UNCERTAIN OUTCOMES AND CLIMATE CHANGE POLICY*

by

Robert S. Pindyck

Massachusetts Institute of Technology

Cambridge, MA 02142

This draft: August 6, 2009

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 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 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 τ, unless one assumes extreme parameter values and/or substantial shifts in the temperature distribution. These results are consistent with moderate abatement policies.

JEL Classification Numbers: Q5; Q54, D81

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

*My thanks to Andrew Yoon for his excellent research assistance, and to Paul Fackler, Larry Goulder, Michael Greenstone, Geoff Heal, Paul Klemperer, Charles Kolstad, Raj Mehra, Steve Newbold, Steve Salant, V. Kerry Smith, Martin Weitzman, and seminar participants at the IMF, Resources for the Future, NBER, Arizona State University, Columbia, Harvard, M.I.T. and UC Berkeley 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 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, ΔT_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 between temperature change and the *growth rate* of GDP as opposed to the level of GDP.

[1] 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.

[2] 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 τ, 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, 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). 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 ΔT should be fat-tailed, but this has the same disturbing welfare implications.[3]

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

[3] 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).

the right-hand tail of the distribution for ΔT 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.[4]

My estimates of $w^*(\tau)$ are generally below 2%, 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 growth rate

[4] 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.

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 ΔT 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.[5]

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_2 equivalent (CO_2e) composite (or individual GHGs) under a "business as usual" (BAU) and one or more abatement scenarios, and resulting future atmospheric

[5] 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).

CO_2e concentrations. (2) Projections of the average or regional temperature 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 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_2e 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_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.[6]

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,

[6] 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 (2008) 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 $\Delta T_t \rightarrow 2\Delta T_H$ as t gets large. This implies that ΔT_t follows the trajectory:[7]

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

Thus if $\Delta T_H = 5$°C, ΔT_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 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. These studies typically use an inverse-quadratic or 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

[7] This allows for possible feedback effects and/or further emissions. As summarized in Weitzman (2009b), the simplest dynamic model relating ΔT_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).

[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.

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.[9]

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.[10]

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 geoengineering), 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

[9] 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 δ_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.

[10] "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°

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 ΔT of 5°C, $C^A = C^B =$.

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.[11]

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,

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

where δ is the rate of time preference, i.e., the rate at which utility is discounted. Thus R_t falls over time as ΔT increases.[12] 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 ΔT_H and γ were known, social welfare would be given by:

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

where

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

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

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

---

[11] 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).

[12] If $2\eta\gamma\Delta T_H > \delta + \eta g_0$, R_t becomes 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 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:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \mathcal{E}_{0,\tau} \int_0^\infty e^{\tilde{\rho_0} - \tilde{\rho_1} t - \tilde{\omega}(1/2)^{t/H}} dt \;, \tag{12}$$

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 tildes to denote that ρ_0, ρ_1, and ω are functions of two random variables.) If, on the other hand, no action is taken to limit warming, social welfare would be:

$$W_2 = \frac{1}{1 - \eta} \mathcal{E}_0 \int_0^\infty e^{\tilde{\rho_0} - \tilde{\rho_1} t - \tilde{\omega}(1/2)^{t/H}} dt \;, \tag{13}$$

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.[13]

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 τ, the abatement-induced limit on any increase in temperature at the horizon H. Clearly the amount and cost of abatement needed will decrease as τ is made larger, so I consider a stringent abatement policy to be one for which τ is "low," which I take to be at or 4(m)-7.11275Tf11.03

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 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_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:

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

where $\Gamma($

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 probability 1; in Figure 4 it happens to be 2.5°C. If τ = 0, then ΔT = 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 (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°C, the "most likely" impact is from 1% to at most 5% of GDP.[14] Of interest is the outer tail of the distribution for this impact. There is some chance that a temperature increase of 3°C or 4°C would have a much larger impact, and we want to know how that affects WTP.

At issue is the value of γ 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 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

[14] 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."[15] 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 ΔT = 3°C, and 1% to 8% of lost GDP for ΔT = 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 ΔT = 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. (3), but they are easily translated into corresponding numbers for γ in eqn. (2). From eqn. (5), $\gamma = 1.79\beta\Delta T/H$. Thus the mean, 17-percent, and 83-percent values for γ are, respectively, $\bar{\gamma}$ = .0001363, γ_1 = .0000450, and γ_2 = .0002295.[16]

Using these three numbers to fit a 3-parameter displaced gamma distribution for γ yields

r_g

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

$$M_\tau(t) = \frac{1}{F(\tau)} \int_{\theta_T}^{\tau} \int_{\theta_\gamma}^{\infty} e^{\tilde{\rho_0} - \tilde{\rho_1} t - \tilde{\omega}(1/2)^{t/H}} f(\Delta T) g(\gamma) d\Delta T d\gamma \tag{16}$$

and

$$M_\infty(t) = \int_{\theta_T}^{\infty} \int_{\theta_\gamma}^{\infty} e^{\tilde{\rho_0} - \tilde{\rho_1} t - \tilde{\omega}(1/2)^{t/H}} f(\Delta T) g(\gamma) d\Delta T d\gamma \quad , \tag{17}$$

where $\tilde{\rho_0}$, $\tilde{\rho_1}$ and $\tilde{\omega}$ are given by eqns. (9), (10) and (11), 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:

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

and

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

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

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

The solution for $w^*(\tau)$ depends 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 d1and

$TRdRteeresfet$

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 η and δ 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, δ 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 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.[18]

Putting aside this debate over the "correct" values of η and δ 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 η and δ: around 2 for η and 0 forR19etatar de aR1 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 γ.)

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

Table 1: WTP, only ΔT Stochastic

τ	Base Case	S = $1.5 S_0$	V = $1.5 V_0$	γ = .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, δ = 0, η = 2, g_0 = .02.

Table 1 shows $w^*(\tau)$ for several values of τ, using the base distribution for ΔT shown in Figure 2, with δ = 0, η = 2, and g_0 = .02. (The parameter γ 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 ΔT is increased by 50%, in each case holding the other two moments fixed. The increase in skewness *reduces* $w^*(\tau)$ for $\tau < 5^\circ$C, because it pushes some of the probability mass from the right to the left tail. For τ = 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, $w^*(3^\circ)$ 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 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 2.3%.

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. (16) to (20). The calculated values of

WTP are shown in Figure 8 for δ = 0, η = 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 τ = 0. To obtain a WTP at or above 2% requires an initial growth rate of only .015 or a lower value of η. The figure also shows the WTP for η = 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, η. It plots w^*(3), i.e., the WTP to ensure $\Delta T_H \leq 3^\circ$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 δ = 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. 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

sl/R327.

and η is below 1.5, $w^*(3)$ is above 3%, and reaches 10% if η = 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 stark. For temperature and impact distributions based on the IPCC and "conservative" parameter values (e.g., δ = 0, η = 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 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 climate sensitivity studies surveyed by the IPCC. Likewise, the calibrated distribution for γ implies a 17% probability of $\gamma \geq .00023$, also consistent with the IPCC and other surveys. A realization in which, say, ΔT = 4.5°C and γ = .00023 would imply that GDP and consumption in 100 years would be 5.7 percent lower than with no increase in temperature.[20] However, the probability of $\Delta T \geq$ 4.5°C *and* $\gamma \geq .00023$ is only about 3.6%. An even more extreme outcome in which ΔT = 7°C (and γ = .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 δ = 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 η = 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.[21] Taking the

[20] If γ = .00023 and ΔT = 4.5°C, $\beta = \gamma H/1.89\Delta T$ = .00270, and from eqn. (3), $L = e^{-\beta(\Delta T)}$ = .947.

[21] 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 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 and from recent IAMs (the current "state of knowledge" regarding warming 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, 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 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

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 ΔT above 5°C, never mind its economic impact, and one could argue á la Weitzman (2009) that we will never have su□cient 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 ΔT 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 e□cient 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.

References

Brock, William A., and M. Scott Taylor, "The Green Solow Model," NBER Working Paper No. 10557, June 2004.

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.

Debreu, Gerard, "A Classical Tax-Subsidy Problem," *Econometrica*, Jan. 1954, 22, 14–22.

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," *American Economic Review*, May 2009, 99, 198–204.

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.

Energy Information Administration, "Comparing Cost Estimates for the Kyoto Protocol," Report No. SR/OIAF/98-03, Oct. 1998.

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," *Review of Environmental Economics and Policy*, Winter 2009, 3, 4–21.

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

Hope, Chris W., "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," Cambridge University Press, 2007a; "Climate Change 2007: Impacts, Adaptation, and Vulnerability," 2007b; "Climate Change 2007: Mitigation of Climate Change," 2007c.

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.

Lucas, Robert E., Jr., *Models of Business Cycles*, Oxford: Basil Blackwell, 1987.

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.**

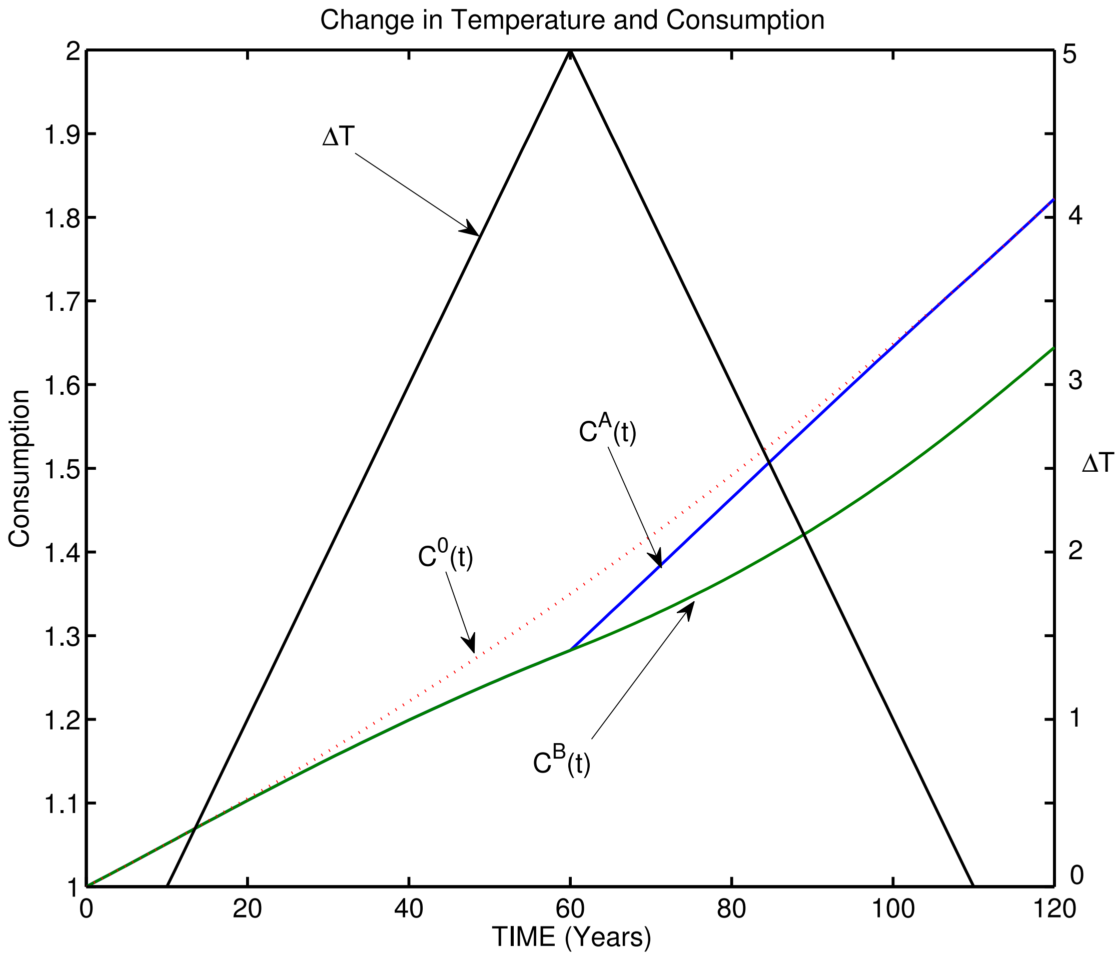


Figure 1: Example of Economic Impact of Temperature Change. (Note temperature increases by 5°C over 50 years and then falls to original level over next 50 years. C^A is consumption when ΔT reduces level, C^B is consumption when ΔT reduces growth rate, and C^0 is consumption with no temperature change.)

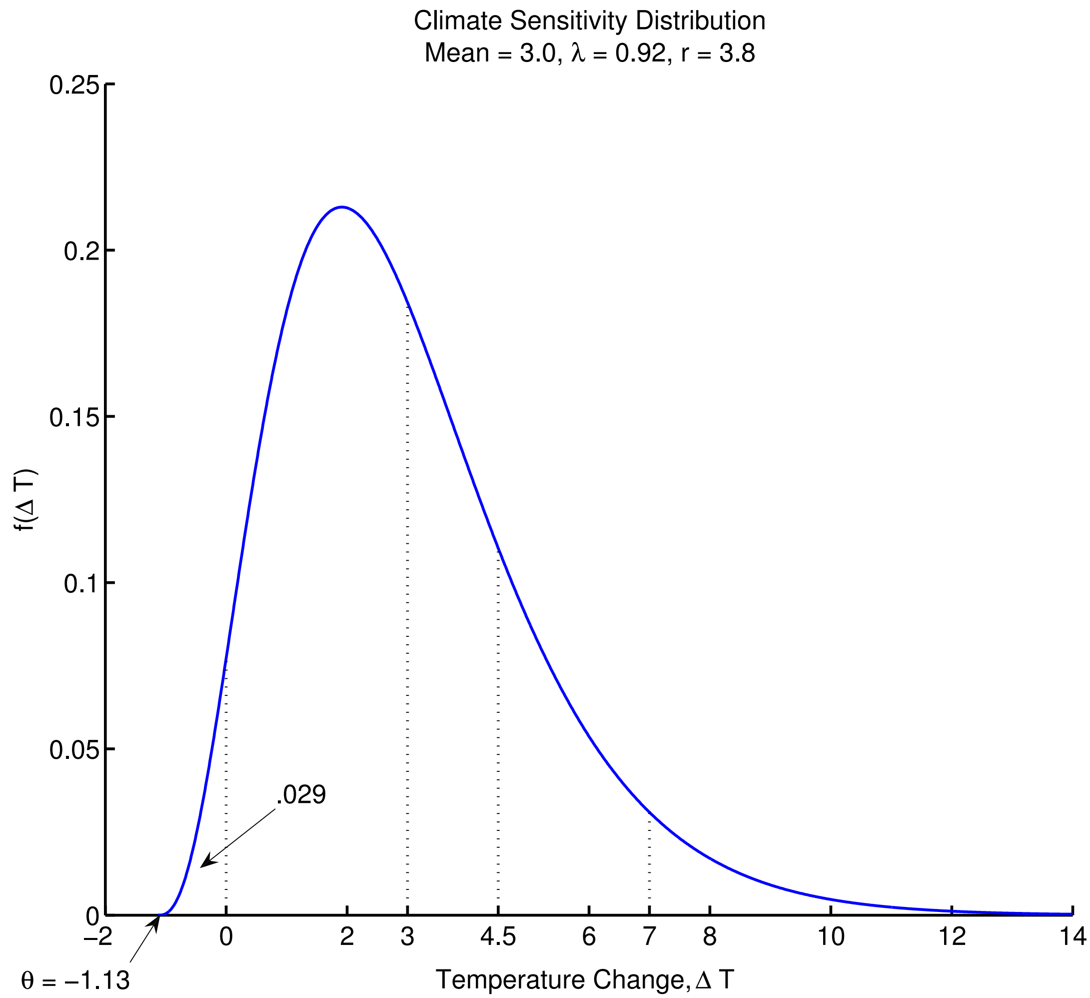
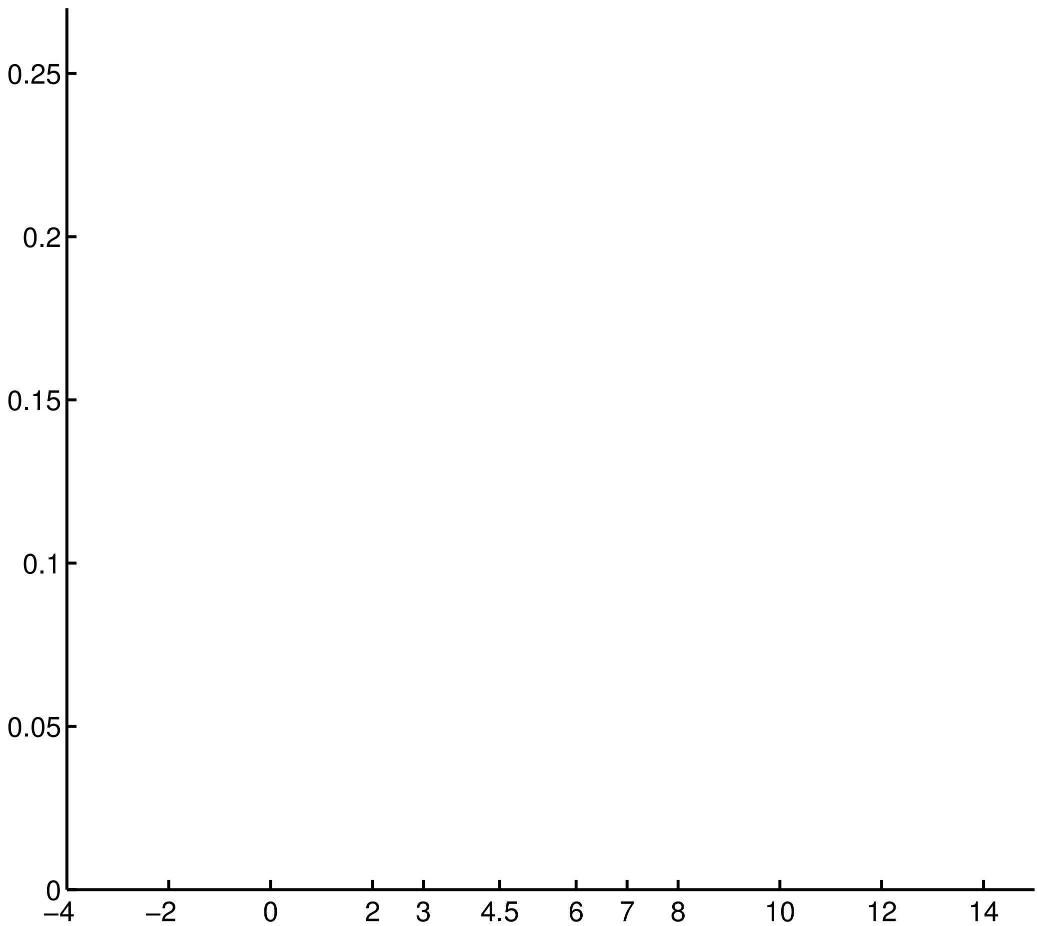


Figure 2: Base Distribution for Temperature Change.



0.25
0.2
0.15
0.1
0.05
0
−4
−2
0
2
3
4.5
6
7
8
10
12
14

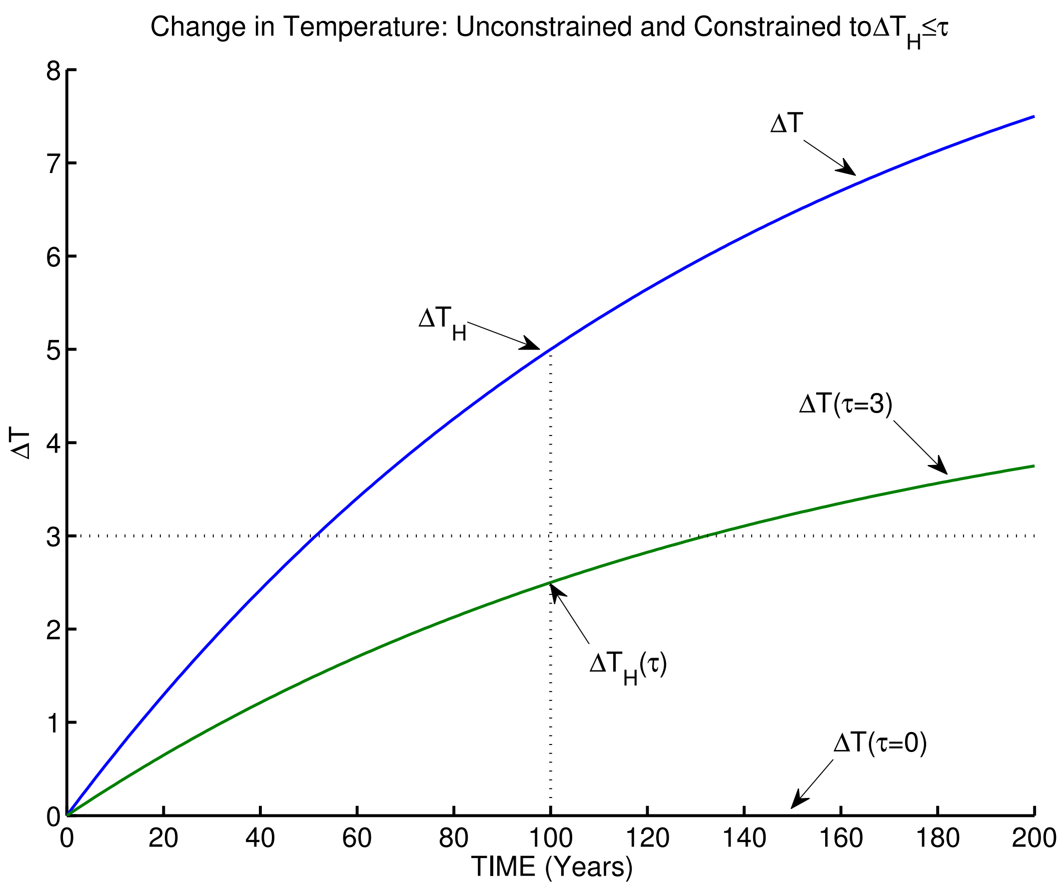


Figure 4: Temperature Change: Unconstrained and Constrained So $\Delta T_H \leq \tau$

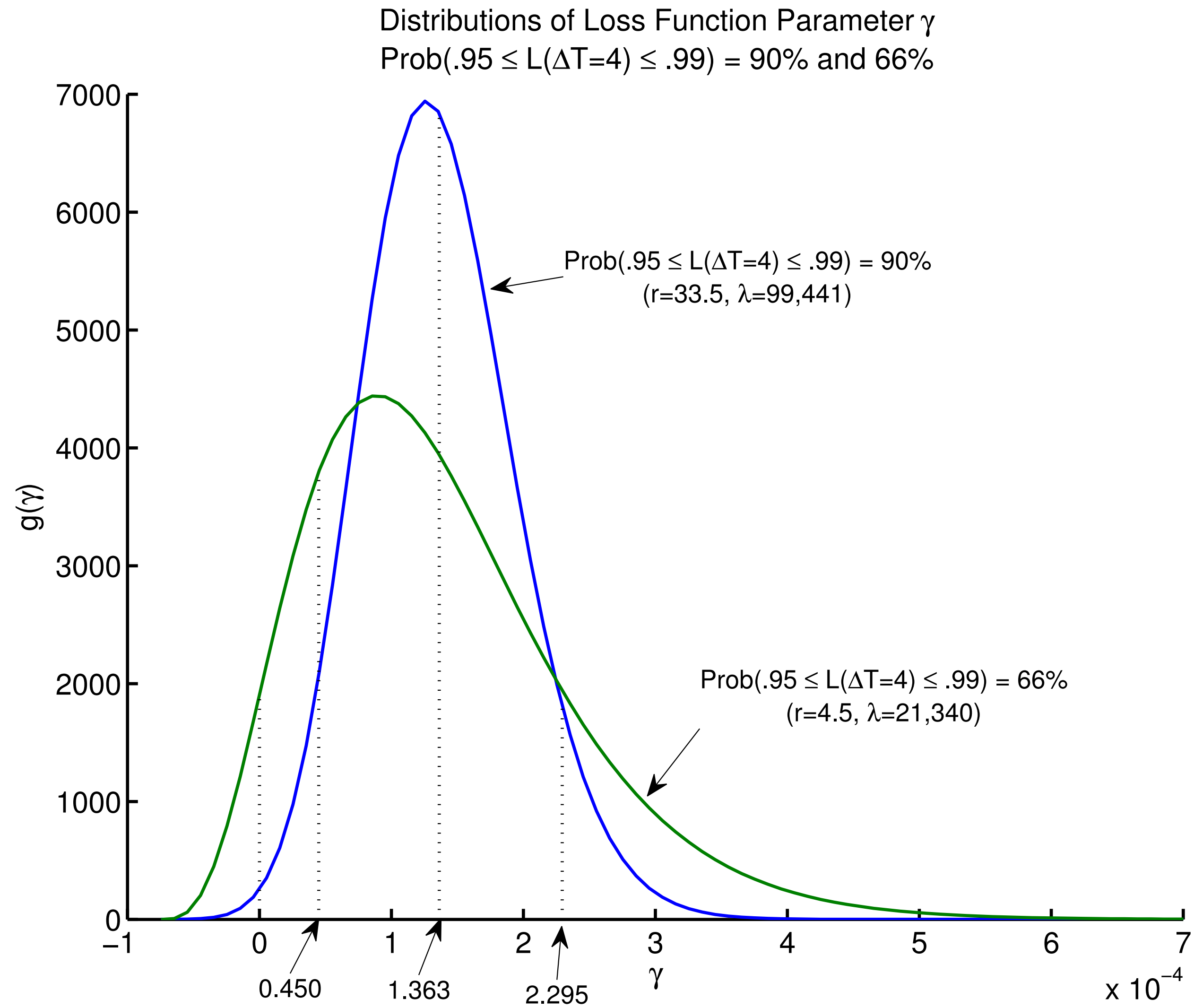


Figure 5: Distributions for Loss Function Parameter γ

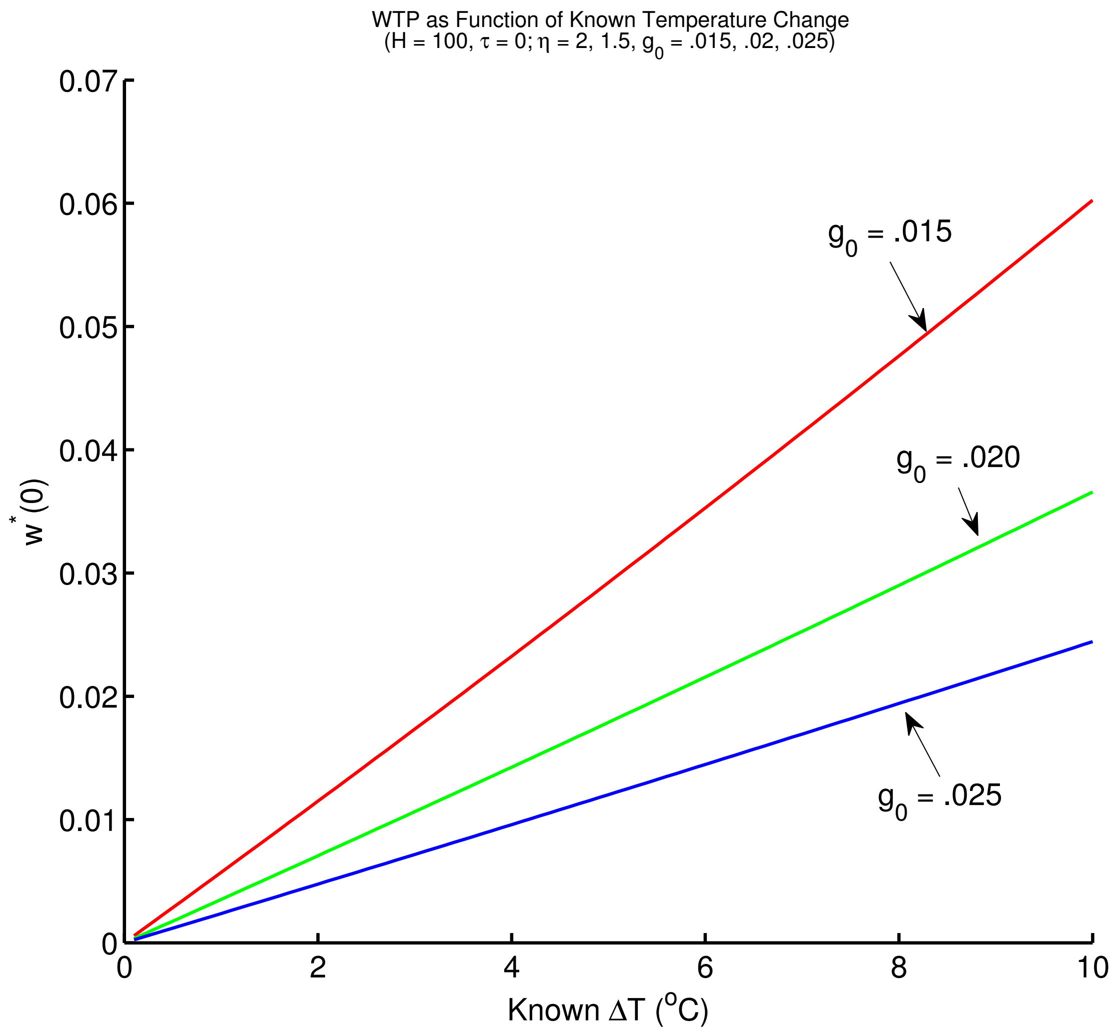
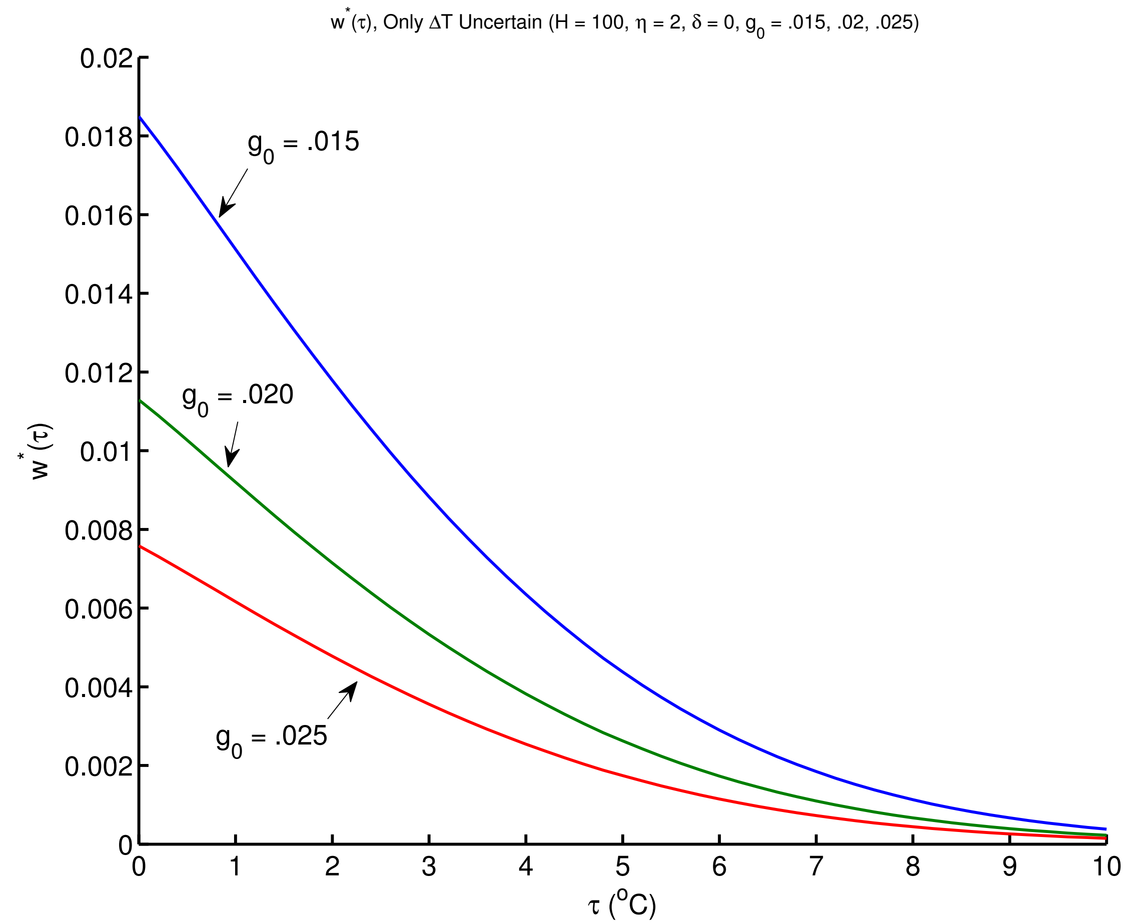


Figure 6: WTP When Temperature Change is Known



w*(τ), Only ΔT Uncertain (H = 100, η = 2, δ = 0, g0 = .015, .02, .025)
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
w*(τ)
g0 = .015
g0 = .020
g0 = .025
0
1
2
3
4
5
6
7
8
9
10
τ (oC)

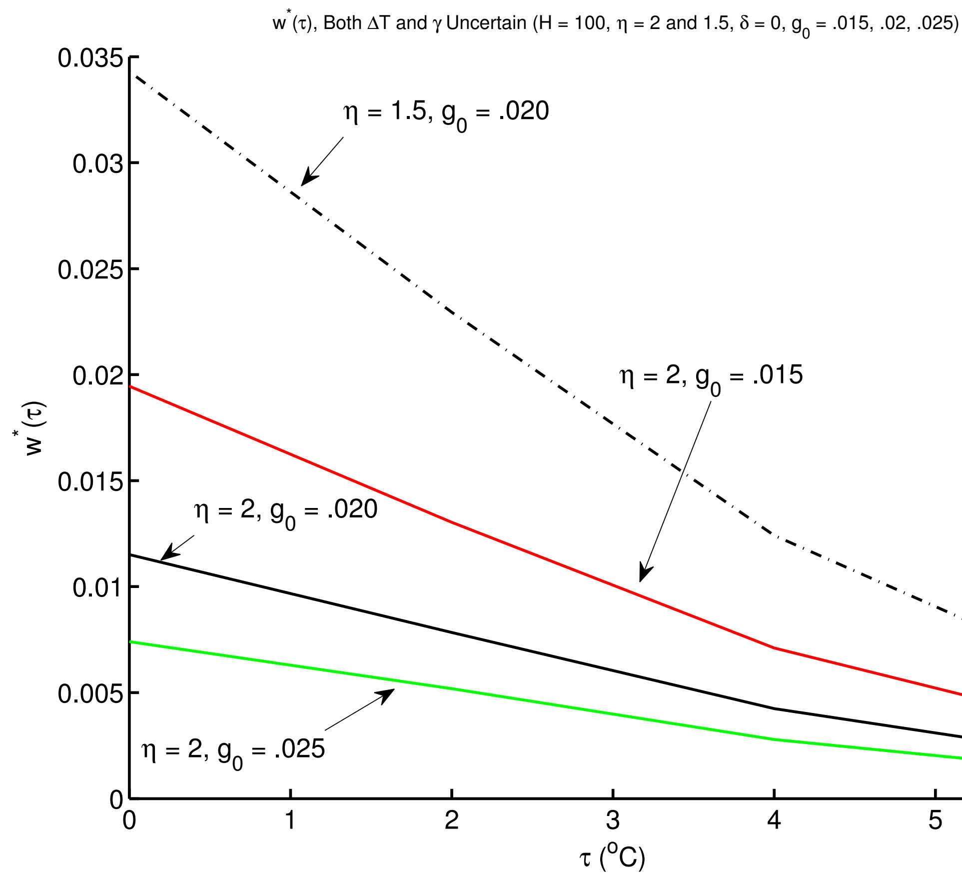


Figure 8: WTP, Both ΔT and γ Uncertain. η = 2 and 1.5, g_0 = .015, .020, .025, and δ = 0

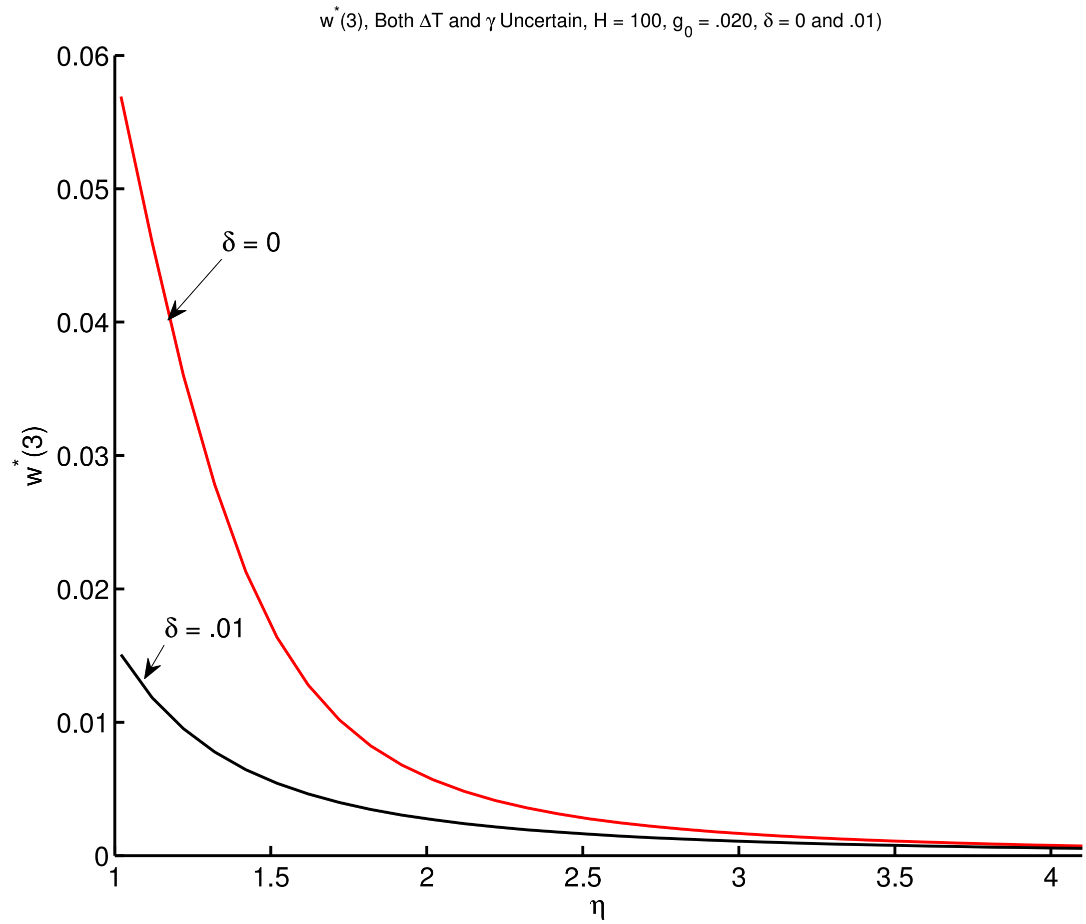


Figure 9: WTP Versus η for τ = 3. g_0 = .020 and δ = 0 and .01

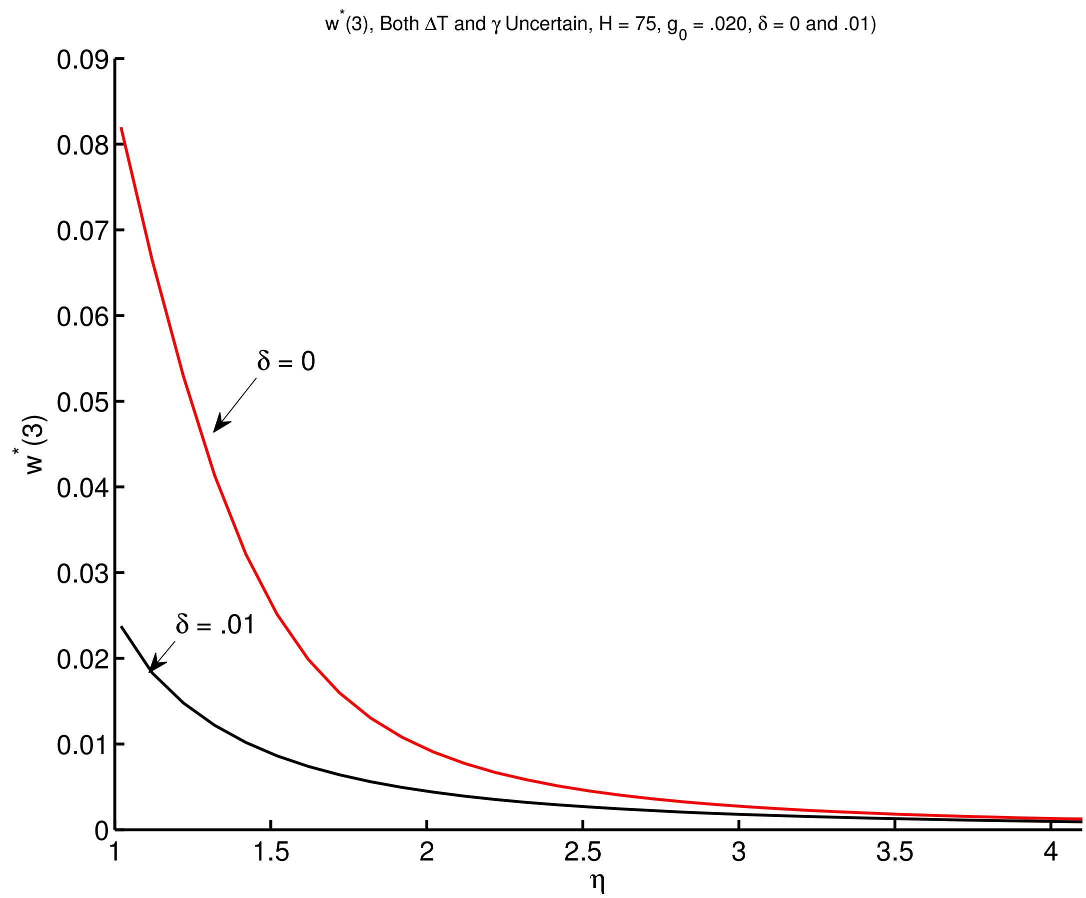


Figure 10: WTP Versus η for τ = 3. H = 75, g_0 = .020, δ = 0 and .01

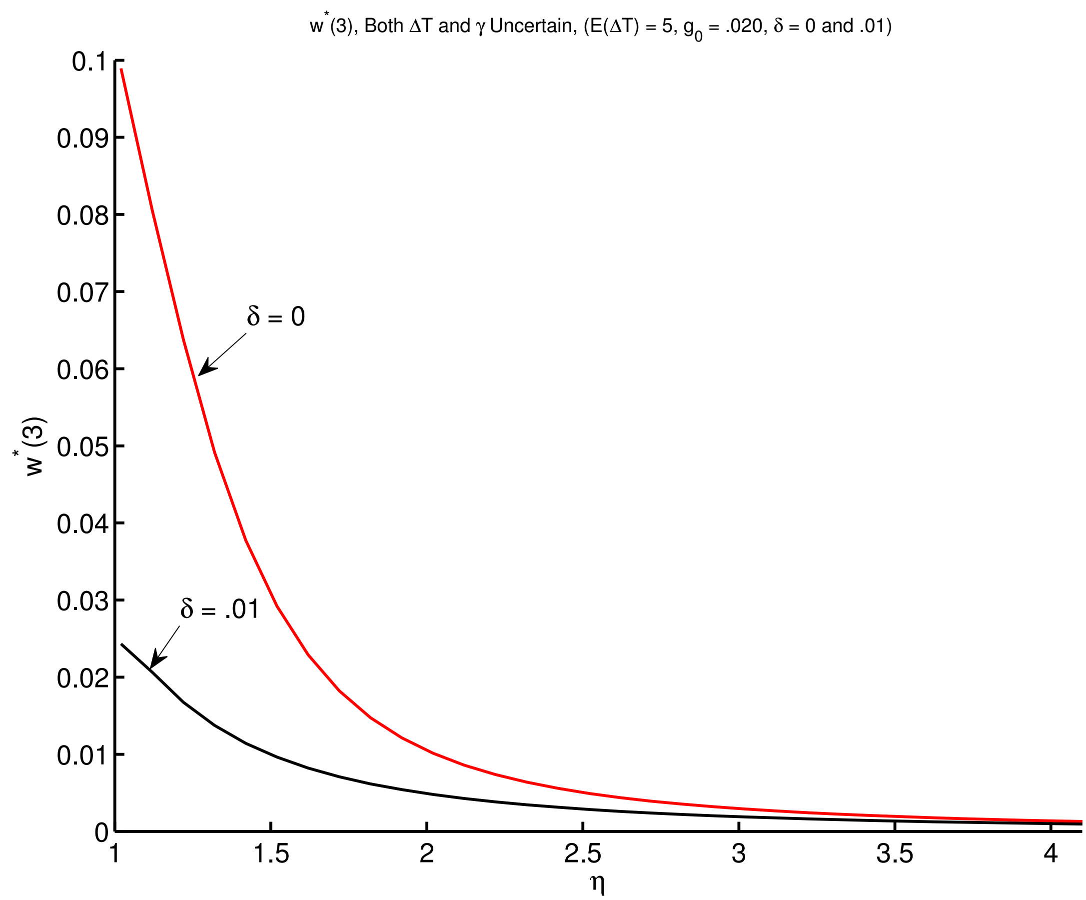


Figure 11: WTP Versus η for τ = 3. $\mathcal{E}(\Delta T_H)$ = 5°C, H = 100, g_0 = .020, δ = 0 and .01