Key Uncertainties in Climate Change Policy: Results from ICAM-2

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Abstract

A critical aspect of climate change decision-making is uncertainties in current understanding of the socio-economic, climatic and biogeochemical processes involved. Decision-making processes are much better informed if these uncertainties are characterized and their implications understood. Quantitative analysis of these uncertainties serve to: inform decision makers about the likely outcome of policy initiatives; and help set priorities for research so that outcome ambiguities faced by the decision-makers are reduced. A family of integrated assessment models of climate change have been developed at Carnegie Mellon. These models are distinguished from other integrated assessment efforts in that they were designed from the outset to characterize and propagate parameter, model, value, and decision-rule uncertainties. The most recent of these models is ICAM 2.0. This model includes demographics, economic activities, emissions, atmospheric chemistry, climate change, sea level rise and other impact modules and the numerous associated feedbacks. The model has over 700 objects of which over 1/3 are uncertain. These have been grouped into seven different classes of uncertain items. The impact of uncertainties in each of these items can be considered individually or in combinations with the others. In this paper we demonstrate the relative contribution of various sources of uncertainty to different outcomes in the model. The analysis shows that climatic uncertainties are most important, followed by uncertainties in damage calculations, economic uncertainties and direct aerosol forcing uncertainties. Extreme uncertainties in indirect aerosol forcing and behavioral response to climate change (adaptation) were characterized by using bounding analyses; the results suggest that these extreme uncertainties can dominate the choice of policy outcomes.

1.0 Introduction

Uncertainties in the scientific and economic aspects of climate change have dominated the debate on climate change policy. On the one hand, there are high economic stakes in adopting policies aimed at reducing greenhouse gas emissions. On the other, there are large uncertainties associated with the potentially significant impacts on human and natural systems. The enormous potential costs and the magnitude of the uncertainties that surround them make decisions about climate change difficult.

The concept of an integrated assessment model of climate change has been described earlier (Dowlatabadi and Morgan 1993a). Earlier versions of ICAM have also been featured in the literature (Lave and Dowlatabadi 1993; Dowlatabadi and Morgan 1993b). In general, integrated assessments involve consideration of the complete causal chain influencing the question being asked. If the question is long-term global climate change then knowledge about: demographics, economics, technological change, resource utilization, biogeochemistry, climatology, ecology, coastal zones, agriculture, health, and human dimensions needs to be integrated in addressing it. Not all integrated assessments involve models, as many of the

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issues may not be amenable to modeling. However, many integrated assessment models are being developed (Dowlatabadi 1995)

ICAM-2 is stochastic simulation framework where the uncertainties in parameters, models, decision rules and criteria are quantified where possible. The DEMOS computational environment used in development and display of ICAM permits propagation of these uncertainties and facilitates systematic uncertainty and sensitivity analyses (Henrion and Morgan 1985; Morgan and Henrion 1990). Value of information calculations are also conducted with ease.

The goals and design philosophy behind ICAM-2 are simple. All major elements of the climate problem are linked, capturing the major feedbacks involved (e.g., damages from climate change affect economic growth, which in turn affects emissions). These elements are incorporated by building simple models that capture the salient points of various aspects that influence the climate problem. Ideally, the simple models capture current scientific understanding of the issues involved; this is done using reduced form models, synthesizing results from other studies, or using by expert judgment. For the various aspects of the model, including the parameters, metrics, and the model structure itself, the relevant uncertainties are characterized and incorporated as explicitly as is feasible (by specifying a probabilistic distribution of a parameter instead of a specific value). Additionally, differences in individual and collective valuations of the outcomes of climate change are captured using alternative decision rules and criteria

ICAM-2 addresses five key questions about global climate change.

- Given our current level of knowledge, can we differentiate between different climate policies in terms of outcomes that matter?
- Which are the most effective policy levers?
- Which uncertainties in the climate problem most contribute to uncertainties in our ability to estimate outcomes that matter?
- How do individual and collective values affect policy outcomes?
- How should research focused on the issue of resolving the policy debate be prioritized?

In this paper we primarily focus on the third question, i.e., which uncertainties in the climate problem have the greatest impact on policy relevant outcomes? Uncertainties in climate change can be divided into three canonical types.

- Parameter Uncertainty: Uncertainties in model parameters that are characterized by probability distributions.
- Model Structure Uncertainty: Uncertainties relating to phenomena where the functional form and perhaps, even the sign are uncertain.
- Belief Uncertainty: Uncertainties in decision rules and decision metrics that arise as result of differences in the personal beliefs of decision makers.

In earlier work we have described the effect of personal beliefs of decision makers -- the decision metrics and rules they choose to use on the policy decision (Kandlikar and Morgan 1995). In this paper we examine the role of uncertainties in model parameters and their impact on policy outcomes. Additionally, we perform preliminary explorations of the role of model structure uncertainty on the policy outcomes.

The rest of the paper is divided as follows: In section 2 we describe the broad framework of ICAM-2. In section 3 brief descriptions of the sub models are provided. In section 4, an analysis of the relative contribution of uncertainties in model parameters is presented. In section 5 conclusions from this study are drawn.

2. Structure of the ICAM Framework

The overall structure of the ICAM-2 framework is shown in Figure 2. Each of the boxes with rounded corners represents a sub model. The sub model labeled "Demographic and Economic Processes" is intended to capture such processes as population growth, economic growth, energy consumption, and technological change. In the "Energy and Land Use" sub model the changes in patterns of land use and emissions of greenhouse gases and particulates brought out about the demographic and economic process are characterized. These emissions together with atmospheric chemistry and loss processes, result in new concentrations of radiatively active gases and particulates, which lead in turn to an alteration in the earth's radiative balance and result in climate change. These processes are represented in the "Atmospheric Composition and Climate" sub model. If climate change is significant, it will result in various physical and ecological changes. Some of these, such as losses to human habitat due to storms and sea level rise, losses to the managed environment (agriculture, fisheries, forestry, etc.) and losses to the unmanaged environment (including species and habitat loss), are observed and valued by people. The impacts of climate change are described in the "Impacts of Climate Change" sub model. Quantifying the extent of these losses allows us to capture the impact on climate change on the human socio-economic system. For

example, the economic consequences of these losses may be fed back into economic processes and used to determine the long term effect of climate change on human economic systems. Alternatively, one could use the long term effect of climate change on ecosystems to guide the choice of policies and responses to climate change.

There are three important ways in which human activities can be modified to respond to the issue of climate change. First, current human activities can be altered in a way that will mitigate the effect on climate (e.g. stop burning fossil fuels). Such alternatives are called abatement. Second, climate change can be allowed to occur, with human activities being modified to accommodate to the resulting changes (build dikes, change crop mix, relocate agriculture etc.). This is referred to as adaptation. Finally, the earth/atmosphere system can be intentionally modified to change its properties (e.g., increase Earth's albedo). These modifications are collectively termed geoengineering. Abatement is included explicitly as policy options in Figure 1. Adaptation and its associated costs, are incorporated within the description of impacts, given that some adaptation is inevitable if climate change occurs.
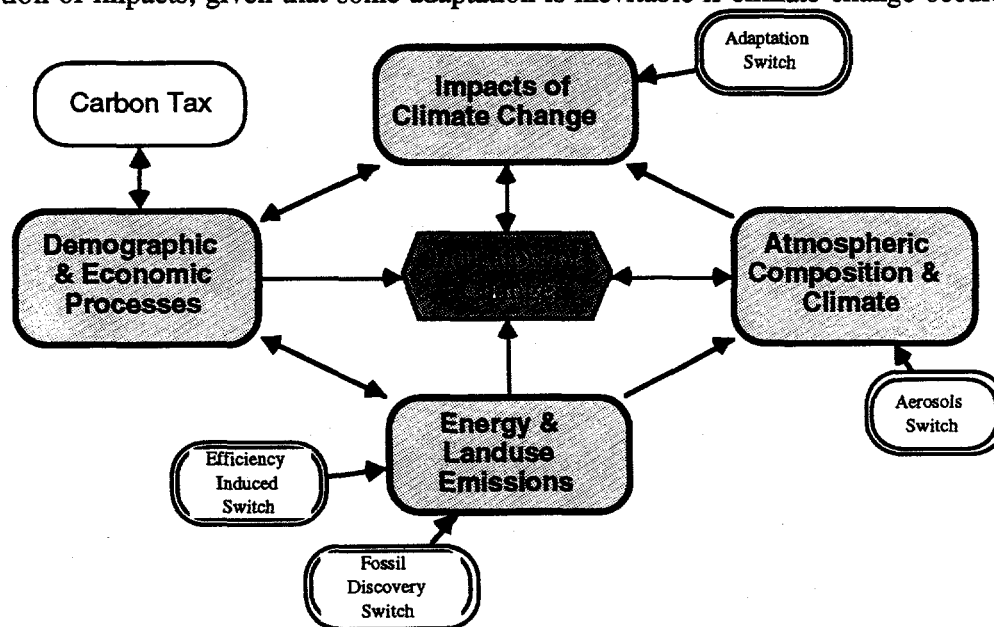

Figure 1. Overview of the ICAM-2 framework. A wide variety of alternative versions, ranging from simple stochastic models consisting of a few variables, to more complex reduced-form models and response surfaces derived from much larger models, may be substituted as sub models. In the current version, the direct policy initiatives available for mitigation of climate change are abatement using carbon tax and indirectly through induced energy efficiency and adaptation to climate change.

In our simplified representation of the world, ICAM-2 has been configured to simulate economic and climate change according to two major model indices: space and time. The model is run for a world divided into the seven United Nations regions: OECD, CIS and

Eastern Europe, China and Centrally Planned Asia, Middle East, Africa, Latin America, and India & South East Asia. The differentiation between regions makes it possible to examine the gross differences in the magnitude of climate change as well as different socio-economic circumstances -- energy mix, population and income growth, land use changes, and availability of resources needed to adapt to a changed climate. Since the future is uncertain, it is important to search for policy options that are likely to be robust in the face of a wide range of possible futures. In general, the range of futures modeled tend to be relatively benign, with slowing population growth, continued technological development, and generally expanding economies. In future analyses it will be important systematically to explore less benign futures in which, for example, parts of less industrialized world sink into permanent poverty and overpopulation, or in which international conflict, pandemics, or sustained economic collapse cause major social and environmental disruptions. It will also be important to explore futures in which dramatic technological progress, such as development of the technology to support a low-cost solar-powered hydrogen economy, occurs with unexpected rapidity. Such considerations, external to the main elements of the climate problem, can completely dominate the policy responses.

3. Description of sub modules

The variables in ICAM can be classified in to six categories: Demographic, Economic, Emissions, Aerosols, Climate and Impacts. Each of the categories include several uncertain parameters. Model simulations are carried out for the seven UN. regions under three policy regimes -- a zero tax option (no action), a moderate tax option that is incremented by $2/ton every five years starting 1990, a high tax option incremented by $20/ton every five years. The description below provides a brief overview of the sub modules in ICAM-2. No attempt is made to provide a detailed description of the model variables and equations[1].

Population Module

Actual population data available for the different regions from 1975 to 1990 was utilized to construct the different growth rates for this time frame. For projections into the future, population trajectories were constructed for ICAM to fit the regional population end points from the United Nations for the year 2100, along with the United Nation's projection of population moving towards zero population growth (ZPG). These trajectories are bounded

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[1] The interested reader can obtain a copy of the model and associated documentation.

by high and low estimates, with the range treated probabilistically for each of the seven U.N. regions with no correlation between the different regions.

Economics Module

Economic growth in ICAM-2 is determined by capital available for investment, growth in the labor force, and the combined labor and capital improvement in productivity. Labor available for economic production is assumed to grow linearly with population, and economic growth is assumed to be a function of the growth in labor and productivity. Costs of abatement (taxes) and economic damages from climate change result in a lowering of regional economic output on an annual basis. Economic output is incremented each year at a rate equal to the rate of productivity growth. Taxes and energy expenditures are assumed to be recirculated into the economy at a deadweight loss of 25% (with a small uncertainty multiplier) i.e., a quarter of the taxes and expenditures every year end up not contributing to the economic growth in the following year.

It important to note that no correlation is assumed between population growth and productivity. A dynamic demography-economy model has yet to be developed. The productivity growth rates are sampled from separate normal distributions defined for each time step, assuming there is no serial correlation. Productivity rates specified for each of the UN. regions by the Energy Modeling Forum (EMF-12) were used.

Emissions Module

The model currently includes emissions of CO_2, CH_4, N_2O, and sulfate aerosols. Natural emissions are assumed to continue at historic levels. Anthropogenic emissions are tied to energy consumption and an uncertain autonomous energy efficiency index. CFC substitutes and other aerosols will be added in future versions. As associations are better understood, feedbacks between anthropogenic activities and feedbacks due to a changed climate can be further tuned.

The anthropogenic carbon dioxide emissions are a function of land-use changes and emissions from burning fossil fuels. The former are expected to decline through time as remaining land is cleared or protected. The latter is a function of known initial emissions (by region), uncertain GDP growth and energy efficiency, fuel prices and abatement policy. Further details about carbon emissions are provided in the discussion on the energy module.

Current methane emissions are taken from IPCC.(Houghton, Jenkins et al. 1990; Houghton, Callander et al. 1992) Eleven sources have been identified. Population growth and economic growth are assumed to influence the rate of methane emissions from such sources as landfills, rice paddies, and enteric fermentation. Simple models using a direct link between these are assumed. For example, rice-paddy emissions are increased in step with the population of the low latitude region. Nitrous oxide emissions have been modeled in a fashion similar to methane. The emissions in any given period depend on feedbacks and influences (yet to be estimated) and previous period emissions.

These factors are important determinants of the nature and magnitude of regional aerosol concentrations. Organic and elemental carbon aerosols and sulfur dioxide are the major culprits and the picture is so complex they need to be considered separately. Sulfur dioxide emissions are primarily a byproduct of fossil fuel combustion. Elemental and organic carbon are associated with incomplete combustion of fuel. This can happen when fossil and biomass fuels are used, as well as during land clearing. Elemental carbon aerosols are dark and can lead to a local increase in radiative absorption. The other aerosols increase the reflectivity of the clear sky as well as enhance cloud formation and reflectivity. In the OECD, steps have been taken to control all of these air pollutants. The historic sequence of control has first, slowed land-clearing and improved combustion efficiencies, then controlled black carbon, and finally sulfur dioxide. In the rest of the world, control of carbon emissions would lead to an associated reduction in aerosol emissions. The short atmospheric lifetime of aerosols leads us to expect that the initial consequence of GHG abatement would be a net *increase* in absorption of radiation by the atmosphere and *exacerbated* climate change (Ball and Dowlatabadi 1995 submitted) The global consequence of different regional loadings of aerosols is not known. However, it can be assumed that perverse climate response to GHG controls is likely to be more pronounced in the Northern Hemisphere especially in regions such as China and the Former Soviet Union.

There are three simplified ideas behind the sulfur emissions calculations:
- Potential sulfur dioxide emissions are tied to the absolute level of energy use.
- Level of sulfur control increase with per capita income.
- Cost of sulfur controls drops through time, so the diffusion of the sulfur control technology is accelerated through regions with currently lower per capita incomes.

In the model, there are increasingly stringent controls placed upon sulfur emissions from 1975 onwards as incomes increase and the control technology grows less expensive.

Energy Module

The Energy module includes four different fuel types - coal, oil, natural gas and non-fossil backstop sources of energy. For the fossil fuels resource limits dictate the pattern of resource scarcity over time. The price of fossil fuels rises as the resources become scarce. The price of the non fossil backstop is determined by the two competing forces - technical change lowering costs and competition for scare resource inputs such as land driving up the cost. Hence the price of energy from non-fossil sources responds to long term technical change and congestion externalities. It is assumed that nuclear energy will play only a minor role in future energy consumption. The total level of energy demand is determined economic growth, technical change (which in this model responds to policies) and the elasticity of demand to change in aggregate energy price index. The price index is calculated for each region separately as the fuel shares in each region differ.

In response to the increasing costs of fuels and taxation of carbon based fuels the demand shifts and results in inter fuel substitution and increased conservation. Inter fuel substitution, a long term response to price change, is calculated using a long run inter fuel substitution elasticity matrix and the relative change in the price of various fuels. Thus, in a nested demand model, first the total new level of energy use is determined; then the share of each fuel type in meeting this demand is calculated. The resulting aggregate fuel prices feedback into the economy and affect economic growth.

Atmospheric Composition and Climate module

The atmospheric composition and climate module links current and future human activity to climate change. Emissions of trace gases and aerosols resulting from fossil fuel emissions and land use change and deforestation are converted into atmospheric concentrations. Atmospheric concentrations of the trace species lead to changes in global and local radiative forcing. The Earth system responds to changes in the radiative forcing through warming and changes in other climatic variables.

Atmospheric trace gas concentrations

A suite of carbon cycle models with varying degrees of complexity were implemented in ICAM-2. All the models are linear system approximations, with carbon emissions as inputs and CO_2 concentration trajectory as output. Mathematically, this can be written as

$$C(t) = \int\limits_{0}^{t} S(\tau)H(t-\tau)\,d\tau$$

where

        C(t) = atmospheric CO_2 concentration

        S(t) = CO_2 source at time t

        H(t) = the impulse response of the ocean-atmosphere system

Several impulse response functions of the form $H(t) = \sum\limits_{i} a_i \exp(-\alpha_i t)$ have been defined. These include a constant air-borne fraction model estimated from historic concentration and emissions data, a double exponential impulse response model (Enting and Newsam 1990) estimated from the box diffusion model of Seigenthaler and Oeschger (1987), a multiple exponential model based on the work by Maier-Reimer and Hasselman (Maier-Reimer and Hasselman 1987). In this paper the latter is used. The biosphere is assumed to be neutral with respect to carbon concentrations. Concentrations of the methane and nitrous oxide in the atmosphere for the uncertain emissions scenarios were calculated. Linear models with single lifetimes were used to describe their persistence in the atmosphere. The atmospheric lifetime of methane was taken to be uniformly distributed between 8-12 years. The atmospheric lifetime of N_2O was taken to be 130-170 years.

The mean areal column burden of anthropogenic sulfate aerosol is related to the sources and sinks of atmospheric sulfates and depends on the quantity of sulfur dioxide emitted, the fractional yield of sulfur dioxide to sulfate, is the sulfate lifetime, is the area of the geographical region in which the material is presumed to be confined. Details can be seen in Ball and Dowlatabadi (1995).

Radiative forcing and climate

The long wave radiative forcing equations for greenhouse gases are taken directly from the Wigley Raper relationships specified in IPCC (Houghton, et al. 1990). Aerosols affect the global climate through short wave forcing. The areal mean short-wave forcing resulting from an increase in aerosol concentration can depends on several parameters including: The global top of the atmosphere radiative flux, the fraction of incident light that is not absorbed by water vapor above the aerosol layer, the fractional cloud cover, the mean albedo of the underlying surface, the fraction of the radiation scattered upwards by the aerosol, the effect of relative humidity and the mean areal column burden of anthropogenic sulfate aerosol

(mol/m^2). The indirect effects, calculated by (Charlson, Schwartz et al. 1992) to be of similar magnitude to the direct effect and estimated even higher by (Kaufmann, Fraser et al. 1991), may have been overestimated. In ICAM-2, indirect aerosol forcing is included. However, because of the enormous uncertainties in the indirect effects we have also performed an order magnitude bounding analysis which assumes that indirect aerosol forcing offsets ("warming") offsets the direct aerosol forcing ("cooling").

Although there is some level of scientific consensus on the effect of anthropogenic emissions on the radiative forcing of the Earth, the translation of this altered forcing to climate change is given to much debate and uncertainty. This is complicated by the fact that climate cannot be adequately described by a single metric, such as global change in forcing, but is variable in its different parameters (temperature, precipitation, seasonality, etc.) on a regional level.

In the face of these difficulties, the climate section of ICAM-2 is comprised of a simplified model based on the distribution of specific climate parameters. To quantify the distribution of these parameters, an expert elicitation of a number of prominent climate scientists has been completed (Morgan and Keith 1995 submitted). These distributions are then used in a simple climate module.

Several key parameters elicited from the climate experts and used in the climate module are:

(1) Mean temperature equilibrium rise in global temperature in response to doubled CO_2 concentrations.

(2) The trajectory of climate response to a prescribed level of forcing -- yielding climate system response time(s).

(3) The temperature gradient from equator to 70°N.

(4) A probability measure of the stability of the climate system after atmospheric concentrations of CO_2 have doubled.

(5) The present day aerosol forcing.

(6) Inter annual variability in temperature by latitude.

(7) Inter annual variability in precipitation by latitude.

To find the global average temperature change, the first two parameters were used in a simple model forced with both long-wave and short-wave terms. The distribution of the temperature across various latitude bands is achieved by using the estimated distribution of

temperature gradients between the equator and 70°N. This is less than ideal, as we do not have Southern Hemisphere parameter values, which at the present time are symmetrically equated to the Northern Hemispheric values . The localized nature of short-wave forcing due to aerosols is captured by separately forcing each latitudinal band with long and short wave forcing and using the results along with the expert specified latitudinal gradient to determine regional temperature change.

Impacts Module

Anthropogenic economic activities almost always involve capital investment in the form of technology. Each time new technology replaces old technology, there is an opportunity to adapt to the impacts of climate change. There are two factors which influence technological adaptation. The first is whether there is foresight about climate change and its impacts. The presence of such foresight provides motivation for technology innovation with future climate conditions in mind. The second factor is the detection of climate change impacts. In the absence of detection, there may be little technological diffusion. If detection and foresight are combined, the new technology can be designed for optimal performance over a period in which climate is changing. In ICAM-2 the market damages are represented by an aggregate function of the climate change and its rate, a damage level benchmarked to an uncertain fractional change in GDP for a 3°C change in temperature, the adaptation rate (typically the turnover time for capital stock) and GDP (Dowlatabadi, Kandlikar et al. 1994). Additionally, the aggregate damage function is sensitive to the structural changes in an economy resulting from long term shifts in income; the fraction of a regional economy that faces economic damages from climate change declines with the decreasing contributions of agriculture and natural resource extraction.

Trying to incorporate non-market losses into the estimates of the effects of climate change is subjective, to say the least. Although market damages are relatively independent of subjective values, the price placed on an ecosystem varies from person to person, especially when weighed against stringent abatement policies. We have explored different functional forms for quantification of non-market damages (Dowlatabadi, Shevliakova et al. 1994). ICAM-2 uses the idea that there is a lower bound to income before the desire to protect the environment can be exercised in the form of a payment. Non market damages also include the notion that there is an upper bound on the willingness to pay to preserve nature. The damage function currently utilized in ICAM-2 follows a logistic form.

4 Uncertainty Analysis

Traditional uncertainty analysis takes place in two stages. The first stage involves the propagation of all parameters uncertainties through the model to obtain probability distributions for model outputs. This is done using Monte Carlo or Stratified Sampling schemes. The second stage involves determining which of the input uncertainties contribute most to uncertainties in the outcomes of interest. Input uncertainties can then be ranked according to their relative contributions. The first stage of the analysis is inherent in ICAM's model structure. Importance ranking can be done using a variety of standardized techniques (See Helton, 1993 for details) we used a *ceteris paribus* Monte Carlo sensitivity approach. The ranking of uncertainties in ICAM was done for seven classes of parameter uncertainties - population, economy, energy, emissions, aerosols, climate and damages. This analysis therefore characterizes the relative importance of uncertainties among these classes.

In this paper we focus on the net discounted per capita utility (in U.S. $) as the policy outcome of interest[2]. Note that our choice of an economic quantity as the primary policy variable has been driven mainly by the relative ease with which such economic quantities can be calculated. In on-going work we have begun develop a multi-attribute decision framework, where ecological and geophysical variables can be individually used or combined with economic variables and the resulting multi-attribute metric used as the primary policy variable. Two alternatives to taking no action were considered, both using annually rising carbon taxes starting in the year 2000. In the moderate abatement strategy, the carbon tax rises at $0.4/Ton Yr. of Carbon In the stringent abatement strategy the carbon tax rate is five times higher, at $2.0/TC Yr. The discounting in these results follows the convention proposed by Thomas Schelling. Discount rates differ by region and are based on per capita growths in income. This leads to China having the highest discount rate at approximately 3%. For other regions' discount rates were between 3 and 1% per annum.

Before we go on to review the results of the uncertainty analysis, it is crucial to note that the demographic and economic uncertainties projected over the next century affect future welfare by a factor 10 to 100 times larger than the climate policies considered. Therefore, if we were to use the per capita discounted GDP (as opposed to *net* per capita discounted GDP) for each the tax options the role of uncertainties in climate science and

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[2] We imply the net discounted per capita utility to be the difference between the per capita utility for each tax option and the no action (zero tax) option.

damages would be drowned in the sea of uncertainty resulting from uncertain population and economic growth.

Outcome Uncertainty

Figure 1 shows the cumulative distribution function for the discounted net per capita utility for four of the seven UN regions. The OECD has low damages from climate because a smaller fraction of it's economy is vulnerable; on the other hand there is small chance that a low tax option may have high payoffs because the OECD places a high value on non market damages.
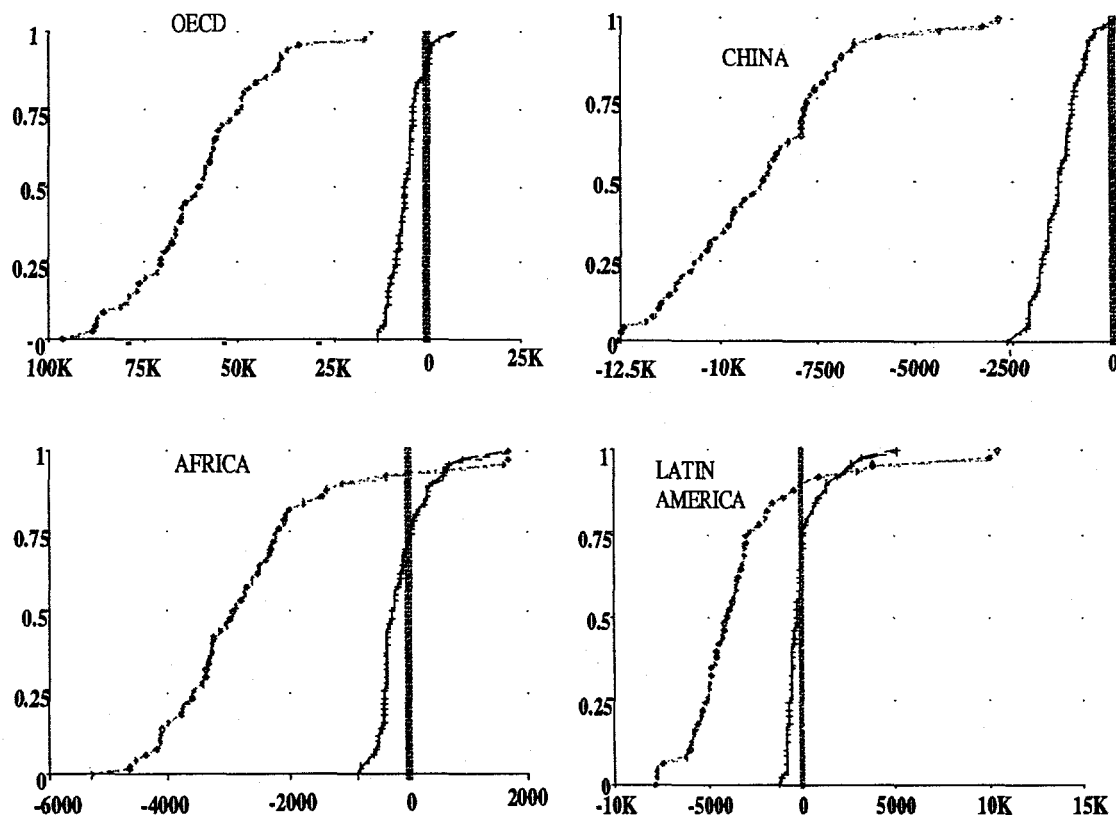

Figure 1: Cumulative distribution functions of per capita net discounted utility (in U.S. $)for four UN. regions. The vertical line through zero is the no tax case, the dark line is the low tax option and light line is the high tax option.

E.Europe & CIS and China have a strong preference for the do nothing option. Aerosol emissions in China E.Europe & CIS are expected to be high because of dependence on coal for energy production. The short atmospheric lifetime of aerosols leads us to expect that the initial consequence of GHG abatement would be a net *increase* in absorption of radiation by

the atmosphere and *exacerbated* climate change (Ball and Dowlatabadi 1995 submitted). Thus a perverse climate response to GHG controls is likely to be more pronounced in the Northern Hemisphere especially in regions such as China and E.Europe & CIS. Additionally, since the Chinese economy is expected to grow at a faster rate than the other regional economies, the Schelling discounting convention applied in ICAM results in larger net costs of abatement for China compared with other regions.

U.N Region	Mean Value(μ)		Std. Deviation(σ)		Upper bound($\mu+\sigma$)		Lower bound($\mu-\sigma$)	
	Tax 1	Tax 2	Tax 1	Tax 2	Tax 1	Tax 2	Tax 1	Tax 2
OECD	-978	-58360	9559	29273	8581	-29087	-10537	-87633
E.Europe& CIS	-5344	-60265	4125	17166	-1219	-43099	-9469	-77431
China	-1313	-8896	591	2204	-722	-6692	-1904	-11100
Middle East	-395	-5556	876	2528	481	-3028	-1271	-8084
Africa	-117	-2667	459	1545	341	-1122	-576	-4212
Latin America	152	-3133	1179	3626	1331	493	-1027	-6759
SE. Asia*	-204	-3269	499	1562	295	-1707	-703	-4831

Table 1. Statistics of net discounted per capita utilities for the seven UN. regions. The expected value of both taxation options are negative for all regions except Latin America, i.e., only Latin America prefers a low tax option over a do nothing option for an expected value decision rule. However, the upper bounds of tax policy 1 for are positive (net benefits) for 5 of the 7 regions. (* Includes India)

Both Africa and Latin America have higher chances that a low tax option might be preferred to a no tax option. African economies are agriculture based and hence are more vulnerable to climate change. They could face significant damages in the future. There are two reasons why Latin America might prefer the low tax option. First, the lower presence of aerosols in the southern hemisphere (~10% of the northern hemisphere) implies that Latin American countries may not benefit from the radiative forcing offset that aerosols provide to economies in the southern hemisphere; as a result Latin America may face higher temperature related damages than the rest of the world. Second, per capita incomes are sufficiently high that non market damages start to play an important role. As can be seen in table 1 other regions India & SE. Asia. and the Middle East have the least expected costs associated with a zero tax strategy. However, for each of these nations there is a 10-40% chance that the low tax option is a better alternative (See table 2) . In table 1 we provide statistical measures for the outcomes of the different policy options. Note that the standard deviations for the low tax

option far exceed the expected values for several regions, a reflection of the enormous uncertainties in the climate problem.

Importance Ranking

Ranking of uncertainties in policy models is done using several approaches of varying complexity; these include differential analysis, response surface approaches and Monte Carlo sensitivity. (Morgan and Henrion 1990; Helton 1993) provide detailed descriptions of these techniques. In this work we use *ceteris paribus* Monte Carlo sensitivity for determining the key model uncertainties in ICAM. A *ceteris paribus* approach involves varying the assumptions regarding one or a class of parameters at a time and comparing the output with the base case. In our analysis the base case corresponds to an uncertainty analysis performed with all parameters uncertain. The model was run again by changing the assumptions regarding each class of parametric uncertainties; the effect of uncertainties in each class was determined by fixing all the relevant parameters to their mean values and comparing the distribution of the output variable to the base case. For example, to determine the effect of economic uncertainties, we set all the economic variables to their mean values and compared the resulting statistics of the per capita net discounted utility with the base case statistics, and derived measures of the relative importance of the economic uncertainties.

Two key results can be observed from table 2. The first is the regional contrast in uncertainty response. For some regions, China and Eastern Europe & CIS ignoring uncertainties in parametric values in all the categories leads to little or no shift in expected value of the policy outcome. These regions, may be less handicapped by uncertainty in establishing policy goals. Other regions, particularly the OECD show enormous swings in the expected outcome when the uncertain parameters in the various classes are set to their mean values. The second is that the uncertainties in climatic/geophysical parameters dominate policy outcome. For all the UN regions excluding uncertainty in these parameters causes the largest shift in the expected outcome for the low tax option. Similar results were also observed for the high tax policy as well. The implications of these findings are quite dramatic; they suggest that climate related parametric uncertainties are more critical to climate change policy than other economic or scientific uncertainties. This holds true for all the regions of the world, despite the differences in the projections of changes in regional mean temperatures.

Region	Base Case	GHG Emissions	Aerosols	Climate	Economics	Population	Energy	Damages
OECD	-978	-846 (13)	-1761 (-80)	-4039 (-313)	-1308 (-34)	-226 (77)	9 (101)	-2057 (-110)
E.Eu & CIS	-5344	-5359 (~0)	-5527 (-3)	-6250 (-17)	-5419 (-1)	-4949 (7)	-4995 (7)	-5899 (-10)
China†	-1313	-1315 (~0)	-1349 (-3)	-1463 (-11)	-1326 (-1)	-1265 (4)	-1259 (-4)	-1329 (-1)
M. East	-395	-383 (3)	-533 (-35)	-709 (-80)	-416 (5)	-406 (-2)	-421 (-7)	-513 (-30)
Africa	-117	-117 (~0)	-135 (-15)	-277 (-136)	-108 (8)	-113 (5)	-113 (3)	-113 (+4)
Lat. Amer.	152	187 (23)	47 (-69)	-308 (-302)	144 (5)	190 (25)	162 (6)	47 (-69)
S.E. Asia	-204	-201 (1)	-245 (-20)	-414 (-103)	-209 (2)	-192 (6)	-184 (10)	-223 (-9)

Table 2. Expected value of net discounted per capita utilities for the seven UN, regions for the low tax policy option. Each column corresponds to the case where uncertainties in parameters in that class are set to their mean values. Values in parentheses are fractional changes in expected value of the outcome relative to the base case.

An important reason for the inclusion of uncertainty in policy models results from the fact that the optimum policy decision may change when uncertainty in parameters is included, i.e., the optimum decision with and with out the inclusion of uncertainty may be different. Clearly, not including uncertainty in parameters that are known to be uncertain is equivalent to not using information that is already available and may lead to sub optimal decisions. Expected Value of Including Uncertainty (EVUI) is a measure that can be used to quantify the gains resulting from including uncertainty; if including uncertainty results in a change in the decision strategy then EVUI is the difference between the old and the new outcomes. If including uncertainty does not lead to a change in the decision strategy, then EVUI is zero. From table 2 we note that EVUI is zero in all but two situations -- for the OECD inclusion of uncertainties in the energy sector causes a shift in preferred policy from the low tax option to the zero tax option resulting in an EVUI of ~ US $ 1000, for Latin America, the inclusion of uncertainty in climatic parameters causes a shift in the preferred policy from zero tax option to the low tax option resulting in an EVUI of ~ US $ 450.

Structural Uncertainty

These results of the previous section particularly the importance of climatic parameters, must be treated with caution because there are several confounding factors that affect the analysis. These include:

• The role of values and beliefs of policy actors
• The role of structural uncertainty

The analysis presented in the previous section is based on a purely economic valuations of market and non market impacts. As we have noted elsewhere (Lave and Dowlatabadi 1993; Kandlikar and Morgan 1995) uncertainty in beliefs and values, i.e., the metrics and decision rules used by different decision makers may dominate scientific and economic uncertainty. A detailed multi-attribute analysis of ICAM-2 that incorporates multiple metrics and actors is in progress.

Certain aspects of the climate science and economics are extremely uncertain; examples include indirect aerosol effects, the role of adaptation to climate change, extreme climatic outcomes & the extent of fossil fuel reserves. It may not be possible to capture qualitative differences in outcomes resulting from extreme uncertainty using a Monte Carlo approach. One approach to quantifying such extreme uncertainty is through the use of order of magnitude and bounding analyses. We have performed a bounding analysis using ICAM-2 for two types of structural uncertainties - the impact of indirect radiative forcing of aerosols, and the role of adaptation.

In addition to the direct back scattering effect, aerosols can also have several indirect effects on radiative forcing. Indirect effects of aerosols include enhanced short-wave albedo of clouds, changes in the horizontal and vertical distribution of water vapor that have the potential for significantly affecting global radiative balance particularly in the tropics (Jones, Roberts et al. 1994). The variability in atmospheric and radiative dynamics of aerosols makes quantification of indirect effects difficult. Not only are the mechanisms of indirect effects poorly understood, they do not all have the same sign (Langer, Rodhe et al. 1992). In order to capture this extreme uncertainty we ran ICAM-2 under the assumption that indirect effects completely offset the direct effects leading to a net zero effect of aerosols on radiative forcing - a reasonable lower bound on the effect of aerosol emissions.

Should the impacts of climate change be detected and judged undesirable, technical and social capabilities will be harnessed to minimize such impacts. However, it is possible that humans may maladapt to climate change either by overcompensation or because shifts in preferences will place a larger fraction of human and economic systems at risk from a changing climate. In order to capture the uncertainty in human behavioral response to climate change, we performed a bounding analysis with no adaptation, under the assumption that humans will adapt and maladapt in equal proportions.

Region	Without Aerosols and Adaptation	Without Aersols	Without Adaptation	Base Case
OECD	0.2	0.4	0.5	0.8
E Europe	0.6	0.7	0.7	0.9
China	1.0	1.0	1.0	1.0
M East	0.6	0.7	0.7	0.9
Africa	0.4	0.5	0.7	0.8
L America	0.4	0.5	0.6	0.7
SE Asia	0.6	0.7	0.7	0.9

Table 3. Probability that the no abatement strategy has the highest pay-off

In table 3, we present the results from the bounding analysis. Comparisons of alternatives with and without adaptation and aerosols makes it clear that with the exception of China, the zero abatement strategy is no longer the attractive option it is for the base case. All the other regions end up favoring a low tax option if the model is run without the effects of adaptation and aerosols. Clearly, extreme uncertainties in the role of aerosol forcing, and in adaptations to climate change make decisions regarding tax policies more difficult.

Conclusions

The role of uncertainties in climate change is complex and requires careful consideration. Using ICAM-2 an integrated assessment model we have evaluated the effect of the various scientific and socio-economic uncertainties on outcome policy variables. The analysis shows that climatic uncertainties are most important, followed by uncertainties in damage calculations, economic uncertainties and direct aerosol forcing uncertainties. Extreme uncertainties in indirect aerosol forcing and adaptation were characterized by using bounding analyses. The results suggest that these extreme uncertainties dominate the choice of policy outcomes.

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