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Beyond Emissions Paths: Rethinking the Climate Impacts of Emissions Protocols in an Uncertain World

Mort D. Webster and David M. Reiner

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives.

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Abstract

As nations engage in the long-term process of negotiating a protocol on controlling greenhouse gas emissions, the danger of costly mistakes looms large, both from doing too little or too much. Researchers try to provide insight and guidance on this difficult problem, many relying on the tools of mathematical simulation models, but two important shortcomings remain in much of the current analysis. One is the treatment of the uncertainty inherent in projections of economic activity over the next century or more; and the other is the way economic activity is modeled to impact the poorly understood physical and biological systems of the earth.

This paper presents several simple illustrations of the performance of current policy proposals in the face of a long-term climate-based goal when uncertainties in economic growth and technology development are made explicit. Several conclusions emerge. Analyses that rely on deterministic emissions paths through time obscure the underlying uncertainties, and explicitly incorporating these uncertainties can produce qualitatively different conclusions. Moreover, apparent differences in the climate impacts of proposals now being debated within the Framework Convention on Climate Change may be negligible when viewed in the light of likely uncertainties. Seeking a less stringent protocol with a higher probability of compliance may thus produce preferable outcomes. Most importantly, the analyses presented are meant to highlight the need for flexibility in any response to climate change, because uncertainty is an unavoidable aspect of the problem.

1. Introduction

Parties to the United Nations Framework Convention on Climate Change (FCCC) are engaged in an arduous series of negotiations on a possible greenhouse gas reduction protocol. These discussions are carried out under the auspices of the Ad-Hoc Group on the Berlin Mandate (AGBM), which was formed in the aftermath of the first meeting of the Conference of the Parties (COP-1) in Berlin in April, 1995 (United Nations, 1995). A major focus of the AGBM is the specific form of “targets and timetables” (Quantified Emissions Limitation and Reduction Objectives (QELROs) in the language of the Climate Convention) for the so-called Annex I parties.[1] If agreed, these would be legally binding restrictions on those countries that sign on to a protocol, restricting their emissions of greenhouse gases according to a particular schedule.

Throughout this process, the negotiators and their respective governments have received volumes of technical advice from the Intergovernmental Panel on Climate Change (IPCC) and the Subsidiary Body on Science and Technology Assessment (SBSTA). These contributions have

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[1] Annex I consists of the industrialized world: the member states of the Organization for Economic Cooperation and Development (OECD) at the time of the signing of the FCCC in 1992, the states of Eastern and Central Europe and the European states of the former Soviet Union. Some recent proposals suggest adding those countries that have recently joined the OECD, including Mexico and the Republic of Korea (*e.g.*, the EU proposal in AGBM, 1997b).

played a valuable role in informing and even guiding the decisions taken by policy-makers. However, our analysis casts a critical eye on a crucial element of the information being provided to that process, namely the incorporation of uncertainty into the analysis of alternative emissions limitation proposals.

Any evaluation of alternative policy responses begins with an attempt to understand what may occur in the absence of action and then estimates the consequences of possible policies. Given the long time scales involved and the interactions between economic and climate systems, efforts to predict the magnitude of future climate change must necessarily rely heavily upon computer-based mathematical modeling. Many of the parameter values used in these models are known only imprecisely, or may be the subject of a contentious debate among experts. The most common approach to account for such uncertainties is to develop *scenarios* by using alternative sets of input assumptions. These scenarios are then used to create forecasts of emissions by inserting the specified input assumptions into the economic models. The discrete projections that are produced drive models of climate, which are in turn subject to additional uncertainties in climate parameterization. The resulting climate changes from different scenarios can then be used to describe the possible impacts of each trajectory.

Any policy designed to achieve a climate objective should, at least, be able to assess the likelihood that it will attain that goal. By neglecting uncertainty and focusing solely on scenario analysis, however, policy modeling efforts are missing crucial insights that could inform decision-makers. Uncertainty is endemic to climate change, and the resulting outcomes under any policy regime are inherently stochastic. Only by directly incorporating uncertainty into the consideration and evaluation of alternative policy measures can the true nature of the difficult decisions begin to emerge: trading off uncertain costs against the risks from an uncertain climate.

To date, the focus on scenarios in the analysis of climate change policy has been ubiquitous. The most widely used set of scenarios consists of emissions trajectories developed by the IPCC (1992). The IPCC developed six possible alternative “emission paths” labeled IS92a – IS92f, each based on different assumptions about population growth, economic growth, energy supply, and other factors affecting greenhouse gas emissions. The IS92 emissions paths have provided a reference for other model-based analyses, both as inputs into climate models and as the basis for comparison with projections by economic-energy models. In particular, IS92a, being the central case, is commonly used as a reference for modeling studies. For example, the Energy Modeling Forum (EMF) based at Stanford University is coordinating an international effort to compare integrated assessment models for climate change, and has used the IS92a trajectory as the basis for its reference scenario (EMF, 1995). Climate modeling studies, most of which are conducted independently of economic analysis, use these standard emissions paths (again, primarily IS92a) as inputs, both for consistency and simplicity.

Emissions scenarios, such as the IS92 paths, are used not only for predicting radiative forcing with “existing policies” but also to establish a counterfactual for examining the climate implications of alternative control proposals. While the current round of negotiations has focused on targets in the near to intermediate term (2005 to 2020), the overall objective of the FCCC is “to achieve…

stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992). This phrasing begs two as yet unanswered (and perhaps unanswerable) questions: (1) what level of damage constitutes "dangerous interference," and, even if such a question could be answered, (2) what is the level of concentrations at which we should stabilize that would avoid such damages? In support of modeling work to address this question, the IPCC has developed a set of emissions trajectories that would stabilize CO_2 concentrations by the year 2400 at 350 ppm (parts per million), 450 ppm, 550 ppm, 650 ppm, 750 ppm, and 1000 ppm (IPCC, 1996).[2] Since carbon dioxide has a relatively long atmospheric lifetime, stabilization can only be achieved if total emissions begin to decline long before the concentration target has been reached. Since most models predict substantial continued growth in global emissions, the more stringent concentration targets would require drastic reductions in CO_2 emissions.

In an influential paper, Wigley, Richels, and Edmonds (1996) responded to the publication of the IPCC paths by demonstrating that different emissions paths can achieve essentially the same stabilization target while having dramatically different costs. Their argument made clear that the choice of the time-path of emissions must be a part of the policy design, in addition to the eventual concentration target.[3] Other recent analyses have attempted to break from the framework of choosing among distinct emissions paths through time, by instead seeking upper and lower limits on emissions trajectories that satisfy prescribed constraints. Such analyses include the work on "safe corridors" by Alcamo and Kreileman (1996) and on "tolerable windows" by Toth *et al.* (1997). Both studies seek a range of emission paths through time that meet both long-term objectives, such as the eventual temperature change, and place limits on the rate of change of objective measures such as temperature, sea level, and economic costs.

Several previous studies have attempted to address uncertainty more directly. Examples include the demonstration of the probability distributions of emissions under no policy (Manne and Richels, 1994), or the distributions of costs under different carbon taxes (Morgan and Dowlatabadi, 1996). Other approaches include the calculation of the value of information by Nordhaus and Popp (1997), who assume probabilities for discrete scenarios and eliminate uncertainty in different time periods. Finally, the most explicit use of uncertainty analysis to provide insight for the current climate policy choices is by Pizer (1997), who examines the change in optimal carbon taxes under uncertainty and the implications of those results for the choice between taxes and tradable emissions permits.

This paper expands beyond these previous approaches to uncertainty analysis, by explicitly relating uncertainty in economic and technological change to the implications for climate of emissions protocols currently being debated by governments. Uncertainty in its various forms is

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[2] For comparison, the concentration of CO_2 was approximately 280 ppm in 1800, 315 ppm in 1957, and 358 ppm in 1994 (IPCC, 1996, p. 76). Unconstrained emissions for the IS92 scenarios produce concentrations in the range of 500–950 ppm by 2100 (IPCC, 1996, p. 83).

[3] Further implications of choosing between alternative emissions paths to achieve a particular target are explored in Manne and Richels (1997).

reviewed in Section 2, distinguishing indeterminate knowledge, which is unquantifiable, from the relatively narrow types of uncertainty that will be investigated in greater depth in later sections. Section 3 then demonstrates the probabilistic nature of the impacts on climate of proposed emission protocols, using several illustrative examples. Once aware that any policy has some probability of avoiding an undesirable amount of climate change, the next question is what level of risk should be chosen. Section 4 provides a theoretical discussion of acceptable risk and the role of the precautionary principle. One serious concern in specifying the stringency of a policy response is the potential for nations to fail to carry out their obligations under an agreement. As a further illustration of how uncertainty analysis can be used for policy, a simple treatment of failed agreements is presented in Section 5. Conclusions and future areas of research are then presented in Section 6.

2. Uncertainties and Indeterminacies in Economic Models

In the debate over climate change, uncertainties are omnipresent. Estimates of future emissions of carbon dioxide are highly uncertain. The main drivers of such projections—rates of economic growth, availability of new energy supply technologies, resource abundance, and energy efficiency improvements in end-use sectors—are all subject to uncertainty. Differences among the economic modeling frameworks themselves can also be expected to yield significant differences in projections. Further, translating these emissions into radiative forcing of climate change, and then to quantitative impacts on climate is subject to significant uncertainty in the climate models used to calculate the system response.[4]

In this paper we sidestep the admittedly important scientific uncertainties in predicting physical impacts from an increase in CO_2 to focus on uncertainty in emissions forecasts. Why is emissions forecasting so uncertain? Although they require extensive data collection to prepare base year data and parameter estimates, the models used to project emissions consist of essentially simple representations of economic activity, coupled with other simple models of energy supply technology choices and their emissions characteristics. Performing long-term predictions with such models requires assumptions about future trends that will *always* be uncertain within a fairly wide range.

In the absence of compelling reasons to do otherwise, most economic simulations extrapolate historical values for input variables using simple linear or exponential trends to model future behavior. Past experience, expert elicitation, or some combination serve as the “reasonable” basis upon which growth is extrapolated. Such methods, while perhaps the only analytically tractable choice, cannot capture unanticipated changes in external conditions or rapid changes in the penetration of new technologies, both of which are likely to arise over the time horizon in question. The inability to capture such behavior can lead to significant errors in prediction.

[4] The impacts on climate might be measured in terms of an increase in mean global surface temperature or degree of sea-level rise.

A classic example of erroneous predictions can be found in the forecasts of electricity demand growth. Figure 1 summarizes the range of projections for summer peak demand for electricity in the United States as a function of the year in which the prediction took place. Presented in such a stark manner, the misplaced assumptions in energy modeling are apparent. In particular, these forecasts reveal two important difficulties in modeling: (1) a reliance on straight-line growth; and (2) an inability to anticipate the repercussions of exogenous change in demand such as the changes precipitated by the Oil Crisis of 1973–79, overall macroeconomic performance, changing demographics, and saturation processes.

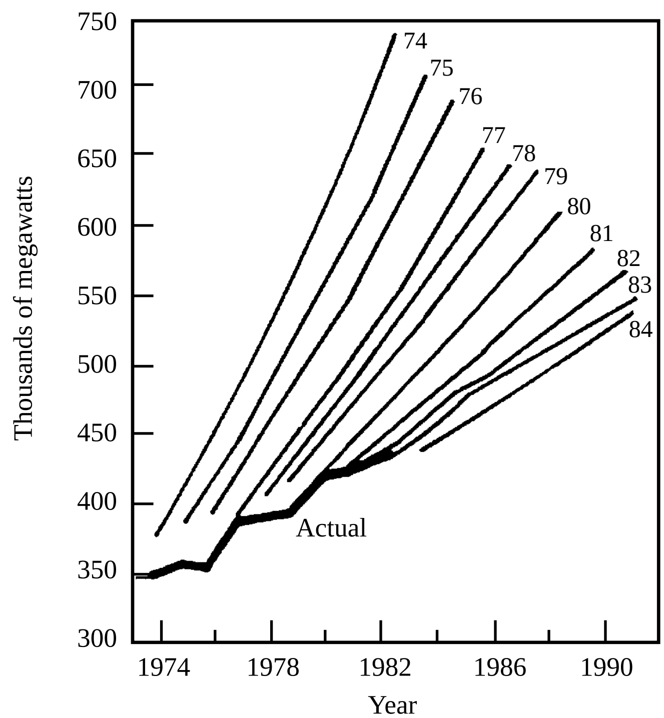

Figure 1. Projections of U.S. electric load growth: Annual 10-year forecasts of summer peak demand. (Source: OTA, 1985, Figure 3-3)

Another source of the limits of any modeling exercise is the rapid, often unanticipated penetration of new technologies. Figure 2 presents the shifts in the shares of sectoral production from different steel manufacturing technologies over the course of a century and a half. As can be seen, it is quite common for a new technology to leap from minimal penetration in a major industrial sector to dominance within a decade or two. In turn, each of these technologies has significantly different implications for energy consumption and emissions.

Unanticipated changes can be grouped into one class of problems for models that might better be classified as "indeterminacies" (Wynne, 1992). Over the time horizons needed for the study of climate change, many unforeseeable developments could render any forecast to be biased in some yet-to-be-determined direction. Volatility in political and economic conditions and hence in energy markets also poses a significant threat to the validity of forecasts and is most likely to affect those regions where the bulk of the growth in emissions is expected to occur.

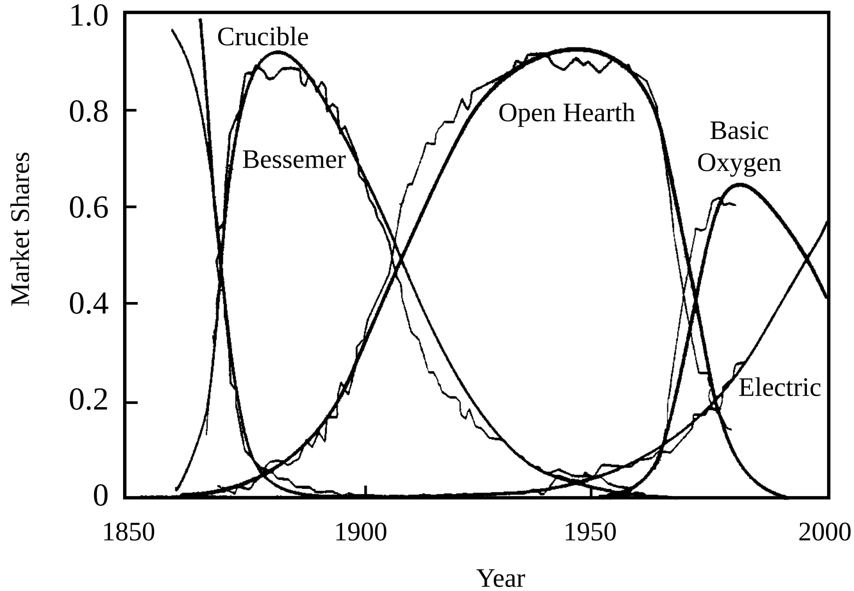

Figure 2. Change in process technology used in American steel manufacturing: Fractional shares of raw steel tonnage produced. (Source: Grübler, 1996, Figure 7)

In the context of climate change, nascent efforts to capture the effects of indeterminacy have concentrated on the possibilities of "surprise," such as non-linearities, threshold effects, or catastrophic impacts in the physical system (Hassol and Katzenberger, 1995; Darmstadter and Toman, 1993). Much work remains to systematically capture the economic and physical impacts of even much-discussed catastrophic events such as a collapse of the thermohaline circulation in the North Atlantic or massive forest dieback (*e.g.*, Manabe and Stouffer, 1994). These phenomena have received widespread attention and some preliminary analysis, but there is no reason to believe that all possible positive and negative feedbacks have been anticipated.

While casting a shadow over any forecast, most of these considerations are not easily amenable to analysis except by using highly speculative "what if" scenarios. Such an exercise requires a series of scenarios to be developed which, while valuable, are virtually impossible to associate with a probability and are thus of questionable service to policy-makers.[5] Moreover, completely unanticipated climatic behavior and physical and socio-economic impacts obviously cannot be captured by even the most ambitious scenario analysis. Nevertheless, the potential for foreseeable and unforeseeable catastrophes plays a powerful role in motivating a precautionary principle; the implication of which will be discussed in Section 4.

[5] Kates and Clark (1996) provide a useful overview of attempts to address "surprises" in environmental policy analysis. But in spite of an optimistic assessment of the prospects of such exercises, they leave little reason to believe that such surprises could easily be incorporated into an analytical framework that leads to quantitative analysis.

Model outputs are also subject to a second class of difficulties that arises from the uncertainty in the values of key parameters that drive these models and that *are* amenable to analysis. Uncertainty in model input parameters can be represented by probability distributions, which, when propagated through a model, produce a distribution of possible future emissions rather than a single discrete emission path. Previously firm conclusions from deterministic studies may now no longer hold. The variance in the distribution of emissions will change over time as a function of the interactions and feedbacks endogenous to the model and of the correlation between the uncertain drivers (Webster, 1997). As a result, the variance of outputs may be quite different from the input variances and furthermore, symmetric input distributions can produce asymmetric output distributions. For example, a uniform distribution in the price of new energy technologies will produce asymmetric changes in emissions because the higher-priced end of the distribution will have no effect while changes in price at the lower end will increase market penetration.

While most studies are quite conscientious in acknowledging the uncertainties in their results, usually only the reference values for the key inputs are used to establish a counterfactual and to present the effects of a policy. Since there has been little effort to move beyond occasional sensitivity analyses, what passes for uncertainty analysis is often simply so-called meta-analysis,0 which presents results of different models, each of which is solved at different respective reference values. A prominent example of such an approach can be found in a recent study at the World Resources Institute by Repetto and Austin (1997), which attempts to trace the divergence in the assessment of economic impacts of a climate change protocol by different researchers to differences in structural assumptions. Structural or model uncertainty, as opposed to parameter uncertainty, refers to uncertainties over whether to include a particular process (*e.g.*, a production sector in an economic model) or over what functional form to use for a process.

It must be emphasized that the conclusions drawn by such meta-studies are not being contested. We readily concede that inter-model differences *are* significant. Owing to different formulations, results may differ significantly across models even when considerable effort is made to ensure the consistency of the input assumptions. Perceiving different models as the means by which uncertainty can be conveyed, policy-makers and interest groups have focused on differences in structural assumptions as responsible for differences in results. While no consensus exists on which model is most appropriate, our study hopes to illustrate, by examining one particular model, that the uncertainty in assumptions about parameters by itself can have profound implications for policy.

In particular, we will apply uncertainty analysis to an assessment of the effects on climate of different carbon abatement protocols. Studies that can relate policy actions to reduced climate impacts are critical to informing the current negotiations, but are also exceedingly contentious as witnessed by the recent debate within the Subsidiary Body on Science and Technology Assessment

(SBSTA) over how such a study should proceed (SBSTA, 1997).[6] While many political and technical disputes simmer at or below the surface of this debate, there has been little effort to adequately represent economic or scientific uncertainties or to explore what is meant by ‘achieving’ a particular climatic objective.

In light of the enormous uncertainty in emissions forecasts, discussed above, conclusions of the form: “Stabilizing CO_2 emissions at 1990 levels would reduce concentrations by XXX ppm and temperature change by Y.Y ˚C” would be erroneous and misleading. Given the wide range in possible emissions under any protocol, the more appropriate question to ask is: “What is the probability of avoiding some undesirable physical impact or set of impacts by implementing a given protocol?” Indeed, one of the major criticisms voiced by both Kuwait and Nigeria in their submissions to SBSTA was that although IS92 emissions paths consist of six scenarios, often only the most common reference, IS92a, and the two “extreme” paths that bracket the range are presented. The use of only the extreme scenarios as alternatives to the reference can lead some policy-makers to “discount either or both of them, because they reflect what some people regard as ‘extreme’ assumptions” (SBSTA, 1997, p. 10). Constrained to debate modeling results that are based on the IS92a path, OPEC countries would, rightly, need to search out a model that shows high costs, or the lowest climate impact, to support their negotiating position. In reality, their position is simply one that is heavily weighted toward cost considerations in the tradeoff between uncertain costs and the risks of climate change, a position that would be more amenable under the present framework. Explicitly incorporating uncertainty into model results would not remove all of the objections to modeling studies but it does provide an opportunity to reduce conflict along certain dimensions and to clarify the policy questions being debated.

Incorporating uncertainty has the potential to move the political debate away from disputes over modeling arcana to more central political questions regarding what constitutes sufficient action toward a pre-determined climate objective. The process of seeking results from different models often acts as a proxy for differences in preferences for action; the use of probability distributions allows for those choices to be made more transparent. Arguments over what actions are sufficient can be located within the presentation of results from a single modeling exercise in a way that would be impossible using results of deterministic studies. In so doing, differences over the central tendency of the modeling results and over the types and ranges of uncertainties, which remain important avenues for future research, might be sheltered from the political debate over what actions should be taken.[7]

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[6] In a similar vein, the Brazilian government has arrived at a concept of “effective emissions,” which explicitly relates emissions to sea-level rise and temperature change using simple coefficients derived from the IPCC MAGICC box-diffusion model (AGBM, 1997c). The results of this analysis are an important first step but provide only a deterministic assessment of climate targets.

[7] Jamieson (1996) takes this argument further, contending that uncertainty is not simply an objective value but one that is constructed by both science and society to serve a number of functional purposes for both policy-makers and scientists themselves. In his words, uncertainty can indirectly bring policy debates to closure by reducing science “to just another playground for competing ideologies.” Scientists, in turn, benefit because “the right amount of uncertainty supports a call for further research” (p. 40).

3. Achieving a Target under Uncertainty

3.1 Evaluating a Protocol under Certainty

Before investigating the implications for climate of different protocols under uncertainty, we first perform a typical scenario analysis under certainty. Current QELRO proposals to the AGBM span a wide range, yet all entail some reduction below 1990 emissions for all Annex I (or OECD) states (Table 1). It would be useful to know what the differences are between these proposals in terms of their impact on CO_2 concentrations. Higher CO_2 concentrations lead to increased radiative forcing of climate change, and to greater potential impacts of this climate change. For simplicity, we will first explore the impacts of protocols on CO_2 concentrations only.

Table 1. Proposals for an Annex I Emissions Protocol to AGBM

Country Submission	Proposed Reduction Below 1990 Levels
AOSIS	20% by 2005
Austria, Germany	10% by 2005 and 15-20% by 2010
Belgium	10-20% by 2010
Denmark	20% by 2005 and 50% by 2030
France	7-10% by 2010
Japan	0-5% by 2012
Netherlands	1-2% per year
Switzerland	10% by 2010
United Kingdom	5-10% by 2010
United States	0% by 2012
Zaire	10% by 2005, 15% by 2010, and 20% by 2020

Sources: AGBM (1997a), Government of Japan (1997), White House (1997)

In the traditional manner of scenario analysis, two idealized protocols are chosen for analysis as representing the extremes of the range of QELRO proposals:

- Stabilization—OECD nations stabilize their CO_2 emissions at 1990 levels; and
- AOSIS[8]—OECD nations stabilize emissions at 20% below 1990 levels by 2010.

In both cases, the emissions of all other countries remain unconstrained. For analytical tractability, both protocols hold OECD emissions to 2010 levels for the remainder of the century.

The traditional method of analyzing these two cases is to use some form of economic-energy model. First, the model is used to project emissions when there are no constraints on emissions; this counterfactual is called the reference case or the "no policy" case. Then, emissions constraints defined by the protocol are imposed, and the model again projects emissions over time. The resulting trajectories are then used to find corresponding CO_2 concentration paths, using a carbon-

[8] The actual proposal put forward by the Alliance of Small Island States (AOSIS) calls for a 20% cut in all Annex I states by 2005.

cycle model. Finally, the concentrations in each case can be compared with a desired target concentration to gauge the relative effectiveness of each protocol.

For the sample analysis presented here and throughout this paper, the economic model used is the MIT Emissions Prediction and Policy Analysis (EPPA) model (Yang *et al*., 1996; Jacoby *et al.*, 1997), which is derived from the OECD's General Equilibrium Environmental (GREEN) model (Burniaux *et al.*, 1992). EPPA is a recursive-dynamic computable general equilibrium model with twelve economic-political regions, ten production sectors, and four consumption sectors. The time horizon for the model simulations is 1990–2100, which EPPA solves for in 5-year time steps. EPPA is the economic component of the Integrated Global System Model (IGSM), which also includes a 2D climate-chemistry model, and the Terrestrial Ecosystems Model (TEM) for measuring impacts on the biosphere (Prinn *et al*., 1997).

As discussed earlier in a more general context, many assumptions in EPPA are uncertain, such as economic growth rates, costs of future energy technologies, and rates of energy efficiency improvement. Scenario analysis, however, requires that we ignore the uncertainty for now and run the model for each policy case using nominal assumptions. The emissions for the no policy case reach nearly 20 GtC by 2100, as shown in Figure 3. The stabilization case requires that the four regions in EPPA that represent the OECD emit no more than their 1990 emissions levels (with no constraints on the eight other regions), and resulting global emissions only increase to 14.7 GtC by 2100. The AOSIS case requires OECD regions to stabilize at the more stringent level of 20% below the 1990 levels, and the resulting global emissions are reduced slightly further, rising to less than 14.1 GtC by 2100.

Figure 4 shows the concentration profiles that correspond to the emissions scenarios in Figure 3.[9] The absence of a protocol would result in the concentration target being exceeded by 100 ppm. The stabilization policy, in contrast, would keep the concentration of CO_2 just below 650 ppm. The AOSIS protocol would keep concentrations below the target with an additional margin of safety of about 20 ppm.

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[9] In this calculation and throughout this paper we neglect the equally important uncertainties in the climate, atmospheric chemistry, and carbon-cycle models. Two important assumptions are that the climate sensitivity is assumed to be 2.5˚C (this is the temperature change that would result from a doubling of the CO_2 concentration after the climate system reaches equilibrium); and that the coefficient of ocean heat uptake in the deep ocean is assumed to be 2.5 cm^2/s (Andrei Sokolov, personal communication, 1997).

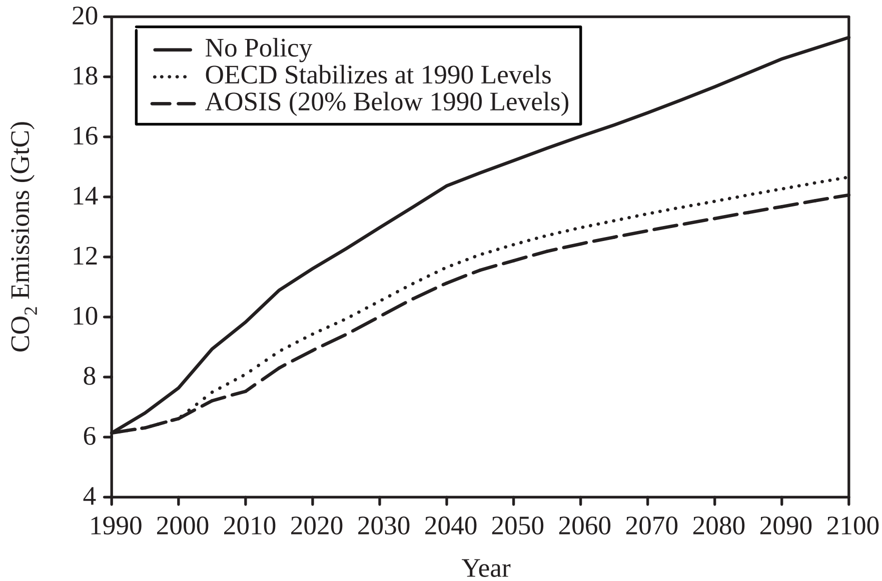

Figure 3. Global CO_2 emissions paths in EPPA for different policies using reference values for input parameters in EPPA model.

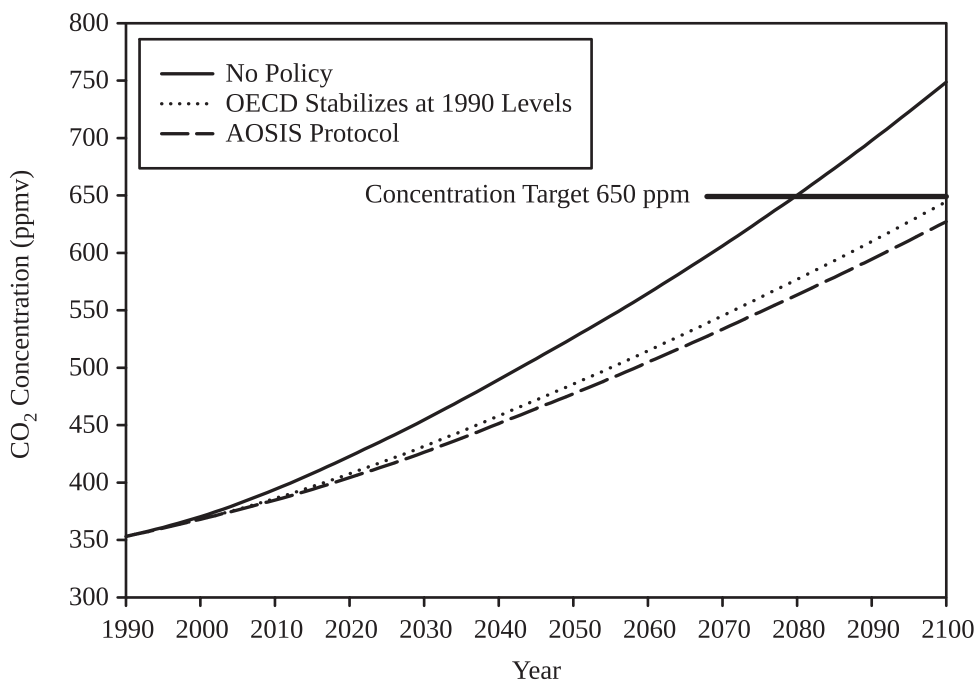

Figure 4. Atmospheric CO_2 concentrations paths for different QELROs using reference values for input parameters in EPPA model.

Although somewhat simplified, the analysis of Figures 3 and 4 is typical of the scenario-based approach commonly performed to support climate policy. Unfortunately, it can lead to misplaced conclusions concerning uncertainty. For instance, given a target of 650 ppm in 2100, one might conclude that the "no policy" case is entirely inadequate, that stabilization at 1990 levels will just meet the target, and that the AOSIS protocol would provide a desirable margin of safety. Simply acknowledging the *presence* of uncertainty, common in studies of climate change, would seem to create a strong preference for the more stringent AOSIS policy in order to protect against an unfavorable resolution of the uncertainty. As will be seen in the remainder of this section, the results from a more rigorous inclusion of uncertainty in the analysis are not nearly so clear.

3.2 Evaluating Policies under Uncertainty

The EPPA model, as with all models, relies upon assumptions for its many numerical parameters, despite great uncertainty over what these values should be. What we would like to know is the effect of these uncertainties on the outcomes of the model, in particular on CO_2 emissions. To investigate this question, we can posit probability distributions that represent our beliefs about possible values for some important parameters, and then find the resulting probability distributions for emissions. Three important parameters in EPPA that represent uncertain future trends in economic growth and technology development are:

- Autonomous energy efficiency improvement rate (AEEI);
- Labor productivity growth rate; and
- Price of carbon-free electricity supply alternatives in the future.

We will use the uncertainty in these parameters to explore the climate implications of proposed emissions reduction protocols.[10]

The probability distributions for these three parameters were derived from subjective assessments of several experts, and are represented as Beta distributions.[11] Although this exercise only examines the uncertainty in these parameters, there are other important uncertainties in the EPPA model that are not accounted for here. Furthermore, it should be stressed that people tend to underestimate uncertainty when making subjective probability assessments, particularly for long-range predictions. Thus, the probability distributions of outcomes shown here are likely to understate the actual uncertainties in these modeling exercises.[12]

We use these subjective probability distributions of parameters to conduct an uncertainty analysis of the EPPA model. The analysis utilizes the Deterministic Equivalent Modeling Method (DEMM), an efficient procedure for propagating uncertainty through models. DEMM finds an approximation for the response of a model, represented as an expansion of orthogonal polynomials derived from, and with greatest accuracy near the maxima of, the probability densities of input parameters (Tatang *et al*., 1997). This approximation and the uncertainty in the parameters are used to obtain probability distributions of CO_2 emissions in each 5-year period over the interval 1990–2100, as well as the distribution for the cumulative carbon emissions. Concentration targets

[10] A detailed exposition of the analytical approach used to address the uncertainty in CO_2 emissions can be found in Webster (1997).

[11] Beta distributions are defined over a finite range.

[12] On the other hand, the correlation between uncertainties can decrease that range of possible outcomes, as demonstrated in Webster (1997). Nevertheless, our experiments suggest that including other economic uncertainties would increase the variance more than accounting for correlation decreases the variance.

can then be evaluated using these probability distributions in order to determine the probability that concentrations will remain below the target.

Once we acknowledge that some uncertainty is intrinsic and irreducible, it becomes clear that it is neither possible nor useful to say whether a policy with a long time frame will or will not achieve a particular target. A more appropriate view is to consider what probability or likelihood that a policy proposal has of meeting a goal, such as limiting temperature rise or CO_2 concentrations. If a policy goal is deemed serious enough to warrant action, then it is important to ensure that such action give a sufficiently high probability of succeeding, so as not to be wasted effort.

For the analysis of policies under uncertainty, we derive an alternative long-term policy goal, which is related to actual proposals in the FCCC process, in place of the concentration target used in Figure 4. The AOSIS states and the European Union have both proposed that warming be limited to 2˚C (EU, 1996; AGBM, 1997d).[13] For purposes of this analysis, we will disregard the difficult question of whether the goal of limiting warming to 2˚C is itself desirable.

Using the MIT 2D-LO climate model (Sokolov and Stone, 1997) we find that a rate of CO_2 concentration increase of roughly 0.7% per year would result in a temperature change of approximately 1.7˚C by 2100.[14] This only accounts for CO_2 and ignores all other greenhouse gases; however, since CO_2 is responsible for roughly two-thirds of the greenhouse effect (Houghton, 1994), this is a reasonable first approximation for an overall 2˚C rise in temperature. Taking this one more step back into the emissions world, a carbon-cycle model (Prinn *et al.*, 1997) is used to find that a typical emissions path that leads to a 0.7% per year increase in concentrations has cumulative emissions of about 1400 GtC.

The average residence time in the atmosphere of CO_2 is fairly long, as much as 45–120 years by some estimates (Wigley, 1993).[15] Although different emissions paths can exist that result in roughly the same level of CO_2 concentration after 100 years (Wigley *et al*., 1996), the alternative emissions paths that give the same concentration tend to have almost the same cumulative carbon emissions. Thus, we will use cumulative emissions of less than 1400 GtC as a proxy for realizing a temperature increase of less than 2˚C by 2100. This illustration is only a first step; a more detailed analysis, which studies the response of carbon-cycle and climate models under uncertainty, is desirable.

In order to most clearly demonstrate the implications of uncertainty for scenario analysis as typically performed, we maintain here the common practice of comparing policies as once-and-for-all decisions. Over a time horizon of 100 years or more, policies should be, and realistically, will be, revised many times as new information comes to light. Modeling the evolution of climate

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[13] Coincidentally (or perhaps not) this 2˚C warming corresponds roughly to what might result from a doubling of CO_2 concentrations ($2 \times CO_2$). Doubling of CO_2 experiments date back over two decades as a standard benchmark scenario for comparing climate models, and originally had no relation to impacts of climate change.

[14] Andrei Sokolov, personal communication, 1997.

[15] The results of the MIT model of the oceanic carbon sink (Prinn *et al*., 1997) suggest a shorter lifetime of 30–60 years, which varies over time with the state of the climate-ocean system (Chien Wang, personal communication, 1997).

policy as a learning process is better captured by sequential decision-making models, such as those of Valverde (1997) and Manne and Richels (1992).

Given our proxy goal of limiting global cumulative emissions to 1400 GtC by 2100, we would like to assess the chances of achieving this goal under different policies. The first question to ask is what the likelihood is of achieving the goal with no action at all. Calculating the probability of emissions being less than or equal to 1400 GtC with no policy, we find a 24% probability that this will meet the target.

Next we take the two idealized QELROs discussed above: AOSIS and stabilization of emissions. The probability densities of cumulative CO_2 emissions for each of the three cases—no policy, stabilization, and AOSIS—are compared in Figure 5. Note that the probability of achieving the goal of emitting less than 1400 GtC by 2100 is the area under each curve to the left of the vertical line. Two results are apparent from the graph. The first is that the likelihood of limiting emissions to less than 1400 GtC is dramatically improved by either of the emissions reduction protocols. This experiment gives the stabilization approach a probability of achieving the target of 91%, and the probability of AOSIS meeting the same target of 95%.

The second implication is that AOSIS, while likely entailing substantially higher costs, does not appear to exhibit a significant advantage over stabilization once uncertainty is accounted for. This adds a perspective that is not visible in the current negotiations in which much of the current focus is on whether the level of stabilization should be 5%, 15%, or 20% of 1990 emissions. Whereas in a scenario-based analysis, such as that presented in Figure 4, the existence of uncertainty appears to make AOSIS a clearly better alternative, in fact, explicit consideration of uncertainty suggests that AOSIS offers little advantage over stabilization. The relevant comparison between stabilization and AOSIS is not between the CO_2 concentrations of 645 ppm *vs*. 625 ppm, but rather between a 91% and a 95% probability of avoiding warming of more than 2˚C.

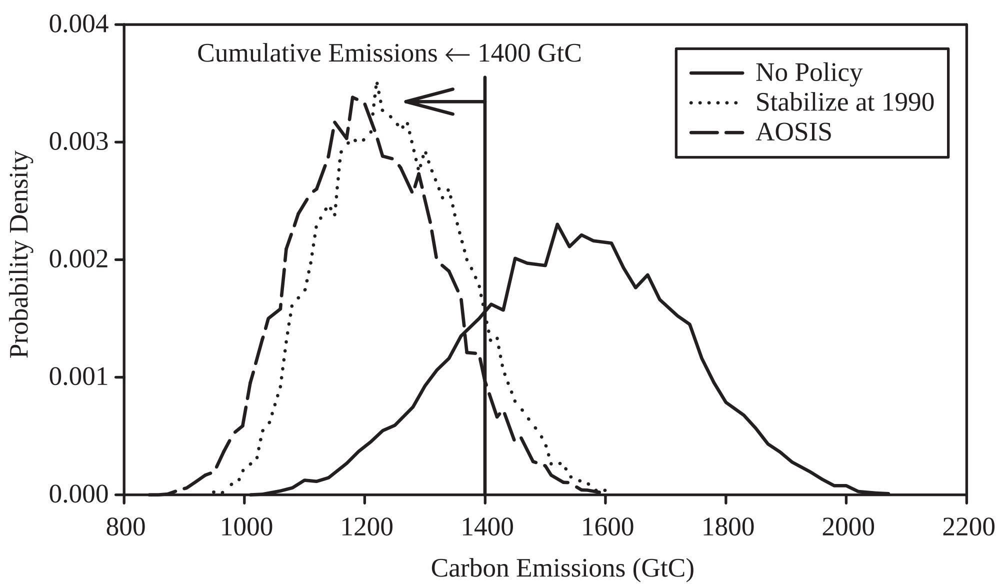

Figure 5: Probability density functions of cumulative emissions for different policies. Area under curves to the left of the vertical line represents the probability that global mean surface temperature will rise by less than 2˚C by 2100.

Why does the AOSIS protocol offer little advantage under uncertainty? Recall that while the OECD nations are constrained in the stabilization and the AOSIS protocols, other nations continue to increase their emissions unconstrained. However, the amount of emissions by the unconstrained nations varies greatly as a result of the uncertainties in economic growth and future technologies. This uncertainty in the emissions of the unconstrained nations dwarfs the differences between stabilizing at 1990 levels *vs*. 20% below.[16] The main benefit of the stabilization and AOSIS protocols arises from the fact that OECD emissions do not continue to grow, not from the precise level at which emissions are stabilized.

4. How Safe is Safe Enough?

From the previous analysis, we have seen that it is not possible to conclude definitively that one policy will achieve a long-term goal while another will not. Rather, different policy proposals have a greater or lesser likelihood of achieving a desired level of carbon concentrations. A choice of the amount of emissions reductions on the basis of climate impact should therefore be considered as an explicit decision about the acceptable level of risk. But this raises the thorny question of what level of risk *is* acceptable. This question has long been debated by risk-analysts and others (see, for example, Derby and Keeney, 1981), without a clear answer emerging.

Instead, we might look to the often-cited “precautionary principle” for help. The precautionary principle seeks to shift the burden of proof from the opponents of a given activity that could degrade the environment to those engaged in that activity. Some governments have explicitly endorsed the precautionary principle. For example, in the wake of the Enquete Commission on climate change, the German Bundestag agreed to apply this principle in all issue areas (Beuermann and Jäger, 1996).[17] It also has been endorsed by numerous international conferences and conventions on environmental issues (Bodansky, 1991). The declaration of the United Nations Economic Commission for Europe’s Bergen conference on sustainable development defines the precautionary principle: “Environmental measures must anticipate, prevent, and attack the causes of environmental degradation. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation” (United Nations, 1990).

[16] Note that this simple example neglects the possibility of severe non-linear impacts or “surprises.” Allowing even a very small probability of surprise *could* make the difference between AOSIS and stabilization extremely significant.

[17] Beuermann and Jäger argue that many of the actual policies pursued by the German government have not, however, corresponded to the tenets of the precautionary principle.

The precautionary principle has been criticized for being unrealistic and impractical as witnessed by the ease with which governments can adopt “principles” but pursue realist policies. Others fear that pursuing such a principle will not simply result in hypocrisy but in real economic damages. For example, Beckerman (1995) worries that reliance on a precautionary principle will pressure governments into “hastily devised, inefficient and expensive environmental regulatory policies that usually involve an unwarranted intervention in the operation of the market” (p. 1). More fundamentally, Bodansky (1991) argues that the precautionary principle is “too vague to serve as a regulatory standard because it does not specify how much caution should be taken” (p. 5). In the end, while it may serve a useful purpose in the political debate, the precautionary principle gives little guidance to policy-makers as to how much caution to use.

Furthermore, the problem is actually even more difficult than deciding how much risk the international community is willing to bear. Unlike the simple illustration in Section 3, in reality we do not have, nor are we likely to have, probability distributions for outcomes under alternative policies. In a problem with the dimensionality and scale of climate change, there are many different types of uncertainty that exist. As discussed in Section 2, many of the uncertainties are in fact indeterminacies, which, even when recognized, have probabilities that cannot be quantified. For example, in the case of ozone-depleting CFCs, it is not that the compounds were not tested for environmental impacts; it was their lack of toxicity along with their ideal thermodynamic properties that led to widespread use of CFCs. At the time, all known health and safety impacts were tested, and it is only in retrospect that we realize that testing for other impacts (depletion of stratospheric ozone) had not even been considered (Bodansky, 1991).

When a choice must be made in the face of indeterminacies, people fill in knowledge gaps with their values. The evidence presented here could lead an observer to distinctly different conclusions regarding policy depending upon their initial predisposition. Probabilistic assessments can help to identify the range of ideological positions that are implicit in many of the debates over climate change. An individual who is particularly concerned with avoiding the costs of regulation might feel that a 24% chance of avoiding serious impact without emissions reductions presents a strong case to postpone any such protocol. On the other hand, someone that places far greater weight on avoiding damages might invoke the precautionary principle to support the AOSIS protocol in order to reduce the risk of serious impacts to 5%, or even lower.[18]

In the midst of this value-laden debate, both scenario and probabilistic assessments have a role in identifying tradeoffs and in providing insights into better approaches to achieve goals once chosen. As Greenberger and Hogan (1987) note, “the real value of modeling is in the understanding and deepening of insights it provides, not in the numbers it produces” (p. 242). The conclusion of Section 3, that AOSIS is only marginally more effective than stabilization once uncertainty is accounted for, is one example of such a qualitative insight made possible by explicit incorporation of uncertainty. Nevertheless, we must be cautious about making definitive

[18] Of course there are many other views besides the extremes. A more moderate decision-maker would probably consider the reduction of the risk of more than 2˚C warming from 76% to 9% worthwhile, but the gain of an additional 4% risk reduction not desirable, subject to cost and damage considerations.

recommendations based on model results. Not only can the traditional practice of scenario analysis be misleading by neglecting the intrinsic uncertainty in climate change, but also accurate probabilistic predictions are not feasible, nor would the problem be completely solved if they were. We must remember that any response to climate change, as with any other political agreement, will be determined on the basis of competing values and interests. Model-based analysis can help to clarify implications to the various interested parties. The next section will use the tool of probabilistic analysis to demonstrate one other issue relevant to the policy debate, that of the probability of compliance with an agreement.

5. Implications of Failed Political Agreements

Thus far we have analyzed the effects of uncertainty in future economic and technological trends upon the impacts of emission reduction policies assuming that the appropriate policy is implemented exactly as designed. One other type of uncertainty that is seldom addressed in policy analysis is the uncertainty in political commitments. Any solution to climate change will require sustained long-term political cooperation, while in fact sustained political commitment is a rarity, especially in the face of economic hardships that emissions constraints are likely to entail.

Most policy analyses represent a particular policy of emissions reductions either as constraints on the emissions of carbon or as carbon taxes. In such mathematical simulations, carbon taxes are paid in full and emissions constraints are precisely met. Furthermore, *all* parties to the agreement meet their commitments. It is especially worth noting that for studies that present an optimal policy, such a policy is only optimal if in fact all parties enact that policy. As with other uncertainties, such recommendations may not be robust if we take account of the fundamental political uncertainty.

In reality, political agreements may fail for many reasons. One way in which parties to an agreement may fail to meet targets is through taking inadequate measures. The effect of such measures may be miscalculated due to precisely the same types of forecast uncertainties discussed in Section 2. The agreement of the Annex I nations to return to 1990 emissions levels by 2000 is an example of a commitment that will not be met by the majority of parties, as shown in Table 2. In fact, the only Annex I region that will definitely meet the targets for 2000 are the Former Soviet Union and Eastern European nations, not because of political commitments undertaken as part of the FCCC, but because of the post-1989 economic collapse, an example of the type of unanticipated external events discussed earlier.

Table 2. Expected Performance of Annex I Regions in Returning to 1990 Levels by 2000

Country/Region	1990 Carbon Emissions	2000 Carbon Emissions	Increase over 1990 Levels
United States	1,337	1,543	+15.4%
Canada	137	160	+16.8%
Western Europe	1,016	1,081	+6.4%
Japan	308	401	+30.2%
Australasia	100	114	+14.0%
Total OECD	2,985	3,421	+14.6%
Former Soviet Union	1,029	733	-28.8%
Eastern Europe	309	278	-6.8%
Total Economies in Transition	1,339	1,012	-24.4%
Total Annex I	4,324	4,433	+2.5%

Source: Derived from Table A9, EIA (1997)

In addition to not taking sufficient measures to meet a target, it is also easy to conceive of a nation intentionally reneging on its obligations, when the targets result in economic hardships.[19] In the face of the unknown but probably significant chance that at least one party to the FCCC may not meet its obligations under a protocol, what are the implications for the policy chosen? More specifically, what are the relative merits of a more stringent protocol met by most parties compared with a less stringent protocol met by all industrialized nations?

Referring back to the many national submissions provided in Table 1, one might assume that the most stringent proposal would have the best chance of meeting a particular climate objective. This is surely true if all nations carry out the stated reductions but is far from certain if we allow for non-compliance. As an illustration, we create another idealized scenario. Suppose, as in Section 3, that the OECD nations commit to the AOSIS protocol, requiring cuts to 20% below 1990 emissions levels. But this time, because of the economic hardships that these reductions entail and a lack of political will domestically, the U.S. does not constrain emissions despite the agreement (*i.e*. the U.S. emits roughly as much carbon as in the no policy case). For simplicity, we assume that all other OECD nations continue to implement the AOSIS protocol even after the U.S. is clearly not reducing emissions. In reality, one nation reneging would clearly reduce the incentive for others to keep their commitments.

The AOSIS protocol is more stringent than the alternative of stabilizing emissions at 1990 levels. How do the cumulative emissions of the AOSIS protocol, without the U.S. complying, compare with an emissions stabilization protocol in which all parties meet the agreement? As in Section 3, we examine the relative effects of these two policy scenarios under the same uncertainties described above. Again using cumulative emissions for 1990–2100 of 1400 GtC as a loose proxy for a 2˚C rise in temperature, what is the probability under each policy that the goal is

[19] Australia has publicly threatened to refuse to participate in any protocol that fails to allow for differentiation of burdens to account for impacts on Australia's trade balance, which is highly dependent on coal exports (McPhedran, 1996; O'Sullivan, 1997). Theoretical investigations of the implications of free-riders for climate change agreements can be found in Nordhaus and Yang (1996) and Hoel (1994).

met? As shown in Figure 6, the AOSIS protocol without the U.S. has significantly less chance of meeting the long-term policy goal than the stabilization protocol. The probability of meeting the target is only 66% for AOSIS without the U.S., as compared with 91% for stabilization with full participation.

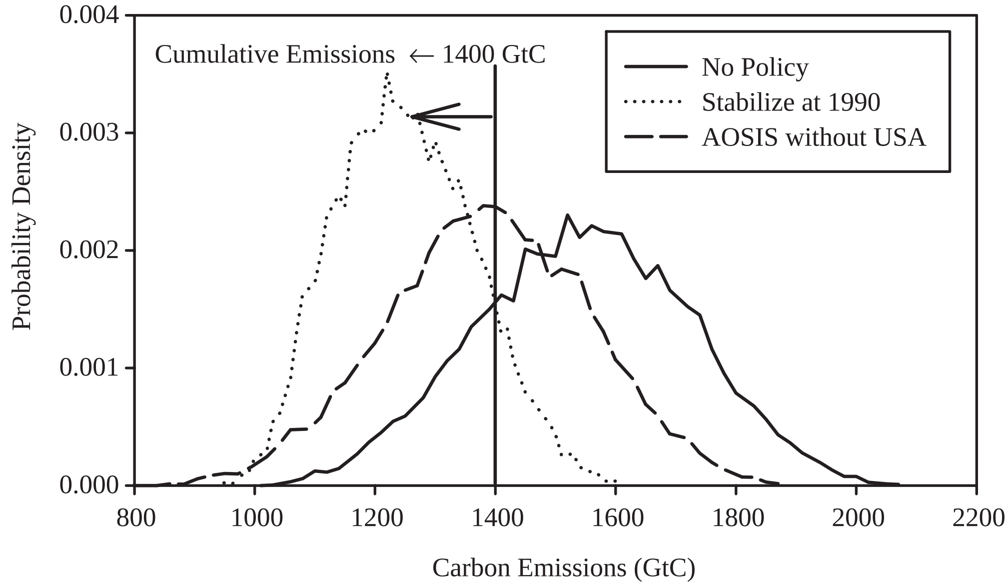

Figure 6. Probability densities of cumulative emissions for no policy, stabilization with participation from all OECD regions, and AOSIS imposed on all OECD regions except for U.S., which is completely unconstrained.

Although this example is highly simplified, it illustrates that the tradeoff between the stringency of a protocol and compliance with that protocol can have dramatic implications for climate. It is, after all, reduced climate impacts that should be the measure against which the success of any protocol is assessed, not the maximum burden that a subset of countries is willing to bear. There is a greater chance of reducing the impact of climate change through agreements that, even if less stringent, are more likely to be complied with. Although this experiment may seem to overstate the case by choosing the U.S., the largest emitter, to be in complete non-compliance, we simply provide this example as a starting point in considering the balance between stringency and compliance. Non-compliance or non-adherence by minor emitters would, obviously, have less dramatic impact and could reverse the policy recommendations. It is not unreasonable, however, to imagine that there may be several countries that only partially comply, which could combine to have as large impact as one major emitter not complying (*e.g.*, the failed commitments to reach 1990 levels by 2000).[20] Furthermore, a failure of one party to meet commitments while other

[20] This example also illustrates the importance of getting the largest CO_2 emitters to agree in the first place. For example, Skolnikoff (1997) notes that the reticence of the U.S. to agree to substantial emissions reductions has greatly reduced prospects for agreement to a stringent protocol.

parties face stringent restrictions, will more likely result in other nations reneging and in an overall loss of credibility for a coordinated international effort.

Thus, gains from a more stringent protocol may well be more than offset if it increases the chances that the agreements may not be met. The issue of political uncertainty is clearly central in crafting an effective and robust international response and has not been given adequate attention in the literature. The success of an agreement will be measured not only by the stringency claimed by a protocol but also by the implementation of said protocol, measured in terms of adherence and compliance.

6. Discussion and Conclusions

This paper has presented several simple illustrations of the ability of current policy proposals to meet a long-term climate impact goal when uncertainties in economic growth and technology development are made explicit. We would remind the reader that a number of caveats and areas for further work remain:

- A probabilistic model is not the *ideal* framework for formulating a response to climate change, it simply provides another set of tools that can be useful in reminding both policy analysts and policy-makers about real-world uncertainties.
- Inter-model differences are an important source of uncertainty and different outcomes, and so the type of exercise presented here would ideally be repeated on several models.
- Conclusions drawn from uncertainty analysis will hold only if rapid, unanticipated, catastrophic change is not present. Since concern over a surprise is a major motivation for addressing climate change, evaluating policies in the presence of a possible surprise should be modeled explicitly.
- Our emphasis on the need for flexible response points to the importance of sequential decision-making, as opposed to the simplistic once-only decision model used here and in most other studies.

Solutions do not emerge from modeling exercises. Climate change, like most environmental problems, is at its heart a question of how society (in this case the international community) deals with risk and the provision of public goods. Any solution must inevitably come from the political arena and an on-going balancing of competing interests and values. Nevertheless, we do maintain that powerful insights, not otherwise available, are provided by explicitly analyzing uncertainty:

1. *Emissions Paths Are Misleading*. The concept of a global path of emissions over time is not a helpful analytical construct because it ascribes a false concreteness to the study of the effects of policy. While quantifying the effects of different policies is an important contribution of modeling, deterministic answers imply a clear preference for one policy over another in the sense that one policy is perceived as coming closer to accomplishing some "goal." We argue that, given underlying uncertainty, no model can predict whether actions will be sufficient. Rather, it is preferable to ask how much more likely one policy is to achieve some goal than another. More useful insights are likely to emerge from such an approach.

2. *Any Response To Climate Change Must Be Flexible*, not only in terms of quantitative targets, but also in terms of the institutions and policy instruments. Although this analysis does not explore the uncertainty in ultimate impacts and in costs of emissions reductions, the same uncertainties that cause a wide range of possible emissions will result in large ranges of cost and impact estimates. Since these uncertainties will not be reduced in the short-term, policy-makers should be prepared to adapt policies for any eventuality.

3. *Interpretation Can Be Ideological, Modelling Exercises Should Not Be*. Relying solely on emissions paths can draw unnecessary attention to model structure, based largely on ideological positions, because comparing point estimates of different modeling results places the entire debate over uncertainty at the level of inter-model differences. The integrity of model comparison exercises could benefit from increased reliance on uncertainty analysis within each model, thereby spanning alternative ideological positions.

4. *The Current Policy Debate Over Emissions Reductions Has Relatively Minor Implications For Climate*. If the goal is to prevent temperature from rising by more than 2˚C in 100 years (or, more accurately, preventing cumulative emissions from exceeding 1400 GtC), then the differences in impact between prominent current proposals are found to be minimal. It is more important to stabilize in the industrialized world at *any* of the levels being considered.

5. *Climate Impacts Should Inform The Tradeoff Between Stringency And Compliance.* Simply assuming that the strictest protocol will provide the best result for climate neglects the fact that outcomes depend significantly upon adherence and compliance assumptions. If, in order to achieve a slightly more stringent protocol, nations negotiate a protocol that is so strict that it encourages countries to defect for a variety of political or economic reasons, then a less stringent target that is more likely to achieve full compliance can have a better chance of reducing the impacts of climate change.

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