Assessing Climate Change under Uncertainty: A Monte Carlo Approach

by

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May 2008

Masters project submitted in partial fulfillment of the
requirements for the Master of Environmental Management degree in
the Nicholas School of the Environment and Earth Sciences of
Duke University
2008

Abstract

Climate change has emerged as one of the most multifaceted manifestations of global change of our time. However, there is less confidence about exactly how the climate will change in the future, and lesser confidence still about the adjustments it will induce to natural and human system. Thus, policy formulation for climate change poses a great challenge because of a problem of decision-making under uncertainty. To facilitate climate policy decision, quantification of the uncertainty in climate outcomes under possible policies is needed. This paper presents an approach to assess climate change under uncertainty using Monte Carlo simulations. Here, I find that in the absence of climate policy, the 95% bound on temperature change in 2100 is 5.79°C. The stringent climate policies with aggressive emissions reductions over time lower significantly the temperature change, compared to no policy case.

Key words: Climate Change, Uncertainty, DICE model, Monte Carlo simulation

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1. Introduction

Climate change has emerged as one of the most multifaceted manifestations of global change of our time. As emphasized in the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC)[1], it is virtually certain that Earth's climate is changing, with most of the warming over the last 50 years "very likely" to be attributable to the increase in atmospheric greenhouse gas concentrations.

However, there is less confidence about exactly how the climate will change in the future, and lesser confidence still about the adjustments it will induce to natural and human systems. Thus, policy formulation for climate change poses a great challenge because it presents a problem of decision-making under uncertainty.[2] The uncertainty in future climate change impacts is large, as is the uncertainty in the costs of potential policies. Rational and economically efficient policy choices will therefore seek to balance the expected marginal costs with the expected marginal benefits.[3] This approach requires that the risks of future climate change be assessed. Given the goal of describing uncertainty in future climate change, we need to characterize the main causes of

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[1] Intergovernmental Panel on Climate Change (IPCC). 2007. *Fourth Assessment Report (AR4): Climate Change 2007*. Nov. 17th.

[2] Manne, A.S., and R.G. Richels, 1995. The greenhouse debate: Economic efficiency, burden sharing and hedging strategies. *Energy Journal*, 16(4).

[3] Webster, M. 2005, Quantifying Uncertainty in Scenarios for Integrated Assessment of Climate Change, *Final Technical Report to Office of Science of the US Department of Energy*, October.

uncertainty in climate impacts. Policy-makers need a way to assess the possible consequences of different decisions, including taking no action, within the context of known uncertainties.

Decision-making under uncertainty is an appropriate framework for the climate problem because of two basic premises: effective mitigation action must be started before the climate changes of concern are actually observed; details of climate over longer periods are likely to remain unpredictable to some degree, and uncertainty in projecting future levels of human activities and technological change is inevitable[4]. Informed climate policy decisions require current estimates of the uncertainty in consequences for a range of possible actions. Further, the use of consistent and well-documented methods to develop these uncertainty estimates will allow us to track the changes in our understanding through time.

There have been many attempts to estimate the sensitivity[5] of the climate to increasing atmospheric greenhouse gas concentrations. Some early efforts attempted to

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[4] Webster, M.D, Forest C.,Reilly J., Babiker M., Kicklighter D.,Mayer M., Prinn R.,Sarofim M.,Sokolov A., Stone P.,Wang C.2003. Uncertainty Analysis of Climate Change and Policy Response, *Climatic Change*, 6(3).

[5] The climate sensitivity refers to the equilibrium surface temperature increase from a doubling of atmosphere CO_2. It determines the magnitude of anthropogenic temperature change from a given radiative forcing. The impact of this change is determined by the severity of climate damages from a given global average temperature change. Thus, the climate sensitivity is the most important uncertain variable for climatic outcome by far. In addition, parameters such as the population growth, the rate of decarbonization, and radiative forcing are of second-level importance. In this paper, I only focus on the climate sensitivity to show the temperature change under uncertainty.

determine the climate sensitivity from observational data.[6] Two decades ago, Gillialand and Schneider[7] scaled the observed temperature increase of both hemispheres to natural and anthropogenic forcings via the framework of a simple upwelling-diffusing model. They pointed out uncertainties in forcing precluded confident assessment of climate sensitivity by such semi-empirical means.

The IPCC[8] has long estimated that climate sensitivity ranges between 1.5°C and 4.5°C without indicating the relative probability of values within this range. Recent studies rely on a variety of methods to determine very different climate sensitivity ranges.

Morgan and Keith[9] produced a range of sensitivity similar to the IPCC range. Tol and de Vos[10], using Bayesian updating from the instrumental temperature record, predicted a 50% chance that the climate sensitivity is above 4.5°C. Mastrandrea and Schneider[11], and Hare and Meinshausen[12] demonstrated that the likelihood of avoiding any given temperature threshold for Dangerous Anthropogenic Inference (DAI) is extremely sensitive to the uncertainty associated with climate sensitivity.

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6 Webster, 2003.

7 Gilliland, R.L. and Schneider, S.H.1984, Volcanic, CO2 and solar forcing of Northern and Southern Hemisphere surface air temperatures, *Nature*,310(38)

8 Mastrandrea,M.D. and Schneider, S.H. 2004, Probabilistic Integrated Assessment of "Dangerous" Climate Change, *Science*, 304(23), April.

9 Morgan, M.G. and Keith, D.W.,1995. Subjective Judgments By Climate Experts, *Environmental Science and Technology*, 29(10).

10 Tol, R.S.J. and de Vos, A.F.,1998, A Bayesian statistical analysis of the enhanced greenhouse effect, *Climatic Change*, 38.

11 Mastrandrea et al. 2004.

12 Hare,B.and Meinshausen,M.2006.How Much Warming Are We Committed To And How Much Can We Avoided?, *Climatic Change*, 75.

O'Neill and Oppenheimer[13] also used a simple model of the type used in the Third Assessment Report (TAR) to produce temperature profiles based on their stabilization profiles, and chose three climate sensitivities within the IPCC range to produce a sensitivity analysis. More recently, a proliferation of probabilistic estimates explicitly based on calculations using observational data have also been presented[14].

However, these previous attempts to describe uncertainty have been limited in significant ways. First, the IPCC's emissions scenarios were not intended to be treated as equally likely, yet some authors have assumed that they were[15]. Next, few studies have examined the uncertainty in future climate change under a policy scenario leading to avoiding dangerous climate change.

Therefore, this paper builds on previous estimates of uncertainty in future climate changes but with two important improvements: (1) I run Monte Carlo simulations with different probability distributions for uncertain parameters and scenarios, based on DICE[16] model output; (2) I estimate uncertainty under three policy scenarios as well as a

[13] O'Neill,B.C. and Oppenheimer,M. 2004. Climate Change Impacts Are Sensitive To The Concentration Stabilization Path, *Proceedings of the National Academy of Sciences*, 101(47).
[14] Andronova and Schlesinger 2001; Gregory et al. 2002; Forest et al. 2002; Hegerl et al. 2006
[15] Ibid.
[16] DICE denotes a family of optimizing global integrated assessment models of climate change. DICE links an optimal economic growth model to a description of anthropogenic climate change with the implied economic impacts. Economic output is described by a constant-returns-to-scale Cobb-Douglas production function with labor and capital as input factors. DICE maximizes a global welfare function (discounted logarithmic utility from consumption) by determining the optimal division of economic output over time into consumption, investment, and emissions abatement. More detail explanation is in Method Section 2.1.

No Policy case, to show the impact of the range of uncertainty in my estimates for temperature change in 2100 and 2200. Using this approach, I provide a more comprehensive picture of the relative likelihood of different future climates than previously available. I also think that such probability distributions provide an important step in a probabilistic analysis of the implications of climate policy decisions to mitigate the greenhouse gases.

In reality, climate policy will be revised as we continue to learn and respond to new information and events. Policy decisions are therefore better modeled as sequential decisions under uncertainty. In order to perform such analyses, however, the uncertainty in projections must first be quantified.

Thus, what I present here is a necessary step to a more sophisticated treatment of climate policy. Section 2 describes the DICE model and Monte Carlo approach method. This is followed in Section 3 by a description of results, including an assessment of the relative magnitude of temperature change by different policy scenario and comparison the impacts on the different carbon taxes over time to lower the temperature change. In section 4, I discuss the conditions of optimal policy under uncertainty in order to maintain sustainable development. Finally, I conclude with the implications for climate change impact in section 5.

2. Method

2.1 DICE model

There are several Integrated Assessment models (IAMs) that have been used for the analysis of emission control policies. These models vary in complexity, structure, and the numerical values of key parameters. No IAM can credibly deal with all important factors nor cover the wide range of value-laden alternatives that need to be considered in real-world policy-making[17]. Nevertheless, IAMs can provide insights via sensitivity analyses of key uncertain parameters, structural elements, and value choices. In this paper, I chose *Nordhaus*'s Dynamic Integrated Climate Economy (DICE)[18] model because of its simplicity and relative transparency. The DICE model is a dynamic model of optimal economical growth that incorporates a simple feedback mechanism between economic activities and climate change. The economic assessment of the threat posed by climate change is based in part on the DICE model.[19] The DICE model is accepted widely within economic and policy circles as one of the authoritative economic analyses of global climate change because it integrates physical and economic mechanisms which underlie

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[17] Roughgarden, T. and Schneider, S.H. 1999. Climate change policy: quantifying uncertainties for damages and optimal carbon taxes, *Energy Policy*, 27.

[18] Nordhaus, W.D.1992. An Optimal Transition Path for Controlling Greenhouse Gases, *Science* 258

[19] Kaufmann, Robert K.1997, Assessing the DICE model: Uncertainty Associated with The Emission and Retention of Greenhouse Gases, *Climatic Change*, 35.

global climate change and its effect on economic wellbeing. The model simulates endogenously the rate at which economic activity emits carbon dioxide and other greenhouse gases, the rate at which these gases accumulate in the atmosphere, the effect of this accumulation on the planet's temperature, and the effect of changes in temperature on economic activity[20].

For each set of parameter values, the model determines the ''optimal'' forecast for future emissions reductions (i.e., abatement policy) by balancing the costs of reducing emissions with the costs of climate change. It assumes perfect markets and the imposition of a time-varying carbon tax to internalize the externality of climate damage into economic decisions dependent on the price of carbon energy[21].

In particular, in a situation where emissions are limited, it is useful to think of the market signal as a "carbon price." This represents the market price or penalty that would be paid by those who use the fossil fuels and thereby generate the CO_2 emissions[22]. The carbon price might be imposed via a "carbon tax," which is like a gasoline tax or a cigarette tax except that it is levied on the carbon content of purchases.

Thus, I think it is meaningful to compare carbon tax of each scenario: baseline

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[20] Ibid.

[21] Nordhaus, William. 2007. *The Challenge of Global Warming: Economic Models and Environmental Policy*. Yale University Press, New Haven.

[22] Ibid.

(*No Policy*), *Nordhaus*'s *Optimal Policy* scenario, *Stern* Review, and *Al Gore* Proposal, because carbon tax is one of approaches to implement effectively climate policy by raising the market price of carbon emissions.

Moreover, carbon taxes approach can easily and flexibly integrate the economic costs and benefits of emissions reductions. It also allows the public to get the revenues from restrictions easily, and it may therefore be seen as fairer and can minimize the distortions caused by the tax system[23].

Thus, using DICE model allows for exploration of the impacts of a wide range of mitigation levels on the potential for exceeding a policy-relevant climate threshold. In this paper, I focus on two types of model output: (1) global average surface temperature in 2100 and 2200; (2) optimal carbon taxes.

2.2 Monte Carlo Simulation

The Monte Carlo Simulation is a technique that converts uncertainties in input variables of a model into probability distributions over output variables. By combining the distributions and randomly selecting values from them, it recalculates the simulated model many times and brings out the probability of the output. It is categorized as a

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[23] Nordhaus, 2007.

sampling method because the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population.[24] The Monte Carlo Simulation is straightforward and flexible. Even if it cannot wipe out uncertainty and risk, it can make them easier to understand by ascribing probabilistic characteristics to the inputs and outputs of a model. Besides, it can be very useful for determining different risks and factors that affect forecasted variables and, therefore, it can lead to more useful predictions.

To examine the relative contributions of uncertain climate parameters (climate sensitivity and radiative forcing), I use a reduced-form version[25] of climate model to generate the Probability Density Functions (PDFs) of temperature change by Monte Carlo simulation. I first identify probability distributions for the uncertain input parameters: defining climate sensitivity as two different probability distributions[26]: (uniform and triangular distributions) and radiative forcing as log-normal distribution.

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[24] Mooney, Christopher Z. 2004, Monte Carlo Simulation, Series: Quantitative Applications in the Social Sciences Series, #116, *SAGE Publications*, June.

[25] Mastrandrea, M.D. and Schneider, S.H., 2005. Probabilistic Assessment of 'Dangerous' Climate Change and Emissions Pathways, *Proceedings of the National Academy of Sciences*, 102 (44).
$\Delta T_{EQ} = (\Delta F / \Delta F_{2X}) \times \Delta T_{2X}$ Where ΔT_{EQ} is the equilibrium temperature increase above pre-industrial levels, ΔF is the radiative forcing in W/m^2 for a particular stabilization level, ΔF_{2X} is the radiative forcing estimate for a doubling of atmosphere CO_2, and ΔT_{2X} is the climate sensitivity. For these calculations, I set ΔT_{2X}=3°C and $\Delta F_{2X} = 3.8 W/m^2$,as suggested by *Nordhuas*.

[26] In this paper, as my focus is the climate sensitivity, I set the climate sensitivity with two different distributions to choose more reasonable distribution under uncertainty.

Then, I also identify the output parameter (temperature change) that needs to be analyzed, and run the simulation with 10,000 iterations.

However, determining a suitable distribution for uncertain input (parameter) is potentially challenging in many cases. In an attempt to avoid the risk, researchers have often chosen to use a uniform distribution, which is sometimes described as "ignorant" [27]. In this paper, I use the uniform prior U[0, 20ºC] from *Frame et al*[28].

Another way to attempt to formulate a more credible distribution[29] would be look back through the literature, to see what climate scientists actually wrote various distributions to the analysis of their datasets. I adopt the IPCC range of 1.5~4.5ºC for the climate sensitivity parameter in the model and assume a simple triangular probability distribution (1.5, 3, 4.5), implying that the central value of 3.0ºC is most likely. As for the probability distribution of radiative forcing, I assume log-normal probability distribution by following previous studies' result[30] (mean: 3.8; standard deviation: 1.2).

These two initial Monte Carlo simulations are run with a baseline scenario (*No Policy*) with each different probability distribution (uniform and triangular distributions) of climate sensitivity (Figure 1). Use of these probability distributions allows me to

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27 Annan, J.D. and Hargreaves, J.C.2008, *Can we believe in high climate sensitivity?* http://arxiv.org/PS_cache/physics/pdf/0612/0612094v1.pdf

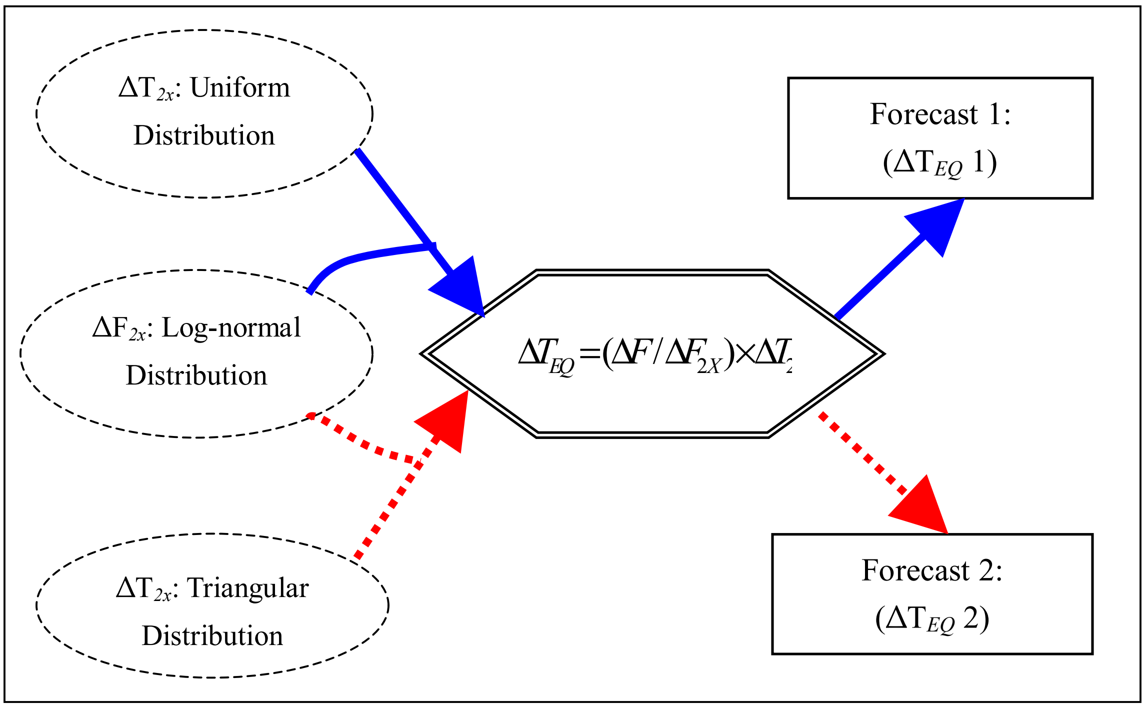
28 Frame, D.J., B.B.Booth, J.A. Kettleborough,D.A. Stainforth, J.M. Gregory, M.Collins and M.R.Allen, 2005. Constraining Climate Forecasts: The Role of Prior Assumptions, *Geophysical Research Letters*, 32.

29 This can be called "Expert Distribution" because this is based on pervious literatures or existing studies.

30 Hansen et al (1988), Lacis et al (1981), and Wigley (1987)

sample a range of uncertainty in climate sensitivity representative of the range reported until now.

Figure 1. Monte Carlo Simulation Process for Choosing Appropriate Probability Distribution of Uncertain Inputs



Further, based on this result, I run next simulations under different climate policy scenarios with time-varying carbon taxes, and then analyze the impacts on temperature change in 2100 and 2200.

In DICE model, baseline (*No Policy*) is an attempt to project from a positive perspective the levels and growth of major economic and environmental variables as would occur with *No Policy*. *Nordhaus*'s *Optimal Policy* scenario is the best possible policy path for emissions reductions given the economic, technological, and geophysical constraints[31]. In this case, emissions are set to maximize the value of net economic consumption.

Next two approaches analyzed here are to call for very sharp emissions reductions in the near term. One of these is an estimate with a very low time discount rate and return on capital in the *Stern Review*. For this, Nordhaus adopted the 0.1-percent–per-year time discount rate advocated by the *Stern Review* and used a dual discount-rate approach: a very low real interest rate (around 1% per year) on climate investments, while the rest of the economy uses current discounting (at around 5½% per year)[32]. The other is motivated by a suggestion made by *Al Gore* for very deep near-term cuts in emissions. *Gore* proposed that U.S. emissions be reduced by 90 percent by 2050 along with other steps such as banning coal-fired plants and enhancing efficiency standards[33].

By simulating temperature change in each scenario, we can see which policy is more efficient for society.

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[31] Nordhaus 2007.
[32] Ibid.
[33] Ibid.

3. Results

3.1 Two Probability Distributions for Uncertain Parameters

To find more appropriate probability distribution for uncertain parameters, I ran initial Monte Carlo simulations of the model with 10,000 iterations, using the uniform and triangular distributions. As can be seen in Figure 1, the uniform distribution U[0, 20°C] actually represents that the temperature change is “likely” (about 71%: blue area in Figure 2) greater than 6°C (=$\Delta T>6°C$). In this case, the resulting uncertainty in temperature change in 2100 is somewhat greater. As for the triangular distribution, probability of $\Delta T>6°C$ is approximately 4% (blue area in Figure 3).

As might be expected, uniform distribution has somewhat greater range than triangular distribution. That is, uniform distribution shows an extreme viewpoint which cannot be reconciled with actual prior scientific opinion. In addition, societies and ecosystem whose average temperature has changed in the course of a century by $\Delta T>6°C$ are located in the *terra incognita* of what any honest economic modeler would have to admit is a planet Earth reconfigured as science fiction[34]. Thus, to apply a plausible distribution to next Monte Carlo simulations, I choose a triangular distribution because this is more reliable to predict the future temperature change.

[34] Weitzman, Martin L. 2007, *The Stern Review of the Economics of Climate Change*, Book report commissioned by JEL (Preliminary)

Figure 2. Forecast 1: Using Uniform Distribution for Climate Sensitivity

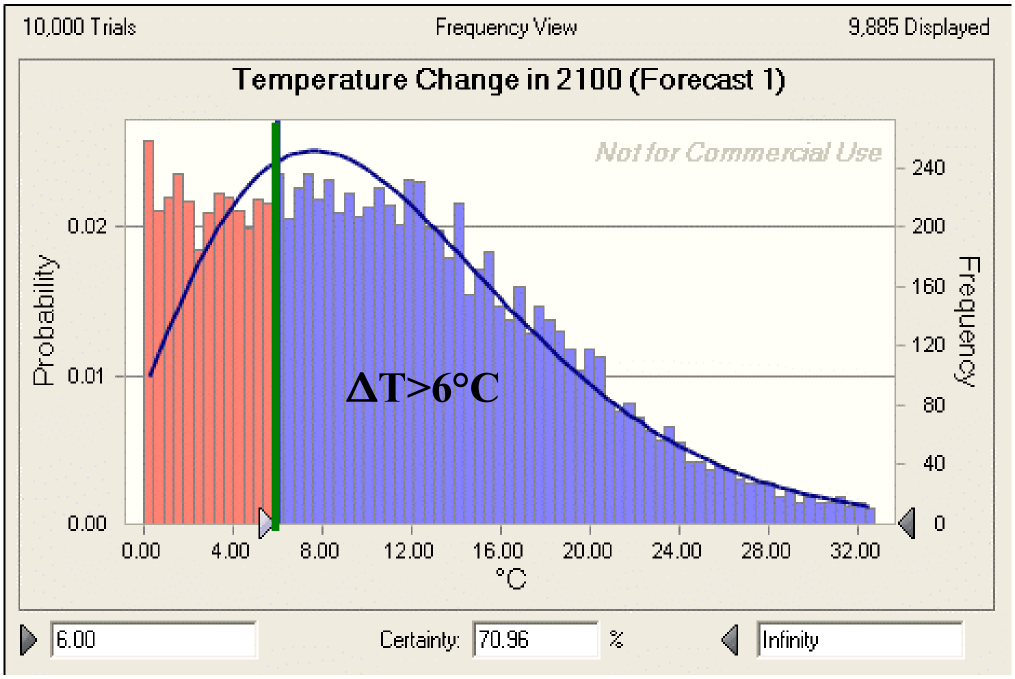
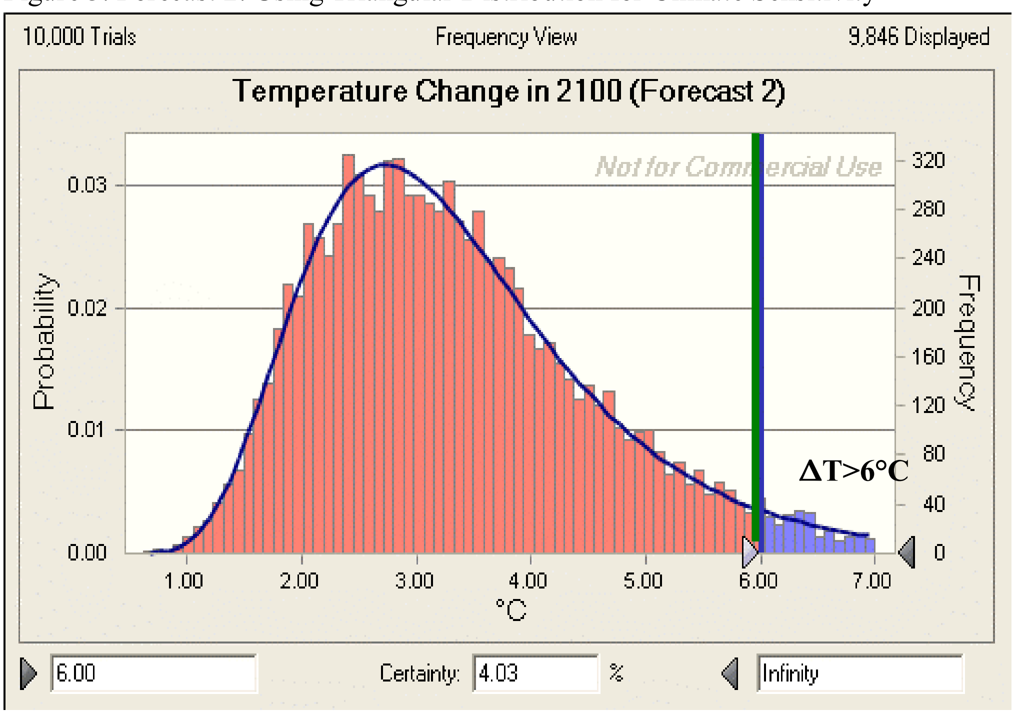


Figure 3. Forecast 2: Using Triangular Distribution for Climate Sensitivity



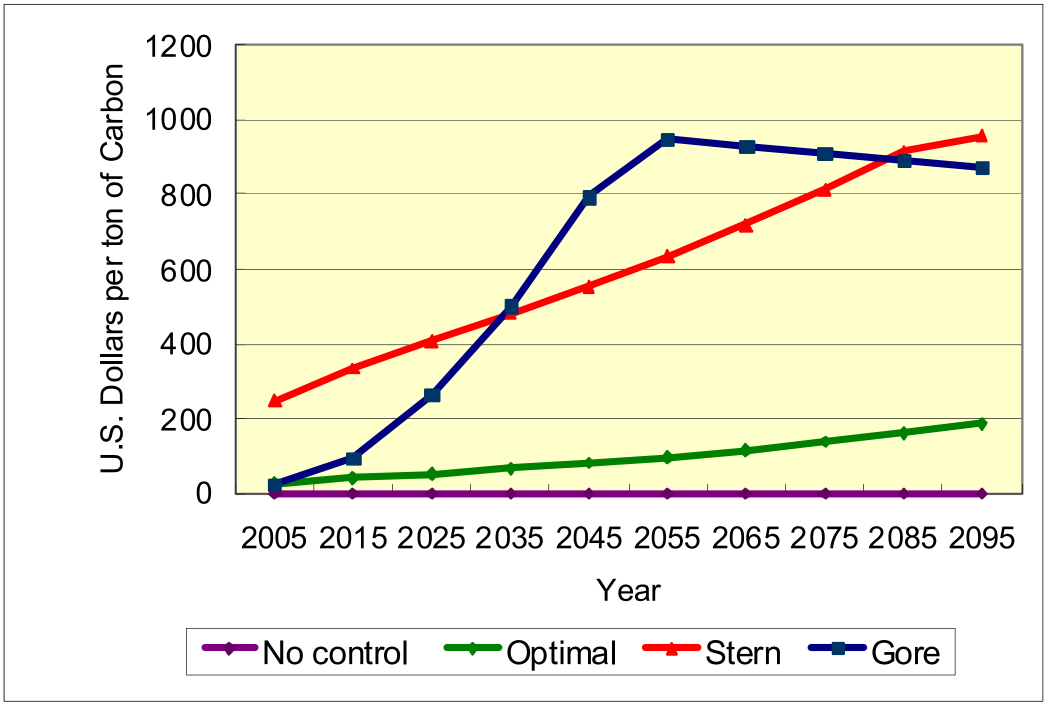
3.2 Uncertainty Analysis with Different Climate Policy Scenarios

Under a price approach, the level of emissions is determined indirectly by the level of the tax[35] or penalty levied on carbon emissions. For example, the carbon price measures the market price to emit 1 ton of carbon through burning fossil fuels or other activities.[36] The key economic question under any policy scenario is whether the price is likely to be high or low, and as a result of this tax, what level of efficient emissions reductions we can achieve to slow global warming. Figure 4 shows the time-varying carbon taxes under different policy scenarios: *No Policy* has little change in tax from 2005 to 2095; *Optimal Policy* increases gradually the carbon tax; *Stern* Review climbs significantly like straight line; *Gore* Proposal rises sharply until 2050, after then the tax declines a little.

[35] According to *Nordhaus*'s highly simplified assumption, the carbon tax is proportional to $(Z \times CS \times Y)/R$, where Z is the ratio of damages to output at 3°C, CS is the climate sensitivity, Y is world output, and R is the average discount factor.

[36] Nordhaus, William D. 2007. To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming, *Review of Environmental Economics and Policy*, 1(1)

Figure 4. Carbon Taxes for Different Climate Policy Scenarios



Based on time-varying carbon taxes, the first run is one in which no policies are taken to slow or reverse greenhouse warming. As shown in Figures 5 and 6, in the absence of any climate policy, the mean temperature increase is 3.38°C by 2100 and 5.87°C by 2200, and median is 3.16°C by 2100 and 5.49°C by 2200.

Figure 5. Baseline (*No Policy*) Scenario in 2100

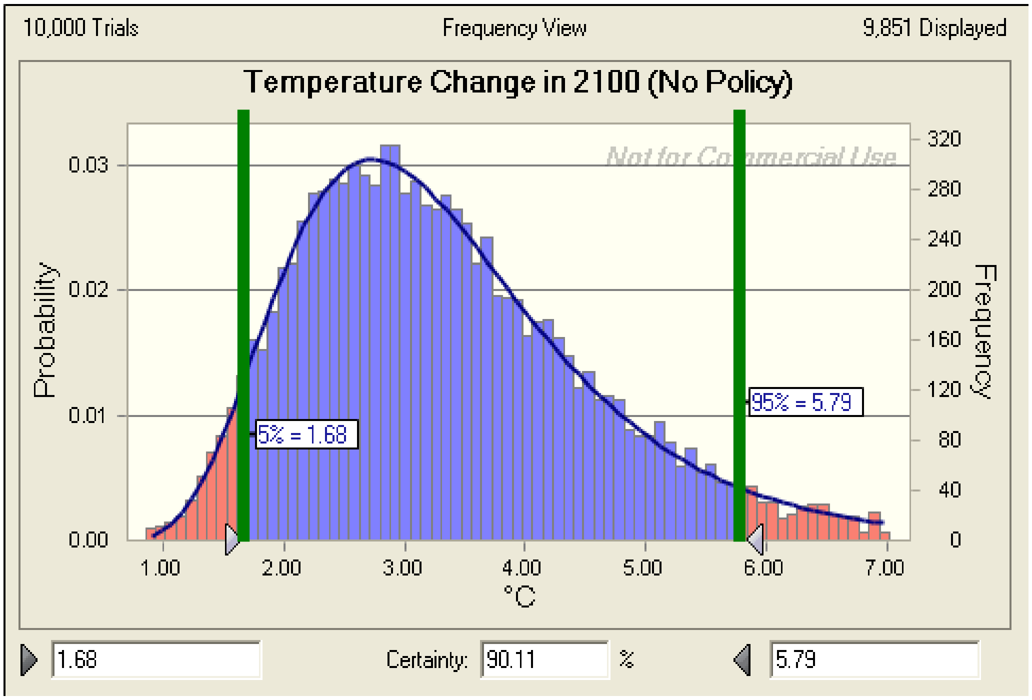
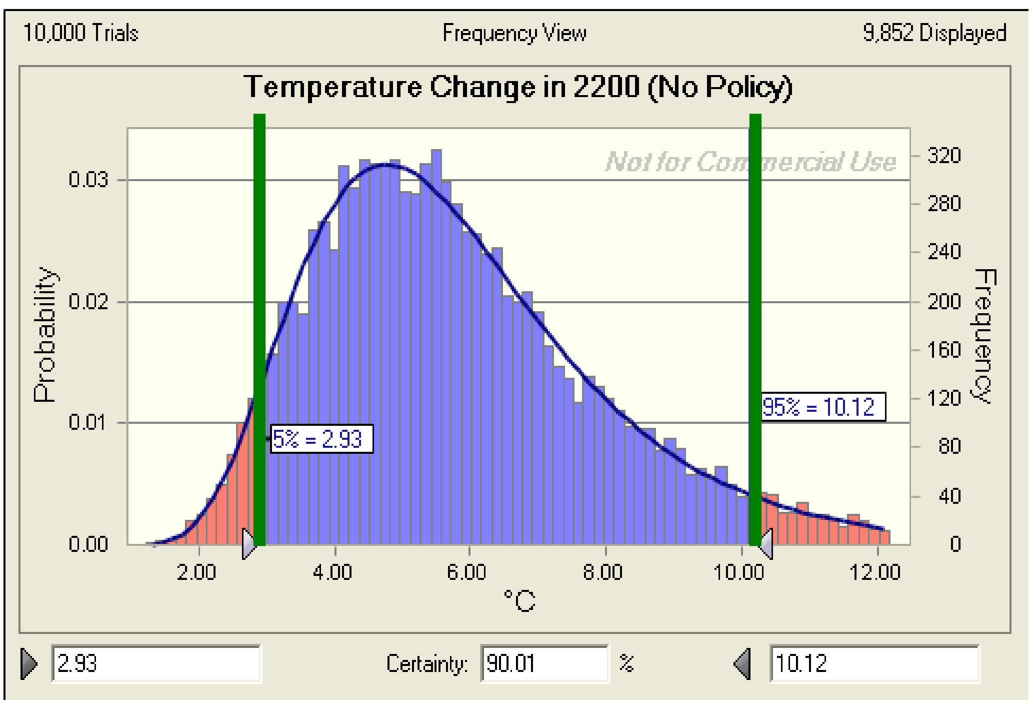


Figure 6. Baseline (*No Policy*) Scenario in 2200



The second case solves for an economically efficient or "optimal" policy to slow climate change. This can be interpreted as the economic optimum with no non-economic constraints. Figures 7 and 8 show that economic optimum has a mean temperature change of 3.03°C by 2100 and 3.80°C by 2200, and median is 2.86°C by 2100 and 3.57°C by 2200.

Figure 7. *Nordhaus* Optimal Scenario in 2100

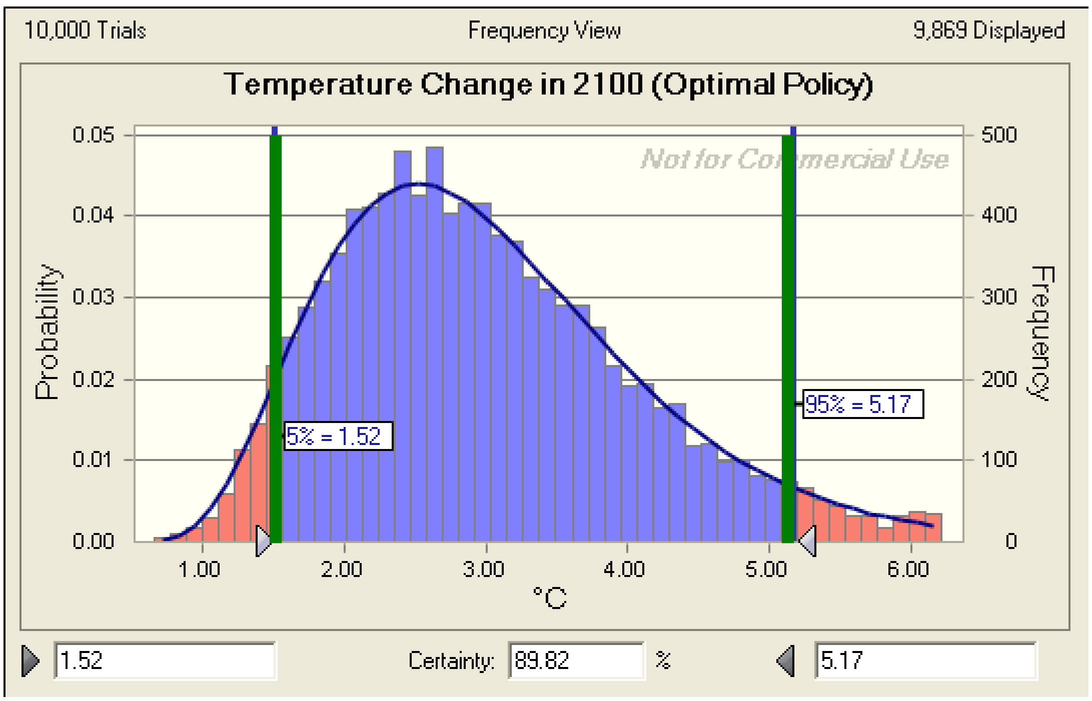
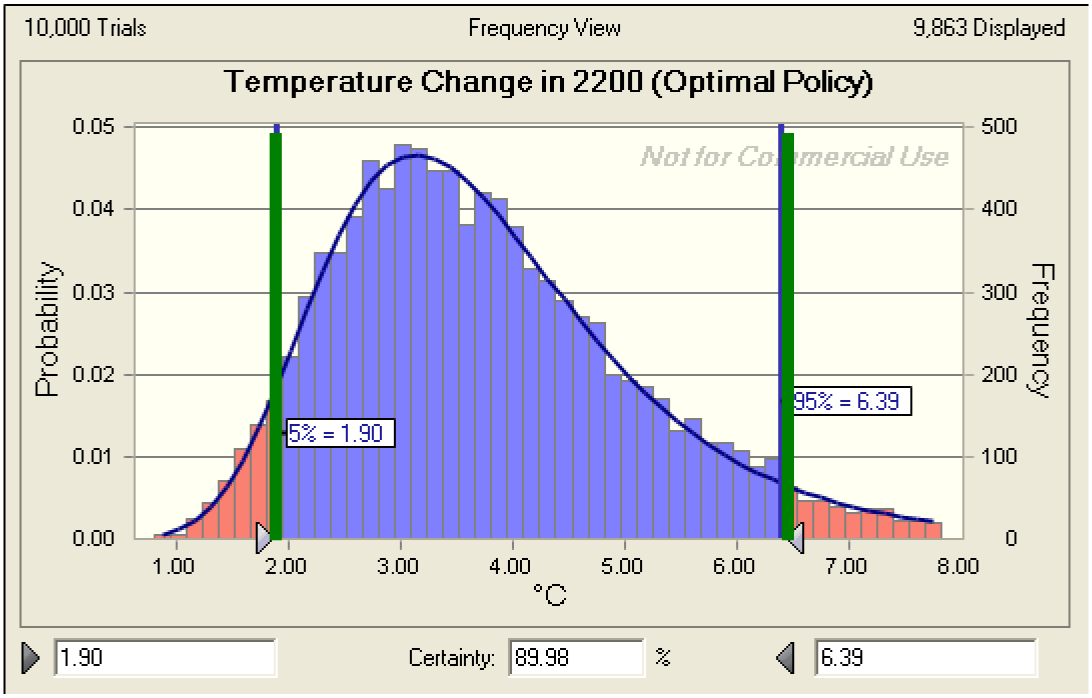


Figure 8. *Nordhaus* Optimal Scenario in 2200



Figures 9 and 10 show that mean temperature change is 1.66°C by 2100 and 1.40°C by 2200, and median is 1.56°C by 2100 and 1.32°C by 2200.

Figure 9. *Stern* Review in 2100

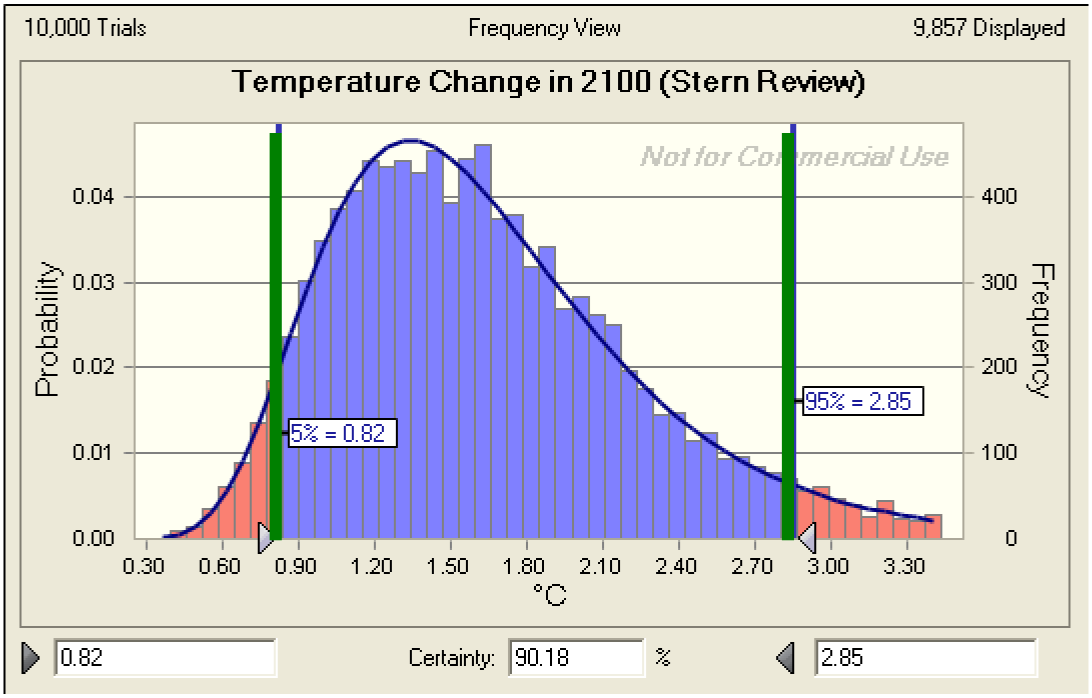
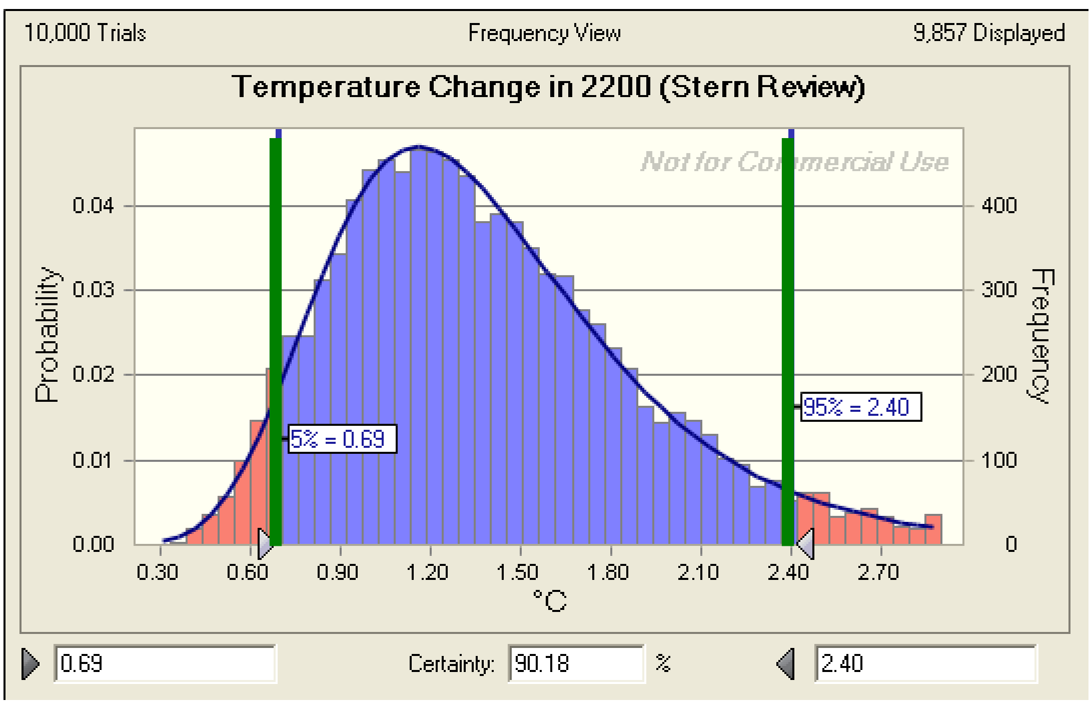


Figure 10. *Stern* Review in 2200



As can be seen in Figures 11 and 12, *Gore* proposal has the lowest mean value (1.63°C) and median is 1.53°C by 2100. However, in 2200 the mean increases a little bit by 1.74°C and median is 1.63°C.

Figure 11. *Gore* Proposal in 2100

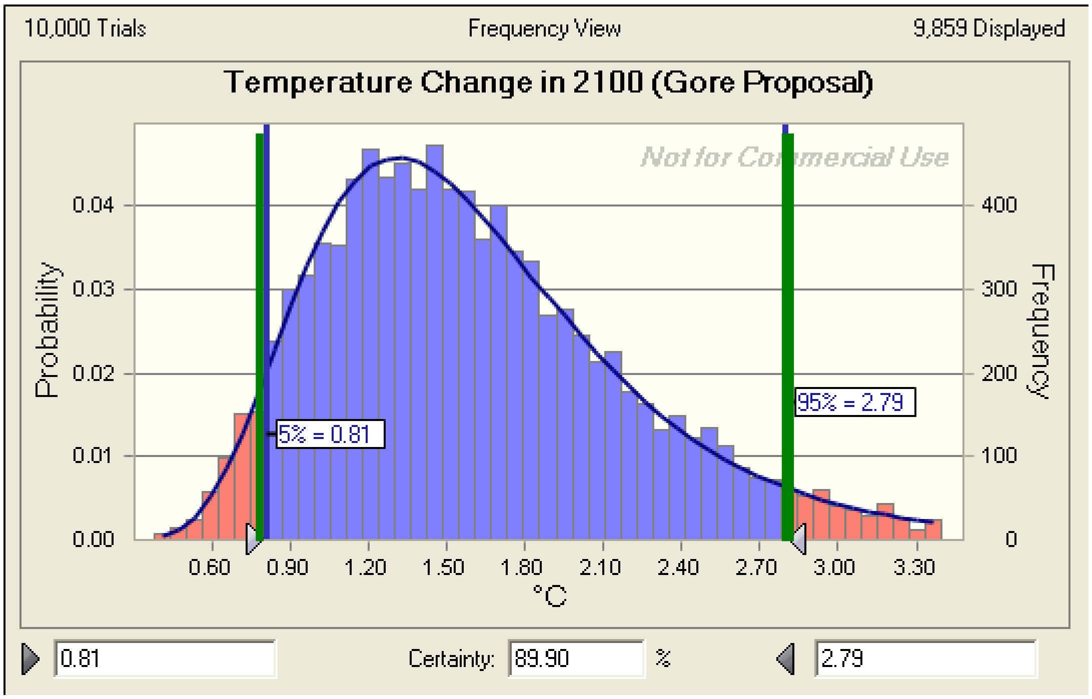


Figure 12. *Gore* Proposal in 2200

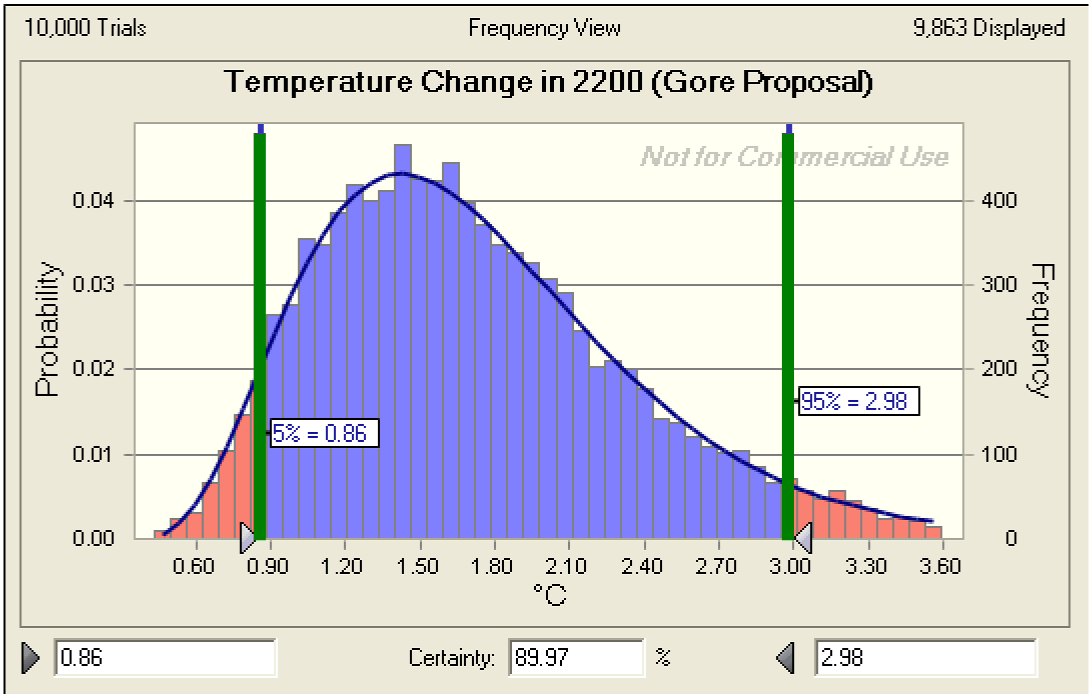


Table 1. Confidence Range (5~95%) of Four Climate Policy Scenarios

Scenario	Confidence Range (5~95%)	
	2100 year	2200 year
No Policy	1.68~5.79°C (mean=3.38)	2.93~10.12 (mean=5.87)
Optimal	1.52~5.17°C (mean=3.03)	1.90~6.39 (mean=3.80)
Stern	0.82~2.85°C (mean=1.66)	0.69~2.40 (mean=1.40)
Gore	0.81~2.79°C (mean=1.63)	0.86~2.98 (mean=1.74)

According to overall result, compared to baseline scenario (*No Policy*), all three climate policy scenarios have lower mean temperature change and narrower confidence range. Table 1 shows that the range gap between baseline scenario and climate policy scenarios is wider in 2200 than in 2100. Moreover, with policy, the mean outcomes tend to be somewhat higher than the modes of the distribution, reflecting the skewed distribution.

At this point, it is interesting to note that the results from *Stern* and *Gore* show very similar outcome although *Stern Review* imposes higher carbon tax than *Gore Proposal* over time. Thus, this represents excessively high carbon tax or sharp emissions reduction in the short-term does not give a substantial improvement on the temperature change and insensitive to reasonable changes in the temperature.

4. Discussion

Economics contains one inconvenient truth about climate-change policy: For any policy to be effective in slowing global warming, it must raise the market price of carbon, which will raise the prices of fossil fuels. Prices can be raised by limiting the number of carbon emissions permits that are available, or by levying a tax on carbon emissions. Economics also teaches us that it is unrealistic to hope that major reductions in emissions can be achieved by hope, environmental ethics, or guilt alone[37]. The only way to have major and durable effects is to raise the price of carbon emissions. Thus, the optimal carbon tax is made by the market price on carbon emissions that balances the incremental costs of reducing carbon emissions with the incremental benefits of reducing climate damages.

In this paper, my intention is to find the implications of temperature change in 2100 and 2200 with time-varying carbon taxes under different policy scenarios, and then to suggest the condition of an efficient policy for decision-making.

As for *No Policy* scenario, its constraint is relaxed and people are free to trade off the costs of climatic change with those of emissions abatement.[38] If the costs of global

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[37] Nordhaus W.D. 1993. Rolling the DICE: An Optimal Transition Path for Controlling GHG's, *Resource and Energy Economics*,15(1).

[38] Even if the government does not enforce firms or people to reduce the emissions by the regulations, emission abatement costs occur. Nevertheless, this cost may be much less than that in climate policy scenarios.

warming are relatively small, the incentive to mitigate carbon emissions will also be small. If the impacts of climatic change are great, however, this policy option would be a relatively poor policy from the point of view of optimizing economic efficiency. This argument can be more appropriate when we compare the result of temperature change in 2200 under *Optimal Policy* scenario with under *No Policy* scenario (Table 1) because major warming tends to be in store due to past emissions and build-in inertia in the climate system. Table 1 shows well how temperature change can change between Without Polic*y* and With Policies in 2200.

Next, the economic problems with the *Stern* and *Gore* strategies are shown by the high emissions-control rates and carbon taxes they assume. The 80~90% emissions control in the short-term requires high carbon taxes up to $1000/ton of carbon (Figure 4). As these prices are extremely large, the economic costs are consequently also large. Table 2 shows that there are clearly big stakes involved in climate-change policy scenarios, and ambitious policy scenarios with such a high carbon tax would prove much more expensive. These scenarios are focused entirely on cutting emissions as much as and as quickly as possible, regardless of cost or any other practical considerations.

Table 2. Benefit-Cost Ratio Relative to *No Policy* Scenario

Scenario	Benefits	Abatement Costs	Benefit-Cost Ratio
	(Trillions of 2005 U.S. $)		
Optimal	5.23	2.16	2.4
Stern	13.53	27.70	0.5
Gore	12.50	33.86	0.4

Finally, in view of the large uncertainties in estimates of climate change, a probabilistic formulation that links many of the structural and data uncertainties and thus acknowledges the wide range of optimal policies is essential to policy analysis. Thus, based on probabilistic assessments, if policy-makers try to follow these goals, carbon tax could achieve a long-term emission reduction target.

5. Conclusion

Analysis of possible future climate changes should include quantification of the uncertainty in climate projections. In this paper, I constructed two different distributions for climate sensitivity and compared four different climate policy scenarios with time-varying carbon taxes. I find that uniform distribution for climate sensitivity shows an extreme viewpoint which cannot be reconcile with actual scientific opinion. I also confirmed that more stringent climate policy scenarios would lead to lower temperature change and narrower confidence range of PDFs.

However, this result implies that the trajectory of optimal carbon tax should rise steadily over time to reflect the rising abatement costs from climate change because undertaking sharp emissions reductions in the short term is not economically advantageous. Moreover, the stringent measures to control CO_2 emissions would be costly even if benefits to emission reduction are considered. Thus, it is important to realize that ideal and efficient climate change policy would be relatively inexpensive and have substantial impact on long-run climate change. For example, the economic consequences of *Gore*'s plan would be severe consequences for economic growth and employment because of technological limits on our ability to cut emissions, the cost of large-scale emissions reductions, and the developing countries' role.[39]

I believe that probabilistic frameworks are an effective tool for scientific assessment. Despite great uncertainty in many aspects of DICE model, prudent actions can substantially reduce the likelihood and thus the risks of dangerous climate change. Thus, I hope this paper can be a contribution to help fill that gap in the literature, providing probability distributions of future climate projections based on current uncertainty.

In reality, decisions today can only be based on the information we have today. The work presented here is one attempt to bring together current knowledge on science and economics to understand the likelihood of future climate outcomes as we understand the science and economics today.

[39] Thernstrom, Samuel. 2007, Crazy Like a Fox, *The American*. April 11. http://www.american.com/archive/2007/april-0407/crazy-like-a-fox/html

Acknowledgements

A special thanks to Professor Richard Anderson for his critical comments, careful scrutiny, continuous input and patience through successive drafts. I also would like to thank Dr. Michael Mastrandrea, for their valuable comments, which improved the focus of the study. I appreciate greatly Kiyoung Chang gave me to his encouragement and support in implementing the study.

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