludes.

## 2. The model

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, namely OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and Southeast Asia, Centrally Planned Asia, and Africa.

The model runs from 1950 to 2200, in time steps of a year. The prime reason for extending the simulation period into the past is the necessity to initialize the climate change impact module. In *FUND*, climate impacts are assumed to depend on the impact of the year before, to reflect the process of adjustment to climate change. Without a proper initialization, climate impacts are misrepresented in the first decades. Scenarios for the period 1950–1990 are based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). Scenarios for the period 2010–2100 are based on the EMF Standardised Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). Note that the original EMF scenario had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 1990–2010 is a linear interpolation between observation and the EMF Scenario. The period 2100–2200 is based on extrapolation.

The scenarios concern economic growth, population growth, urban population, autonomous energy efficiency improvements, decarbonization of the energy use, and methane and nitrous oxide emissions.

The scenarios of economic and population growth are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only

affects urban population. Population also changes with climate-induced migration between the regions.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, and the impact of climate change on coastal zones, agriculture, extreme weather, natural ecosystems and malaria.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The carbon cycle is a five-box model, with geometric depletion in four boxes and no depletion in the fifth. The models are calibrated to Schimel et al. (1996). Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine et al. (1990). The global mean temperature is governed by a geometric build-up to its equilibrium (determined by radiative forcing), with a lifetime of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Global mean sea level is also geometric, with its equilibrium determined by the temperature and a lifetime of 50 years. These lifetimes result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996). *FUND* also calculates hurricane activity, winter precipitation, and winter storm activity because these feed into the damage module. These factors depend linearly on the global mean temperature.

The climate impact module is fully described in Tol (1996). The damage module has two units of measurement: people and money. People can die (heat stress, malaria, tropical cyclones), not die (cold stress), or migrate. These effects, like all impacts, are monetized. Damage can be due to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 2.5°C). Benchmark estimates can be found in Table 1. Damage in the rate of temperature change slowly fades at a speed indicated in Table 2. Damage is calculated through a second-order polynomial in climatic change. Damage is distinguished between tangible (market) and intangible (non-market) effects. Tangible damages affect investment and consumption; through investment, economic growth is affected; through consumption, welfare is affected. Intangible damages affect welfare. Relative vulnerability to climate change changes with economic development in many ways. The importance of agriculture fall with per capita income growth, and so do malaria incidence and the inclination to migrate. Heat stress increases with urbanization. The valuation of impacts on non-marketed goods and services increases with per capita income.

The costs of emission reduction are calibrated to the survey results of Hourcade et al. (1996) supplemented with results of Rose and Stevens (1993) for developing countries. For the poorer regions, only a small number of cost estimates is available, leading to unrealistic regional

Table 1  
Monetized estimates of the impact of global warming (in  $10^9$  US\$)

Region	Species	Life	Agric.	Sea	Extreme	Total
Level (global mean temperature: + 2.5°C; sea level: + 50 cm; hurricane activity: + 25%; winter precipitation: + 10%; extratropical storm intensity: + 10%)						
OECD-A	0.0	-1.0	-5.3	0.9	2.5	-2.9
OECD-E	0.0	-1.1	-6.0	0.3	0.3	-6.5
OECD-P	0.0	-0.5	-6.1	1.5	5.5	0.3
CEE#fSU	0.0	3.7	-23.2	0.1	0.2	-19.1
ME	0.0	3.5	3.1	0.1	0.0	6.6
LA	0.0	67.0	7.3	0.2	0.0	74.5
S&SEA	0.0	81.4	15.8	0.2	0.6	98.8
CPA	0.0	58.4	-22.2	0.0	0.1	36.3
AFR	0.0	22.5	5.4	0.1	0.0	28.0

Rate (global mean temperature: 0.04°C/year; other variables follow)

OECD-A	0.3	0.2	0.3	0.2	0.2	1.2
OECD-E	0.3	0.2	0.0	0.2	0.0	0.7
OECD-P	0.2	0.1	0.0	0.3	0.4	1.0
CEE&fSU	0.1	0.1	0.0	0.0	0.0	0.2
ME	0.0	0.0	0.1	0.0	0.0	0.2
LA	0.0	0.4	0.1	0.1	0.0	0.6
S&SEA	0.0	0.3	0.1	0.1	0.0	0.6
CPA	0.0	0.2	0.3	0.0	0.0	0.5
AFR	0.0	0.0	0.1	0.0	0.0	0.2

Source: After Tol (1995,1996).

Table 2  
Duration of damage memory per category<sup>a</sup>

Category	Years	Category	Years
Species loss	100	Immigration	5
Agriculture	10	Emigration	5
Coastal protection	50	Wetland (tangible)	10
Life loss	15	Wetland (intangible)	50
Tropical cyclones	5	Dryland	50

Source: After Tol (1996).

<sup>a</sup>Damage is assumed to decline geometrically at a rate of 1-l/lifetime.

variations. Therefore, regional relative costs are shrunk to the global average. This particularly influence the developing regions, for which much less information on emission abatement costs is available. Costs are represented by a quadratic function. Table 3 displays the parameters. Roughly, a 1% cut in emissions (from baseline) in one year costs 0.02% of GDP; a 10% cut costs 2%.

*FUND* distinguishes generations of decision-makers. Each decision-maker has control over a ten-year period only, but does optimize the net present welfare of her region from the start of the control period up to 2200. Each decision-maker exactly knows the emission reduction efforts of all decision-makers in all regions at all times. The distinction between generations of decision-

Table 3  
Parameters of the emission reduction cost function<sup>a</sup>

OECD-A	2.0789	CEE&fSU	2.0488	S&SEA	2.1268
OECD-E	2.3153	ME	2.1041	CPA	1.9544
OECD-P	2.2171	LA	2.1253	AFR	2.0931

Source: After Hourcade et al. (1996) and Rose and Stevens (1993).

<sup>a</sup>The proportional loss of GDP  $C$  in year  $t$  of proportional emission reduction  $R$  in year  $t$  follows from  $C_t = aR_t$ . Costs and reduction are relative to the situation of uncontrolled emissions in year  $t$  (note that abatement in earlier years shifts this baseline). The costs to GDP are modelled as a deadweight loss to the economy. Emission reduction is brought about by a permanent shift in energy- and carbon intensity.

makers has two implications. Firstly, in a cost-benefit analysis, a decision-maker not only has to match her decisions with those of other regions, but also with the decisions of other generations. The equilibrium is found iteratively. Secondly, the definition of intertemporal cost-effectiveness vanishes, as there is no decision-maker controlling the entire time period.

The quantification of the uncertainties about the parameters of *FUND* is largely based on expert knowledge, that is, my qualitative interpretation of an informal selection of the literature and informal talks with topical experts. Table 4 provides an overview of the assumptions made for the analysis of parameter uncertainty. The modal values equal the best guesses.<sup>2</sup> Distribution and spread are based on the literature (Harvey, 1996a,b; Fankhauser, 1994; Hope et al., 1993; Hope and Maul, 1996; Hourcade et al., 1996; Kheshgi et al., 1997; Lutz, 1996; Lutz et al., 1997; Morgan and Keith, 1995; Nordhaus, 1994b; Pate-Cornell, 1996; Plambeck and Hope, 1996; Plambeck et al., 1997; Schimmelpfennig, 1996; Shlyakhter and Kammen, 1992; Titus and Narayanan, 1996; Tol, 1995; Yohe, 1991; Yohe and Wallace, 1996; Zapert et al., 1998), but, since *FUND* is a different model, many adjustments needed to be made. No formal methodology is used for this, as available methods (excepting the most elaborate ones) only deliver pseudo-reproducibility and pseudo-objectivity (cf. Morgan and Henrion, 1990, for an overview of methods).

<sup>2</sup> Four different statistics are used as central estimates of both parameters and outcomes: best guess, mode, mean, and median. The best guess of a parameter is its most likely value, and thus the mode of its probability distribution. The best guess of an output variable follows from *FUND* if all parameters assume their modes. Because the model is non-linear, the best guess of an output variable is different than its mode, which coincides with the peak in its probability density. Mean and median are defined as the probability-weighted average and the 50-percentile, respectively. The median is the preferred way of reporting outcomes, as the median is more robust to outliers than is the mean.

Table 4  
Description of parameter uncertainty

Parameter	Distribution	Characteristics		Parameters	
Climate sensitivity (per doubling CO <sub>2</sub> )	Gamma	Mode	2.50	$\alpha$	8.1270
		Mean	2.85	$\beta$	0.3508
		S.D.	1.00		
Sea level sensitivity (per °C)	Gamma	Mode	0.31	$\alpha$	5.9957
		Mean	0.36	$\beta$	0.0613
		S.D.	0.15		
Hurricane sensitivity (per °C)	Normal	Mean	0.00	$\mu$	0.00
		S.D.	0.10	$\sigma$	0.10
Flood sensitivity (per °C) S.D.	Normal	Mean	0.04	$\mu$	0.04
		S.D.	0.04	$\sigma$	0.04
Storm sensitivity (per °C)	Normal	Mean	0.02	$\mu$	0.02
		S.D.	0.02	$\sigma$	0.02
Atm. lifetime CH <sub>4</sub>	Triangular	Mode	8.6	a	8.0
		Mean	10.2	b	16.0
		S.D.	1.3	c	8.6
Atm. lifetime N <sub>2</sub> O	Triangular	Mode	120	a	100
		Mean	130	b	170
		S.D.	15	c	120
Lifetime temperature Lifetime sea level	Triangular	Mode	50	a	25
		Mean	58	b	100
		S.D.	16	c	50
Atm. lifetimes CO <sub>2</sub>	Normal <sup>a</sup>	Mean	363; 74; 17; 2	$\mu$	Mean
		S.D.	Half mean	$\sigma$	S.D.
Driving scenarios <sup>b</sup>	Normal	Mean	1.0	$\mu$	1.0
		S.D.	0.1	$\sigma$	0.1
Emission reduction <sup>c</sup>	Gamma	Mean	1.21	$\alpha$	5.8284
		S.D.	0.50	$\beta$	0.2071
Impacts <sup>d</sup>	Normal	Mean	1.0	$\mu$	1.0
		S.D.	0.5	$\sigma$	0.5
VOSL <sup>e</sup>	Gamma	Mean	1.0	$\alpha$	2.6180
		S.D.	1.0	$B$	0.6180
Lifetime impacts	Normal <sup>a</sup>	Mean	Table 2	$\mu$	Mean
		S.D.	Quarter mean	$\sigma$	S.D.

<sup>a</sup>Knotted at zero.

<sup>b</sup>Multiplier of economic growth, population growth, AEEI, ACEI and exogenous emissions land-use change.

<sup>c</sup>Multiplier of emission reduction cost function.

<sup>d</sup>Multiplier of impact due to/on species, heat, cold, malaria, agriculture, hurricane (life and property), floods, winter storms, migration, coastal protection, dry land, wet land.

<sup>e</sup>Value of a statistical life; multiplier of VOSL, which is time and region-dependent, equalling 240 times the per capita income.

### 3. Business as usual

Emissions are not reduced in the business as a usual scenario. Fig. 1 shows a selection of the results for this scenario. The results are for a Monte Carlo simulation with 1000 replications, that is, *FUND* is run 1000 times with parameters randomly drawn from the distributions of Table 4. The results (1000 drawings, 250 years, nine regions, etc.) are summarized for the world as a whole for the years 2000, 2025, 2050, 2075, and 2100. Displayed are the 5-, 50-, and 95-percentiles, that is, the median and the bounds of the 90%-confidence interval. Although an integrated model, *FUND* omits some feedback mechanisms so that, for extreme parameter combinations, unrealistic results emerge. Outliers can therefore not

be trusted, and the output is summarized with the robust median and 90%-confidence interval.

The population in 2100 is projected to lie somewhere between 8 and 14 billion people, with a central estimate of 10.5 billion. This is the conventional wisdom to which *FUND* is calibrated (Bulatao et al., 1990; see also Lutz et al., 1997). World income lies somewhere between 140 and 400 trillion dollar, with a central estimate of 220 trillion dollar. This integrates population growth and per capita economic growth, as well as feedbacks from climate impact. Industrial emissions of carbon dioxide rise to between 21 and 76 billion tonnes of carbon per year in 2100, with a central estimate of 35 billion tonnes. *FUND* is pessimistic about the chance of carbon emissions to be reduced by other forces than climate policy.

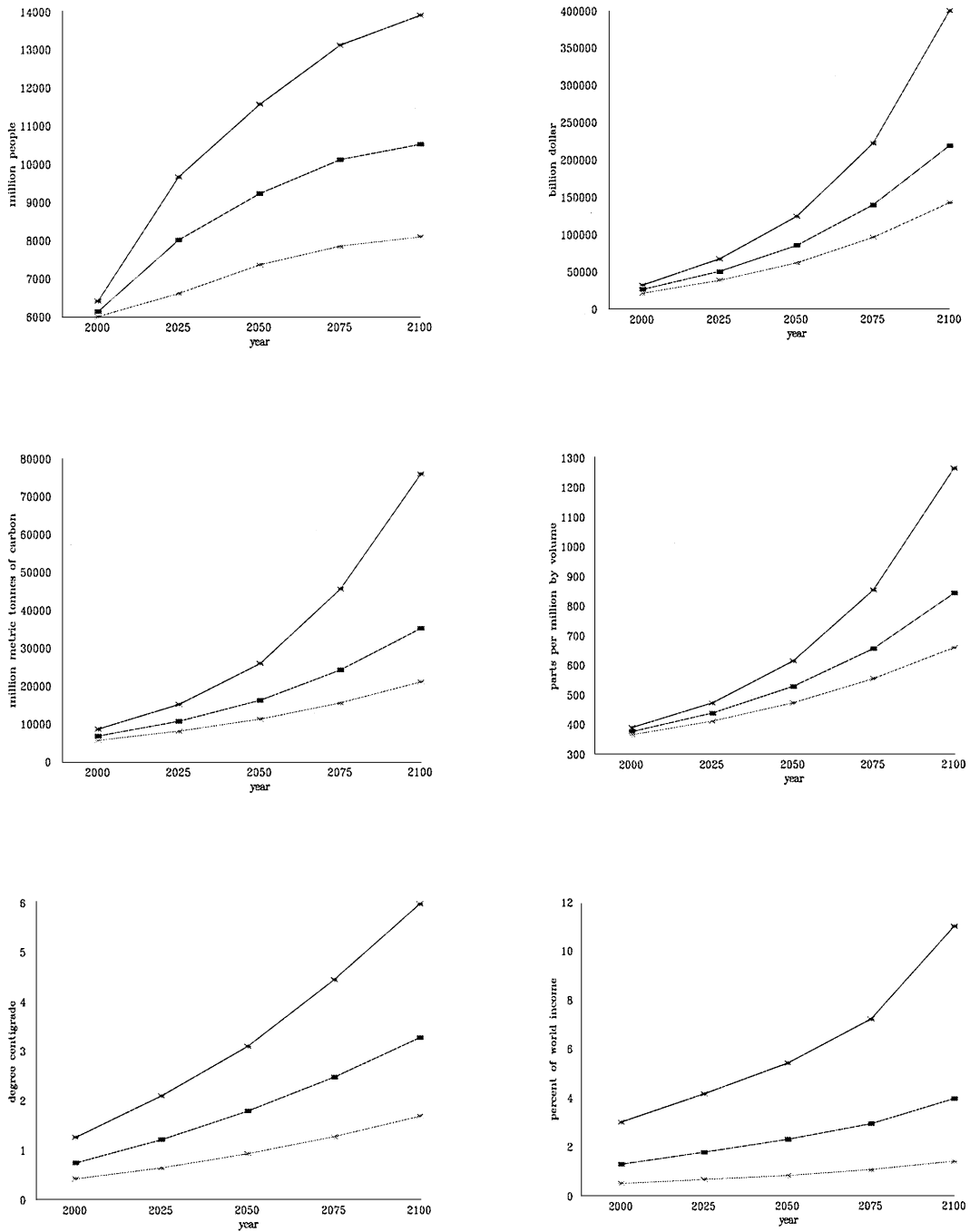


Fig. 1. Key variables and their uncertainties in the business as usual scenario. Displayed are, from left to right and from top to bottom, population, income, industrial carbon dioxide emissions, atmospheric concentrations of carbon dioxide, surface air temperature, and climate change impacts. All figures are global. Filled squares are medians, asterisks the bounds of 90% confidence intervals. Results are for a Monte Carlo simulation with 1000 replications.

As a result, concentrations of carbon dioxide end up between 660 and 1260 ppm in 2100, with a central estimate of 840 ppm. Khesghi et al. (1997) find a range of 100 ppm solely due to uncertainties in the carbon cycle. The global mean temperature rises to between 1.6 and 6.0°C by 2100, with a central estimate of 3.3°C. This is at

the high side compared to other studies, resulting from *FUND*'s high emissions.

The impacts of climate change, expressed as a percentage of world income, lie somewhere between -1.4 and -11.0% in 2100, with a central estimate of -3.9%. Positive impacts are not excluded, but dominated by

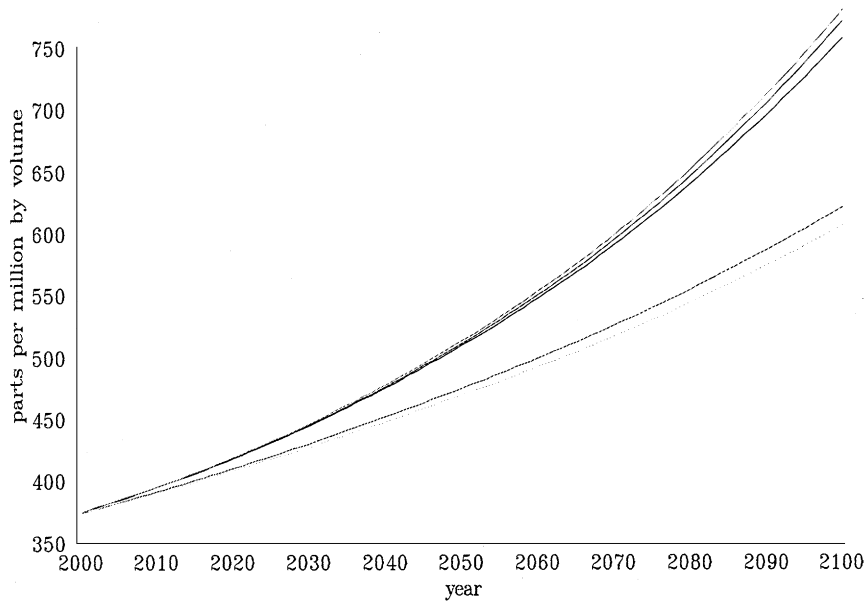


Fig. 2. Atmospheric concentrations of carbon dioxide for, from top to bottom, business as usual, non-cooperative optimal control under certainty, non-cooperative optimal control under uncertainty, cooperative optimal control under certainty, and cooperative optimal control under uncertainty. All policies are evaluated with all parameters set to their best guesses.

negative ones. Impacts are already high in 2000 (– 0.5 to – 3.0%) because of the rapid climate change during this period.

#### 4. Optimal policies

Various decision rules may guide emission reduction policies. One such rule is to optimize social welfare. This is the long-term, macro-economic version of (project-oriented) cost–benefit analysis. The negative impacts of climate change and greenhouse gas emission reduction are traded off such that their sum is minimized, or, in this case, net present welfare is maximized. To account for uncertainty, the expected value of welfare is used.

There are two complications. Firstly, decisions are taken by successive policy makers. It is here assumed that policy makers control a period of ten years, starting in 1990, and know exactly what their predecessors have done, and their successors will do (cf. Tol, 1998, for alternatives). Welfare is discounted to the start of the decade under control, and ranges from then till 2200. Secondly, decisions are taken by policy makers of different countries or, in the case of *FUND*, nine world-regions. It is here assumed that policy makers either do not cooperate but maximize the welfare of their regions while being perfectly knowledgeable of other policy makers actions, or cooperate so as to maximize the sum of regional welfares.

Fig. 2 displays optimal trajectories of the atmospheric concentration of carbon dioxide for the cooperative and

non-cooperative scenarios. For comparison, the business as usual scenario, and the cooperative and non-cooperative optima under certainty are also displayed. Optimal policies are calculated under uncertainty, and then evaluated with all parameters fixed to their best guesses (coinciding with the modes of the probability distributions of Table 4). Emission control is stricter under uncertainty than under certainty. The uncertainty about the impact of climate change dominates the uncertainty about the costs of greenhouse gas emission reduction. The same conclusion is drawn by, *inter alia*, Nordhaus (1994a) and Tol (1995). See Hope (1994) for a contrary view. This effect is less pronounced in case of international cooperation, because the base level of emission reduction under certainty is higher in this case, taking away part of the risks of climate change and adding to the risks of emission reduction.

Fig. 3 displays the median and 90%-confidence intervals of the atmospheric concentration of carbon dioxide, world income, climate impacts, and direct reduction costs for cooperative reduction under uncertainty, and compares these to the business as usual scenario. Even the most stringent of the optimal scenarios has little effect on CO<sub>2</sub> concentrations and hence on impact. On the other hand, the policy costs little, either directly or in its consequences on income.

#### 5. Safe policies

An alternative decision rule, apparently one preferred by politicians, is to define a maximum allowable

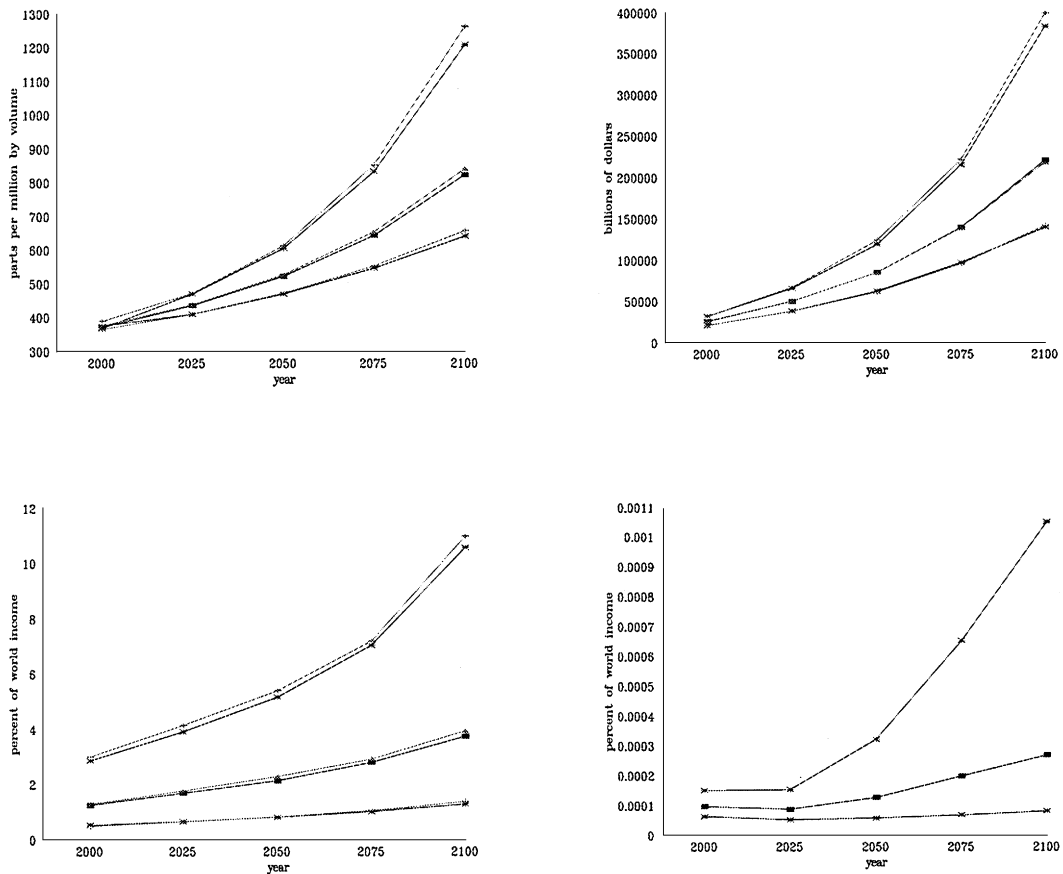


Fig. 3. Key variables and their uncertainties in the cooperative optimum under uncertainty scenario. Displayed are, from left to right and from top to bottom, atmospheric concentrations of carbon dioxide, income, climate change impacts, and direct emission reduction costs. All figures are global. Filled squares are medians, asterisks the bounds of 90% confidence intervals. For comparison, business as usual results are displayed (filled triangles and pluses). Results are for a Monte Carlo simulation with 1000 replications.

atmospheric concentration of carbon dioxide. This is problematic as such maxima are inherently arbitrary. Furthermore, policy makers control concentrations only indirectly through emissions. Since ‘minimum costs’ (cost-effectiveness) cannot be defined with successive decision makers (Lind and Schuler, 1996; Tol, 1998), a concentration target needs to be translated to emission targets per period, decades in this case. Wigley et al. (1996) try to do this, based on arguments which have a ring of cost-efcacy (cf. Ha-Duong et al., 1997). I here use their global emissions trajectory aimed at a stabilization of 550 ppm, and do not allow for international trading of emission permits, so that emission targets are defined per region (cf. Tol, 1999).

Emission constraints can be interpreted in various ways. Fig. 4 displays the consequences of three alternatives for the atmospheric concentration of carbon dioxide, again with policies calculated under uncertainty but evaluated under certainty. Firstly, uncertainties can be ignored, with all parameters fixed at their best guesses. In *FUND*, concentrations then stabilize a little below 550 ppm (because the business as usual scenario and the

carbon cycle model deviate from Wigley et al., 1996). Secondly, the constraint can be interpreted as a constraint on the expected emissions. Fig. 3 shows that this interpretation is slightly stricter than the constraint on best guesses. Thirdly, the constraint can be interpreted as a constraint on the median emissions. Fig. 3 shows that this interpretation is more lenient. As shown above, the uncertainty about emissions is skewed to higher emissions, with the mean being greater than the median being greater than the mode. This results cannot be generalized because, firstly, the assumptions about the probability distributions are somewhat arbitrary and, secondly, best guess (i.e., all parameters set at their most likely values) and mode (i.e., the most likely outcome) do not coincide in a non-linear model.

Fig. 5 displays the medians and 90%-confidence intervals of the atmospheric concentration of carbon dioxide, world income, climate impacts, and direct reduction costs for 550 ppm scenario of Wigley et al. (1996), and compares these to the business as usual scenario. Concentrations may well rise above 550 ppm. Income is notably but not dramatically lower. Impacts are also

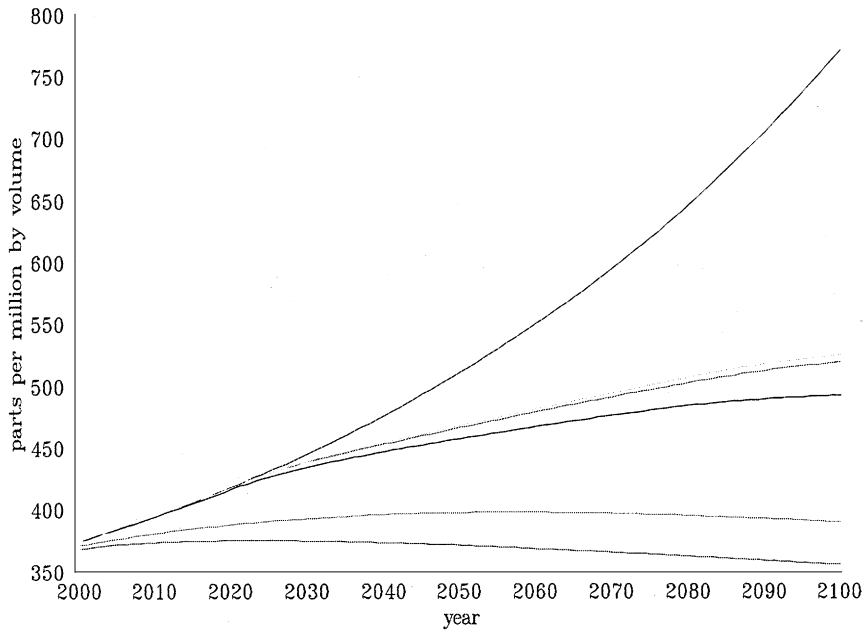


Fig. 4. Atmospheric concentrations of carbon dioxide for, from top to bottom, business as usual, three scenarios meeting the emission constraints of Wigley et al. (1996) for the median, best guess, and expectation, and a scenario with emission reduction set at 3% in all regions in all years, and one at 5%.

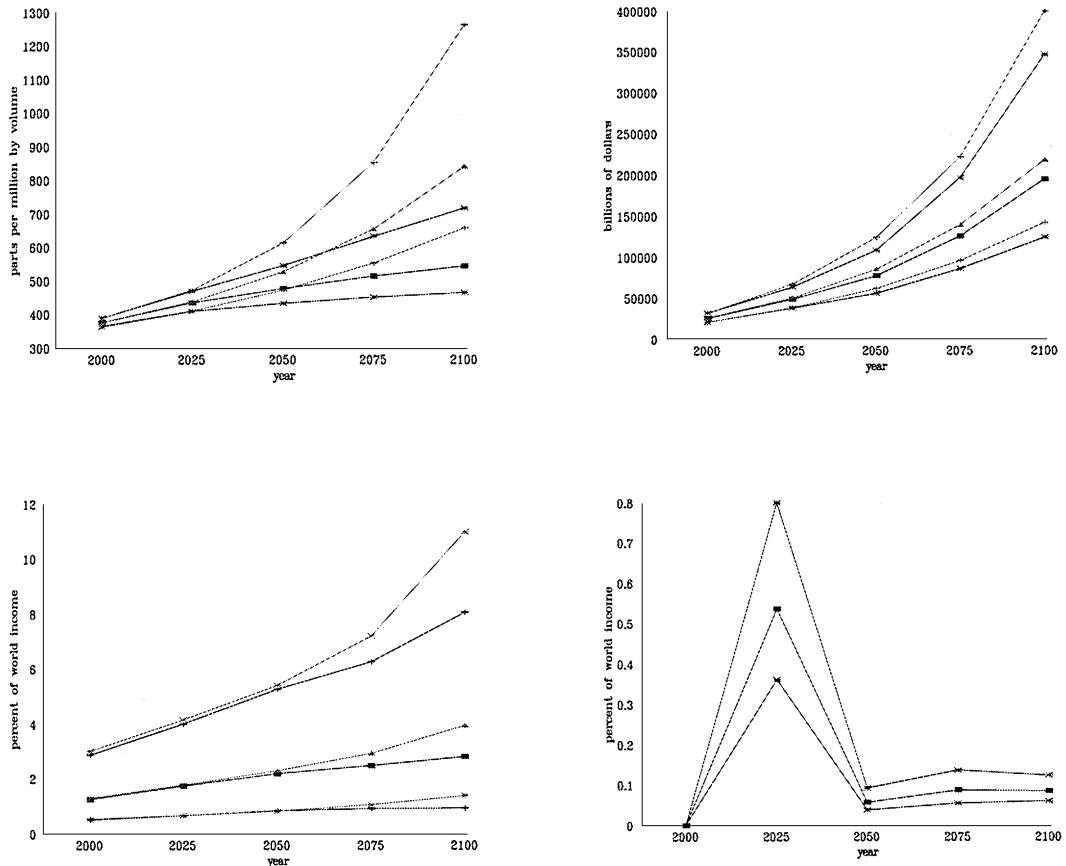


Fig. 5. Key variables and their uncertainties in Wigley et al. (1996) scenario aiming at 550 ppm, implemented under certainty without international trade in emission permits. Displayed are, from left to right and from top to bottom, atmospheric concentrations of carbon dioxide, income, climate change impacts, and direct emission reduction costs. All figures are global. Filled squares are medians, asterisks the bounds of 90% confidence intervals. For comparison, business as usual results are displayed (filled triangles and pluses). Results are for a Monte Carlo simulation with 1000 replications.

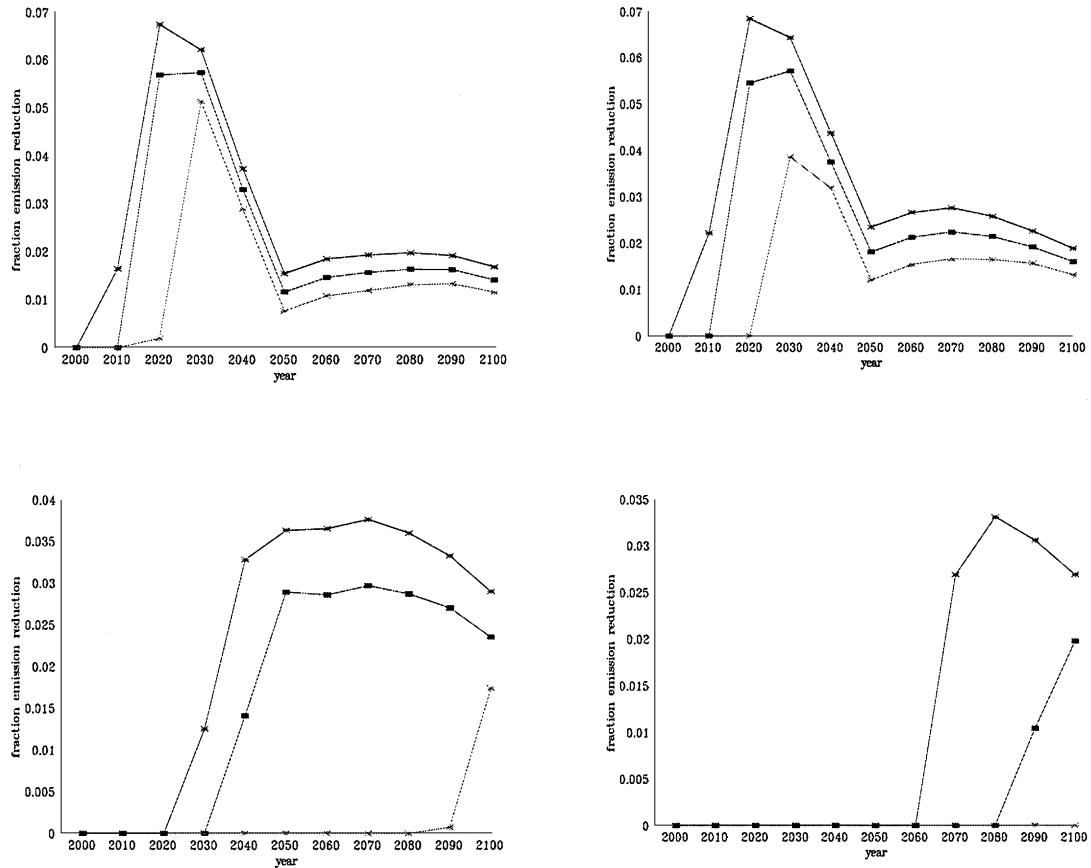


Fig. 6. Emission reduction needed to meet the constraints of Wigley et al. (1996) aiming at 550 ppm in each possible future for, from left to right and from top to bottom, OECD-America, Central and Eastern Europe and the former Soviet Union, Centrally Planned Asia, and Africa. Filled squares are medians, asterisks the bounds of 90% confidence intervals. Results are for a Monte Carlo simulation with 1000 replications.

reduced, particularly at the longer term. Note also that the 95-percentile decreases faster than the median. Reduction costs are much higher than in the optimal scenarios, but still not very high. Reduction costs are very unevenly distributed over time (a known feature of this scenario; cf. Tol, 1998), and its 95-percentile reaches 0.8% of world income in 2025.

Although illustrative with regard to the properties of the model, the above analysis is unrealistic. The state of the world in 2050 is very uncertain from our perspective, but it will not be from the perspective of a decision maker in 2050. Fig. 6 displays the reduction effort of meeting the emission constraints in each of a range of possible futures, for OECD-America, Central and Eastern Europe and the former Soviet Union, Centrally Planned Asia and Africa. For OECD-A and CEE&fSU, the main uncertainty is when the sharp emission reduction peak will be necessary. It will occur somewhere between 2020 and 2040 depending on the baseline. For Centrally Planned Asia and Africa, there is no sharp reduction peak. The uncertainties of CPA are skewed – the median is distinctly closer to the upper bound than to the lower.

There is even a fair chance that no emission reductions are required before 2080. The date of emission reduction in Africa may even lie beyond 2100.

Fig. 5 shows that, even though with a emission reduction regime aiming at 550 ppm, the central estimates of the impacts of climate change are still high, not to speak of the upper percentiles. Note that the global aggregate hides some winners of climate change and hence also nations and sectors which suffer more than the world average. 550 ppm may thus be considered not to avoid dangerous interference on the impact side. At the same time, the costs of emission reduction are not that high (although these also hide national and sectorial differences). In *FUND*, the direct costs of emission reduction (as a fraction of income) are about  $2R^2$ , with  $R$  the emission reduction (as a fraction of total emissions). A 10% emission reduction (in one year, compared to the baseline) thus costs about 2% of GDP. If we assume that 1% of GDP is about the maximum tolerable, then 7% emission reduction is the maximum. However, emission reduction costs are uncertain. If we want to be 95% sure that costs do not exceed 1% of GDP, then the maximum

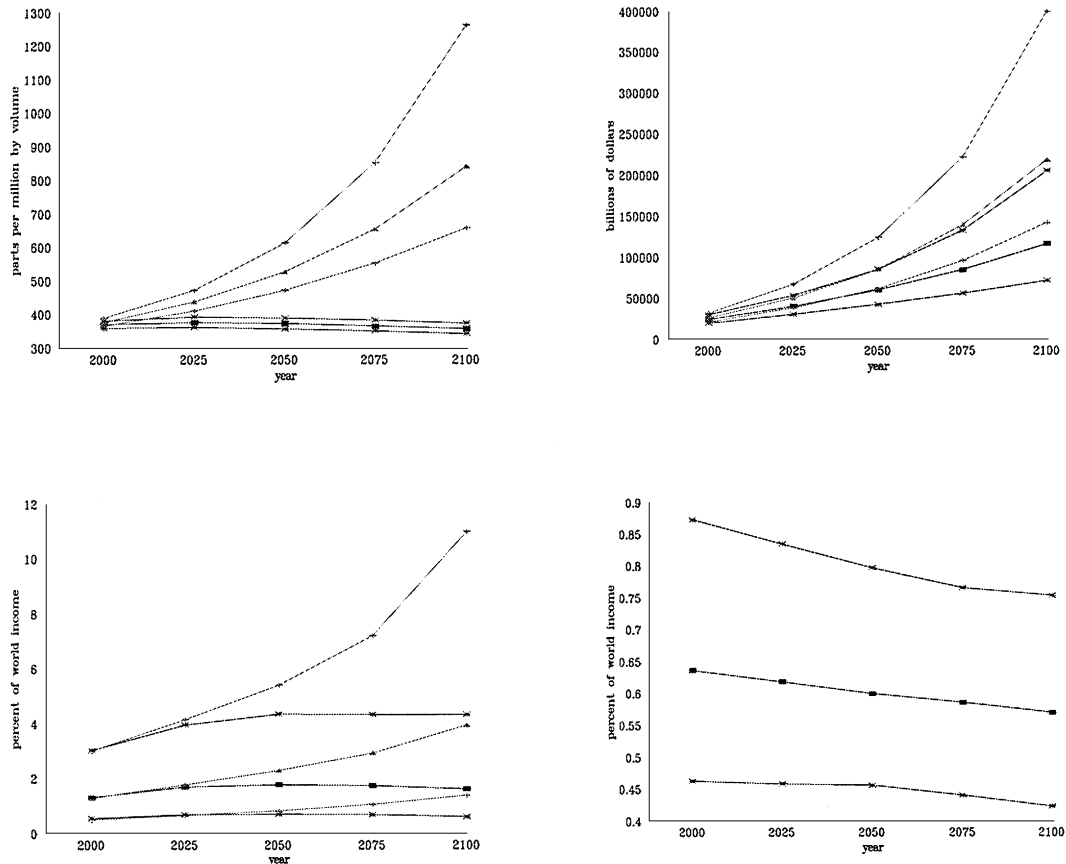


Fig. 7. Key variables and their uncertainties in the maximum emission reduction scenario. Displayed are, from left to right and from top to bottom, atmospheric concentrations of carbon dioxide, income, climate change impacts, and direct emission reduction costs. All figures are global. Filled squares are medians, asterisks the bounds of 90% confidence intervals. For comparison, business as usual results are displayed (filled triangles and pluses). Results are for a Monte Carlo simulation with 1000 replications.

emission reduction is 5% (according to the Gamma distribution of Table 4). Fig. 4 displays the resulting concentrations. For comparison, the results for a more conservative maximum of 3% are also displayed.

Fig. 7 displays the median and 90%-confidence intervals of the atmospheric concentration of carbon dioxide, world income, climate impacts, and direct reduction costs for a scenario in which all regions and all periods reduce emissions by 5% per year from baseline, and compares these to the business as usual scenario. Concentrations remain below 400 ppm, but the loss in income is considerable, even though the direct costs do not exceed 1%. Impacts are also reduced at the longer term, due to the slow workings of the climate, but, partly because of the higher vulnerability (rises with falling income), are still high.

## 6. Conclusions

Uncertainty is one of the most important aspects of climate change. The analysis of the business as usual

scenario illustrates this with ever-widening confidence intervals around the central estimates of key variables. Note that only parameter uncertainty is taken into account. Structural changes or omitted feedbacks are not considered. Uncertainty about the uncertainty is ignored, as is the possibility of multiple baselines. Parameter uncertainty, however, serves to illustrate a number of points.

In a welfare optimizing framework, uncertainty is a reason to increase emission control, and relatively more so in case regions do not cooperate with each other. However, optimizing net present welfare under uncertainty does not imply atmospheric stabilization. International cooperation has greater influence on optimal emission control than does uncertainty.

In a setting aimed at stabilizing atmospheric concentrations, uncertainty has mixed effects. Meeting emissions targets in expectation, or with a 50% chance can lead to lower or higher reduction than in case the future is known with certainty. The answer depends on the symmetry of the uncertainty about emissions, and is complicated by the fact that the best guess and modal

emissions do not coincide in a non-linear model. Further research is needed.

If emission targets are to be met in each possible future, then the main uncertainty Annex I countries face is when the time for sharp emission reduction will come. In the scenario of Wigley et al. (1996) aiming at a stabilization at 550 ppm, hefty emission control may start a decade earlier or later under uncertainty than under certainty. For non-Annex countries, the main uncertainty is when – if ever – emission reduction will be required. The difference can amount to a number of decades.

Emission reduction aimed at stabilization of atmospheric carbon dioxide at a level of 550 ppm does not prevent substantial chances on severe climate change impacts. The model shows that median monetized impact in 2100 falls from 3 to 2% of world income, but the 95-percentile remains high at 8%. Driving emission reduction to an (arbitrary) maximum of 5% per year, impacts will stay below 4% with 95% probability. The economic cost, however, is substantial.

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