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Robert S. Pindyck

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1050 Massachusetts Avenue

Cambridge, MA 02138

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Uncertain Outcomes and Climate Change Policy  
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**ABSTRACT**

Focusing on tail effects, I incorporate distributions for temperature change and its economic impact in an analysis of climate change policy. I estimate the fraction of consumption  $w^*(\tau)$  that society would be willing to sacrifice to ensure that any increase in temperature at a future point is limited to  $\tau$ . Using information on the distributions for temperature change and economic impact from studies assembled by the IPCC and from “integrated assessment models” (IAMs), I fit displaced gamma distributions for these variables. Unlike existing IAMs, I model economic impact as a relationship between temperature change and the growth rate of GDP as opposed to its level, so that warming has a permanent impact on future GDP. The fitted distributions for temperature change and economic impact generally yield values of  $w^*(\tau)$  below 2%, even for small values of  $\tau$ , unless one assumes extreme parameter values and/or substantial shifts in the temperature distribution. These results are consistent with moderate abatement policies.

Robert S. Pindyck  
Sloan School of Management  
MIT, Room E52-453  
50 Memorial Drive  
Cambridge, MA 02139  
and NBER  
RPINDYCK@MIT.EDU

# 1 Introduction.

Economic analyses of climate change policies often focus on a set of “likely” scenarios — those within a roughly 66 to 90 percent confidence interval — for emissions, increases in temperature, economic impacts, and abatement costs. It is hard to justify the immediate adoption of a stringent abatement policy given these scenarios and consensus estimates of discount rates and other relevant parameters.<sup>1</sup> I ask whether a stringent policy might be justified by a cost-benefit analysis that accounts for a full distribution of possible outcomes.

Recent climate science and economic impact studies provide information about less likely scenarios, and allow one to at least roughly estimate the distributions for temperature change and its economic impact. I show how these distributions can be incorporated in and affect conclusions from analyses of climate change policy. As a framework for policy analysis, I estimate a simple measure of “willingness to pay” (WTP): the fraction of consumption  $w^*(\tau)$  that society would be willing to sacrifice, now and throughout the future, to ensure that any increase in temperature at a specific horizon  $H$ ,  $\Delta T_H$ , is limited to  $\tau$ . Whether the reduction in consumption corresponding to a particular  $w^*(\tau)$  is *sufficient* to limit warming to  $\tau$  is a separate question which I do not address. Thus I avoid having to make projections of GHG emissions and atmospheric concentrations, or estimate abatement costs. Instead I focus directly on uncertainties over temperature change and its economic impact.<sup>2</sup>

My analysis is based on the current “state of knowledge” regarding global warming and its impact. In particular, I use information on the distributions for temperature change from scientific studies assembled by the IPCC (2007) and information about economic impacts from recent “integrated assessment models” (IAMs) to fit displaced gamma distributions for these variables. But unlike existing IAMs, I model economic impact as a relationship between temperature change and the *growth rate* of GDP as opposed to the level of GDP.

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<sup>1</sup>An exception is the Stern Review (2007), but as Nordhaus (2007), Weitzman (2007), Mendelsohn (2008) and others point out, that study makes assumptions about temperature change, economic impact, abatement costs, and discount rates that are well outside the consensus range.

<sup>2</sup>By “economic impact” I mean to include any adverse impacts resulting from global warming, such as social, medical, or direct economic impacts.

This distinction is justified on theoretical and empirical grounds, and implies that warming can have a permanent impact on future GDP. I then examine whether “reasonable” values for the remaining parameters (e.g., the starting growth rate and the index of risk aversion) can yield values of  $w^*(\tau)$  above 2 or 3% for small values of  $\tau$ , which might support stringent abatement. Also, by transforming the displaced gamma distributions, I show how  $w^*(\tau)$  depends on the mean, variance, and skewness of each distribution, which provides additional insight into how uncertainty drives WTP.

To explore the case for stringent abatement, I use a counterfactual — and pessimistic — scenario for temperature change: Under “business as usual” (BAU), the atmospheric GHG concentration immediately increases to twice its pre-industrial level, which leads to an (uncertain) increase in temperature at the horizon  $H$ , and then (from feedback effects or further emissions) a gradual further doubling of that temperature increase.

This paper builds on recent work by Weitzman (2009), but takes a very different approach. Weitzman addresses our lack of knowledge about the right-hand tail of the distribution for temperature change,  $\Delta T$ . Suppose there is some underlying probability distribution for  $\Delta T$ , but its variance is unknown and is estimated through ongoing Bayesian learning. Weitzman shows that this “structural uncertainty” implies that the posterior-predictive distribution of  $\Delta T$  is “fat-tailed,” i.e., approaches zero at a less than exponential rate (and thus has no moment generating function). If welfare is given by a power utility function, this means that the expected loss of future welfare from warming is infinite, so that society should be willing to sacrifice *all* current consumption to avoid future warming. In another paper, Weitzman (2009b) presents an alternative argument, based on the underlying mechanism of GHG accumulation and its effect on temperature, for why the distribution of  $\Delta T$  should be fat-tailed, but this has the same disturbing welfare implications.<sup>3</sup>

Weitzman provides insight into the nature of the uncertainty underlying climate change policy, but his results do not readily translate into a policy prescription, e.g., what percentage of consumption society should sacrifice to avoid warming. What his results *do* tell us is that

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<sup>3</sup>For a related discussion of inherent uncertainty over climate sensitivity, and a model that implies a fat-tailed distribution for  $\Delta T$ , see Roe and Baker (2007).

the right-hand tail of the distribution for  $\Delta T$  may matter most for policy, and we know very little about that tail. In other words, because of its focus on the middle of the distribution of outcomes, traditional cost-benefit analysis may be misleading.

I utilize a (thin-tailed) three-parameter displaced gamma distribution for temperature change, which I calibrate using estimates of its mean and confidence intervals inferred from the studies surveyed by the IPCC. Besides its simplicity and reasonable fit to the IPCC studies, this approach has two advantages. First, a thin-tailed distribution avoids infinite welfare losses (or the need to arbitrarily bound the utility function to avoid infinite losses). Second, the skewness or variance of the distribution can be altered while holding the other moments fixed, providing additional insight into tail effects.

I specify an economic impact function that relates temperature change to the growth rate of GDP and consumption, and calibrate the relationship using damage functions from several IAMs. Although these damage functions are based on levels of GDP, I can calibrate a growth rate function by matching estimates of GDP/temperature change pairs at a specific horizon. I then use the distribution of GDP level reductions at that horizon to fit a displaced gamma distribution for the growth rate impact.

After fitting gamma distributions to temperature change and growth rate impact, I calculate WTP based on expected discounted utility, using a constant relative risk aversion (CRRA) utility function. In addition to the initial growth rate and index of risk aversion, WTP is affected by the rate of time preference (the rate at which future utility is discounted). I set this rate to zero, the “reasonable” (if controversial) value that gives the highest WTP.<sup>4</sup>

My estimates of  $w^*(\tau)$  are generally below 2%, even for  $\tau$  around 2 or 3°C. This is because there is limited weight in the tails of the calibrated distributions for  $\Delta T$  and growth rate

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<sup>4</sup>Newbold and Daigneault (2008) also studied implications of uncertainty for climate change policy. They combined a distribution for  $\Delta T$  with CRRA utility and functions that translate  $\Delta T$  into lost consumption to estimate WTP. They assume there is a “true” value for  $\Delta T$  and focus on how distributions from different studies could be combined to obtain a (Bayesian) posterior distribution. They solve for the parameters of a distribution derived by Roe and Baker (2007) for each of 21 studies that estimated 5th and 95th percentiles, and combined the resulting distributions in two ways: (1) averaging them, which (“pessimistically”) assumes the studies used the same data but different models, and yields a relatively diffuse posterior distribution; and (2) multiplying them, which (“optimistically”) assumes the studies used the same model but independent datasets, and yields a relatively tight posterior distribution.

impact. Larger estimates of WTP result for particular combinations of parameter values (e.g., an index of risk aversion close to 1 and a low initial GDP growth rate), or if I assume an accelerated rate of warming (i.e., the distribution for  $\Delta T$  applies to a shorter horizon). But overall, given the current “state of knowledge” of warming and its impact, my results are consistent with moderate abatement. Of course the “state of knowledge” is evolving and new studies might lead to changes in the distributions. The framework developed here could then be used to evaluate the policy implications of such changes.

This paper ignores the implications of the opposing irreversibilities inherent in climate change policy and the value of waiting for more information. Immediate action reduces the largely irreversible build-up of GHGs in the atmosphere, but waiting avoids an irreversible investment in abatement capital that might turn out to be at least partly unnecessary, and the net effect of these irreversibilities is unclear. I focus instead on the nature of the uncertainty and its application to a relatively simple cost-benefit analysis.<sup>5</sup>

The next section explains in more detail the methodology used in this paper and its relationship to other studies of climate change policy. Section 3 discusses the probability distribution for temperature change and how it can be transformed to estimate mean, variance and skewness effects. Section 4 discusses the economic impact function and the corresponding uncertainty. Section 5 shows estimates of willingness to pay and its dependence on free parameters, and Section 6 concludes.

## 2 Background and Methodology.

Most economic analyses of climate change policy have five elements: (1) Projections of future emissions of a CO<sub>2</sub> equivalent (CO<sub>2</sub>e) composite (or individual GHGs) under a “business as usual” (BAU) and one or more abatement scenarios, and resulting future atmospheric

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<sup>5</sup>A number of studies have examined the policy implications of this interaction of uncertainty and irreversibility, but with mixed results, showing that policy adoption might be delayed or accelerated. See, for example, Kolstad (1999b), Gollier, Jullien and Treich (2000), and Fisher and Narain (2003), who use two-period models for tractability; and include Kolstad (1996a), Pindyck (2000, 2002) and Newell and Pizer (2003), who use multi-period or continuous-time models. For a discussion of these and other studies of the interaction of uncertainty and irreversibility, see Pindyck (2007).

CO<sub>2</sub>e concentrations. (2) Projections of the average or regional temperature changes likely to result from higher CO<sub>2</sub>e concentrations. (3) Projections of lost GDP and consumption resulting from higher temperatures. (This is probably the most speculative element because of uncertainty over adaptation to climate change, e.g., through shifts in agriculture, migration, etc.) (4) Estimates of the cost of abating GHG emissions by various amounts. (5) Assumptions about social utility and the rate of time preference, so that lost consumption from abatement can be weighed against future gains in consumption from reduced warming. This is essentially the approach of Nordhaus (1994, 2008), Stern (2007), and others who evaluate abatement policies using integrated assessment models (IAMs) that project emissions, CO<sub>2</sub>e concentrations, temperature change, economic impact, and costs of abatement.

Each of these five elements of an IAM-based analysis is subject to considerable uncertainty. However, by estimating WTP instead of evaluating specific policies, I avoid having to deal with abatement costs and projections of GHG emissions. Instead, I focus on uncertainty over temperature change and its economic impact as follows.

## 2.1 Temperature Change.

According to the most recent IPCC report (2007), growing GHG emissions would likely lead to a doubling of the atmospheric CO<sub>2</sub>e concentration relative to the pre-industrial level by the end of this century. That, in turn, would cause an increase in global mean temperature that would “most likely” range between 1.0°C to 4.5°C, with an expected value of 2.5°C to 3.0°C. The IPCC report indicates that this range, derived from a “summary” of the results of 22 scientific studies the IPCC surveyed, represents a roughly 66- to 90-percent confidence interval, i.e., there is a 5 to 17-percent probability of a temperature increase above 4.5°C.<sup>6</sup>

The 22 studies themselves also provide rough estimates of increases in temperature at the outer tail of the distribution. In summarizing them, the IPCC translated the implied outcome distributions into a standardized form that allows comparability across the studies,

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<sup>6</sup>The atmospheric CO<sub>2</sub>e concentration was about 300 ppm in 1900, and is now about 370 ppm. The IPCC (2007) projects an increase to 550 to 600 ppm by 2100. The text of the IPCC report is vague as to whether the 1.0°C to 4.5°C “most likely” range for  $\Delta T$  in 2100 represents a 66% or a 90% confidence interval.

and created graphs showing multiple outcome distributions implied by groups of studies. As Weitzman (2008) has argued, those distributions suggest that there is a 5% probability that a doubling of the CO<sub>2</sub>e concentration relative to the pre-industrial level would lead to a global mean temperature increase of 7°C or more, and a 1% probability that it would lead to a temperature increase of 10°C or more. I fit a three-parameter displaced gamma distribution for  $\Delta T$  to these 5% and 1% points and to a mean temperature change of 3.0°C. This distribution conforms with the distributions summarized by the IPCC, and can be used to study “tail effects” by calculating the impact on WTP of changes in the distribution’s variance or skewness (holding the other moments fixed).

I assume that the fitted gamma distribution for  $\Delta T$  applies to a 100-year horizon  $H$  and that  $\Delta T_t \rightarrow 2\Delta T_H$  as  $t$  gets large. This implies that  $\Delta T_t$  follows the trajectory:<sup>7</sup>

$$\Delta T_t = 2\Delta T_H [1 - (1/2)^{t/H}] , \quad (1)$$

Thus if  $\Delta T_H = 5^\circ\text{C}$ ,  $\Delta T_t$  reaches 2.93°C after 50 years, 5°C after 100 years, 7.5°C after 200 years, and then gradually approaches 10°C.

## 2.2 Economic Impact.

Most economic studies of climate change relate  $\Delta T$  to GDP through a “loss function”  $L(\Delta T)$ , with  $L(0) = 1$  and  $L' < 0$ , so that GDP at some horizon  $H$  is  $L(\Delta T_H)\text{GDP}_H$ , where  $\text{GDP}_H$  is but-for GDP in the absence of warming. These studies typically use an inverse-quadratic or exponential-quadratic function.<sup>8</sup> This implies that if temperatures rise but later fall, GDP could return to its but-for path with no permanent loss.

There are reasons to expect warming to affect the growth rate of GDP as opposed to

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<sup>7</sup>This allows for possible feedback effects and/or further emissions. As summarized in Weitzman (2009b), the simplest dynamic model relating  $\Delta T_t$  to the GHG concentration  $G_t$  is the differential equation

$$d\Delta T/dt = m_1[\ln(G_t/G_0)/\ln 2 - m_2\Delta T_t] .$$

Assuming  $G_t$  initially doubles to  $2G_0$ ,  $\Delta T_t = \Delta T_H$  at  $t = H$ , and  $\Delta T_t \rightarrow 2\Delta T_H$  as  $t \rightarrow \infty$ , implies eqn. (1).

<sup>8</sup>The inverse-quadratic loss function used in the current version of the Nordhaus (2008) DICE model is  $L = 1/[1 + \pi_1\Delta T + \pi_2(\Delta T)^2]$ . Weitzman (2008) introduced the exponential loss function  $L(\Delta T) = \exp[-\beta(\Delta T)^2]$ , which, as he points out, allows for greater losses when  $\Delta T$  is large.



the level. First, some effects of warming are likely to be permanent: for example, destruction of ecosystems from erosion and flooding, extinction of species, and deaths from health effects and weather extremes. Second, resources needed to counter the impact of higher temperatures would reduce those available for R&D and capital investment, reducing growth. Adaptation to rising temperatures is equivalent to the cost of increasingly strict emission standards, which, as Stokey (1998) has shown with an endogenous growth model, reduces the rate of return on capital and lowers the growth rate.<sup>9</sup>

Finally, there is empirical support for a growth rate effect. Using historical data on temperatures and precipitation over the past 50 years for a panel of 136 countries, Dell, Jones, and Olken (2008) have shown that higher temperatures reduce GDP growth rates but not levels. The impact they estimate is large — a decrease of 1.1 percentage points of growth for each 1°C rise in temperature — but significant only for poorer countries.<sup>10</sup>

I assume that in the absence of warming, real GDP and consumption would grow at a constant rate  $g_0$ , but warming will reduce this rate:

$$g_t = g_0 - \gamma \Delta T_t \tag{2}$$

This simple linear relation was estimated by Dell, Jones, and Olken (2008), and can be viewed as at least a first approximation to a more complex loss function.

If temperatures increase but are later reduced through stringent abatement (or geo-engineering), eqn. (2) will have very different implications for future GDP than a level loss function  $L(\Delta T)$ . Suppose, for example, that temperature increases by 0.1°C per year for 50 years and then decreases by 0.1°C per year for the next 50 years. Figure 1 compares two

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<sup>9</sup>Suppose total capital  $K = K_p + K_a(T)$ , with  $K'_a(T) > 0$ , where  $K_p$  is directly productive capital and  $K_a(T)$  is capital needed for adaptation to the temperature  $T$  (e.g., stronger retaining walls and pumps to counter flooding, new infrastructure and housing to support migration, more air conditioning and insulation, etc.). If all capital depreciates at rate  $\delta_K$ ,  $\dot{K}_p = \dot{K} - \dot{K}_a = I - \delta_K K - K'_a(T)\dot{T}$ , so that the rate of growth of  $K_p$  is reduced. See Brock and Taylor (2004) for a related analysis.

<sup>10</sup>“Poor” means below-median PPP-adjusted per-capita GDP. Using World Bank data for 209 countries, “poor” by this definition accounts for 26.9% of 2006 world GDP, which implies a roughly 0.3 percentage point reduction in world GDP growth for each 1°C rise in temperature. In a follow-on paper (2009), they estimate a model that allows for adaptation effects, so that the long-run impact of warming is smaller than the short-run impact. They find a long-run decrease of 0.51 percentage points of growth for each 1°C rise in temperature, but again only for poorer countries.

consumption trajectories:  $C_t^A$ , which corresponds to the exponential-quadratic loss function  $L(\Delta T) = \exp[-\beta(\Delta T)^2]$ , and  $C_t^B$ , which corresponds to eqn. (2). The example assumes that without warming, consumption would grow at 0.5 percent per year — trajectory  $C_t^0$  — and both loss functions are calibrated so that at the maximum  $\Delta T$  of 5°C,  $C^A = C^B = .95C^0$ . Note that as  $\Delta T$  falls to zero,  $C_t^A$  reverts to  $C_t^0$ , but  $C_t^B$  remains permanently below  $C_t^0$ .

Uncertainty is introduced into eqn. (2) through the parameter  $\gamma$ . Using information from a number of IAMs, I obtain a distribution for  $\beta$  in the exponential loss function:

$$L(\Delta T) = e^{-\beta(\Delta T)^2} , \quad (3)$$

which applies to the *level* of GDP. I translate this into a distribution for  $\gamma$  using the trajectory for GDP and consumption implied by eqn. (2) for a temperature change-impact combination projected to occur at horizon  $H$ . From eqns. (1) and (2), the growth rate is  $g_t = g_0 - 2\gamma\Delta T_H[1 - (1/2)^{t/H}]$ . Normalizing initial consumption at 1, this implies:

$$C_t = e^{\int_0^t g(s)ds} = \exp \left\{ -\frac{2\gamma H \Delta T_H}{\ln(1/2)} + (g_0 - 2\gamma\Delta T_H)t + \frac{2\gamma H \Delta T_H}{\ln(1/2)}(1/2)^{t/H} \right\} . \quad (4)$$

Thus  $\gamma$  is obtained from  $\beta$  by equating the expressions for  $C_H$  implied by eqns. (3) and (4):

$$\exp \left\{ -\frac{2\gamma H \Delta T_H}{\ln(1/2)} + (g_0 - 2\gamma\Delta T_H)H + \frac{\gamma H \Delta T_H}{\ln(1/2)} \right\} = \exp\{g_0 H - \beta(\Delta T_H)^2\} , \quad (5)$$

so that  $\gamma = 1.79\beta\Delta T_H/H$ .

The IPCC does not provide standardized distributions for lost GDP corresponding to any particular  $\Delta T$ , but it does survey the results of several IAMs. As discussed in Section 4, I use the information from the IPCC along with other studies to infer means and confidence intervals for  $\beta$  and thus  $\gamma$ . As with  $\Delta T$ , I fit a displaced gamma distribution to the parameter  $\gamma$ , which I use to study implications of impact uncertainty on WTP.

### 2.3 Willingness to Pay.

Given the distributions for  $\Delta T$  and  $\gamma$ , I posit a CRRA social utility function:

$$U(C_t) = C_t^{1-\eta}/(1-\eta) , \quad (6)$$

where  $\eta$  is the index of relative risk aversion (and  $1/\eta$  is the elasticity of intertemporal substitution). I calculate the fraction of consumption — now and throughout the future — society would sacrifice to ensure that any increase in temperature at a specific horizon  $H$  is limited to an amount  $\tau$ . That fraction,  $w^*(\tau)$ , is the measure of willingness to pay.<sup>11</sup>

An issue in debates over climate change policy is the social discount rate (SDR) on consumption. The Stern Review (2007) used a rate just over 1 percent; critiques by Nordhaus (2007), Weitzman (2007) and others argue for a rate closer to the private return on investment (PRI), around 5 to 6 percent. As Stern (2008) makes clear, the SDR could differ from the PRI, in part because a social investment can affect the consumption trajectory. In my model the consumption discount rate is endogenous; in the Ramsey growth context,

$$R_t = \delta + \eta g_t = \delta + \eta g_0 - 2\eta\gamma\Delta T_H [1 - (1/2)^{t/H}] , \quad (7)$$

where  $\delta$  is the rate of time preference, i.e., the rate at which utility is discounted. Thus  $R_t$  falls over time as  $\Delta T$  increases.<sup>12</sup> The “correct” value of  $\delta$  is itself a subject of debate; I will generally set  $\delta = 0$  because one of my objectives is to determine whether any combination of “reasonable” parameter values can yield a high WTP.

If  $\Delta T_H$  and  $\gamma$  were known, social welfare would be given by:

$$W = \int_0^\infty U(C_t) e^{-\delta t} dt = \frac{1}{1-\eta} \int_0^\infty e^{\rho_0 - \rho_1 t - \omega(1/2)^{t/H}} dt , \quad (8)$$

where

$$\rho_0 = -2(1-\eta)\gamma H \Delta T_H / \ln(1/2) , \quad (9)$$

$$\rho_1 = (\eta - 1)(g_0 - 2\gamma\Delta T_H + \delta) , \quad (10)$$

$$\omega = 2(\eta - 1)\gamma H \Delta T_H / \ln(1/2) . \quad (11)$$

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<sup>11</sup>The use of WTP as a welfare measure goes back at least to Debreu (1954), was used by Lucas (1987) to estimate the welfare cost of business cycles, and was used in the context of climate change (with  $\tau = 0$ ) by Heal and Kriström (2002) and Weitzman (2008).

<sup>12</sup>If  $2\eta\gamma\Delta T_H > \delta + \eta g_0$ ,  $R_t$  becomes negative as  $\Delta T$  grows. This is entirely consistent with the Ramsey growth model, as pointed out by Dasgupta et al (1999). They provide a simple example in which climate change results in a 2% annual decline in global consumption, and thus a negative consumption discount rate. Of course other models also imply a declining discount rate; see, e.g., Cropper and Laibson (1999).

Suppose society sacrifices a fraction  $w(\tau)$  of present and future consumption to ensure that  $\Delta T_H \leq \tau$ . Then social welfare at  $t = 0$  would be:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \mathcal{E}_{0,\tau} \int_0^\infty e^{\tilde{\rho}_0 - \tilde{\rho}_1 t - \tilde{\omega}(1/2)^{t/H}} dt \quad , \quad (12)$$

where  $\mathcal{E}_{0,\tau}$  denotes the expectation at  $t = 0$  over the distributions of  $\Delta T_H$  and  $\gamma$  conditional on  $\Delta T_H \leq \tau$ . (I use tildes to denote that  $\rho_0$ ,  $\rho_1$ , and  $\omega$  are functions of two random variables.) If, on the other hand, no action is taken to limit warming, social welfare would be:

$$W_2 = \frac{1}{1 - \eta} \mathcal{E}_0 \int_0^\infty e^{\tilde{\rho}_0 - \tilde{\rho}_1 t - \tilde{\omega}(1/2)^{t/H}} dt \quad , \quad (13)$$

where  $\mathcal{E}_0$  again denotes the expectation over  $\Delta T_H$  and  $\gamma$ , but now with  $\Delta T_H$  unconstrained. Willingness to pay to ensure that  $\Delta T_H \leq \tau$  is the value  $w^*(\tau)$  that equates  $W_1(\tau)$  and  $W_2$ .<sup>13</sup>

## 2.4 Policy Implications.

The case for any abatement policy will depend as much on the cost of that policy as it does on the benefits. I do not estimate abatement costs — I only estimate WTP as a function of  $\tau$ , the abatement-induced limit on any increase in temperature at the horizon  $H$ . Clearly the amount and cost of abatement needed will decrease as  $\tau$  is made larger, so I consider a stringent abatement policy to be one for which  $\tau$  is “low,” which I take to be at or below the expected value of  $\Delta T$  under a business-as-usual (BAU) scenario, i.e., about 3°C.

I examine whether the fitted displaced gamma distributions for  $\Delta T$  and  $\gamma$ , along with “reasonable” values of the remaining economic parameters can yield values of  $w^*(\tau)$  greater than 2 or 3% for  $\tau \approx 3^\circ\text{C}$ . I also explore “tail effects” by transforming the distributions to increase skewness or variance while keeping the other moments fixed, and calculating the resulting change in  $w^*(\tau)$ . Finally, to explore the case for a stringent abatement policy, I focus on conservative parameter assumptions, in the sense of leading to a higher WTP.

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<sup>13</sup>As a practical matter, I calculate WTP using a finite horizon of 500 years. After some 200 years the world will likely exhaust the economically recoverable stocks of fossil fuels, so that GHG concentrations will fall. In addition, so many other economic and social changes are likely that the relevance of applying CRRA expected utility over more than a few hundred years is questionable.

### 3 Temperature Change.

The IPCC (2007a) surveyed 22 scientific studies of *climate sensitivity*, the increase in temperature that would result from an anthropomorphic doubling of the atmospheric CO<sub>2</sub>e concentration. Given that a doubling (relative to the pre-industrial level) by the end of the century is the IPCC's consensus prediction, I treat climate sensitivity as a rough proxy for  $\Delta T$  a century from now. Each of the studies surveyed provided both a point estimate and information about the uncertainty around that estimate, such as confidence intervals and/or probability distributions. The IPCC translated these results into a standardized form so that they could be compared, created graphs with multiple distributions implied by groups of studies, and estimated that the studies implied an expected value of 2.5°C to 3.0°C for climate sensitivity. How one aggregates the results of these studies depends on beliefs about the underlying models and data. Although this likely overestimates the size of the tails, I will assume that the studies used the same data but different models, and average the results. This is more or less what Weitzman (2009) did, and my estimates of the tails from the aggregation of these studies are close to (but slightly lower) than his. To be conservative, I use his estimate of a 17% probability that a doubling of the CO<sub>2</sub>e concentration would lead to a mean temperature increase of 4.5°C or more, a 5% probability of a temperature increase of 7.0°C or more, and a 1% probability of a temperature increase of 10.0°C or more. Thus the 5% and 1% tails of the distribution for  $\Delta T$  clearly represent extreme outcomes; temperature increases of this magnitude are outside the range of human experience.

I fit a displaced gamma distribution to these summary numbers. Letting  $\theta$  be the displacement parameter, the distribution is given by:

$$f(x; r, \lambda, \theta) = \frac{\lambda^r}{\Gamma(r)} (x - \theta)^{r-1} e^{-\lambda(x-\theta)} , \quad x \geq \theta , \quad (14)$$

where  $\Gamma(r)$  is the Gamma function:

$$\Gamma(r) = \int_0^\infty s^{r-1} e^{-s} ds$$

The moment generating function for this distribution is:

$$M_x(t) = \mathcal{E}(e^{tx}) = \left( \frac{\lambda}{\lambda - t} \right)^r e^{t\theta} \quad (15)$$

Thus the mean, variance and skewness (around the mean) are given by  $\mathcal{E}(x) = r/\lambda + \theta$ ,  $\mathcal{V}(x) = r/\lambda^2$ , and  $\mathcal{S}(x) = 2r/\lambda^3$  respectively.

Fitting  $f(x; r, \lambda, \theta)$  to a mean of 3°C, and the 5% and 1% points at 7°C and 10°C respectively yields  $r = 3.8$ ,  $\lambda = 0.92$ , and  $\theta = -1.13$ . The distribution is shown in Figure 2. It has a variance and skewness around the mean of 4.49 and 9.76 respectively. Note that this distribution implies that there is a small (2.9 percent) probability that a doubling of the CO<sub>2</sub>e concentration will lead to a *reduction* in mean temperature, and indeed this possibility is consistent with several of the scientific studies. The distribution also implies that the probability of a temperature increase of 4.5°C or greater is 21%.

Later I will want to change the mean, variance or skewness while keeping the other two moments fixed. Denote the scaling factors for these moments by  $\alpha_M$ ,  $\alpha_V$ , and  $\alpha_S$ , respectively. (Setting  $\alpha_S = 1.5$  increases the skewness by 50%.) Using the equations for the moments, to change the skewness by a factor of  $\alpha_S$  while keeping the mean and variance fixed, replace the original values of  $r$ ,  $\lambda$ , and  $\theta$  with  $r_1 = r/\alpha_S^2$ ,  $\lambda_1 = \lambda/\alpha_S$ , and  $\theta_1 = \theta + (1 - 1/\alpha_S)r/\lambda$ . Likewise, to change the variance by a factor  $\alpha_V$  while keeping the mean and skewness fixed, set  $r_1 = \alpha_V^3 r$ ,  $\lambda_1 = \alpha_V \lambda$ , and  $\theta_1 = \theta + (1 - \alpha_V^2)r/\lambda$ . Finally, to change the mean by a factor  $\alpha_M$  while keeping the other moments fixed, keep  $r$  and  $\lambda$  the same but set  $\theta_1 = \alpha_M \theta + (\alpha_M - 1)r/\lambda$ , which simply shifts the distribution to the right or left.

Figure 3 shows the effects of increasing the skewness or variance by 50% while keeping the other moments fixed. With an increase in skewness, there is some shift of variation towards the right-hand tail, but the effects are negligible: the probabilities of a  $\Delta T$  of 7°C (10°C) or greater remain 5% (1%). Increasing the variance by 50% while holding the skewness and mean fixed thickens both tails; the probability of  $\Delta T \geq 5^\circ\text{C}$  increases to 7%, and the probability of  $\Delta T \geq 10^\circ\text{C}$  remains 1%.

Recall that the distribution for  $\Delta T$  pertains to a point in time,  $H$ , and I assume that temperature follows the trajectory of eqn. (1), so that  $\Delta T_t \rightarrow 2\Delta T_H$  as  $t$  gets large. This is illustrated in Figure 4, which shows a trajectory for  $\Delta T$  when it is unconstrained (and  $\Delta T_H$  happens to equal 5°C), and when it is constrained so that  $\Delta T_H \leq \tau = 3^\circ\text{C}$ . Note that even when constrained,  $\Delta T_H$  is a random variable and (unless  $\tau = 0$ ) will be less than  $\tau$  with

probability 1; in Figure 4 it happens to be  $2.5^{\circ}\text{C}$ . If  $\tau = 0$ , then  $\Delta T = 0$  for all  $t$ .

## 4 Economic Impact.

What would be the economic impact (broadly construed) of a temperature increase of  $7^{\circ}\text{C}$  or greater? One might answer, as Stern (2007, 2008) does, that we simply do not (and cannot) know, because we have had no experience with this extent of warming, and there are no models that can say much about the impact on production, migration, disease prevalence, and a host of other relevant factors. Of course we could say the same thing about the probabilities of temperature increases of  $7^{\circ}\text{C}$  or more, which are also outside the range of the climate science models behind the studies surveyed by the IPCC. This is essentially the argument made by Weitzman (2009a), but in terms of underlying “structural uncertainty” that can never be resolved even as more data arrive over the coming decades. But if large temperature increases are what really matter, this gives us no handle on policy.

Instead, I take IAMs and related models of economic impact at face value and treat them analogously to the climate science models. These models yield a rough consensus regarding possible economic impacts: for temperature increases up to  $4^{\circ}\text{C}$ , the “most likely” impact is from 1% to at most 5% of GDP.<sup>14</sup> Of interest is the outer tail of the distribution for this impact. There is some chance that a temperature increase of  $3^{\circ}\text{C}$  or  $4^{\circ}\text{C}$  would have a much larger impact, and we want to know how that affects WTP.

At issue is the value of  $\gamma$  in eqn. (2). Different IAMs and other economic studies suggest different values for this parameter, and although there are no estimates of confidence intervals (that I am aware of), intervals can be inferred from some of the variation in the suggested values. I therefore treat this parameter as stochastic and distributed as gamma, as in eqn. (14). I further assume that  $\gamma$  and  $\Delta T$  are independently distributed, which is realistic given that they are governed by completely different physical/economic processes.

Based on its own survey of impact estimates from four IAMs, the IPCC (2007b) concludes

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<sup>14</sup>This consensus might arise from the use of similar ad hoc damage functions in various IAMs.

that “global mean losses could be 1–5% of GDP for 4°C of warming.”<sup>15</sup> In addition, Dietz and Stern (2008) provide a graphical summary of damage estimates from several IAMs, which yield a range of 0.5% to 2% of lost GDP for  $\Delta T = 3^\circ\text{C}$ , and 1% to 8% of lost GDP for  $\Delta T = 5^\circ\text{C}$ . I treat these ranges as “most likely” outcomes, and use the IPCC’s definition of “most likely” to mean a 66 to 90-percent confidence interval. Using the IPCC range and, to be conservative, assuming it applies to a 66-percent confidence interval, I take the mean loss for  $\Delta T = 4^\circ\text{C}$  to be 3% of GDP, and the 17-percent and 83-percent confidence points to be 1% of GDP and 5% of GDP respectively. These three numbers apply to the value of  $\beta$  in eqn. (3), but they are easily translated into corresponding numbers for  $\gamma$  in eqn. (2). From eqn. (5),  $\gamma = 1.79\beta\Delta T/H$ . Thus the mean, 17-percent, and 83-percent values for  $\gamma$  are, respectively,  $\bar{\gamma} = .0001363$ ,  $\gamma_1 = .0000450$ , and  $\gamma_2 = .0002295$ .<sup>16</sup>

Using these three numbers to fit a 3-parameter displaced gamma distribution for  $\gamma$  yields  $r_g = 4.5$ ,  $\lambda_g = 21,341$ , and  $\theta_g = \bar{\gamma} - r_g/\lambda_g = -.0000746$ . This distribution is shown in Figure 5. For comparison, I also fit the distribution assuming the 1% to 5% loss of GDP for  $\Delta T = 4^\circ\text{C}$  represents a 90-percent confidence interval; it is also shown in Figure 5.

## 5 Willingness to Pay.

I assume that by giving up a fraction  $w(\tau)$  of consumption now and throughout the future, society can ensure that at time  $H$ ,  $\Delta T_H$  will not exceed  $\tau$ . Specifically, the distribution for  $\Delta T$  is cut off at  $\tau$  and rescaled to integrate to 1.<sup>17</sup> Using the CRRA utility function of eqn. (6) and the growth rate of consumption given by eqn. (2),  $w^*(\tau)$  is the *maximum* fraction of consumption society would sacrifice to keep  $\Delta T_H \leq \tau$ . As explained in Section 2,  $w^*(\tau)$  is found by equating the social welfare functions  $W_1(\tau)$  and  $W_2$  of eqns. (12) and (13).

Given the distributions  $f(\Delta T)$  and  $g(\gamma)$  for  $\Delta T$  and  $\gamma$  respectively, denote by  $M_\tau(t)$  and

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<sup>15</sup>The IAMs surveyed by the IPCC include Hope (2006), Mendelsohn et al (1998), Nordhaus and Boyer (2000), and Tol (2002). For a recent overview of economic impact studies, see Tol (2009).

<sup>16</sup>If  $L$  is the loss of GDP corresponding to  $\Delta T$ ,  $1 - L = \exp[-\beta(\Delta T)^2] = \exp[-.557\gamma H\Delta T]$ .  $H = 100$  and  $\Delta T = 4^\circ\text{C}$ , so  $.97 = e^{-223.5\bar{\gamma}}$ ,  $.99 = e^{-223.5\gamma_1}$ , and  $.95 = e^{-223.5\gamma_2}$ . Using instead the 4.5% midpoint of the 1% to 8% range of lost GDP for  $\Delta T = 5^\circ\text{C}$  from Dietz and Stern (2008), we would have  $\bar{\gamma} = .000165$ .

<sup>17</sup>The expected value of  $\Delta T_H$  is  $\mathcal{E}(\Delta T | \tau) = (\int_0^\tau x f(x) dx) / (\int_0^\tau f(x) dx) < \tau$ .



$M_\infty(t)$  the time- $t$  expectations

$$M_\tau(t) = \frac{1}{F(\tau)} \int_{\theta_T}^\tau \int_{\theta_\gamma}^\infty e^{\tilde{\rho}_0 - \tilde{\rho}_1 t - \tilde{\omega}(1/2)^{t/H}} f(\Delta T) g(\gamma) d\Delta T d\gamma \quad (16)$$

and

$$M_\infty(t) = \int_{\theta_T}^\infty \int_{\theta_\gamma}^\infty e^{\tilde{\rho}_0 - \tilde{\rho}_1 t - \tilde{\omega}(1/2)^{t/H}} f(\Delta T) g(\gamma) d\Delta T d\gamma \quad , \quad (17)$$

where  $\tilde{\rho}_0$ ,  $\tilde{\rho}_1$  and  $\tilde{\omega}$  are given by eqns. (9), (10) and (11),  $\theta_T$  and  $\theta_\gamma$  are the lower limits on the distributions for  $\Delta T$  and  $\gamma$ , and  $F(\tau) = \int_{\theta_T}^\tau f(\Delta T) d\Delta T$ . Thus  $W_1(\tau)$  and  $W_2$  are:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \int_0^\infty M_\tau(t) dt \equiv \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} G_\tau \quad (18)$$

and

$$W_2 = \frac{1}{1 - \eta} \int_0^\infty M_\infty(t) dt \equiv \frac{1}{1 - \eta} G_\infty \quad . \quad (19)$$

Setting  $W_1(\tau)$  equal to  $W_2$ , WTP is given by:

$$w^*(\tau) = 1 - [G_\infty / G_\tau]^{\frac{1}{1-\eta}} \quad . \quad (20)$$

The solution for  $w^*(\tau)$  depends on the distributions for  $\Delta T$  and  $\gamma$ , the horizon  $H$ , and the parameters  $\eta$ ,  $g_0$ , and  $\delta$ . It is useful to determine how  $w^*$  varies with  $\tau$ ; the cost of abatement is a decreasing function of  $\tau$ , so given estimates of that cost, one could use these results to determine abatement targets.

## 5.1 Parameter Values.

Putting aside the distributions for  $\Delta T$  and  $\gamma$ , what are reasonable values for the index of relative risk aversion  $\eta$ , the rate of time discount  $\delta$ , and the base level real growth rate  $g_0$ ? As we will see, estimates of WTP depend strongly on these parameters. Also, in the context of a (deterministic) Ramsey growth model with a growth rate  $g$ , the consumption discount rate is  $R = \delta + \eta g$ , so if  $\eta = 2$  and  $\delta = g = .02$  (all reasonable numbers),  $R = .06$ .

The finance and macroeconomics literature has estimates of  $\eta$  ranging from 1.5 to 6, and estimates of  $\delta$  ranging from .01 to .04. The growth rate  $g$ , measured directly from historical data, is in the range of .02 to .025. Thus the Ramsey rule puts the consumption discount rate

in the range of 3% to over 10%, but that rate should be viewed as something close to a private return on investment (PRI). Indeed, most estimates of  $\eta$  and  $\delta$  are based on investment and/or short-run consumption and savings behavior. The social discount rate (SDR) can differ considerably from the PRI, especially for public investments that involve long time horizons and strong externalities. It has been argued, for example, that for intergenerational comparisons,  $\delta$  should be close to zero, because although most people would value a benefit today more highly than a year from now, there is no reason why society should impose those preferences on the well-being of our great-grandchildren relative to our own. Likewise, while values of  $\eta$  well above 2 may be consistent with the (relatively short-horizon) behavior of investors, we might apply lower values to welfare comparisons involving future generations.<sup>18</sup>

Putting aside this debate over the “correct” values of  $\eta$  and  $\delta$  for intergenerational comparisons, I want to determine whether current assessments of uncertainty over temperature change and economic impact generate a high WTP and thus justify the immediate adoption of a stringent abatement policy. I will therefore stack the deck, so to speak, in favor of our great-grandchildren and use relatively low values of  $\eta$  and  $\delta$ : around 2 for  $\eta$  and 0 for  $\delta$ . Also, WTP is a decreasing function of the base growth rate  $g_0$  in eqn. (7), so I will use a range of .015 to .025 for that parameter.

## 5.2 No Uncertainty.

Removing uncertainty provides some intuition for the determinants of WTP and its dependence on some of the parameters. If the trajectory for  $\Delta T$  and the impact of that trajectory on economic growth were both known with certainty, eqns. (18) and (19) would simplify to:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \int_0^\infty e^{\rho_0 - \rho_1 t - \omega(1/2)^{t/H}} dt \quad , \quad (21)$$

and

$$W_2 = \frac{1}{1 - \eta} \int_0^\infty e^{\rho_0 - \rho_1 t - \omega_\tau(1/2)^{t/H}} dt \quad , \quad (22)$$

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<sup>18</sup>For arguments in favor of low values for  $\eta$  and  $\delta$  and low SDRs, see Heal (2009), Stern (2008) and Summers and Zeckhauser (2008). For opposing views, see Nordhaus (2007) and Weitzman (2007).

where  $\omega = 2(\eta - 1)\bar{\gamma}H\Delta T_H/\ln(1/2)$  and  $\omega_\tau = 2(\eta - 1)\bar{\gamma}\tau/\ln(1/2)$ . (I am using the mean,  $\bar{\gamma}$ , as the certainty-equivalent value of  $\gamma$ .)

I calculate the WTP to keep  $\Delta T$  zero for all time, i.e.,  $w^*(0)$ , over a range of values for  $\Delta T$  at the horizon  $H = 100$ . For this exercise, I set  $\eta = 2$ ,  $\delta = 0$ , and  $g = .015, .020$ , and  $.025$ . The results are shown in Figure 6. The graph says that if, for example,  $\Delta T_H = 6^\circ\text{C}$  and  $g_0 = .02$ ,  $w^*(0)$  is about  $.022$ , i.e., society should be willing to give about 2.2% of current and future consumption to keep  $\Delta T$  at zero instead of  $6^\circ\text{C}$ .<sup>19</sup> Although  $w^*(0)$  is considerably larger if  $\Delta T_H$  is *known* to be  $8^\circ\text{C}$  or more, such temperature outcomes have low probability.

Note that for any known  $\Delta T_H$ , a lower initial growth rate  $g_0$  implies a higher WTP. The reason is that lowering  $g_0$  lowers the entire trajectory for the consumption discount rate  $R_t$ . That rate falls as  $\Delta T$  increases (and can eventually become negative), but its starting value is  $\delta + \eta g_0$ . The damages from warming (a falling growth rate as  $\Delta T$  increases) are initially small, making estimates of WTP highly dependent on the values for  $\delta$ ,  $\eta$ , and  $g_0$ .

### 5.3 Uncertainty Limited to Temperature Change.

I now turn to the effects of uncertainty over  $\Delta T$ . I will assume that the loss function is deterministic, with the parameter  $\gamma$  fixed at its mean value  $\bar{\gamma} = .0001363$ . Eqns. (16) and (17) then simplify as follows:

$$M_\tau(t) = \frac{1}{F(\tau)} \int_{\theta_T}^\tau e^{\tilde{\rho}_0 - \tilde{\rho}_1 t - \tilde{\omega}(1/2)^{t/H}} f(\Delta T) d\Delta T \quad (23)$$

and

$$M_\infty(t) = \int_{\theta_T}^\infty e^{\tilde{\rho}_0 - \tilde{\rho}_1 t - \tilde{\omega}(1/2)^{t/H}} f(\Delta T) d\Delta T \quad , \quad (24)$$

where now  $\bar{\gamma}$  replaces  $\gamma$  in  $\tilde{\rho}_0$ ,  $\tilde{\rho}_1$  and  $\tilde{\omega}$ .

Figure 7 shows  $w^*(\tau)$  for  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .015, .020$ , and  $.025$ . Observe that WTP is below 2%, even for  $\tau = 0$ , and is closer to 1% if  $g_0 = .020$  or  $.025$ . A feasible (i.e., attainable using a realistic abatement policy) value for  $\tau$  is probably around  $2^\circ\text{C}$ , which makes WTP considerably smaller.

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<sup>19</sup>Remember that the “known  $\Delta T$ ” is not constant, and applies only to time  $t = H$ .  $\Delta T$  follows the trajectory given by eqn. (1).

Table 1: WTP, only  $\Delta T$  Stochastic

$\tau$	Base Case	$S = 1.5S_0$	$V = 1.5V_0$	$\gamma = .0002726$
0	.0113	.0106	.0126	.0232
1	.0092	.0084	.0107	.0190
3	.0053	.0049	.0069	.0112
5	.0026	.0026	.0038	.0056
7	.0011	.0013	.0017	.0024
10	.0002	.0004	.0003	.0005

*Note:* Each entry is  $w^*(\tau)$ , fraction of consumption society would sacrifice to ensure that  $\Delta T_H \leq \tau$ .  $H = 100$  years,  $\delta = 0$ ,  $\eta = 2$ ,  $g_0 = .02$ .

Table 1 shows  $w^*(\tau)$  for several values of  $\tau$ , using the base distribution for  $\Delta T$  shown in Figure 2, with  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .02$ . (The parameter  $\gamma$  in the loss function is again fixed at  $\bar{\gamma} = .0001363$ .) The first column duplicates the low WTP numbers shown in Figure 7. The next two columns show how  $w^*(\tau)$  changes when the skewness or variance of the distribution for  $\Delta T$  is increased by 50%, in each case holding the other two moments fixed. The increase in skewness *reduces*  $w^*(\tau)$  for  $\tau < 5^\circ\text{C}$ , because it pushes some of the probability mass from the right to the left tail. For  $\tau = 7^\circ\text{C}$  or more,  $w^*(\tau)$  is increased, but only modestly, because even with this increase in skewness, the probability of a  $\Delta T$  of  $7^\circ\text{C}$  or more is very low. A 50% increase in the variance of the distribution (holding the mean and skewness fixed) increases  $w^*(\tau)$  for all values of  $\tau$ , but only modestly. For example,  $w^*(3^\circ)$  increases from 0.53% of consumption to 0.69%.

Of course this ignores uncertainty over the loss function. The last column of Table 1 shows  $w^*(\tau)$  for the original distribution of  $\Delta T$ , but a doubling of the parameter  $\gamma$ . This has a substantial effect on the WTP, roughly doubling all of the base case numbers. But  $w^*(0)$  is still only about 2.3%.

## 5.4 Uncertainty Over Temperature and Economic Impact.

I now allow for uncertainty over both  $\Delta T$  and the impact parameter  $\gamma$ , using the calibrated distributions for each. WTP is now given by eqns. (16) to (20). The calculated values of

WTP are shown in Figure 8 for  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .015$ ,  $.020$ , and  $.025$ . Note that if  $g_0$  is  $.02$  or greater, WTP is always less than  $1.2\%$ , even for  $\tau = 0$ . To obtain a WTP at or above  $2\%$  requires an initial growth rate of only  $.015$  or a lower value of  $\eta$ . The figure also shows the WTP for  $\eta = 1.5$  and  $g_0 = .02$ ; now  $w^*(0)$  reaches  $3.5\%$ .

Figure 9 shows the dependence of WTP on the index of risk aversion,  $\eta$ . It plots  $w^*(3)$ , i.e., the WTP to ensure  $\Delta T_H \leq 3^\circ\text{C}$  at  $H = 100$  years, for an initial growth rate of  $.02$ . Although  $w^*(3)$  is below  $2\%$  for moderate values of  $\eta$ , it comes close to  $6\%$  if  $\eta$  is reduced to 1 (the value of  $\eta$  used in Stern (2007)). The reason is that while future utility is not discounted (because  $\delta = 0$ ), future consumption is implicitly discounted at the initial rate  $\eta g_0$ . If  $\eta$  (or for that matter  $g_0$ ) is made smaller, potential losses of future consumption have a larger impact on WTP. Finally, Figure 9 also shows that discounting future utility, even at a very low rate, will considerably reduce WTP. If  $\delta$  is increased to  $.01$ ,  $w^*(3)$  is again below  $2\%$  for all values of  $\eta$ .

We have seen that large values of WTP are obtained only for fairly extreme combinations of parameter values. However, these results are based on distributions for  $\Delta T$  and the impact parameter  $\gamma$  that were fitted to studies in the IPCC's 2007 report, as well as concurrent economic studies, and those studies were actually done several years prior to 2007. Some more recent studies indicate that "most likely" values for  $\Delta T$  in 2100 might be higher than the  $1.0^\circ\text{C}$  to  $4.5^\circ\text{C}$  range given by the IPCC. For example, a recent report by Sokolov et al (2009) suggests an expected value for  $\Delta T$  in 2100 of around  $4$  to  $5^\circ\text{C}$ , as opposed to the  $3.0^\circ\text{C}$  expected value that I have used.

Suppose, for example, that the distribution for  $\Delta T_H$  based on the IPCC is correct, but warming is accelerated so that it now applies to a shortened horizon of  $H = 75$  years. Figure 10 duplicates Figure 9 except that  $H = 75$ . Observe that if  $\delta = 0$  and  $\eta$  is close to 1,  $w^*(3)$  reaches  $8\%$ . (However,  $w^*(3)$  is much lower if  $\delta = .01$ .)

Alternatively, we could shift the entire distribution for  $\Delta T_H$  so that the mean is  $5^\circ\text{C}$ , corresponding to the upper end of the  $4$  to  $5^\circ\text{C}$  range in Sokolov et al (2009). Figure 11 duplicates Figure 9 except that the mean of  $\Delta T_H$  has been increased from  $3^\circ\text{C}$  to  $5^\circ\text{C}$ , with the other moments of the distribution left unchanged, and  $H$  again 100 years. Now if  $\delta = 0$

and  $\eta$  is below 1.5,  $w^*(3)$  is above 3%, and reaches 10% if  $\eta = 1$ . Thus there are parameter values and plausible distributions for  $\Delta T$  that yield a large WTP, but that are outside of what is at least the current consensus range.

## 5.5 Policy Implications.

The policy implications of these results are stark. For temperature and impact distributions based on the IPCC and “conservative” parameter values (e.g.,  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .02$ ), WTP to prevent *any* increase in temperature is around 2% or less. And if the policy objective is to ensure that  $\Delta T$  in 100 years does not exceed its expected value of 3°C (a much more feasible objective), WTP is lower still.

There are two reasons for these results. First, there is limited weight in the tails of the distributions for  $\Delta T$  and  $\gamma$ . The distribution calibrated for  $\Delta T$  implies a 21% probability of  $\Delta T \geq 4.5^\circ\text{C}$  in 100 years, and a 5% probability of  $\Delta T \geq 7.0^\circ\text{C}$ , numbers consistent with the climate sensitivity studies surveyed by the IPCC. Likewise, the calibrated distribution for  $\gamma$  implies a 17% probability of  $\gamma \geq .00023$ , also consistent with the IPCC and other surveys. A realization in which, say,  $\Delta T = 4.5^\circ\text{C}$  and  $\gamma = .00023$  would imply that GDP and consumption in 100 years would be 5.7 percent lower than with no increase in temperature.<sup>20</sup> However, the probability of  $\Delta T \geq 4.5^\circ\text{C}$  *and*  $\gamma \geq .00023$  is only about 3.6%. An even more extreme outcome in which  $\Delta T = 7^\circ\text{C}$  (and  $\gamma = .00023$ ) would imply about a 9 percent loss of GDP in 100 years, but the probability of an outcome this bad or worse is only 0.9%.

Second, even if  $\delta = 0$  so that utility is not discounted, the implicit discounting of consumption is significant. The initial consumption discount rate is  $\rho_0 = \eta g_0$ , which is at least .03 if  $\eta = 2$ . And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve much smaller losses in earlier years.

Although these estimates of WTP do not support the immediate adoption of a stringent GHG abatement policy, they do not imply that no abatement is optimal. For example, 2% of GDP is in the range of cost estimates for compliance with the Kyoto Protocol.<sup>21</sup> Taking the

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<sup>20</sup>If  $\gamma = .00023$  and  $\Delta T = 4.5^\circ\text{C}$ ,  $\beta = \gamma H / 1.89 \Delta T = .00270$ , and from eqn. (3),  $L = e^{-\beta(\Delta T)^2} = .947$ .

<sup>21</sup>See the survey of cost studies by the Energy Information Administration (1998), and the more recent

U.S. in isolation, a WTP of 2% amounts to about \$300 billion per year, a rather substantial amount for GHG abatement. And if, e.g.,  $w^*(3) = .01$ , a \$150 billion per year expenditure on abatement would be justified if it would indeed limit warming to 3°C.

## 6 Conclusions.

I have approached climate policy analysis from the point of view of a simple measure of “willingness to pay”: the fraction of consumption  $w^*(\tau)$  that society would sacrifice to ensure that any increase in temperature at a future point is limited to  $\tau$ . This avoids having to make projections of GHG emissions and atmospheric concentrations, or estimate abatement costs. Instead I could focus directly on uncertainties over temperature change and over the economic impact of higher temperatures. Also, I modeled economic impact as a relationship between temperature change and the growth rate of GDP as opposed to its level. Using information on the distributions for temperature change and economic impact from studies assembled by the IPCC and from recent IAMs (the current “state of knowledge” regarding warming and its impact), I fit displaced gamma distributions for  $\Delta T$  and an impact parameter  $\gamma$ . I then examined whether “reasonable” values for the remaining parameters could yield values of  $w^*(\tau)$  above 2% or 3% for small values of  $\tau$ , which might support stringent abatement, and found that for the most part they could not.

For “conservative” parameter values, e.g.,  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .015$  or  $.02$ , WTP to prevent *any* increase in temperature is only around 2%, and is well below 2% if the objective is to keep  $\Delta T$  in 100 years below its expected value of 3°C. Given what we know about the distributions for temperature change and its impact, it is difficult to obtain a large WTP unless  $\eta$  is reduced to 1.5 or less, or we assume warming will occur at a more accelerated rate than the IPCC projects. There are two reasons for these results: limited weight in the tails of the distributions for  $\Delta T$  and  $\gamma$ , and the effect of consumption discounting.

It is an understatement to say that caveats are in order. First, although I have incorporated what I believe to be the current consensus on the distributions for temperature

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country cost studies surveyed in IPCC (2007c).

change and its impact, this consensus may be wrong, especially with respect to the tails of the distributions. Indeed, some recent studies suggest that warming could be greater and/or more rapid than the IPCC suggests. We have no historical or experimental data from which to assess the likelihood of a  $\Delta T$  above  $5^{\circ}\text{C}$ , never mind its economic impact, and one could argue á la Weitzman (2009) that we will never have sufficient data because the distributions are fat-tailed, implying a WTP of 100% (or at least something much larger than 2%). In addition, the loss function of eqn. (2) is linear, and a convex relationship between  $\Delta T$  and the growth rate  $g_t$  may be more realistic.

The real debate among economists is not so much over the need for some kind of GHG abatement policy, but rather whether a stringent policy is needed now, or instead abatement should begin slowly or be delayed for some time. My results are consistent with beginning slowly. In addition, beginning slowly has other virtues. It is likely to be dynamically efficient because of discounting (most damages will occur in the distant future) and because of the likelihood that technological change will reduce the cost of abatement over time. Also, there is an “option value” to waiting for more information before adopting a stringent policy that imposes large sunk costs on consumers. Over the next ten or twenty years we may learn much more about climate sensitivity, the economic impact of higher temperatures, and the cost of abatement, in part from ongoing research, and in part from the accumulation of additional data.



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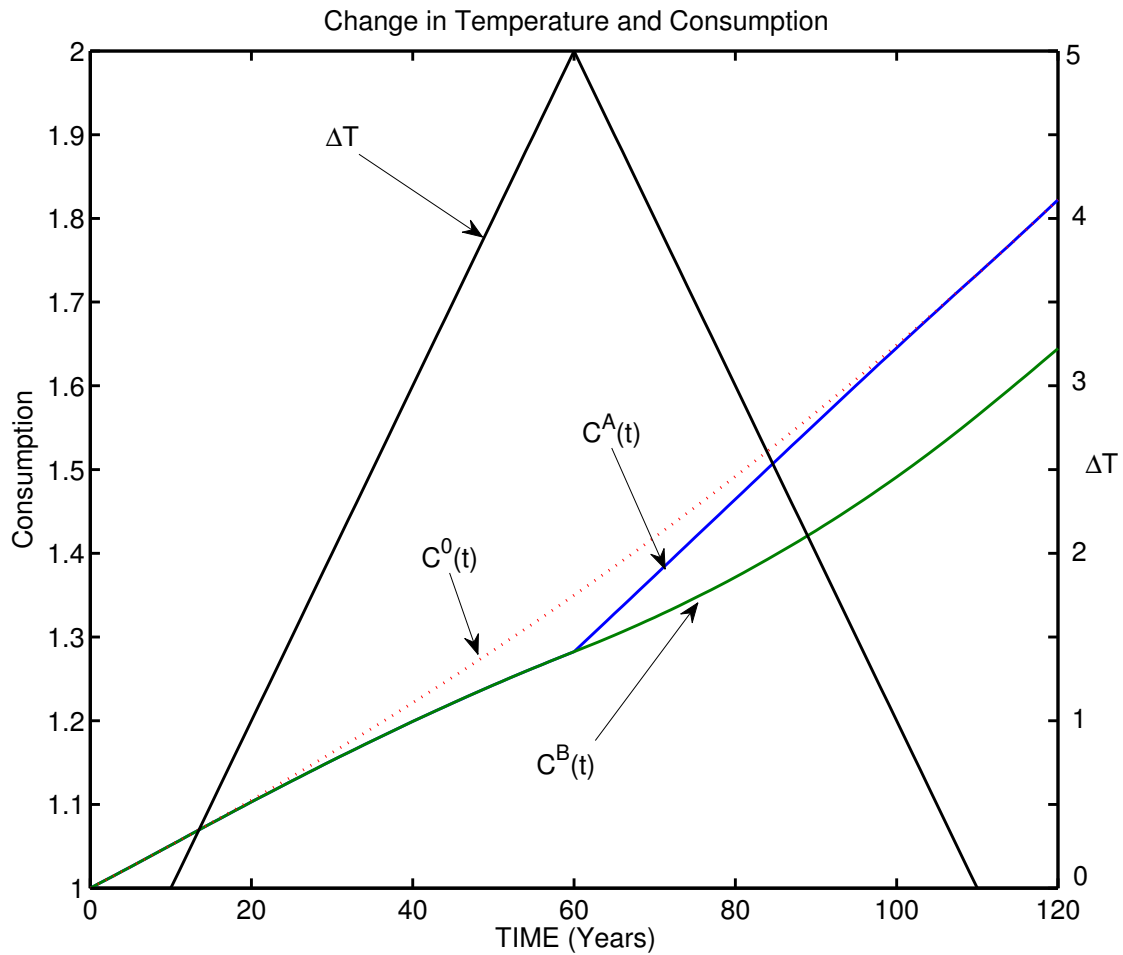


Figure 1: Example of Economic Impact of Temperature Change. (Note temperature increases by  $5^{\circ}\text{C}$  over 50 years and then falls to original level over next 50 years.  $C^A$  is consumption when  $\Delta T$  reduces level,  $C^B$  is consumption when  $\Delta T$  reduces growth rate, and  $C^0$  is consumption with no temperature change.)

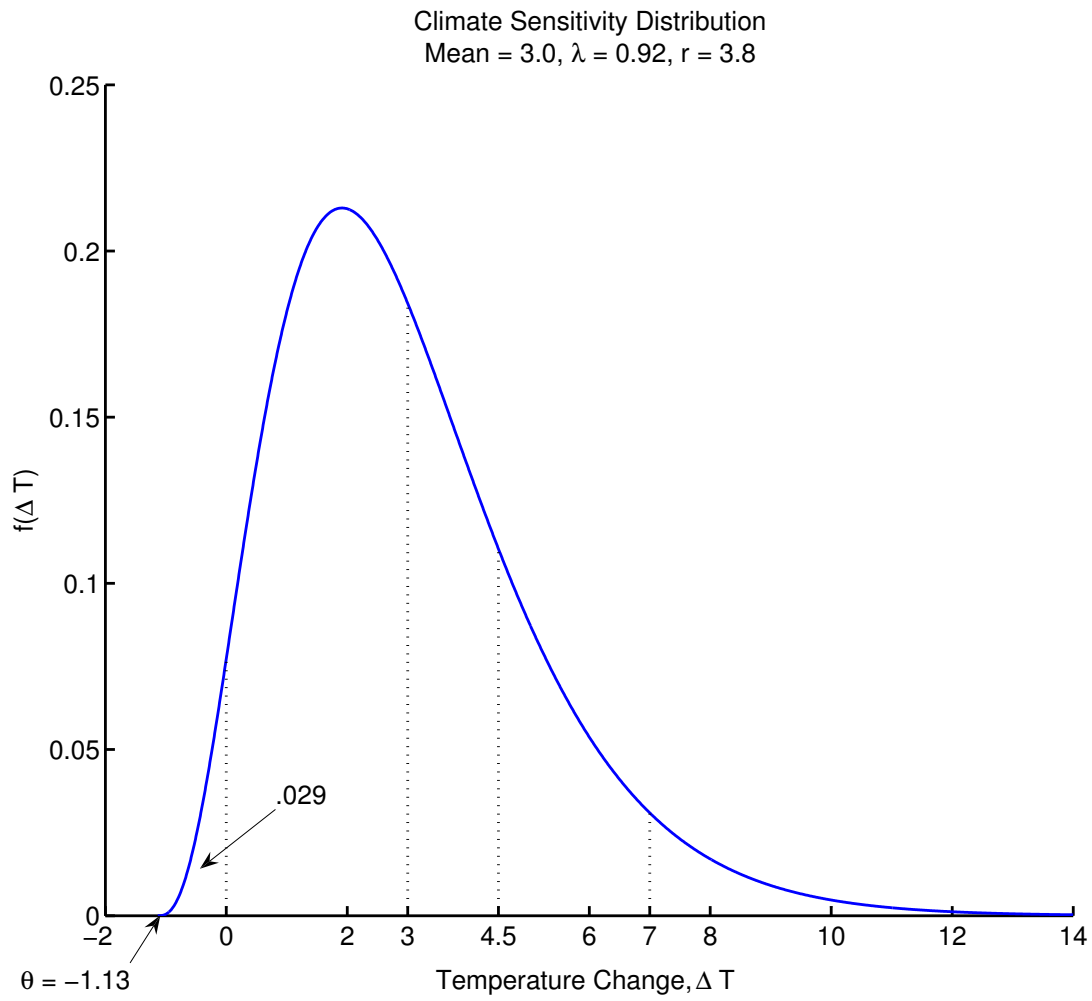


Figure 2: Base Distribution for Temperature Change.

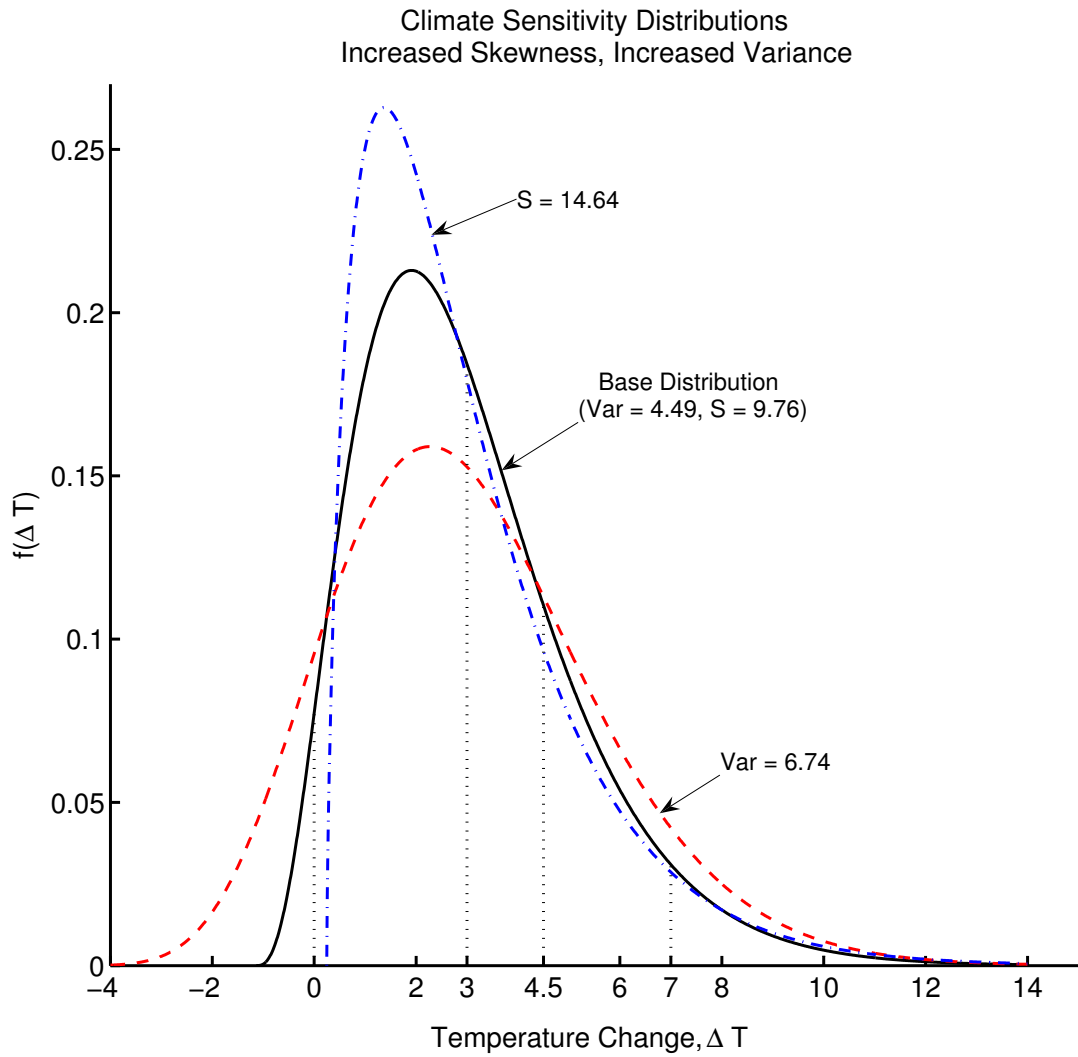


Figure 3: Temperature Change Distribution: 50% Increase in Variance, Skewness

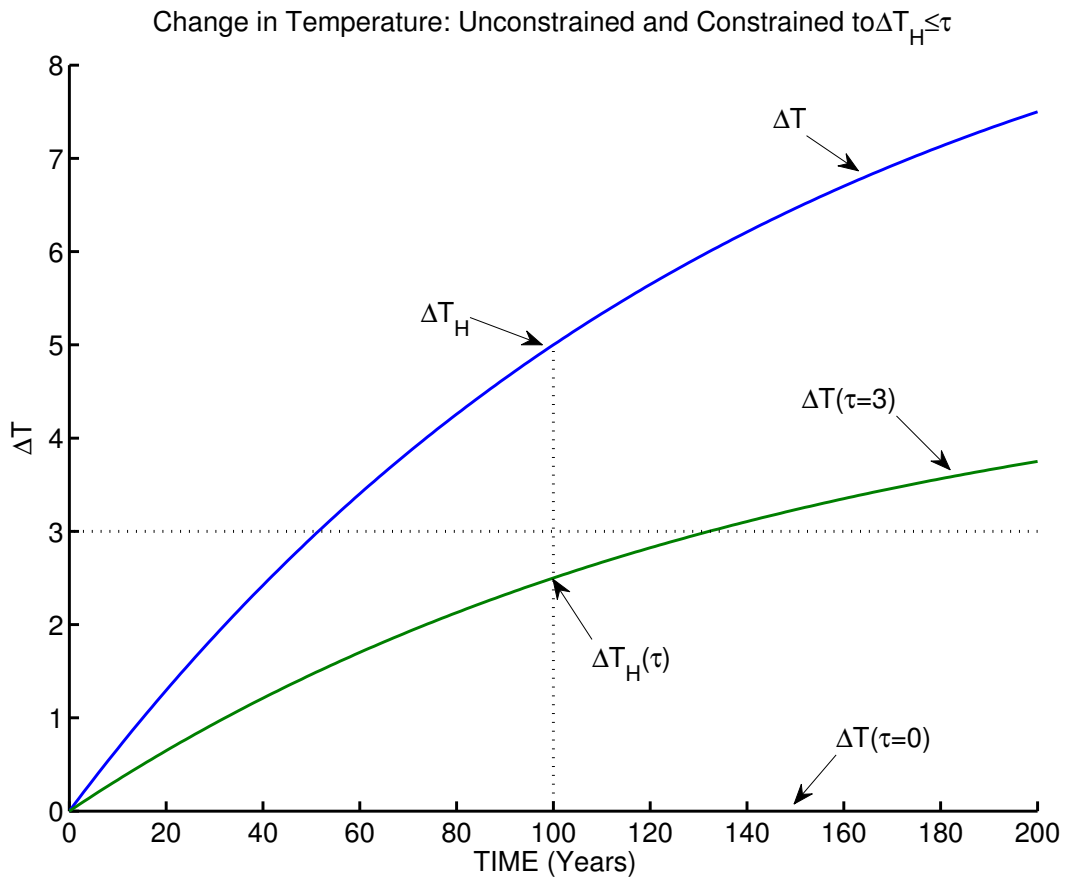


Figure 4: Temperature Change: Unconstrained and Constrained So  $\Delta T_H \leq \tau$

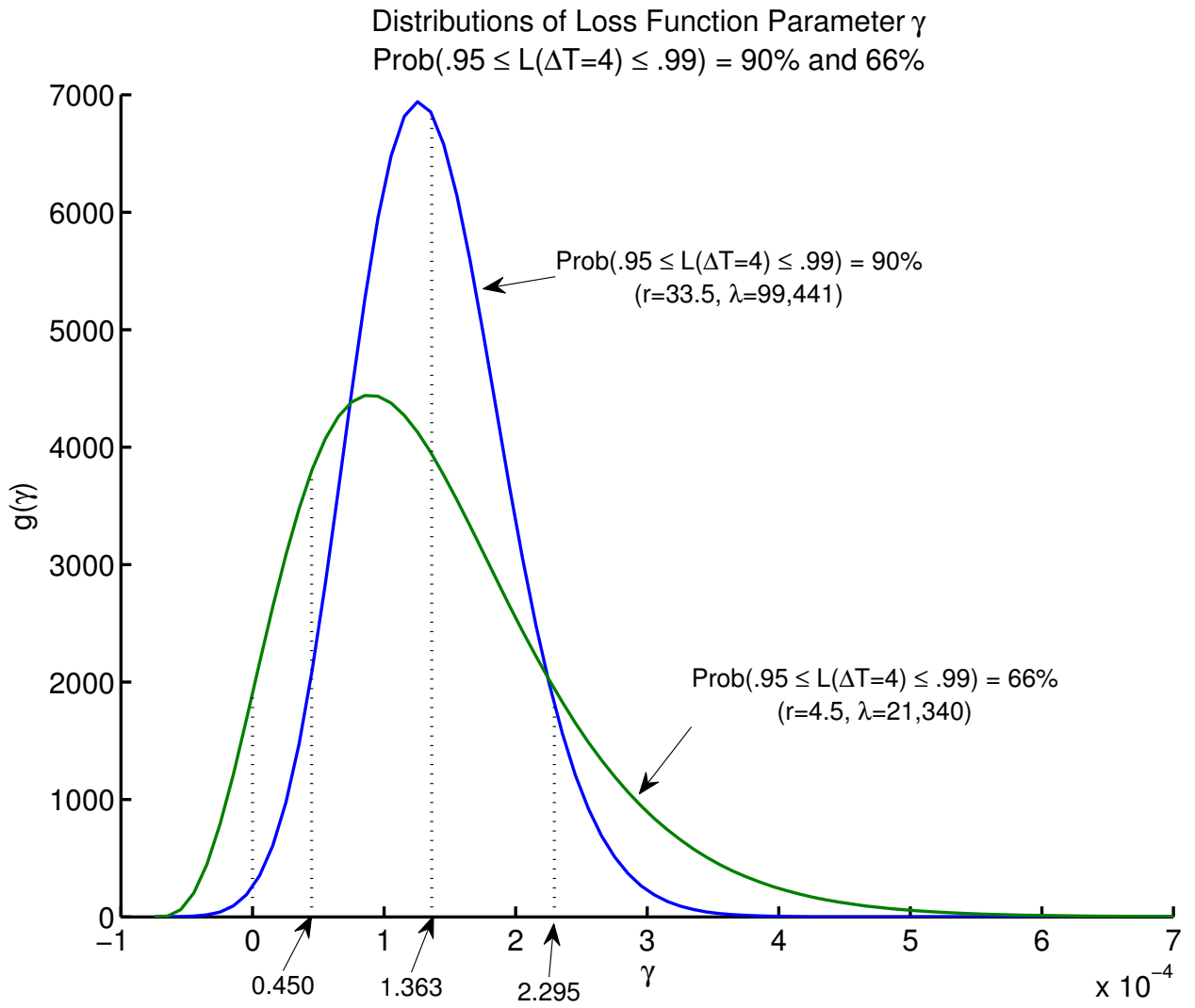


Figure 5: Distributions for Loss Function Parameter  $\gamma$



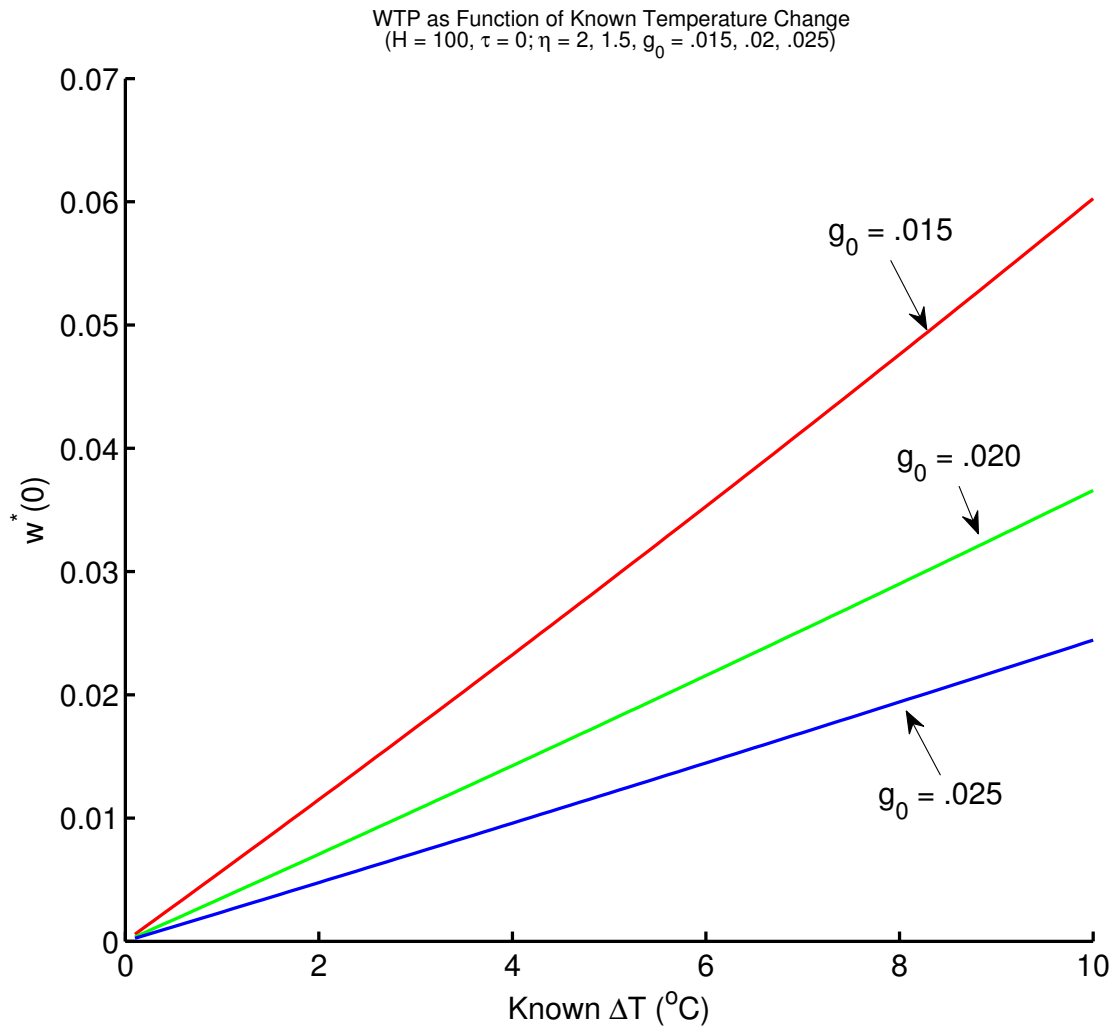


Figure 6: WTP When Temperature Change is Known

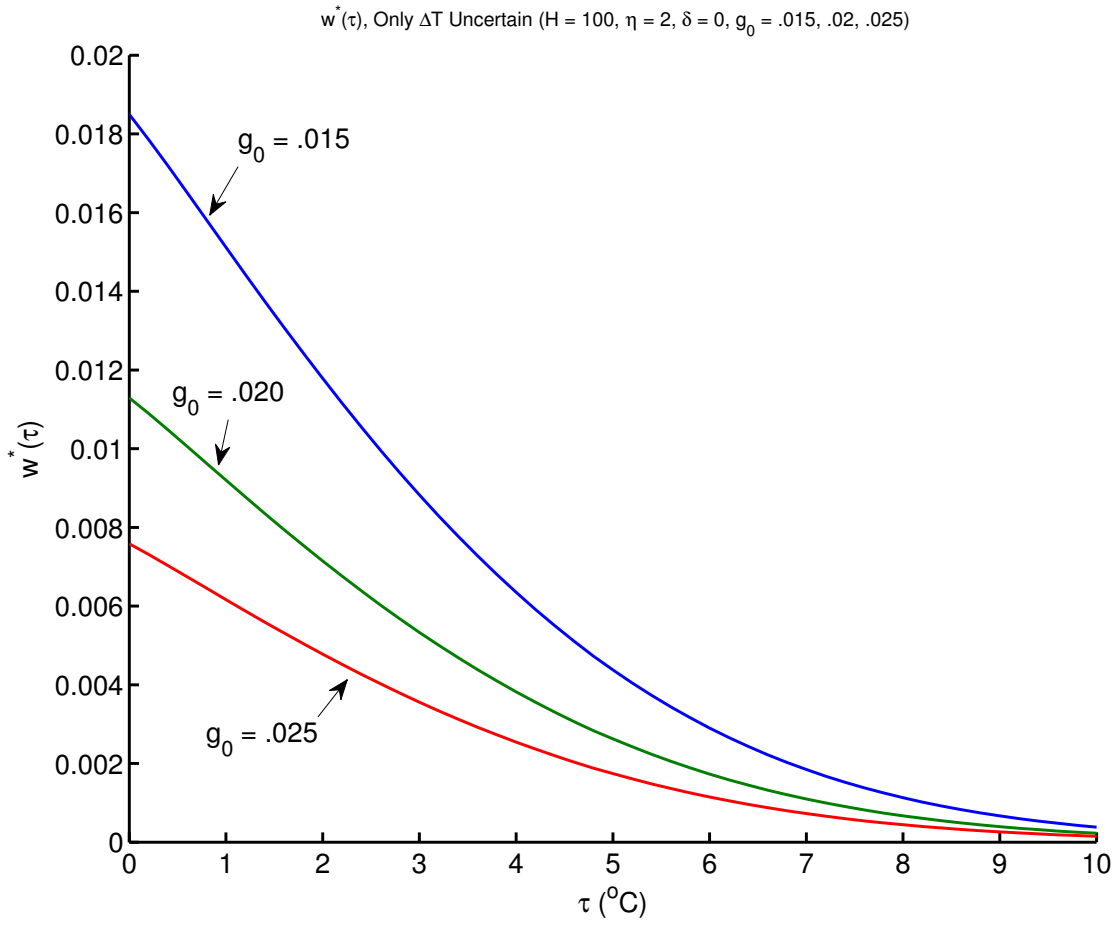


Figure 7: WTP for Base Distribution of  $\Delta T$ ,  $\eta = 2, \delta = 0$

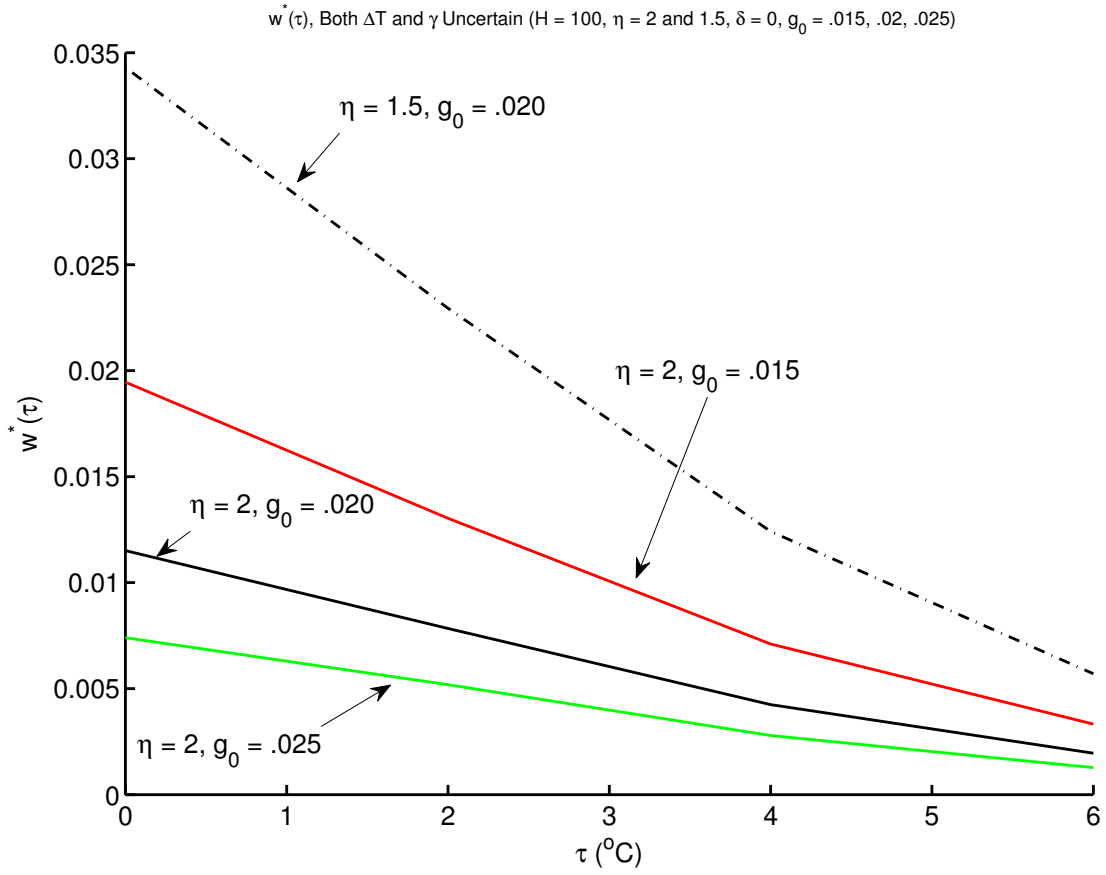


Figure 8: WTP, Both  $\Delta T$  and  $\gamma$  Uncertain.  $\eta = 2$  and  $1.5$ ,  $g_0 = .015, .020, .025$ , and  $\delta = 0$

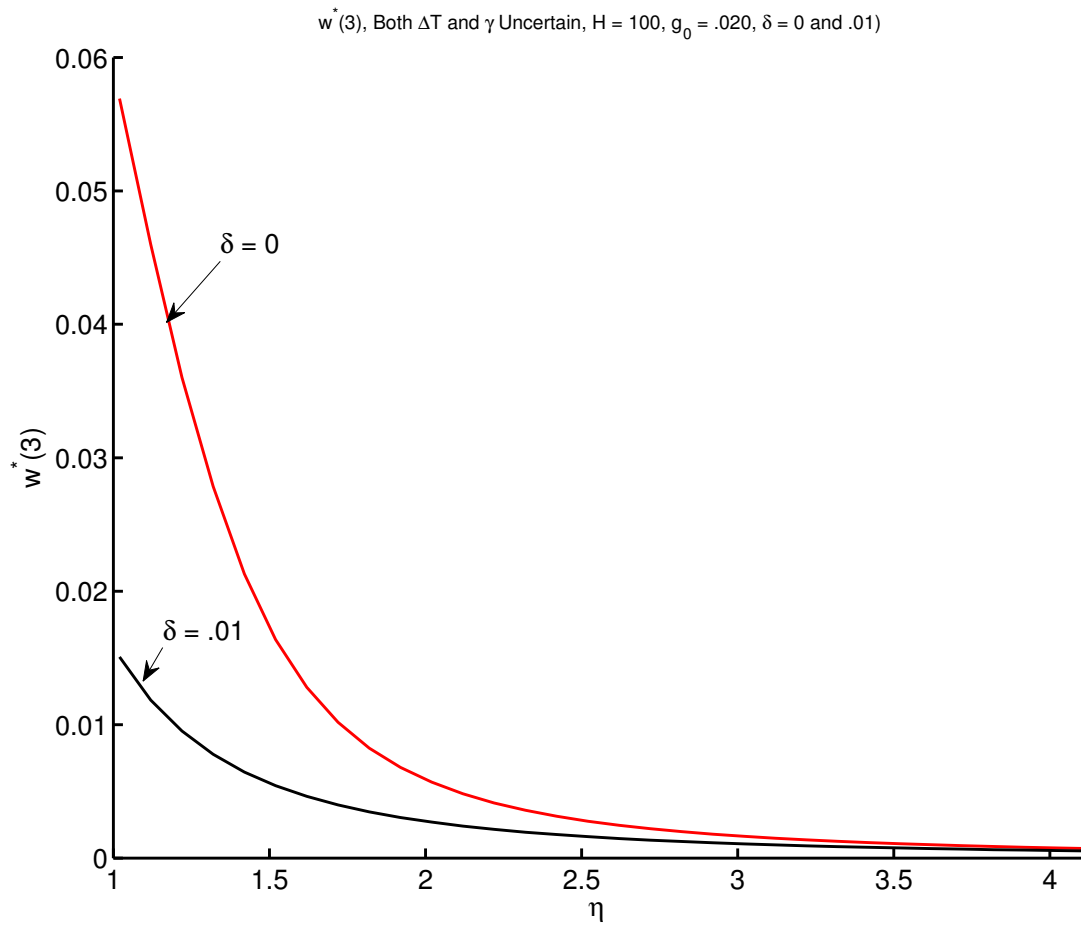


Figure 9: WTP Versus  $\eta$  for  $\tau = 3$ .  $g_0 = .020$  and  $\delta = 0$  and  $.01$

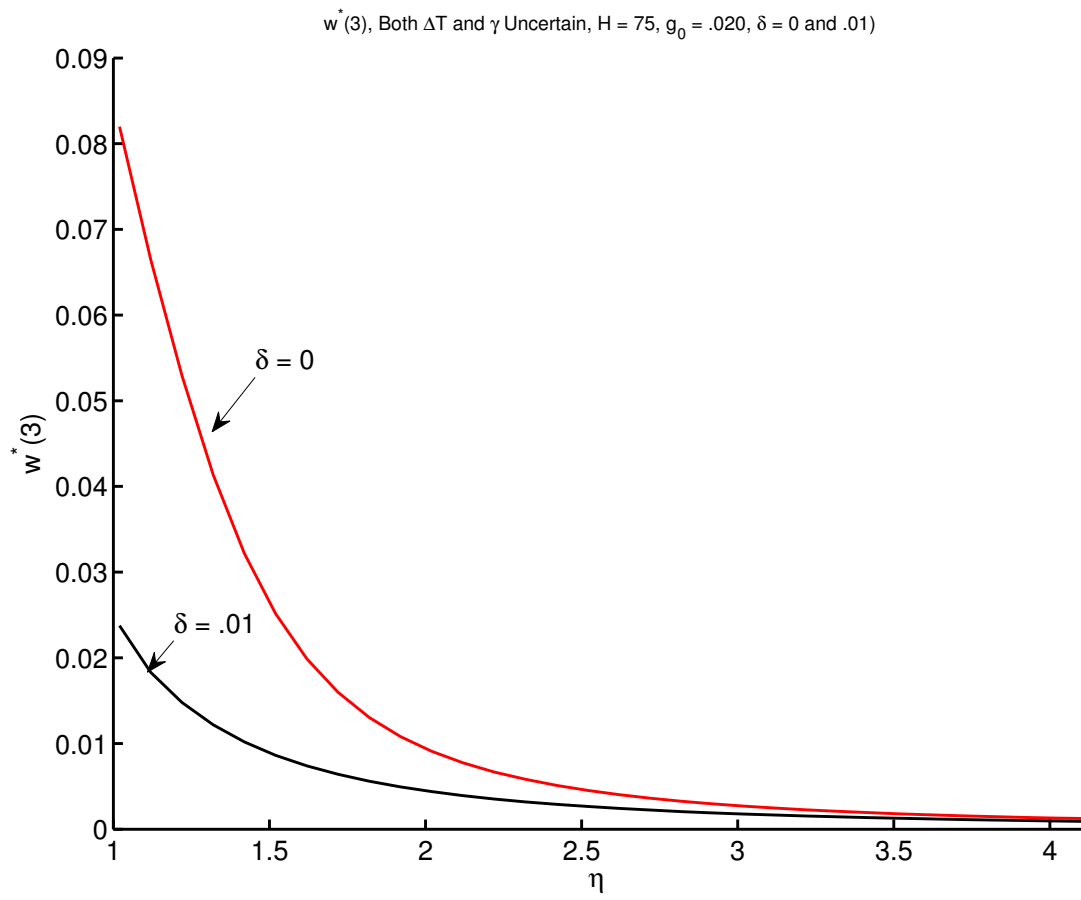


Figure 10: WTP Versus  $\eta$  for  $\tau = 3$ .  $H = 75$ ,  $g_0 = .020$ ,  $\delta = 0$  and  $.01$

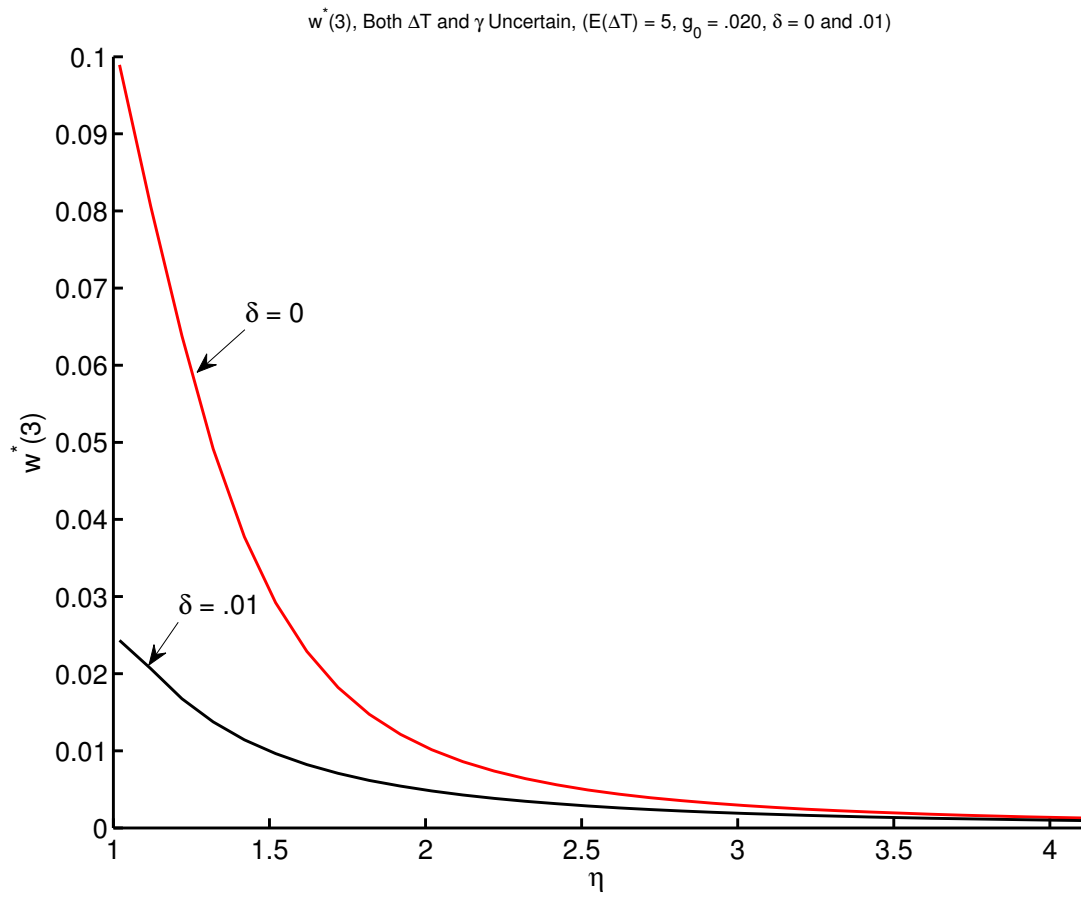


Figure 11: WTP Versus  $\eta$  for  $\tau = 3$ .  $\mathcal{E}(\Delta T_H) = 5^\circ\text{C}$ ,  $H = 100$ ,  $g_0 = .020$ ,  $\delta = 0$  and  $.01$