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Climate Change Decision-making: Model & Parameter Uncertainties Explored

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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 2.1. This model includes representation of the processes of demographics, economic activity, emissions, atmospheric chemistry, climate and sea level change and impacts from these changes and policies for emissions mitigation, and adaptation to change. The model has over 800 objects of which about one half are used to represent uncertainty. In this paper we show, that when considering parameter uncertainties, the relative contribution of climatic uncertainties are most important, followed by uncertainties in damage calculations, economic uncertainties and direct aerosol forcing uncertainties. When considering model structure uncertainties we find that the choice of policy is often dominated by model structure choice, rather than parameter uncertainties.

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,

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integrated assessments involve consideration of as much of the causal chain influencing the question being asked as knowledge permits. 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 issues may not be amenable to modeling. However, many integrated assessment models are being developed around the world (Dowlatabadi 1995).

The goals and design philosophy behind ICAM-2.1 are simple. All major elements of the climate problem are linked, capturing the major feedbacks and joint probabilities involved (e.g., damages from climate change affect economic growth, which in turn affects emissions). Each of these elements of the climate problem is developed as process or statistical module capturing the salient aspects. These modules capture current scientific understanding of each of the elements of the problem. This is accomplished through the use of: direct modeling of various processes; response surfaces that use statistical estimation of larger systems; and through characterization of expert judgments. 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. This is accomplished through definition of probabilistic conditions for state variables and parameters, as well as through consideration of different model structures.[1]

ICAM-2 has been developed to address four key questions about global climate change.

- Given our current level of knowledge, can we differentiate between different climate policies in terms of outcomes that various decision-makers value?
- If we were to take action, 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 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? The answer to this question is

1 The DEMOS computational environment is used in development of ICAM. This environment 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.

is a first step towards addressing the question of research priorities. 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 is uncertain.
- Value Uncertainty: Uncertainties in decision rules and decision metrics that arise as a result of differences in the personal beliefs of decision makers. Technically, these are represented as parameter and model uncertainties. However, in decision-analysis, these are often treated separately.

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 (Lave and Dowlatabadi 1993; 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 policy outcomes.

The rest of the paper is organized as follows. In Section 2 the overall ICAM framework is described. In section 3 the various modules in ICAM-2 are briefly described. Description of uncertainty propagation and results from ICAM-2 are presented in section 4. The results from systematic sensitivity and uncertainty analyses, of input parameters, as they affect model outcomes are presented in Section 5. In section 6 the role of model structure uncertainties are explored. The summary of our findings can be found in Section 7.

2. Structure of the ICAM Framework

The overall structure of the ICAM-2 framework is shown in Figure 1. Each of the rounded boxes represents a sub-model. Arrows between the sub-models denote interactions. For example, the sub-model labeled "Demographic and Economic Processes" is used to capture the processes of population growth, economic growth, impacts of taxation, and accounting of the costs and benefits of climate change and policy. Elements within this sub-model affect and are affected by elements in the "Energy & Landuse Emissions" and the "Impacts of Climate Change" sub-models. The hexagon in the center of the figure is a collection point where various indicators of global change calculated in the various sub-models are compiled together. These are specified for seven world regions, over a simulation period spanning the period of 1975 to 2100, with a constant time step of 5 years. The nodes with double boundaries are switches permitting alternative specification of model structure.

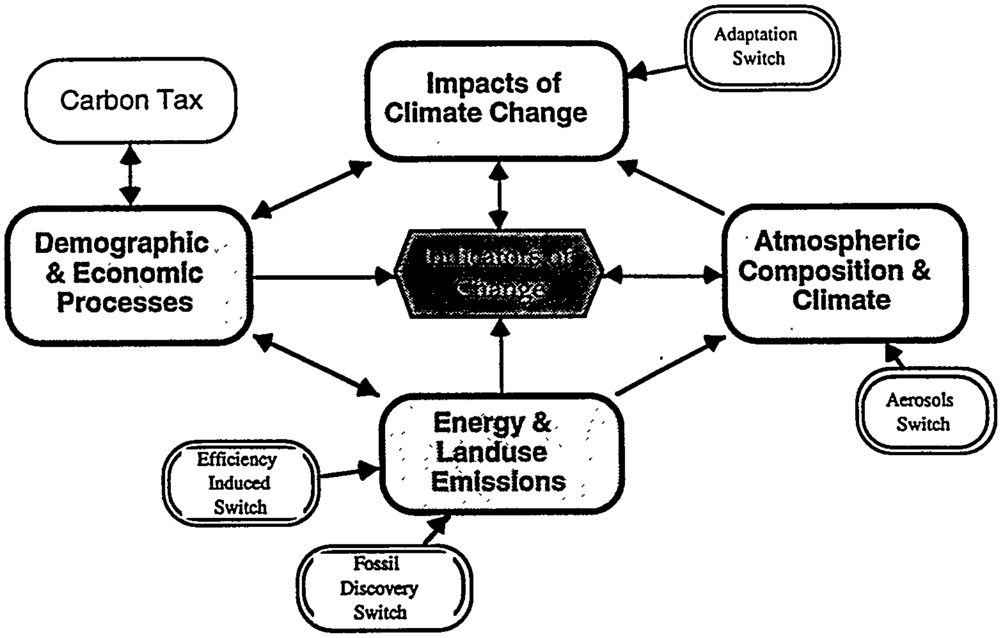

Figure 1. Overview of the ICAM-2 framework. A wide variety of alternative versions, ranging from simple stochastic models consisting of a few variables, to more complex reduced-form models and response surfaces derived from much larger models, may be substituted as sub-models. In the current version,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

In the "Energy and Land Use" sub-model the changes in patterns of energy use, land use and emissions of greenhouse gases and aerosols resulting from socio-economic processes and policies are characterized. Emissions of trace gases act as perturbations to their bio-geochemical cycles and lead to changes in atmospheric concentration of radiatively active gases and aerosols. This change leads to an alteration in the earth's radiative balance and 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 long-term impact of 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, *abatement*, where current human activities are altered to reduce emissions of radiatively active gases and aerosols (e.g., stop burning fossil fuels). Second, *adaptation*, where human activities are modified to accommodate to the consequences of climate and sea level change (e.g., build dikes, relocate agriculture, etc.). Finally, *geo-engineering*, where the earth/atmosphere system is intentionally modified to change its properties to reduce the magnitude of climate change (e.g., increase Earth's albedo). In the current version of ICAM 2, abatement is explored as an explicit policy option, and adaptation is modeled as an endogenous process.[2] In earlier versions of ICAM, and separate research we have presented the relative costs and risks of geo-engineering (Keith and Dowlatabadi 1992; Dowlatabadi and Morgan 1993b).

In a 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 seven regions [3]: 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 to explore systematically less benign futures in which, for example, parts of the 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.

[2] Hope et al, (1993) explore the properties of adaptation policies explicitly.
[3] These regional aggregations mirror those adopted by the United Nations.

3. Description of modules

The variables in ICAM can be classified as belonging to six categories: (i) demographic, (ii) economic, (iii) emissions, (iv) aerosol formation, (v) climate change , and (vi) impacts. Each of the categories include many uncertain parameters. The description below provides a brief overview of the sub-modules in ICAM-2. [4]

Population Module

The population module considers a single age cohort and changes populations through births and deaths. These key parameters and changes to these parameters through time have been calibrated to reproduced past trends and reflect the range of populations projected for 2000, 2025, and 2100 by the United Nations. This simple probabilistic model is specified for each of the seven regions with joint distributions of key parameters between the different regions, and between economic growth and the process of demographic transition.

Economics Module

Economic growth in ICAM-2 is determined by capital available for investment, growth in the labor force, and improvement in combined labor and capital productivity. Labor is assumed to grow linearly with population, and changes in productivity are specified exogenously, as a set of joint probability distributions.. At each period, the capital available for growth is calculated and incremented by the combined growth in labor and productivity. The capital available is determined by the level of activity in the previous period and impacts of policy (due to taxes and resource use changes) and economic damages from climate and sea level change. Efficiency in tax recirculation is an uncertain variable, and uncertainties in resource use impacts have necessitated consideration of different model structures.

Emissions Module

The model currently includes emissions of CO_2, CH_4, N_2O, SO_2, and organic & elemental carbon aerosols. Natural emissions are assumed to continue at historic levels. Anthropogenic emissions are tied to land use, industrial activity, fuel mix, technical change, and policy choice.

The anthropogenic CO_2 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

[4] A copy of the model and associated documentation can be obtained by contacting the authors.

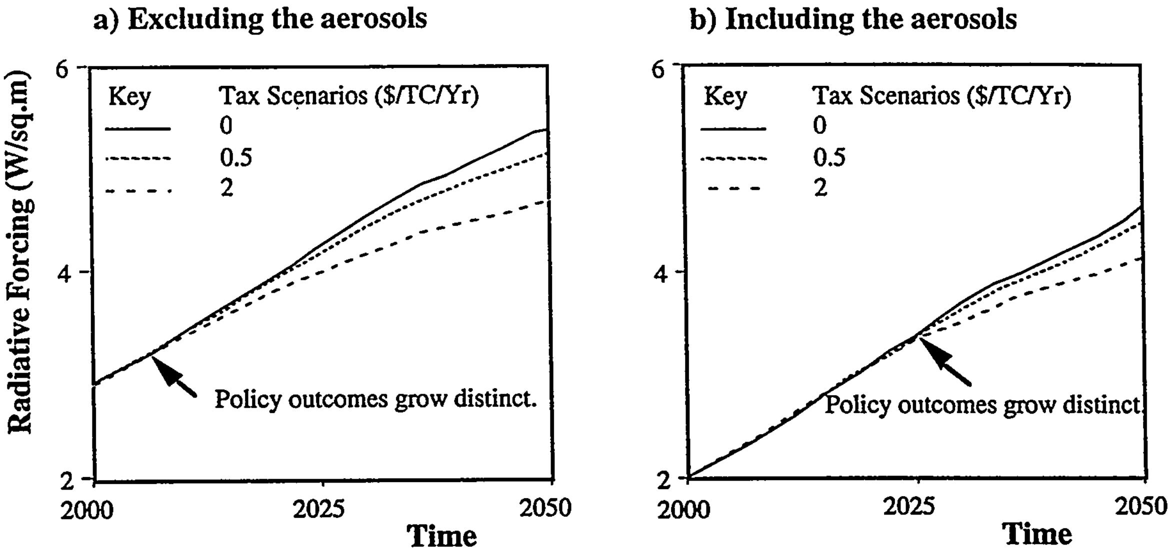

Figure 2. Globally averaged mean radiative forcing projections are presented without aerosol effects in 2a, and with aerosol effects in 2b. Two features are evident: i) inclusion of aerosols reduces total forcing in the year 2000 by 1 Wm^{-2}, and ii) the point at which the impact of carbon taxes can be felt as a reduction in radiative forcing (indicated with the arrow) is delayed by 20 years.

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) and are represented by eleven independent distributions. The future evolution of some of these sources are affected by climate change, others by anthropogenic activity. The former have not been modeled. The latter have been modeled using simple schemes. For example, rice-paddy emissions are increased in step with low income populations. Methane emissions from coal and natural gas are determined by production levels and assumed to decline through time (at an uncertain rate) with technical progress. Nitrous oxide emissions have been modeled in a fashion similar to methane.

Organic and elemental carbon aerosols and sulfur dioxide are 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 environmental management has first, slowed land-clearing and improved combustion efficiencies, then controlled emissions of black carbon, and finally emissions of 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, see Figure 2. 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 simple ideas behind the sulfur emissions calculations:

- The potential SO_2 emissions are tied to the level of energy use, and fuel mix.
- The level of sulfur control increases with per capita income.
- The cost of sulfur controls drops through time and the diffusion of the sulfur control technology is accelerated through regions with currently lower per capita incomes.

Thus, the model simulations lead to increasingly stringent controls placed upon sulfur emissions.

Energy Module

The energy module includes four different fuel types - coal, oil, natural gas and non-fossil backstop. According to the traditional perspective on fossil fuels, resource limits dictate the pattern of resource scarcity over time. The price of fossil fuels rises as resources grow scarce. The price of the non-fossil backstop is determined by the two competing forces - technical change lowering costs in the short run, and pressure on land use raising costs in the long run. The level and pattern of energy demand in each region is determined by: economic growth, technical change (which can be treated as being either independent of or responsive to policy), the price elasticity of energy demand, and inter-fuel substitution.

Atmospheric Composition

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.

The carbon cycle model implemented in ICAM-2 is a linear system approximation with carbon emissions as inputs and CO_2 concentration trajectory as output, using a multiple exponential model based on the work by Maier-Reimer and Hasselman (1987). The biosphere is assumed to be neutral with respect to carbon concentrations. Concentrations of methane and nitrous oxide in the atmosphere for the uncertain emissions scenarios are calculated using linear models with single lifetime approximations. The atmospheric lifetime of methane is taken to be uniformly distributed between 8-12 years. The atmospheric lifetime of N_2O is taken to be distributed between 130-170 years.

The mean areal column burden of anthropogenic sulfate aerosol is related to the sources and sinks of atmospheric sulfates which depend on: the quantity of sulfur dioxide emitted, the fraction oxidized to sulfate aerosols, the sulfate lifetime, and the area of the geographical region in which the material is presumed to be confined (Ball and Dowlatabadi 1995).

Radiative Forcing and Climate Module

The long wave radiative forcing equations for greenhouse gases are taken directly from the Wigley Raper relationships specified in IPCC (Houghton, Jenkins 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 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. Our formulation is similar to that of Charlson *et al,* (1992) and yields direct and indirect forcing of similar magnitude.

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 is inadequately described by a single metric, such as mean global temperature change, and is an ensemble of statistical properties for a number of parameters (temperature, precipitation, wind, etc.) over different spatial and temporal scales. In the face of these difficulties, the climate module in ICAM-2 is comprised of a simplified model informed by expert judgments about the distribution and response of specific climate parameters to perturbations in radiative forcing. These parameters were quantified using an extensive and detailed expert elicitation protocol (Morgan and Keith 1995). Sixteen prominent climate scientists were interviewed and the perspective of each is modeled separately.

The key parameters elicited as probability distributions and used in the climate module are:

- Mean temperature equilibrium rise in global temperature in response to doubled CO_2 concentrations.
- The trajectory of climate response to a prescribed level of forcing -- yielding climate system response time(s).
- The temperature gradient from the equator to 70°N in response to doubled forcing.
- The present day aerosol forcing.
- Change in inter annual variability in temperature by latitude in response to doubled forcing.
- Change in inter annual variability in precipitation by latitude in response to doubled forcing.
- A probability measure of the stability of the climate system after atmospheric concentrations of CO_2 have doubled.

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 did not collect Southern Hemisphere parameter values — which generally less well known. In our current formulation these are symmetrically equated to 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 of service while 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 structural changes in the economy. These changes have traditionally led to lower vulnerabilities due to industrialization and declining shares of agriculture and natural resource extraction to the overall economy.

Incorporation of non-market losses into the estimates of the effects of climate change is subjective. Although it is appropriate to note, that market impacts are also subjective. The "prices" accepted as firm signals of market damages are not necessarily reflective of "worth," which is subjectively determined and varies from person to person. We have explored different functional forms for the quantification of non-market damages (Dowlatabadi, Shevliakova et al. 1994). In ICAM-2 we posit that actual loss is bounded by income levels. This leads to logistic response curves to increasing levels of climate change. In addition, we also make an attempt to capture the global, as well as the local, nature of non-market damages. The relative weighting of the these two elements of non-market damages is uncertain. Finally, long-term psychological adaptation to a changed environment is also explored as an alternative model structure for capturing loss of utility due to impacts of climate and sea level change on the unmanaged environment.

4 Uncertainty Analysis

Traditional uncertainty analysis takes place in two stages. The first stage involves the propagation of all parameter uncertainties through the model to obtain probability distributions for model outputs, conditional on input values and model structures. The technique and results obtained are presented in this section. The second stage involves analysis of the relationship between outcomes and inputs. The analytical findings are discussed in Section 5.

Sampling and Propagation of Uncertainty

The software environment in which ICAM has been implemented permits use of variants of the Monte Carlo approach to perform propagation of parametric uncertainties. The m inputs to the model are treated as uncertain, and a representative sample is generated from a suitably chosen uncertainty distribution. The model is then run iteratively for each vector of sampled inputs. Let x_i, $i=1,..n$ denote independent sample input vectors (for m input variables) and let $y_i=H(x_i)$ be the sample output variable for each input vector x_i, where the model H corresponds to ICAM. The n samples y_i are then used to characterize the uncertainty distributions for each output variable. In this section we briefly discuss the sampling techniques used in ICAM and the techniques we used for sensitivity analysis.

The best known methods for sampling a probability distribution are random sampling techniques which are based on the use of a pseudo random number generator to approximate a uniform distribution, U(0,1) with n samples. The specific values for each input variable are selected by inverting the n samples over the cumulative distribution function. A random sample has the property that successive points are independent. However, in most applications, the actual relationship between successive points in a sample has no real significance, hence the independence/randomness of a sample for approximating a uniform distribution is not critical (Knuth 1976) and uniformity properties are central to the design of sampling techniques. This implies that constrained or stratified sampling techniques are more appealing.

Latin Hypercube Sampling (LHS) is a form of stratified sampling which can yield relatively precise estimates of the distribution function (Iman and Helton 1985). In LHS, the range of each x_i is divided into nonoverlapping intervals of equal probability. One value from each interval is selected at random with respect to the probability density in the interval. The n values thus obtained for x_1 are paired in a random manner with the n values of x_2 and these n pairs are combined with n values of x_3 and so on to form n k-tuplets. The LHS technique provides better uniformity properties when compared to random sampling methods and requires far fewer samples to estimate the model output distribution.

Probabilistic Nature of Outcomes

In this paper we focus on the net discounted per capita utility (in US $) as the policy outcome of interest. Net discounted per capita utility is defined to be the difference between the per capita utility for each tax option and the no action (zero tax) option. As described by Dowlatabadi (1995) in ICAM 2.1 the ecological (non-market) and economic (market) impacts are weighted subjectively in the utility function of the decision maker. In the results that follow equal weights have been given to the two categories.

Two alternatives to taking no action are considered, both using annually rising carbon taxes starting in the year 2000. In the moderate abatement strategy, the carbon tax rises at

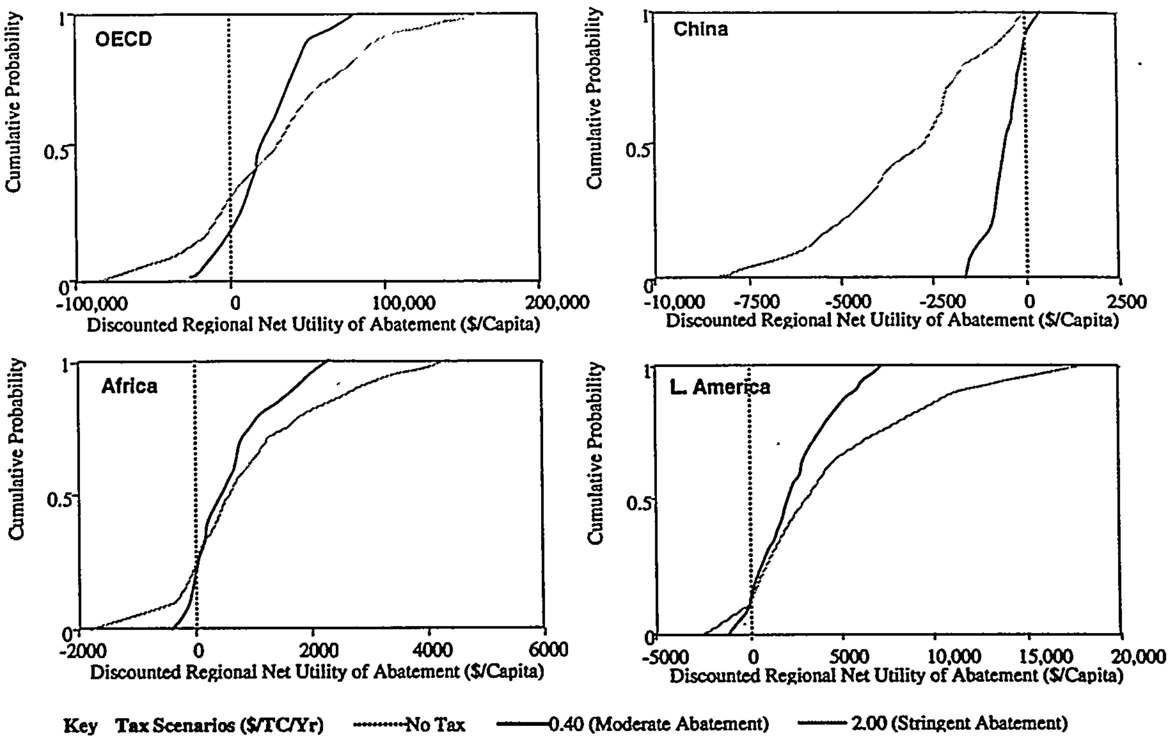

Figure 2: Cumulative distribution functions of per capita net discounted utility (in US $) for four regions. The vertical line through zero is the no tax case, the dark line is the low tax option and the light line is the high tax option. Forty realizations of the model have been used to generate these curves. Each datum along the CDF is an equi-probable discounted utility (over the period 1990 to 2100) for the specified region.

$0.4/Ton Yr. of Carbon. In the stringent abatement strategy the carbon tax rate is five times higher, at $2.0/TC Yr..[5] Inter-temporal discounting follows the convention proposed by Schelling (1994). Discount rates evolve through time and vary by region. They are based on per capita growths in income. In general, China has the highest discount rate at approximately 3.5% (averaged over the simulation period), while the other regions' discount rates are 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 impacts and policies considered. Therefore, if we were to use the per capita discounted GDP (as opposed to *net* per capita discounted GDP for the tax options), the role of uncertainties in climate science, and the damages would be drowned in the sea of uncertainty resulting from uncertainty in other aspects of global change over the long-term.

[5] The choice of a tax rate rising with time has a theoretical justification related to assumptions of monotone increase in climate perturbation and economic activity.

Table 1: **Expected policy outcomes for various regions and a qualitative description of the various factors that lead to these outcomes.**

Region	Policy Outcome A: no action B: moderate abatement C: stringent abatement	Key Driver of Policy Choice
OECD	A	High non-market damages, greater climate change.
EE & CIS	A	High emissions of aerosols, and coal based economy.
China	A	High emissions of aerosols, and coal based economy.
Middle East	A	Oil based economy, little climate change, low vulnerability to climate change.
Africa	A	High vulnerability to climate change, little climate change, and low concentrations of aerosols.
Latin America	B	High non-market damages and low concentration of aerosols.
S.E. Asia	A	High damages and coal based economy.

The cumulative distribution function for the discounted net per capita utility for four of the seven regions modeled are depicted in Figure 3. The OECD has low damages from climate because a smaller fraction of its economy is vulnerable. In this region there is a small chance that a low tax option may have high payoffs because the OECD places a high value on non-market damages.

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 impacts. 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 results in larger net costs of abatement for China compared with other regions

Table 2: Statistics of net discounted per capita utilities for each region.

Region	Mean Value(μ)		Std. Deviation(σ)		Upper bound (μ+σ)		Lower bound (μ−σ)	
	B	C	B	C	B	C	B	C
OECD	-1000	-58500	9500	29300	8500	-29200	-10500	-87800
E. Europe & CIS	-5350	-60300	4100	17200	-1250	-43100	-9450	-77500
China	-1300	-8900	600	2200	-700	-6700	-1900	-11100
Middle East	-400	-5600	850	2550	450	-3050	-1250	-8150
Africa	-120	-2600	450	1550	330	-1050	-570	-4150
Latin America	150	-3150	1200	3650	1050	500	-1050	-6800
SE. Asia	-200	-3250	500	1550	300	-1700	-700	-4800

As depicted in Table 1, only in the case of Latin America is there an *expected* benefit associated with choosing an abatement policy. Their choice of a moderate abatement policy is interpreted as being the consequence of high non-market and market damages, absence of aerosols, and greater climate change.

Concern about uncertainties and errors of omission in calculation of climate change impacts have led us to consider whether policy choices shift in the proximity of the expected outcome. For a summary of this analysis please see Table 2. Here, all but two regions would benefit from a moderate abatement policy with a probability of 0.24 (if the net benefits are normally distributed). Latin America would enjoy a similar probability of benefit if a stringent abatement policy is adopted.

5.0 Sensitivity Analysis and Importance Ranking

There are many commonly used formal and informal techniques for performing importance ranking / sensitivity analysis of model inputs. In a review of the literature Helton (1993) describes several approaches for performing sensitivity analysis. These include 1) Informal ranking schemes 2) Taylor's series expansions & Differential Sensitivity approaches 3)

Fourier Amplitude Sensitivity Test and 4) Monte Carlo based Input-Output Correlation approaches. It is widely accepted that the Monte Carlo based approach provides the most robust overall approach for sensitivity analysis and below we provide a brief description (Morgan and Henrion 1990; Helton 1993).

Importance ranking using Monte Carlo simulations is possible through the use of regression based techniques. The simplest approach is to perform a multiple linear regression analysis between the input samples and the model output. The standardized regression coefficients (SRC) associated with the individual input variables provide a measure of the relative importance of each model input when the model output response is linear in nature. If inputs are correlated then it is possible to evaluate the effect of each input variable on the model output using partial correlation coefficients (Iman and Conover 1982) which account for correlations among input variables by removing the effect of all other inputs on the model output. Partial correlation coefficients (PCC) measure the contribution of each input to the model output as long as the model has linear behavior in the range of model inputs. If the model response is non linear but monotonic, then partial correlations on rank transformations of model inputs and output provide a reliable measure for importance ranking (Iman et al., 1995). Partial rank correlation coefficient (PRCC) is the most frequently used measure for importance ranking because it is simple to use and implement and it breaks the linearity requirement of the other measures. A list of model input parameters ranked using PRCC in the order of their importance to the model outcome of choice — in this case the per capita *net* impact of a moderate abatement policy — is presented in Table 3.

Value of Information (VOI) in policy models can be estimated for a variety of levels of knowledge. These include: Expected Value of Perfect Information (EVPI), Expected Value of Imperfect Information(EVIPI), and Expected Value of Including Uncertainty (EVIU). In this work we use Expected Value of Including Uncertainty (EVIU) (Henrion, 1982) as the VOI metric. This approach involves varying the assumptions regarding one or a class of parameters at one 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 is run again by changing the assumptions regarding each class of parametric uncertainties; the effect of uncertainties in each class is determined by fixing all the relevant parameters at 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.

Table 3: Model parameters ranked in the order of their importance to the net impact of low tax policy per-capita.

Rank	OECD	E.Eu.& CIS	China	M. East	Africa	Lat. Amer	S. Asia
1	Climate Sensitivity	Climate Sensitivity	Tax Recycling Losses	Tax Recycling Losses	Pole to Equator Temp. Gradient	Climate Sensitivity	Tax Recycling Losses
2	Tax Recycling Losses	Tax Recycling Losses	Initial Fuel Quantities	Scarcity Price Hike	Climate Sensitivity	Pole to Equator Temp. Gradient	Pole to Equator Temp. Gradient
3	Non-market Impacts	Scattering Cross Section	Climate Sensitivity	Climate Response Time	Tax Recycling Losses	Tax Recycling Losses	Oil Elasticity
4	Scarcity Price Hike	Non-market Impacts	Pole to Equator Temp. Gradient	Pole to Equator Temp. Gradient	Scarcity Price Hike	Scarcity Price Hike	Climate Response Time
5	Lifetime of SO_4	Climate Response Time	Adaptation Rate	Sulfate Fraction	Power of Impact Function	Non-market Impacts	Change in Cloud Top Reflectivity

Descriptions of the uncertain parameters identified in the table:

- Adaptation rate specifies how well a region may cope with and ameliorate climate change impacts once they have been detected.
- Change in cloud top reflectivity is a measure of how aerosols affect the albedo of clouds.
- Climate response time is the e-folding time for the establishment of a new climate equilibrium.
- Climate sensitivity is the equilibrium response of the climate system to a change in global radiative forcing.
- Initial fuel quantities determine the fuel mix used in each region. In China, the level of coal and renewable energy consumption are not well specified.
- Lifetime of SO_4 is the expected atmospheric lifetime of sulfates once formed.
- Non-market impacts are the level of utility lost due to impacts of climate change on the natural environment.
- Oil elasticity is the cross price elasticity of the inter-fuel substitution matrix.
- Pole to equator temperature gradient is currently about 40°C and believed to decline with increased global mean temperatures. The future value for this parameter is uncertain.
- Power of impact function determines the severity of market impacts for a given change in mean regional temperatures.
- Scarcity price hike is the factor by which oil and gas prices rise in response to a perceived shortage.
- Scattering cross-section is a physical property of aerosols contributing to their clear sky albedo enhancement.
- Sulfate fraction determines the fraction of SO_2 emissions which are oxidized to form sulfate aerosols.
- Tax recycling losses are the losses to the economy from inefficient taxation or recirculation.

Table 4: **Expected value of including uncertainties (net discounted per capita utilities 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 percentage changes in expected value of the outcome relative to the base case.**

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)

Inclusion of uncertainty may alter policy decision. This can be due to asymmetric distribution of outcomes, or the decision-maker not being risk-neutral. Clearly, not including uncertainty in parameters that are known to be uncertain is equivalent to disregarding available information and may lead to sub-optimal decisions. Expected Value of Including Uncertainty (EVIU) 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 EVIU is zero.

Two general conclusions can be drawn from the entries in Table 4. The first conclusion is that different regions exhibit different EVIUs. For some regions (e.g., China , 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 conclusion is that the uncertainties in climatic/geophysical parameters dominate policy outcomes. In all the regions, excluding uncertainty in these parameters causes the largest shift in the expected outcome for the moderate abatement policy. While not presented here, similar results were also observed for the stringent abatement policy. The implications of these findings is that, for this formulation of ICAM, climate related parametric uncertainties may be more critical to climate change policy than other uncertainties. This conclusion holds for most regions, despite the regional differences in the projected mean temperatures.

We also note that the inclusion of uncertainty causes a shift in policy options in two cases, i.e., EVIU is zero in all but two situations where the sign of the relative outcome due to policy changes across the row of entries for a given region -- 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 $ 978/capita. For Latin America, the inclusion of uncertainty in climatic parameters causes a shift in the preferred policy from the zero tax option, to the low tax option resulting in an EVUI of US $ 152/capita. The fact that EVIU is zero in most situations is related to the discrete nature of policies considered. A continuous policy space would yield a range of results for each category of uncertainty considered. However, the robustness of the discrete options considered here make them more politically desirable.

7.0 Structural Uncertainty

The results of the previous sections, particularly the importance of climatic parameters, are contingent on a specific decision metric (discounted net utility per capita) and a particular model structure. A feature of the climate problem is that the multitudes of decision-makers value a wide range of decision-metrics, and that our knowledge of long-term global change is limited and many different structural models may be posited. More specifically, the apparent dominance of the economic paradigm, and general circulation models of climate is not an argument against admissibility of alternative problem formulations. Elsewhere we are developing a more comprehensive approach to capturing uncertainty in beliefs and values. Here we focus on an exploration of the impact of different model structures on climate policy decisions

Many aspects of both climate science and economics are uncertain, examples include: choice of discounting scheme, the role of policy in technology forcing, the magnitude of the fossil fuel resources, and the mechanisms and magnitude of adaptation to climate change impacts. In this section we first provide a brief description of the alternative structures developed for ICAM 2.1 to represent the competing paradigms for each domain of uncertainty. The implication of these structural uncertainties on outcomes is then explored.

Discounting

There have been many discussions about the advisability of discounting in inter-generational decision-making. The prevalent strategy is to discount public goods at an appropriate social discount rate. Such a discount rate would be applied uniformly to outcomes for all world regions. While the actual discount rate has been subject to much debate, 4% per annum has been the consensus figure adopted by modelers of integrated climate change. This is one model structure, while there is also an alternative structure based on a proposal by Schelling (1994). Schelling argues that intergenerational discounting should be based on regional prospects for growth per capita. Thus, the discount rate varies with economic prospects and performance. The implications of both models are explored.

Technical Change

Technical change is the engine of economic growth. Surprisingly however, little is known about the origin of innovation, and the interaction between technical change and policy. The consensus approach has been to specify technical change as an exogenous parameter. A notable example of this approach is the assumption made that technical change will inevitably lead to ever improving energy efficiency. The value usually adopted for this improvement is between 0.5% and 1% per year. More recently, Grübler (1995) has suggested a linear model linking the change in energy efficiency improvements to economic growth. This is one model structure. The alternative is based on our research refuting this model and showing that technology responds to circumstance (Oravetz and Dowlatabadi 1995). In this model, firm policy signals lead to sustained technical change.

Aerosols

In the first and second IPCC scientific assessments of climate change (Houghton, Jenkins et al. 1990; Houghton, Callander et al. 1992), the role of aerosols in climate forcing were largely ignored. More recently, there has been significant evidence that at present the radiative forcing of aerosols may be of the same order of magnitude as that due to changes in greenhouse gas concentrations. Two alternative model structures are explored here: one simply ignores the role of aerosols, the other calculates their impact on regional climates.

Adaptation

The issue of adaptation is closely tied to that of technical change. Nordhaus (1994) argues that after adaptation, some losses will persist in perpetuity. For example, a 3°C change in global average temperature is estimated to lead to a permanent economic loss of .25% to 2% of GNP. This suggests that today, all other factors held constant, conducting business grows more expensive the warmer one's location. But, the truth is that it is inappropriate to hold all other factors constant. The changes in other factors are part of the local adaptation patterns. We have devised two models, one in which damages due to climate change occur in perpetuity, another in which after the impacts have been detected, adaptation leads to eventual (once lags in learning what to do are included) dissipation of the losses.

Oil & gas reserves

Ever since the advent of Hotelling's (1931) thesis on exhaustible resources there has been a tendency to model oil and gas as resources close to imminent exhaustion. However, experience has shown that a more dynamic model of resource discovery and extraction is needed. In the classical model, the resource base is fixed and known with some precision. Cumulative use leads to price hikes due to scarcity and consumer behavior takes care of the needed adjustments in demand. In our alternative model, perceived scarcity leads to price hikes, but these price hikes also spur producers to make new discoveries (augmenting known reserves and lowering prices).

Results

A brief summary of the results of exploring model structure uncertainty have been reproduced in Table 5. In the top half of this table the structure of the model examined is specified. In the bottom half the outcome of interest for each region and the world as a whole is recorded.

Six different model formulation are explored. The structure of each model is determined by the entries in a specific column at the top half of the table. Rows specify the two alternative model structures for each domain of model uncertainty. Only a subset of the possible combinations are reproduced here. The subset reproduced here has been chosen to illustrate how structural assumptions can systematically change outcomes.

Table 5: **Probability, as a function of different model structures, that a $4.00/ton carbon tax that begins in the year 2000 and increases by $4.00/ton every five years through the year 2100 will have a positive net present value.**

Model Alternatives	Six Alternative Model Structures					
Model:	1	2	3	4	5	6
Discounting: ❑ - applied at the same level globally; ● - based on regional growth per cap.	❑	●	●	●	●	●
Technological change: ❑ - occurs autonomously; ● - induced by carbon tax.	❑	❑	●	●	●	●
Aerosols: ❑ - radiative effects excluded; ● - radiative effects included.	❑	❑	❑	●	●	●
Adaptation to climate impacts: ❑ - impacts are permanent; ● - adaptation occurs after detection.	❑	❑	❑	❑	●	●
Oil & gas: ❑ - reserves exhausted by 2050; ● - new reserves will be discovered.	❑	❑	❑	❑	❑	●

Region	Probability that a moderate abatement policy will have a positive net present value					
China	0.05	0.10	0.10	0.05	0.05	0.00
E. Europe & FSU	0.20	0.65	0.70	0.40	0.15	0.05
India & SE Asia	0.40	0.40	0.55	0.30	0.25	0.15
Africa	0.40	0.50	0.60	0.30	0.25	0.20
Middle East	0.45	0.50	0.55	0.40	0.20	0.15
OECD	0.50	0.85	1.00	0.60	0.60	0.30
Latin America	0.60	0.70	0.95	0.70	0.70	0.25
World	0.25	0.70	0.95	0.55	0.45	0.15

The outcome used to explore model behaviour is a simply the probability that a moderate abatement policy would have a positive payback. These probabilities are reported in the bottom half of the table for the various regions and the world as a whole. The regions have been arranged from China, where abatement is least likely to lead to a positive payback in

Model *1*, to Latin America where it has a chance 0.6 of leading to a positive payback. The models *1 - 6* have been ordered so that the probability of success (reading from left to right) first rises, and then falls. This general pattern is repeated in all regions, but the magnitude of model structure impact on outcome varies by region. Finally, note that the aggregate outcome exhibits the same trend but without revealing a pattern of regional influence on the global aggregate. In some regions (China and Africa) the outcomes are relatively more robust with respect to model structure uncertainty. These phenomena are due to the distributional properties of the outcome chosen.

8.0 Conclusions

The role of uncertainties in climate change is complex and requires careful consideration. Using ICAM-2 we have evaluated the effect of the various scientific and socio-economic uncertainties on outcome variables. When only considering parameter uncertainties, the uncertainties in climatic and atmospheric sciences appear to dominate those due to socio-economic parameter uncertainties and impacts for all but the fastest growing regions (China and S.E. Asia). When exploring the expected value of including uncertainties (EVIU) climate science uncertainties exhibit the highest values.

When structural uncertainties in models are considered, the outcomes can be systematically shifted towards or away from making abatement policies attractive. Thus, if a model is chosen where discounting is according to the scheme proposed by Schelling and technology for improved energy efficiency is accelerated by the abatement policy, there is a 0.95 probability that a moderate abatement policy would have a positive payback. However, inclusion of aerosol effects, adaptation effects, and larger oil and gas reserves reduce the probability of positive payback to 0.15.

These observations may be seen as suggesting that when the domain of uncertainty is extended to include model uncertainties, the key uncertainties in the climate problem shift from being natural science focused to being social science focused. An alternative interpretation is that perhaps natural scientists have been developing more generalized models where different assumptions about process can be represented by broader uncertainty ranges specified for key parameters. Thus, exclusion of model uncertainties would lead to a systematic bias in evaluation of areas where new knowledge can help improve climate policy decision-making.

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