UNCERTAINTY, EXTREME OUTCOMES, AND CLIMATE CHANGE POLICY*

by

Robert S. Pindyck
Massachusetts Institute of Technology
Cambridge, MA 02142

This draft: March 28, 2009

Abstract: Focusing on tail effects — low probability but very adverse outcomes — 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 τ. 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 the level of GDP. This allows warming to have a permanent impact on future GDP. I find that the fitted distributions for temperature change and economic impact yield values of $w^*(\tau)$ above 2 or 3% for small values of τ only for extreme parameter values and/or substantial shifts in the temperature distribution — which does not support the immediate adoption of a stringent abatement policy.

JEL Classification Numbers: Q5; Q54, D81

Keywords: Environmental policy, climate change, global warming, uncertainty, catastrophic outcomes.

---

*My thanks to Paul Fackler, Michael Greenstone, Paul Klemperer, Charles Kolstad, Raj Mehra, Steve Newbold, V. Kerry Smith, and Martin Weitzman, as well as seminar participants at the IMF, Resources for the Future, Arizona State University, and Columbia University for helpful comments and suggestions.

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.[1] 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, and especially the tails — low probability but very adverse outcomes — 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 to ensure that any increase in temperature at a specific horizon H is limited to τ. Whether the reduction in consumption corresponding to a particular $w^*(\tau)$ is *sufficient* to limit warming to τ 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.[2]

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

[1] An exception is the Stern Review (2007), but as Nordhaus (2007), Weitzman (2007b), 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.

[2] By "economic impact" I mean to include any adverse impacts resulting from global warming, such as social, medical, or direct economic impacts.

between temperature change and the *growth rate* of GDP as opposed to the level of GDP. 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 τ, thereby supporting immediate 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.

This paper builds on recent work by Weitzman (2008, 2009) on climate change, but takes a very different approach. Weitzman (2009) examines implications of our lack of knowledge about the right-hand tail of the distribution for temperature change, ΔT. Suppose there is some underlying probability distribution for ΔT, 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 ΔT is "fat-tailed," i.e., approaches zero at a less than exponential rate (and thus has no moment generating function).[3] If welfare is given by a power utility function, this means that the *expected* loss in future welfare from warming is infinite. Thus unless we arbitrarily bound the utility function, society should be willing to sacrifice *all* current consumption to avoid future warming. In another paper, Weitzman (2008) presents an alternative argument, based on the underlying mechanism of GHG accumulation and its effect on temperature, for why the distribution of ΔT should be fat-tailed, but this has the same disturbing welfare implications.[4]

Weitzman provides considerable insight into the nature of the uncertainty underlying climate change policy, but his results do not readily translate into a policy prescription, e.g., whether society should be willing to sacrifice some specific percentage of current consumption to avoid warming. What his results *do* tell us is that the right-hand tail of the distribution for ΔT — and not the middle of the distribution — is what probably matters most for

[3] Weitzman (2007a) develops implications of this kind of "structural uncertainty" for asset pricing.

[4] For a related discussion of inherent uncertainty over climate sensitivity, and a model that implies a fat-tailed distribution for ΔT, see Roe and Baker (2007).

policy, and that we know very little about that tail. In other words, because of its focus on expected values and the middle of the distribution of outcomes, traditional cost-benefit analysis may be misleading as a policy tool.

My analysis is based on 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 "estimated" 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 can 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.[5]

I obtain estimates of $w^*(\tau)$ that are generally below 3%, even for τ around 2 or 3°C. This is because there is limited weight in the tails of the calibrated distributions for ΔT and

[5]Newbold and Daigneault (2008) also studied implications of uncertainty for climate change policy. They combined a distribution for ΔT with CRRA utility and functions that translate ΔT into lost consumption to estimate WTP. They assume there is a "true" value for ΔT 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.

growth rate impact. Somewhat larger estimates of WTP result for particular combinations of parameter values (e.g., an index of risk aversion close to 1 and an initial GDP growth rate of 1.5%), or if I assume that the rate of warming is accelerated (e.g., the distribution for ΔT applies to a horizon of 75 rather than 100 years). But overall, given the current "state of knowledge" regarding warming and its impact, my results do not support the immediate adoption of a stringent abatement policy.

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. I focus instead on the nature of the uncertainty and its application to a relatively simple cost-benefit analysis.[6]

In the next section, I explain 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_2 equivalent (CO_2e) composite (or individual GHGs) under a "business as usual" (BAU) and one or more abatement scenarios, and resulting future atmospheric CO_2e concentrations. (2) Projections of the average temperature change (or regional temperature

[6] 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 (19996b), 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).

changes) likely to result from higher CO_2e 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 society's pure rate of time preference, so that lost consumption from abatement can be weighed against future gains in consumption from smaller increases in temperature. This is essentially the approach of Nordhaus (1994, 2008), Stern (2007), and others that evaluate abatement policies using "Integrated Assessment Models" (IAMs) that project emissions, CO_2e concentrations, temperature change, the economic impact of warming, 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_2e 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.[7]

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,

[7] The atmospheric CO_2e 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 ΔT in 2100 represents a 66% or a 90% confidence interval.

and created graphs showing multiple outcome distributions implied by groups of studies. As Weitzman (2008a) has argued, those distributions suggest that there is a 5% probability that a doubling of the CO_2e 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 ΔT 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 ΔT applies to a 100-year horizon H, and that temperature increases linearly to its value at H and then continues to increase indefinitely at the same rate. Thus a ΔT_H of 5°C implies that ΔT grows from zero at an arithmetic rate of .05°C per year, i.e., $\Delta T_t = .05t$.

2.2 Economic Impact.

Existing economic studies of climate change relate ΔT 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 GDP_H is but-for GDP in the absence of warming. Most studies use an inverse-quadratic function or an exponential-quadratic function.[8] 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 the level. First, some of the effects of warming (especially substantial 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 floods, droughts, sickness, etc. resulting from higher temperatures would reduce those available for R&D and capital investment, reducing growth. Finally, there is empirical

[8]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 ΔT is large.

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.[9]

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:

$$g_t = g_0 - \gamma \Delta T_t \tag{1}$$

This simple linear relation was estimated by Dell, Jones, and Olken (2008), fits the data well, 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. (1) 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 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. (1). 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 ΔT of 5°C, $C^A = C^B = .95C^0$. Note that as ΔT falls to zero, C_t^A reverts to C_t^0, but C_t^B remains permanently below C_t^0.

I introduce uncertainty into eqn. (1) through the parameter γ. I use information from a number of IAMs to obtain a distribution for β in the exponential loss function:

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

which applies to the *level* of GDP, and then translate this into a distribution for γ. To do this translation, I use the trajectory for GDP and consumption implied by eqn. (1) for a

[9] "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 a rise in temperature 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 this is again significant only for poorer countries.

temperature change-impact combination projected to occur at horizon H, so that the growth rate is $g_t = g_0 - \gamma(\Delta T_H/H)t$. Normalizing initial consumption at 1, this implies:

$$C_t = e^{\int_0^t g(s)ds} = e^{g_0 t - \gamma(\Delta T/2H)t^2} \quad . \tag{3}$$

Thus γ is obtained from β by equating the expressions for C_H implied by eqns. (2) and (3):

$$e^{g_0 H - (\gamma H/2)\Delta T} = e^{g_0 H - \beta(\Delta T)^2} \quad , \tag{4}$$

so that $\gamma = 2\beta\Delta T_H/H$.

The IPCC does not provide standardized distributions for lost GDP corresponding to any particular ΔT, 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 β and thus γ. As with ΔT, I fit a displaced gamma distribution to the parameter γ, which I use to study implications of impact uncertainty on WTP.

2.3 Willingness to Pay.

Given the distributions for ΔT and γ, I posit a CRRA social utility function:

$$U(C_t) = C_t^{1-\eta}/(1-\eta) \quad , \tag{5}$$

where η 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 τ. That fraction, $w^*(\tau)$, is the measure of willingness to pay.[10]

An issue in recent 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 (2007b) and others argue that the rate should be closer to the private return on investment (PRI), around 5 to 6 percent. As Stern (2008) makes clear, the SDR could differ substantially from the PRI, especially over long horizons, in part because

[10]Defining and measuring willingness to pay along these lines was, to my knowledge, first suggested (for $\tau = 0$) by Heal and Kriström (2002), and has also been used by Weitzman (2008).

the social investment being evaluated will affect the consumption trajectory. In my model the consumption discount rate is endogenous; in the context of a Ramsey growth model,

$$R_t = \delta + \eta g_t = \delta + \eta g_0 - \eta\gamma\Delta T_t \ , \tag{6}$$

where δ is the pure rate of time preference and the rate at which utility is discounted. Thus R_t falls over time as ΔT increases.[11] The "correct" value of δ 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 the trajectory for ΔT and the value of γ were known, social welfare would be given by:

$$W = \int_0^\infty U(C_t)e^{-\delta t}dt = \frac{1}{1-\eta}\int_0^\infty e^{-\rho_0 t - \omega t^2}dt \ , \tag{7}$$

where

$$\rho_0 = \delta + (\eta - 1)g_0 \ , \tag{8}$$

and

$$\omega = \tfrac{1}{2}(1-\eta)\gamma\Delta T/H \ . \tag{9}$$

Note that if $\eta > 1$, $\omega < 0$ and the integral in (7) blows up. Thus the estimation of WTP must be based on some finite horizon, which I set to be $N = 400$ years. This is realistic because after some 200 years the world will likely exhaust the economically recoverable stocks of fossil fuels, so that GHG emissions and atmospheric concentrations will diminish. In addition, so many other economic and social changes are likely to occur that the relevance of applying CRRA expected utility over more than a few hundred years is questionable.

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:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1-\eta}\mathcal{E}_{0,\tau}\int_0^N e^{-\rho_0 t - \tilde{\omega} t^2}dt \ , \tag{10}$$

[11] Note that R_t can become negative as ΔT 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 there are other models that also imply a declining discount rate; see, e.g., Cropper and Laibson (1999).

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

$$W_2 = \frac{1}{1-\eta}\mathcal{E}_0 \int_0^N e^{-\rho_0 t - \tilde{\omega} t^2} dt \ , \tag{11}$$

where $\mathcal{E}_0$ again denotes the expectation over ΔT_H and γ, but now with ΔT_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.

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. My model does not include estimates of abatement costs — instead I estimate WTP as a function of τ, the abatement-induced limit on any increase in temperature at the horizon H. Clearly the amount of abatement needed, and thus the cost, will decrease as τ is made larger, so I consider a stringent abatement policy to be one for which τ is "low." Given my focus on extreme outcomes, I consider "low" to be at or below the expected value of the temperature increase under a business-as-usual (BAU) scenario, i.e., about 3°C.

I examine whether the fitted displaced gamma distributions for ΔT and γ, along with "reasonable" values of the remaining economic parameters can yield values of $w^*(\tau)$ greater than 2 or 3% for $\tau \approx 3$°C. I also explore "tail effects" by transforming the gamma distributions to increase skewness or variance while keeping the other moments fixed, and calculating the resulting change in $w^*(\tau)$. Finally, because the fundamental question I address is whether a case can be made for the immediate adoption of a stringent abatement policy, I focus on conservative parameter assumptions, in the sense of leading to a higher WTP.

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_2e 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

ΔT 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 leads over-estimates 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_2e 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 ΔT 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 θ be the displacement parameter, the distribution is given by:

$$f(x; r, \lambda, \theta) = \frac{\lambda^r}{\Gamma(r)}(x-\theta)^{r-1}e^{-\lambda(x-\theta)} \quad , \quad x \geq \theta \ , \tag{12}$$

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:

$$M_x(t) = \mathcal{E}(e^{tx}) = \left(\frac{\lambda}{\lambda - t}\right)^r e^{t\theta} \tag{13}$$

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_2e 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 α_M, α_V, and α_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 α_S while keeping the mean and variance fixed, replace the original values of r, λ, and θ 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 α_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 α_M while keeping the other moments fixed, keep r and λ 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 ΔT 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 $\Delta T \geq 5$°C increases to 7%, and the probability of $\Delta T \geq 10$°C remains 1%.

Recall that the distribution for ΔT pertains to a point in time, H. In modeling the impact on GDP growth, I assume that temperature increases linearly at the annual (arithmetic) rate of $\Delta T_H/H$, and then continues to increase indefinitely at this same rate. This is illustrated in Figure 4, which shows a trajectory for ΔT when it is unconstrained (so that ΔT_H happens to equal 5°C), and when it is constrained so that $\Delta T_H \leq \tau = 3$°C. Note that even when constrained, ΔT_H is a random variable and (unless $\tau = 0$) will be less than τ with probability 1; in Figure 4 it happens to be 2.5°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°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°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 (2009), 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 formulation.

Instead, I treat IAMs and related models of economic impact analogously to the climate science models. Just as there is a consensus regarding a "most likely" range for ΔT, there is a consensus regarding the corresponding likely range of economic impacts: for temperature increases up to 4°C, the "most likely" impact is in the range of 1% to at most 5% of GDP.[12] What is of interest is the outer tail of the distribution for this economic impact. There is some small probability that a temperature increase of 3.0°C (the expected value for ΔT) would have a much larger impact, and we want to know how that affects WTP.

At issue is the value of γ in eqn. (1). 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. (12). I further assume that γ and ΔT 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

[12]This consensus might arise from the use of the same or similar ad hoc damage functions in various IAMs. As Nordhaus (2008, p. 51) points out, "The damage functions continue to be a major source of modelling uncertainty ... ."

that "global mean losses could be 1–5% of GDP for 4°C of warming."[13] 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 $\Delta T = 3$°C, and 1% to 8% of lost GDP for $\Delta T = 5$°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 $\Delta T = 4$°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 β in eqn. (2), but they are easily translated into corresponding numbers for γ in eqn. (1). From eqn. (4), $\gamma = 2\beta\Delta T/H$. Thus the mean, 17-percent, and 83-percent values for γ are, respectively, $\bar{\gamma} = .0001523$, $\gamma_1 = .0000503$, and $\gamma_2 = .0002565$.[14]

Using these three numbers to fit a 3-parameter displaced gamma distribution for γ yields $r_g = 4.5$, $\lambda_g = 19{,}100$, and $\theta_g = \bar{\gamma} - r_g/\lambda_g = -.0000833$. This distribution is shown in Figure 5. For comparison, I also fit the distribution assuming the 1% to 5% loss of GDP for $\Delta T = 4$°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, ΔT_H will not exceed a maximum level τ. Of course ΔT is stochastic, so ΔT_H will be less than τ.[15] I also assume that whatever the value of ΔT_H, ΔT will continue to increase indefinitely at the (arithmetic) rate $(\Delta T_H/H)t$.

Using the CRRA utility function of eqn. (5) and the growth rate of consumption given by eqn. (1), I calculate WTP as the maximum fraction of consumption, $w^*(\tau)$, that society would be willing to sacrifice to keep $\Delta T_H \leq \tau$. As explained in Section 2, $w^*(\tau)$ is found by

[13]The IAMs surveyed by the IPCC include Hope (2006), Mendelsohn et al (1998), Nordhaus and Boyer (2000), and Tol (2002).

[14]If L is the loss of GDP corresponding to ΔT, $1 - L = \exp[-\beta(\Delta T)^2] = \exp[-\gamma H \Delta T/2]$. $H = 100$ and $\Delta T = 4$°C, so $.97 = e^{-200\bar{\gamma}}$, $.99 = e^{-200\gamma_1}$, and $.95 = e^{-200\gamma_2}$. Using instead the 4.5% midpoint of the 1% to 8% range of lost GDP for $\Delta T = 5$°C from Dietz and Stern (2008), we would have $\bar{\gamma} = .000184$.

[15]The expected value of ΔT_H is $\mathcal{E}(\Delta T \mid \tau) = \left(\int_0^\tau x f(x)dx\right) / \left(\int_0^\tau f(x)dx\right) < \tau$.

equating the social welfare functions $W_1(\tau)$ and W_2 of eqns. (10) and (11).

Given the distributions $f(\Delta T)$ and $g(\gamma)$ for ΔT and γ respectively, denote by $M_\tau(t)$ and $M_\infty(t)$ the time-t expectations

$$M_\tau(t) = \frac{1}{F(\tau)} \int_{\theta_T}^{\tau} \int_{\theta_\gamma}^{\infty} e^{-\rho_0 t - \tilde{\omega} t^2} f(\Delta T) g(\gamma) d\Delta T d\gamma \tag{14}$$

and

$$M_\infty(t) = \int_{\theta_T}^{\infty} \int_{\theta_\gamma}^{\infty} e^{-\rho_0 t - \tilde{\omega} t^2} f(\Delta T) g(\gamma) d\Delta T d\gamma \quad , \tag{15}$$

where ρ_0 and $\tilde{\omega}$ are given by eqns. (8) and (9), θ_T and θ_γ are the lower limits on the distributions for ΔT and γ, and $F(\tau) = \int_{\theta_T}^{\tau} f(\Delta T) d\Delta T$. Thus $W_1(\tau)$ and W_2 are:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1-\eta} \int_0^N M_\tau(t) dt \equiv \frac{[1 - w(\tau)]^{1-\eta}}{1-\eta} G_\tau \tag{16}$$

and

$$W_2 = \frac{1}{1-\eta} \int_0^N M_\infty(t) dt \equiv \frac{1}{1-\eta} G_\infty \quad . \tag{17}$$

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

$$w^*(\tau) = 1 - [G_\infty / G_\tau]^{\frac{1}{1-\eta}} \quad . \tag{18}$$

The solution for $w^*(\tau)$ will depend on the distributions for ΔT and γ, the horizon H, and the parameters η, g_0, and δ. It is useful to determine how w^* varies with τ; the cost of abatement is a decreasing function of τ, so given estimates of that cost, one could use these results to determine reasonable abatement (or rather temperature) targets. Also of interest is the extent to which, for any given τ, $w^*(\tau)$ is driven by the tails of the distributions for ΔT and γ, which I explore below by changing the variance and skewness of these distributions.

5.1 Parameter Values.

Putting aside the distributions for ΔT and γ, what are reasonable values for the behavioral and economic parameters, i.e., the index of relative risk aversion η, the rate of time discount δ, 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 literature has numerous estimates of η, ranging from 1.5 to 6. Estimates of δ in the finance and macroeconomics literature range from .01 to .04. The growth rate g can be measured directly from historical data, and 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 the private return on investment (PRI). Indeed, estimates of η and δ in the finance and macroeconomics literature 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 very long time horizons and strong externalities. It has been argued, for example, that for public investments involving future generations, δ should be close to zero, on the grounds that even though 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 η 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.[16]

It is not my objective to debate the "correct" values of η and δ that should be applied to comparisons involving future generations. However, I need values of η, δ, and g_0 to calculate WTP. Because I want to determine whether the immediate adoption of a stringent abatement policy (i.e., a high WTP) can be justified by current assessments of uncertainty over temperature change and economic impact, I will stack the deck, so to speak, in favor of our great-grandchildren and use relatively low values of η and δ: around 2 for η, and $\delta = 0$. Also, WTP is a decreasing function of the base growth rate g_0 that appears in eqn. (6), so I will use the relatively low range of .015 to .025 for that parameter.

[16]For arguments in favor of low values for η and δ and low SDRs, see Heal (2008), Stern (2008) and Summers and Zeckhauser (2008). For opposing views, see Nordhaus (2007) and Weitzman (2007b).

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 ΔT and the impact of that trajectory on economic growth were both known with certainty, eqns. (16) and (16) would simplify to:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1-\eta} \int_0^N e^{\rho_0 t - \omega_\tau t^2} dt \quad , \tag{19}$$

and

$$W_2 = \frac{1}{1-\eta} \int_0^N e^{\rho_0 t - \omega t^2} dt \quad , \tag{20}$$

where $\omega = \frac{1}{2}(1-\eta)\bar{\gamma}\Delta T/H$ and $\omega_\tau = \frac{1}{2}(1-\eta)\bar{\gamma}\tau/H$. (I am using the mean, $\bar{\gamma}$, as the certainty-equivalent value of γ. Also, $N = 400$.)

I calculate the WTP to keep ΔT zero for all time, i.e., $w^*(0)$, over a range of values for ΔT 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, $\Delta T_H = 6$°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 ΔT at zero instead of 6°C.[17]

Note that for any known ΔT_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 ΔT increases (and can eventually become negative), but its starting value is $\delta + \eta g_0$. The damages from warming (a falling growth rate as ΔT increases) are initially small, making estimates of WTP highly dependent on the values for δ, η, and g_0.

5.3 Uncertainty Limited to Temperature Change.

I now turn to the effects of uncertainty over ΔT. I will assume that the loss function is deterministic, with the parameter γ fixed at its mean value $\bar{\gamma} = .0001523$. Eqns. (14) and (15) then simplify as follows:

$$M_\tau(t) = \frac{1}{F(\tau)} \int_{\theta_T}^{\tau} e^{-\rho_0 t - \tilde{\omega} t^2} f(\Delta T) d\Delta T \tag{21}$$

[17] Remember that the "known ΔT" is not constant, and applies only to time $t = H$. For example, ΔT = 6°C means the temperature will increase linearly from 0 at $t = 0$ to 6°C at $t = H$, and then continue increasing at the same rate.

and

$$M_\infty(t) = \int_{\theta_T}^{\infty} e^{-\rho_0 t - \tilde{\omega} t^2} f(\Delta T) d\Delta T \quad , \tag{22}$$

where now $\tilde{\omega} = \frac{1}{2}(1-\eta)\bar{\gamma}\Delta T/H$.

Figure 7 shows $w^*(\tau)$ for $\delta = 0$, $\eta = 2$, and $g_0 = .015$, .020, and .025. Observe that WTP is at or below 2%, even for small values of τ, and is closer to 1% if $g_0 = .020$ or .025. Although $w^*(0)$ is considerably larger if ΔT_H is *known* to be 6°C or more (see Figure 6), such temperature outcomes have low probability. A feasible (i.e., attainable using a realistic abatement policy) value for τ is probably around 2°C, so WTP is likely to be below the cost.

Table 1 shows $w^*(\tau)$ for several values of τ, using the base distribution for ΔT shown in Figure 2, with $\delta = 0$, $\eta = 2$, and $g_0 = .02$. (The parameter γ in the loss function is again fixed at $\bar{\gamma} = .0001523$.) 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 ΔT is increased by 50%, in each case holding the other two moments fixed. The increase in skewness *reduces* $w^*(\tau)$ for $\tau < 5$°C, because it pushes some of the probability mass from the left to the right tail. For $\tau = 7$°C or more, $w^*(\tau)$ is increased, but only modestly, because even with this increase in skewness, the probability of a ΔT of 7°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 τ, but only modestly. For example, $w^*(3°)$ increases from .58% of consumption to .76%.

Of course this ignores uncertainty over the loss function. The last column of Table 1 shows $w^*(\tau)$ for the original distribution of ΔT, but a doubling of the parameter γ. This has a substantial effect on the WTP, roughly doubling all of the base case numbers. But $w^*(0)$ is still only about 2.5%.

5.4 Uncertainty Over Temperature and Economic Impact.

I now allow for uncertainty over both ΔT and the impact parameter γ, using the calibrated distributions for each. WTP is now given by eqns. (14) to (18). 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

Table 1: WTP, only ΔT Stochastic

τ	Base Case	$S = 1.5S_0$	$V = 1.5V_0$	$\gamma = .0003046$
0	.0123	.0115	.0138	.0256
1	.0100	.0092	.0117	.0212
3	.0058	.0054	.0076	.0127
5	.0029	.0029	.0042	.0065
7	.0012	.0014	.0019	.0028
10	.0003	.0004	.0004	.0006

Note: Each entry is $w^*(\tau)$, fraction of consumption society would sacrifice to ensure that $\Delta T_H \leq \tau$. $H = 100$ years, $N = 400$ years, $\delta = 0$, $\eta = 2$, $g_0 = .02$.

is .02 or greater, WTP is always less than 1.3%, even for $\tau = 0$. To obtain a WTP above 2% requires an initial growth rate of only .015 or a lower value of η. The figure also shows the WTP for $\eta = 1.5$ and $g_0 = .02$; now $w^*(0)$ reaches 4%.

Figure 9 shows the dependence of WTP on the index of risk aversion, η. It plots $w^*(3)$, i.e., the WTP to ensure $\Delta T_H \leq 3°$C at H = 100 years, for an initial growth rate of .02. Although $w^*(3)$ is below 2% for moderate values of η, it comes close to 6% if η is reduced to 1 (the value of η 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 ηg_0. If η (or for that matter g_0) is made smaller, potential losses of future consumption have a larger impact on WTP. Note that $w^*(3)$ begins to increase as η is increased beyond 3. This is the effect of the $\tilde{\omega} t^2$ term in eqns. (10) and (11), which becomes large as t grows. Finally, Figure 9 also shows that discounting future utility, even at a very low rate, will considerably reduce WTP. If δ is increased to .01, $w^*(3)$ is again below 2% for all values of η.

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 ΔT and the impact parameter γ 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 ΔT in 2100 might be higher than the 1.0°C to 4.5°C range given by the IPCC. For example, a recent report by Sokolov et al

(2009) suggests an expected value for ΔT in 2100 of around 4 to 5°C, as opposed to the 3.0°C expected value that I have used.

Suppose, for example, that the distribution for ΔT_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 η is close to 1, $w^*(3)$ is above 7%. (However, $w^*(3)$ is much lower if $\delta = .01$.) In addition, $w^*(3)$ rises rapidly as η increases beyond 3, and in fact blows up as η approaches 4. This last result is an artifact of the model's specification. Note from eqn. (9) that $\tilde{\omega}$ becomes a larger negative number as η is increased, so that $\tilde{\omega}t^2$ can becomes very large as t approaches the limit N. (If N is reduced to 300 years, $w^*(3)$ continues to decrease as η is increased to 4.)

Alternatively, we could shift the entire distribution for ΔT_H so that the mean is 5°C, corresponding to the upper end of the 4 to 5°C range in Sokolov et al (2009). Figure 11 duplicates Figure 9 except that the mean of ΔT_H has been increased from 3°C to 5°C, with the other moments of the distribution left unchanged, and H is again 100 years. Now if $\delta = 0$ and η is below 1.5, $w^*(3)$ is above 4%, and reaches 10% if $\eta = 1$. Thus there are parameter values and plausible distributions for ΔT 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 rather stark. For temperature 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 ΔT 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 ΔT and γ. The distribution that I have calibrated for ΔT implies a 21% probability of $\Delta T \geq 4.5$°C in 100 years, and a 5% probability of $\Delta T \geq 7.0$°C, numbers consistent with the range of climate sensitivity studies surveyed by the IPCC. Likewise, the calibrated distribution for γ implies a 17% probability of $\gamma \geq .00026$, also consistent with the IPCC and other surveys. A realization in which, say, $\Delta T = 4.5°\text{C}$ and $\gamma = .00026$ would imply that GDP and consumption in 100 years would be 5.7 percent lower than with no increase in temperature.[18] However, the probability of $\Delta T \geq 4.5°\text{C}$ *and* $\gamma \geq .00026$ is only about 3.6%. An even more extreme outcome in which $\Delta T = 7°\text{C}$ (and $\gamma = .00026$) 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.

Finally, although the low values of WTP that I have calculated would argue against the immediate adoption of a *stringent* GHG abatement policy, these results do not imply that *no* abatement is optimal. Taking the U.S. in isolation, a WTP of 2% amounts to about \$300 billion per year, a rather substantial amount for GHG abatement. And if, for example, $w^*(3) = .01$, 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 τ. 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 (2007) and from recent IAMs (the current "state of knowledge" regarding warming

[18] If $\gamma = .00026$ and $\Delta T = 4.5°\text{C}$, $\beta = \gamma H/2\Delta T = .00289$, and from eqn. (2), $L = e^{-\beta(\Delta T)^2} = .943$.

and its impact), I fit displaced gamma distributions for ΔT and an impact parameter γ. I then examined whether "reasonable" values for the remaining parameters could yield values of $w^*(\tau)$ above 2% or 3% for small values of τ, thereby supporting immediate stringent abatement. I 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 it is well below 2% if the objective is to keep ΔT 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 η 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 ΔT and γ, 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 change and its impact, one could argue that this consensus is wrong, especially with respect to the tails of the distributions. We have no historical or experimental data from which to assess the likelihood of a ΔT above 5°C, never mind its economic impact, but at least some recent studies suggest that warming could be greater and/or more rapid than the IPCC suggests. In addition, the loss function specified in eqn. (1) is linear, and it may be that a convex relationship between ΔT and the growth rate g_t is more realistic. And one could argue, as Weitzman (2009) has, 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%).

The real debate among economists is not so much over whether we should adopt some kind of GHG abatement policy, but rather over whether a stringent policy is needed now, or instead abatement should begin slowly or be delayed altogether. My results support a "begin slowly" policy. In addition, beginning slowly has other virtues. First, 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. Second, there is an "option value" to waiting for more information before adopting a policy (and especially a stringent policy) that imposes sunk costs on consumers. In particular, 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.

References

Cropper, Maureen, and David Laibson, "The Implications of Hyperbolic Discounting for Project Evaluation," Chap. 16 in P. Portney and J. Weyant, Eds., *Discounting and Intergenerational Equity*, Resources for the Future, 1999.

Dasgupta, Partha, Karl-Göran Mäler, and Scott Barrett, "Intergenerational Equity, Social Discount Rates, and Global Warming," Chap. 7 in P. Portney and J. Weyant, Eds., *Discounting and Intergenerational Equity*, Resources for the Future, 1999.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken, "Climate Change and Economic Growth: Evidence from the Last Half Century," NBER Working Paper No. 14132, June 2008.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken, "Temperature and Income: Reconciling New Cross-Sectional and Panel Estimates," NBER Working Paper No. 14680, January 2009.

Dietz, Simon, and Nicholas Stern, "Why Economic Analysis Supports Strong Action on Climate Change: A Response to the *Stern Review*'s Critics," *Review of Environmental Economics and Policy*, Winter 2008, **2**, 94–113.

Fisher, Anthony C., and Urvashi Narain, "Global Warming, Endogenous Risk, and Irreversibility," *Environmental and Resource Economics*, 2003, **25**, 395–416.

Gollier, Christian, Bruno Jullien, and Nicolas Treich, "Scientific Progress and Irreversibility: An Economic Interpretation of the 'Precautionary Principle'," *Journal of Public Economics*, 2000, **75**, 229-253.

Heal, Geoffrey, "Climate Economics: A Meta-Review and Some Suggestions," NBER Working Paper 13927, April 2008.

Heal, Geoffrey, and Bengt Kriström, "Uncertainty and Climate Change," *Environmental and Resource Economics*, June 2002, **22**, 3–39.

Hope, C., "The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern," *Integrated Assessment*, 2006, **6**, 1–16.

Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2007: The Physical Science Basis," Technical Report, 2007a.

Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2007: Impacts, Adaptation, and Vulnerability," Technical Report, 2007b.

Kolstad, Charles D., "Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions," *Journal of Environmental Economics and Management*, 1996a, **31**, 1-18.

Kolstad, Charles D., "Fundamental Irreversibilities in Stock Externalities," *Journal of Public Economics*, 1996b, **60**, 221-233.

Mendelsohn, Robert, "Is the *Stern Review* an Economic Analysis?" *Review of Environmental Economics and Policy*, Winter 2008, **2**, 45–60.

Mendelsohn, Robert, W.N. Morrison, M.E. Schlesinger, and N.G. Andronova, "Country-Specific Market Impacts of Climate Change," *Climatic Change*, 1998, **45**, 553–569.

Newbold, Stephen C., and Adam Daigneault, "Climate Response Uncertainty and the Expected Benefits of Greenhouse Gas Emissions Reductions," unpublished manuscript, U.S. Environmental Protection Agency, October 2008.

Newell, Richard G, and William A. Pizer, "Regulating Stock Externalities Under Uncertainty," *Journal of Environmental Economics and Management*, 2003, **46**, 416-32.

Nordhaus, William D., *Managing the Global Commons*, M.I.T. Press, 1994.

Nordhaus, William D., "A Review of the *Stern Review on the Economics of Climate Change*," *Journal of Economic Literature*, Sept. 2007, 686–702.

Nordhaus, William D., *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, 2008.

Nordhaus, William D., and J.G. Boyer, *Warming the World: Economic Models of Global Warming*, M.I.T Press, 2000.

Pindyck, Robert S., "Irreversibilities and the Timing of Environmental Policy," *Resource and Energy Economics*, July 2000, **22**, 233-259.

Pindyck, Robert S., "Optimal Timing Problems in Environmental Economics," *Journal of Economic Dynamics and Control*, July 2002, **26**, 1677-1697.

Pindyck, Robert S., "Uncertainty in Environmental Economics," *Review of Environmental Economics and Policy*, Winter 2007.

Roe, Gerard H., and Marcia B. Baker, "Why is Climate Sensitivity So Unpredictable?" *Science*, October 26, 2007, **318**, 629–632.

Sokolov, A.P., P.H. Stone, C.E. Forest, R. Prinn, M.C. Sarofim, M. Webster, S. Paltsev, C.A. Schlosser, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B. Felzer, and H.D. Jacoby, "Probabilistic Forecast for 21st Century Climate Based on Uncertainties in Emissions (without Policy) and Climate Parameters," MIT Joint Program on the Science and Policy of Global Change, Report No. 169, January 2009.

Stern, Nicholas, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, 2007.

Stern, Nicholas, "The Economics of Climate Change," *American Economic Review*, May 2008, **98**, 1–37.

Summers, Lawrence, and Richard Zeckhauser, "Policymaking for Posterity," NBER Working Paper, 2008, forthcoming in *Journal of Risk and Uncertainty.*

Tol, Richard S.J., "Estimates of the Damage Costs of Climate Change," *Environmental and Resource Economics*, 2002, **21**, 47–73 (Part 1: Benchmark Estimates), 135–160 (Part 2: Dynamic Estimates).

Weitzman, Martin L., "Prior-Sensitive Expectations and Asset-Return Puzzles," *American Economic Review*, 2007(a).

Weitzman, Martin L., "A Review of the *Stern Review on the Economics of Climate Change*," *Journal of Economic Literature*, Sept. 2007(b), 703–724.

Weitzman, Martin L., "Some Dynamic Economic Consequences of the Climate-Sensitivity Inference Dilemma," unpublished manuscript, Feb. 2008.

Weitzman, Martin L., "On Modeling and Interpreting the Economics of Catastrophic Climate Change," *Review of Economics and Statistics*, February 2009.

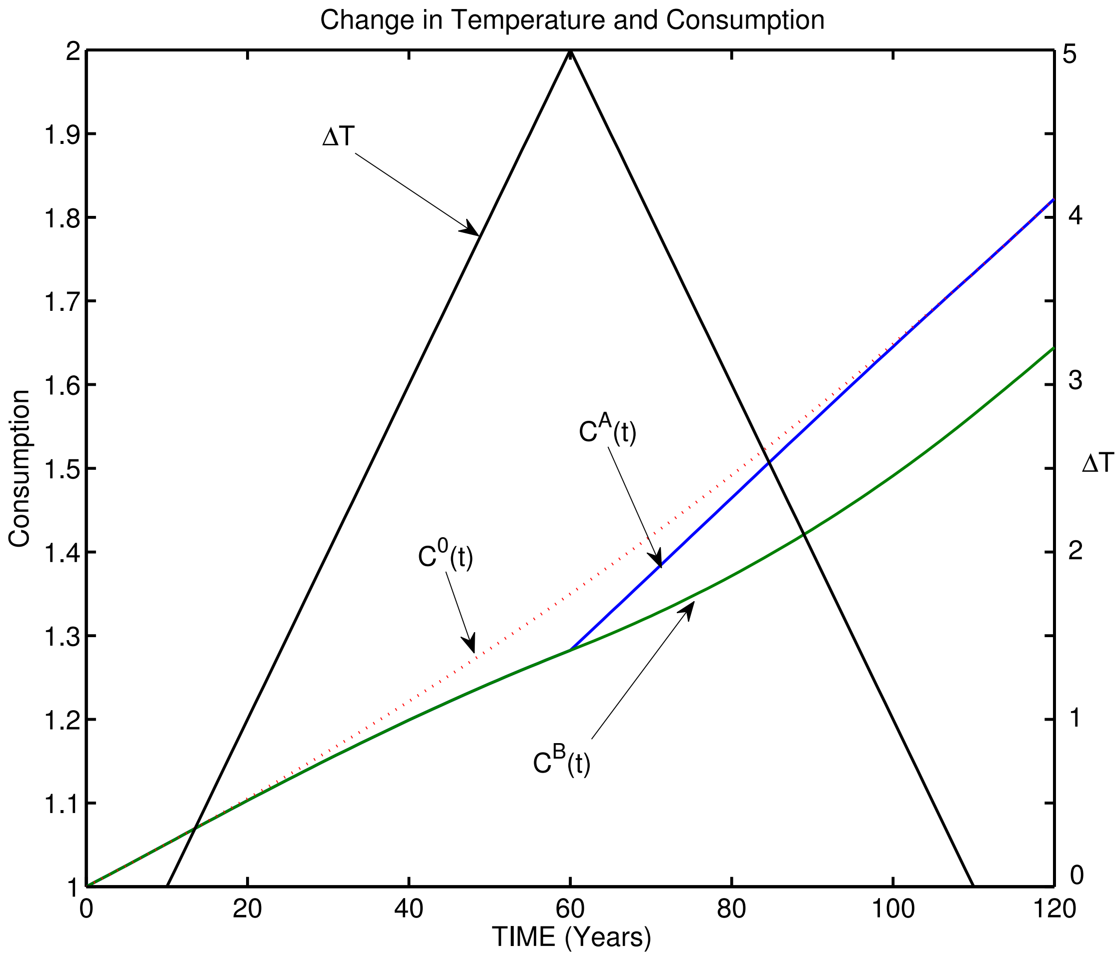

Figure 1: Example of Economic Impact of Temperature Change. (Note temperature increases by 5°C over 50 years and then falls to original level over next 50 years. C^A is consumption when ΔT reduces level, C^B is consumption when ΔT reduces growth rate, and C^0 is consumption with no temperature change.)

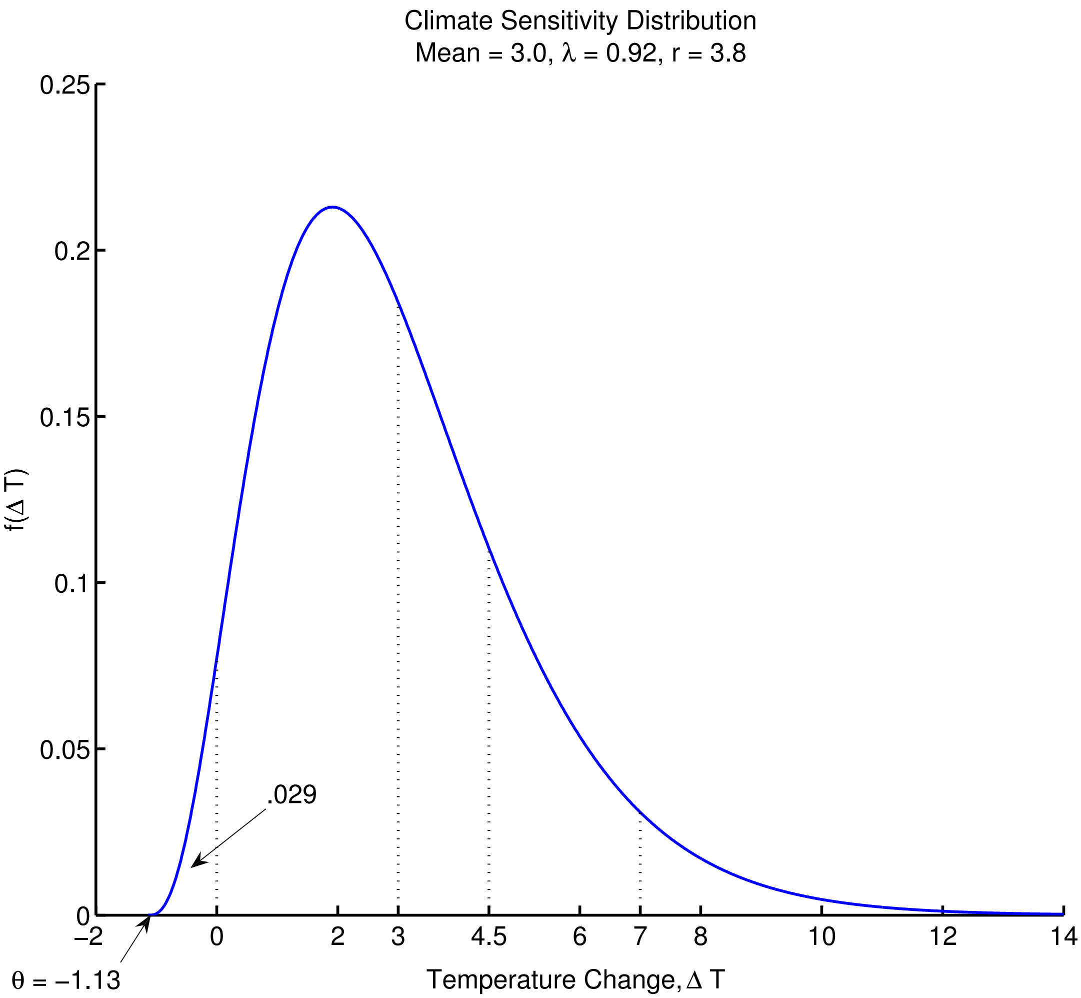

Figure 2: Base Distribution for Temperature Change.

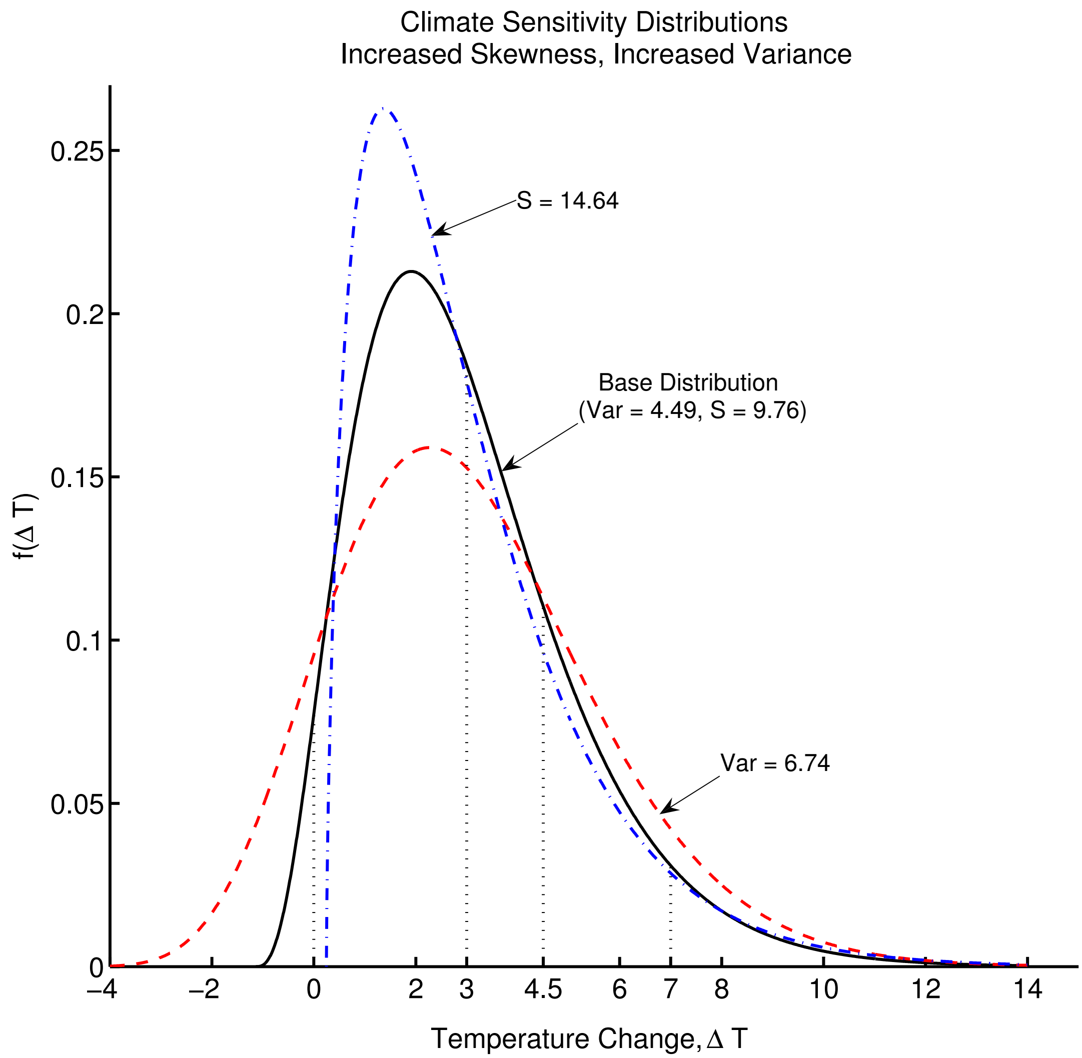

Figure 3: Temperature Change Distribution: 50% Increase in Variance, Skewness

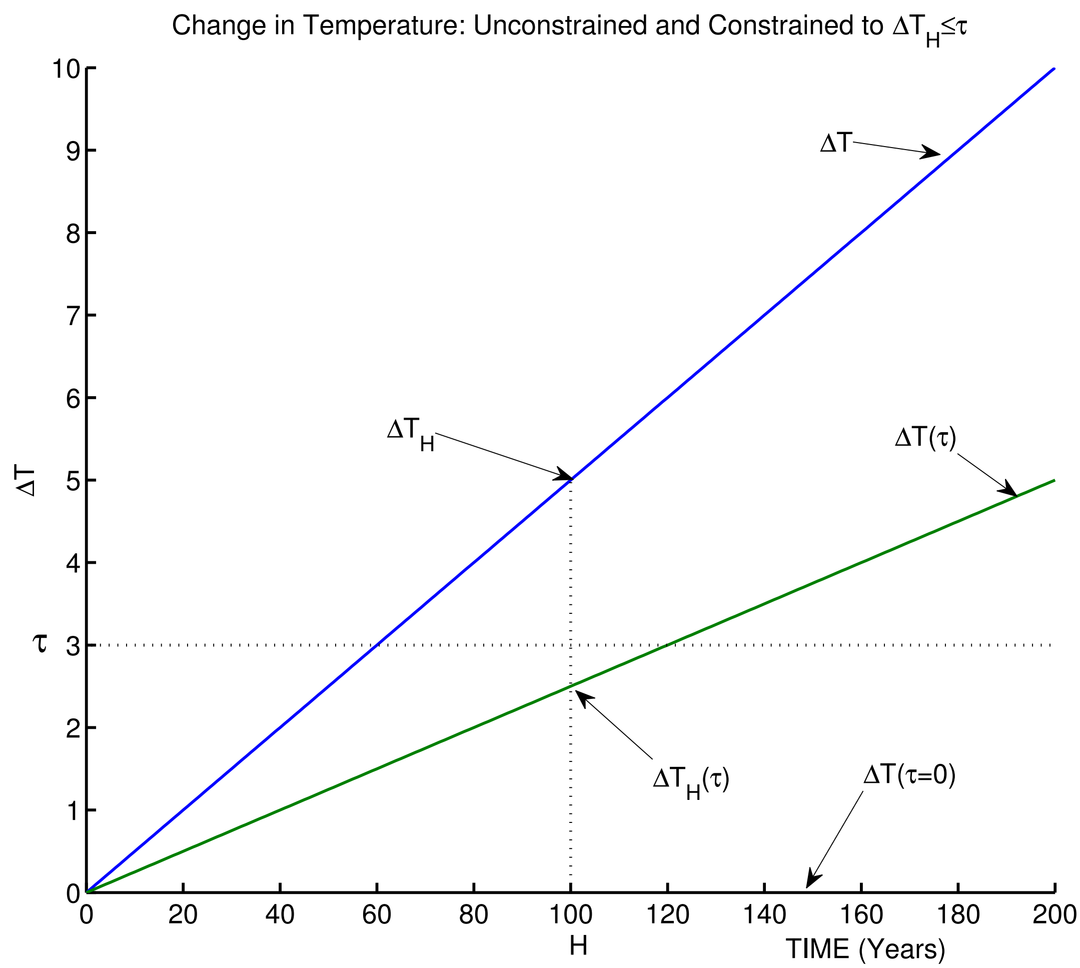

Figure 4: Temperature Change: Unconstrained and Constrained So $\Delta T_H \leq \tau$

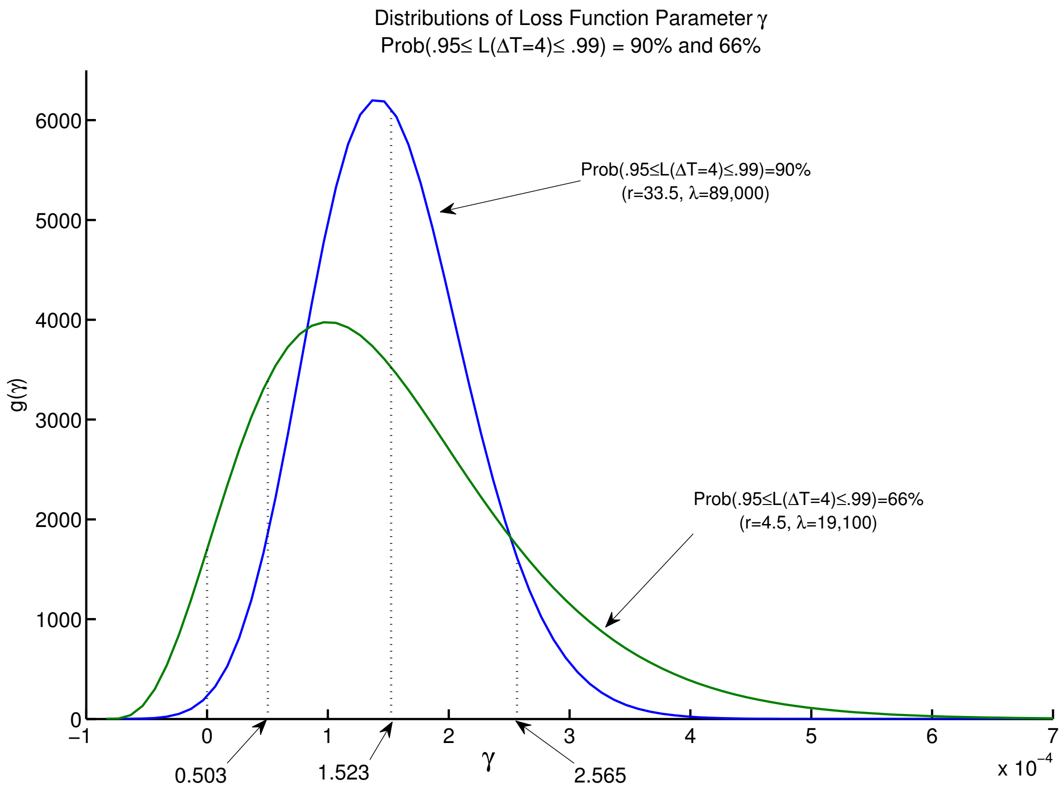

Figure 5: Distributions for Loss Function Parameter γ

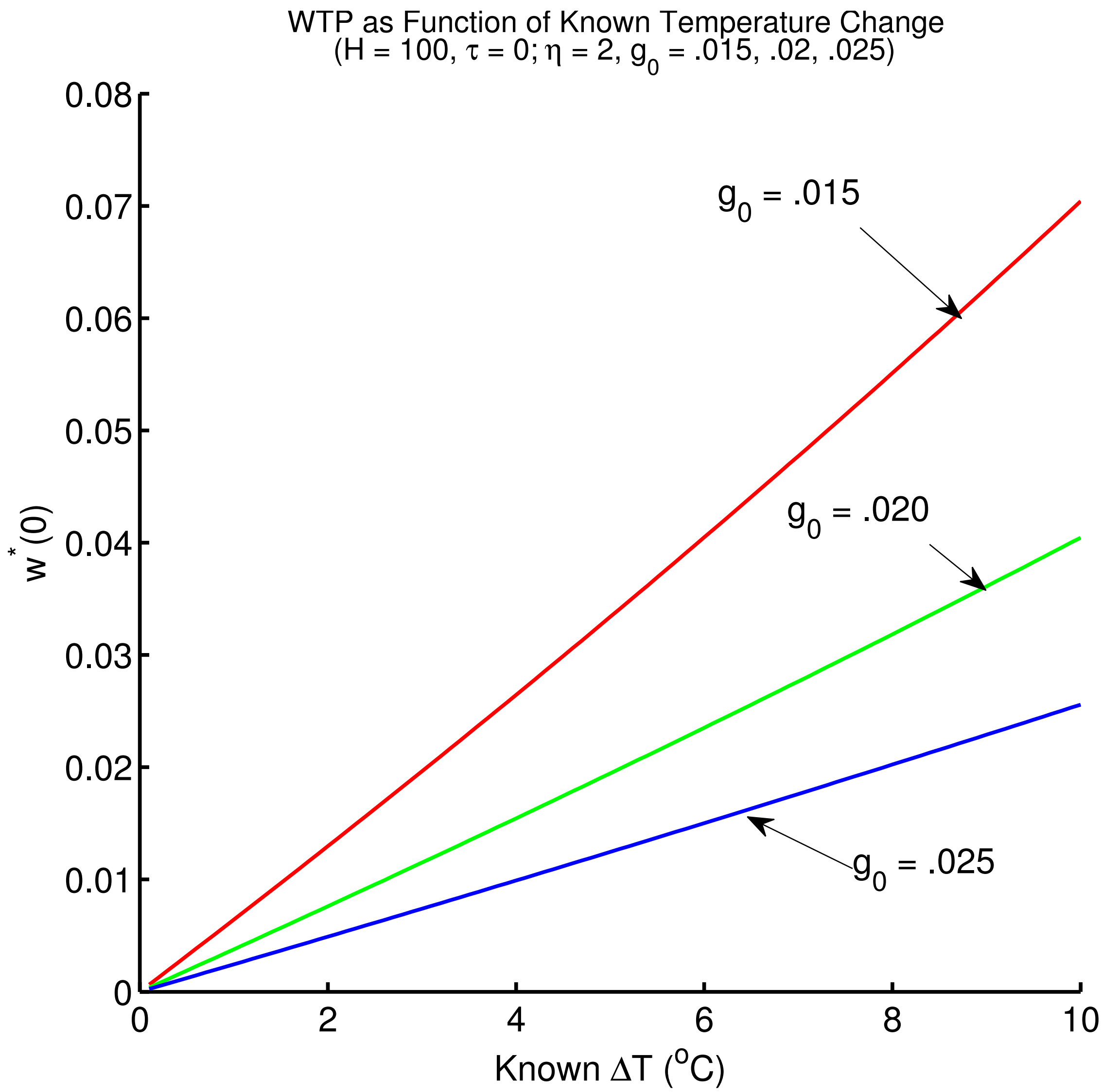

Figure 6: WTP When Temperature Change is Known

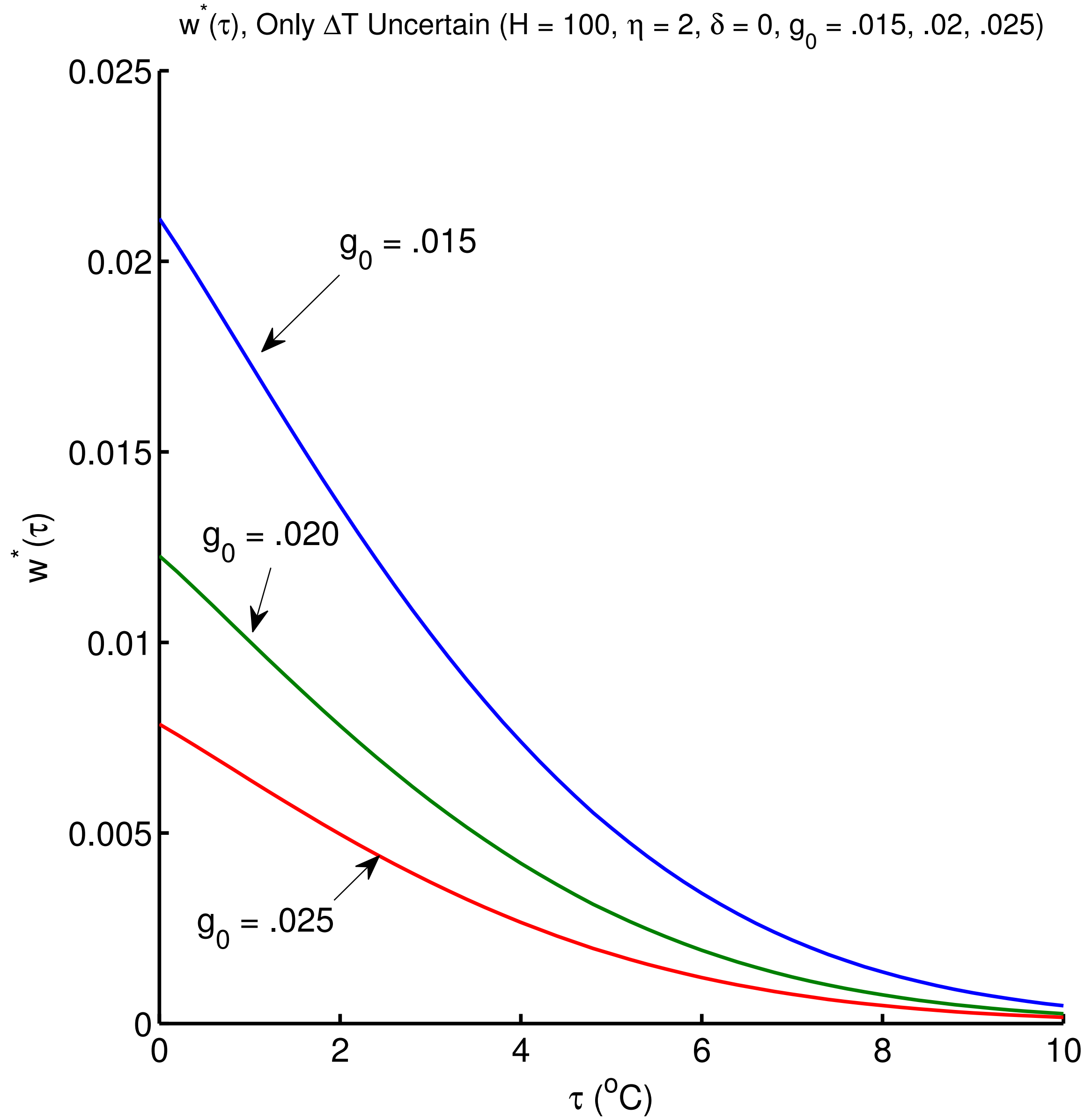

Figure 7: WTP for Base Distribution of ΔT, $\eta = 2$, $\delta = 0$

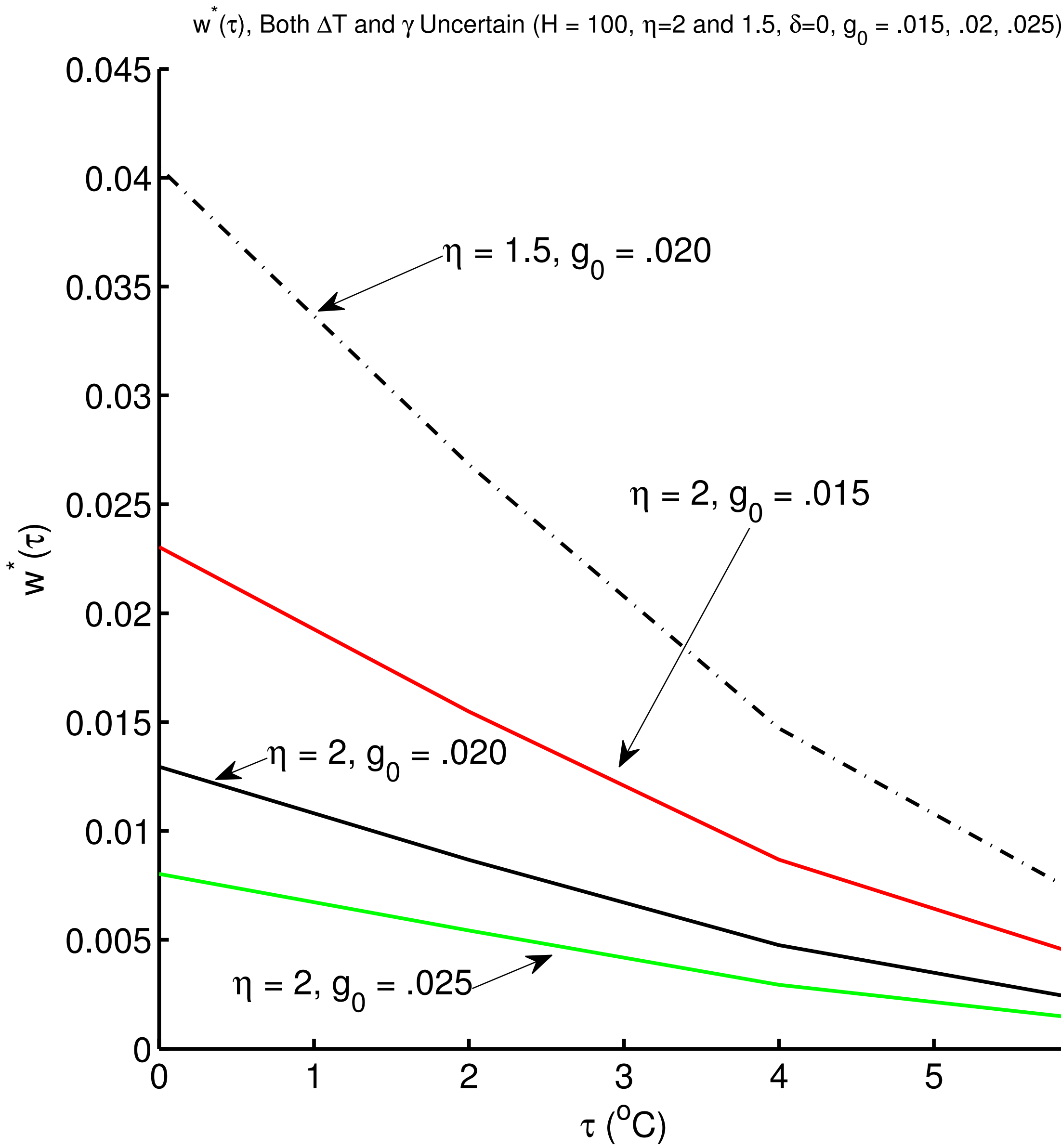

Figure 8: WTP, Both ΔT and γ Uncertain. $\eta = 2$ and 1.5, $g_0 = .015$, .020, .025, and $\delta = 0$

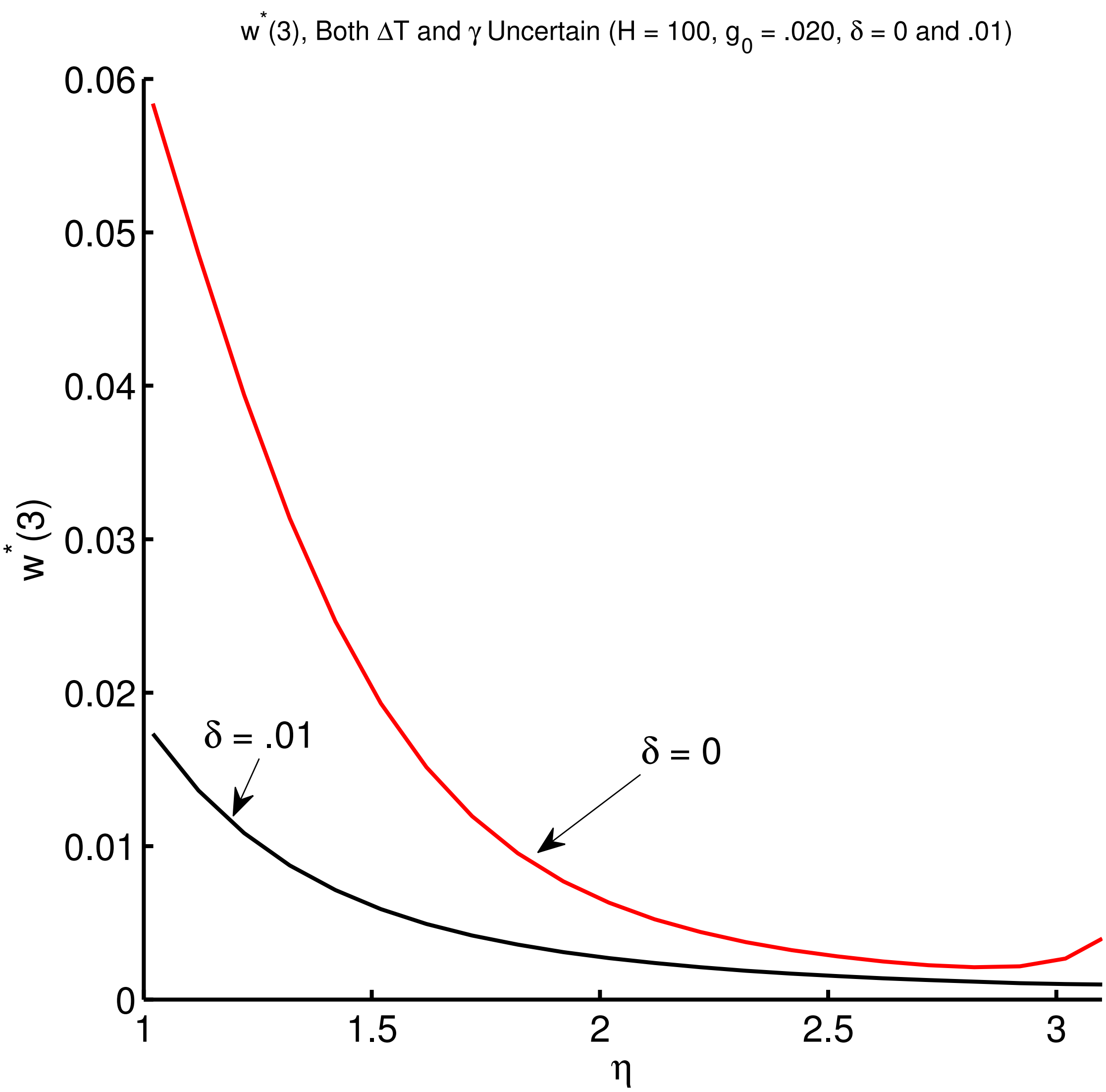

Figure 9: WTP Versus η for $\tau = 3$. $g_0 = .020$ and $\delta = 0$ and .01

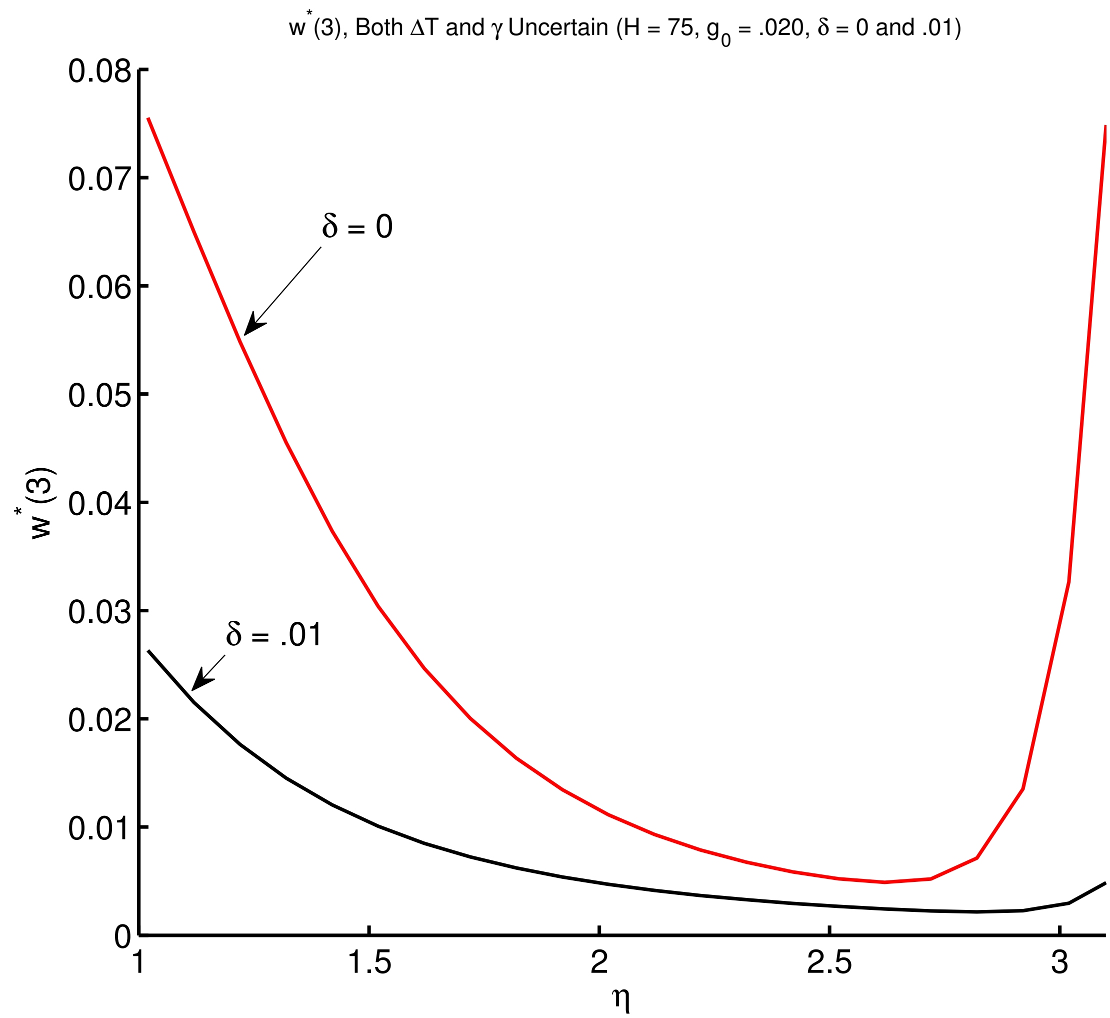

Figure 10: WTP Versus η for $\tau = 3$. $H = 75$, $g_0 = .020$, $\delta = 0$ and .01

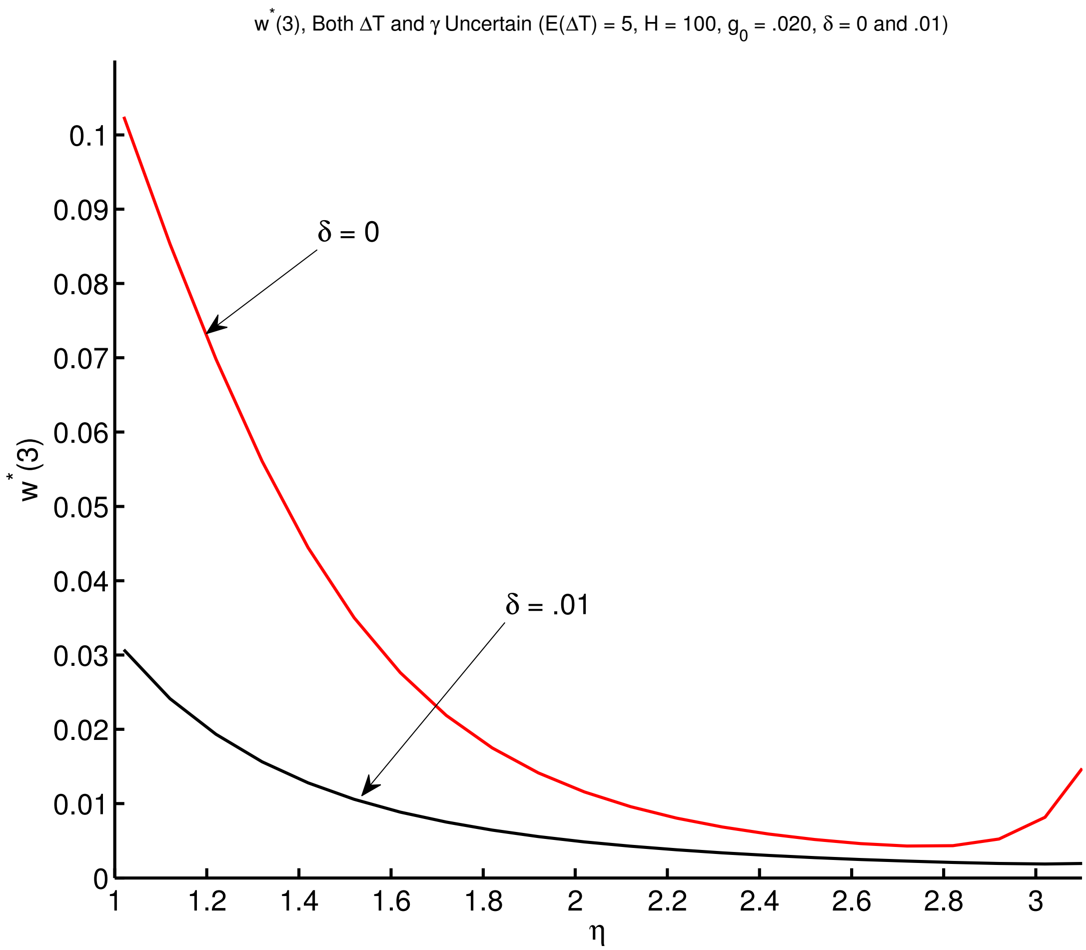

Figure 11: WTP Versus η for $\tau = 3$. $\mathcal{E}(\Delta T_H) = 5°\text{C}$, $H = 100$, $g_0 = .020$, $\delta = 0$ and .01