

# UNCERTAIN OUTCOMES AND CLIMATE CHANGE POLICY\*

by

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

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**Abstract:** I incorporate distributions for temperature change and its economic impact in an analysis of climate change policy. As a measure of willingness to pay (WTP), I estimate the fraction of consumption  $w^*(\tau)$  that society would be willing to sacrifice to ensure that any increase in temperature at a future point is limited to  $\tau$ . Using information on distributions for temperature change and economic impact from recent studies assembled by the IPCC and others, I fit displaced gamma distributions for these variables. These fitted distributions, which roughly reflect the “state of knowledge” regarding warming and its impact, generally yield values of  $w^*(\tau)$  below 2%, even for small values of  $\tau$ , consistent with moderate abatement policies. I also calculate WTP for shifts in the mean and standard deviation of the temperature distribution, and show how WTP, and thus the demand for abatement, are driven more by outcome uncertainty than expected outcomes.

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# 1 Introduction.

Economic analyses of climate change policies often focus on “likely” scenarios — those within a roughly 66 to 90 percent confidence interval — for emissions, temperature, economic impacts, and abatement costs. It is hard to justify the immediate adoption of a stringent abatement policy given these scenarios and consensus estimates of discount rates and other relevant parameters.<sup>1</sup> I ask (1) whether a stringent policy might be justified by a cost-benefit analysis that accounts for a full distribution of possible outcomes; and (2) whether the demand for abatement depends more on expected outcomes or on outcome uncertainty.

Recent climate science and economic impact studies allow one to at least roughly estimate the distributions for temperature change and its economic impact.<sup>2</sup> 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  $H$ , is limited to  $\tau$ . Whether the reduction in consumption corresponding to a particular  $w^*(\tau)$  is *sufficient* to limit warming to  $\tau$  is a separate question which I do not address. In effect, I focus only on the “demand side” of climate policy.

I treat the studies upon which I draw as the current “state of knowledge” of global warming and its impact. Using 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), I fit gamma distributions for these variables. Unlike most IAMs, however, I model economic impact as a relationship between temperature change and the growth rate of GDP as opposed to its level. This distinction is justified on theoretical and empirical grounds, and implies that warming can have a per-

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

<sup>2</sup>“Economic impact” is meant to include any adverse effects of global warming, such as social, medical, or direct economic impacts.

manent impact on future GDP. I then examine whether reasonable values for the remaining parameters (e.g., the starting growth rate and the index of risk aversion) can yield values of  $w^*(\tau)$  above 2 or 3% for small values of  $\tau$ , which might support stringent abatement. I also show how  $w^*(\tau)$  depends on the mean versus standard deviation of future temperature, and I calculate “iso-WTP” curves — combinations of means and standard deviations for which WTP is constant. This 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 work by Weitzman (2009a), but takes a very different approach. Suppose there is some underlying probability distribution for temperature change, 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 temperature is “fat-tailed,” i.e., approaches zero at a less than exponential rate.<sup>3</sup> 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. This result, however, does not translate into a policy prescription, e.g., what percentage of consumption society should sacrifice to avoid warming.

I utilize a (thin-tailed) 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 avoids infinite welfare losses (or the need to arbitrarily bound the utility function to avoid infinite losses). Also, the variance or mean of the distribution can be altered while holding other moments fixed, providing additional insight into effects of uncertainty.

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<sup>3</sup>Weitzman (2009b) presents an alternative argument, based on the mechanism of GHG accumulation and its effect on temperature, for why the temperature distribution should be fat-tailed. For a related model that implies a fat-tailed distribution, see Roe and Baker (2007).

To model economic impact, I relate 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 (along with 66% confidence intervals) at a specific horizon. I then use the distribution for GDP reductions to fit a gamma distribution for the growth rate impact.

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

My estimates of  $w^*(\tau)$  are generally below 2%, even for  $\tau$  around 2 or 3°C. This is because there is limited weight in the tails of the calibrated distributions for temperature and growth rate impact. Larger estimates of WTP result for certain parameter values (e.g., an index of risk aversion close to 1 and a low initial GDP growth rate), or if I assume a much larger expected temperature increase. 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 framework can also be used to examine the relative importance of expected outcomes versus outcome uncertainty, which I do by varying the mean and standard deviation of the temperature distribution and calculating the resulting WTPs.

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

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<sup>4</sup>Newbold and Daigneault (2010) also studied implications of uncertainty for climate policy, combining a temperature distribution with CRRA utility and functions that translate temperature into lost consumption to estimate WTP. They focus on how temperature 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 by: (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. Their “pessimistic” approach yields WTP estimates similar to mine.

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 dynamic cost-benefit analysis.<sup>5</sup>

The next section explains 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 Section 4 discusses the economic impact function and corresponding probability distribution. Section 5 shows estimates of willingness to pay, and its dependence on free parameters and on the expectation versus standard deviation of temperature change. Section 6 discusses some fundamental modeling issues and concludes.

## 2 Background and Methodology.

Most economic analyses of climate change policy have five elements: (1) Projections of future emissions of a CO<sub>2</sub> equivalent (CO<sub>2</sub>e) composite (or individual GHGs) under a “business as usual” (BAU) and one or more abatement scenarios, and resulting future atmospheric CO<sub>2</sub>e concentrations. (2) Projections of the average or regional temperature changes likely to result from higher CO<sub>2</sub>e concentrations. (3) Projections of lost GDP and consumption resulting from higher temperatures. (This is probably the most speculative element because of uncertainty over adaptation to climate change.) (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 (2008), Stern (2007), and others who evaluate abatement policies using IAMs that project emissions, CO<sub>2</sub>e concentrations, temperature change, economic impact, and costs of abatement.

Each of these five elements of an IAM-based analysis is subject to considerable uncer-

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<sup>5</sup>Studies that examined the policy implications of this interaction of uncertainty and irreversibility have mixed results, showing that policy adoption might be delayed or accelerated. See, for example, Kolstad (1999b), and Fisher and Narain (2003), who use two-period models for tractability; and 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).

tainty. By estimating WTP instead of evaluating specific policies, I avoid having to estimate abatement costs and make projections about GHG emissions. Instead, I focus on uncertainty over temperature change and its economic impact as follows.

## 2.1 Temperature Change.

According to the most recent IPCC report (2007), growing GHG emissions would likely lead to a doubling of the atmospheric CO<sub>2</sub>e concentration relative to the pre-industrial level by mid-century, which would “most likely” cause an increase in global mean temperature between 2.0°C to 4.5°C by 2100, with an expected value of 2.5°C to 3.0°C. The IPCC report indicates that this range, derived from the results of 22 scientific studies the IPCC surveyed, represents a roughly 66- to 90-percent confidence interval, i.e., there is a 5 to 17-percent probability of a temperature increase above 4.5°C.<sup>6</sup>

The 22 studies themselves also provide rough estimates of increases in temperature at the outer tail of the distribution. In summarizing them, the IPCC translated the implied outcome distributions into a standardized form that allows comparability across the studies, and created graphs showing multiple distributions implied by groups of studies. As Weitzman (2008) has argued, those distributions suggest that there is a 5% probability that a doubling of the CO<sub>2</sub>e concentration relative to the pre-industrial level would lead to a global mean temperature increase,  $T$ , 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  $T$  to these 5% and 1% points and to a mean temperature change of 3.0°C. This distribution conforms well with the distributions summarized by the IPCC.

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

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

Thus if  $T_H = 5^\circ\text{C}$ ,  $T_t$  reaches  $2.93^\circ\text{C}$  after 50 years,  $5^\circ\text{C}$  after 100 years,  $7.5^\circ\text{C}$  after 200

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<sup>6</sup>The atmospheric CO<sub>2</sub>e concentration was about 300 ppm in 1900, and is now about 380 ppm. The IPCC (2007) projects an increase to 550 to 600 ppm by 2050-60. The text of the IPCC report is vague as to whether “most likely” represents a 66% or a 90% confidence interval.

years, and then gradually approaches 10°C.<sup>7</sup>

## 2.2 Economic Impact.

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

There are several reasons to expect warming to affect the growth rate of GDP as opposed to the level. First, some effects of warming will be permanent; e.g., destruction of ecosystems from erosion and flooding, extinction of species, and deaths from weather extremes. A growth rate effect allows warming to have a permanent impact. Second, there is theoretical support for a growth rate effect. The resources needed to counter the impact of warming will reduce those available for R&D and capital investment, reducing growth. Adaptation to rising temperatures is equivalent to the cost of increasingly strict emission standards, which, as Stokey (1998) has shown with an endogenous growth model, reduces the rate of return on capital and lowers the growth rate.<sup>9</sup>

Finally, there is empirical support for a growth rate effect. Using historical data on temperatures and precipitation over 50 years for a panel of 136 countries, Dell, Jones, and Olken (2008, 2009) have shown that higher temperatures reduce GDP growth rates but not

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

$$dT/dt = m_1[\ln(G_t/G_0)/\ln 2 - m_2T_t] .$$

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

<sup>8</sup>The inverse-quadratic loss function used in the recent version of the Nordhaus (2008) DICE model is  $L = 1/[1 + \pi_1T + \pi_2(T)^2]$ . Weitzman (2008) introduced the exponential loss function  $L(T) = \exp[-\beta(T)^2]$ , which, as he points out, allows for greater losses when  $T$  is large.

<sup>9</sup>Suppose total capital  $K = K_p + K_a(T)$ , with  $K'_a(T) > 0$ , where  $K_p$  is directly productive capital and  $K_a(T)$  is capital needed for adaptation to the temperature increase  $T$  (e.g., stronger retaining walls and pumps to counter flooding, new infrastructure and housing to support migration, more air conditioning and insulation, etc.). If all capital depreciates at rate  $\delta_K$ ,  $\dot{K}_p = \dot{K} - \dot{K}_a = I - \delta_K K - K'_a(T)\dot{T}$ , so the rate of growth of  $K_p$  is reduced. See Brock and Taylor (2010) and Fankhauser and Toll (2005) for related analyses.

levels. The impact they estimate is large, — a decrease of 1.1 percentage points of growth for each 1°C rise in temperature — although significant only for poorer countries.<sup>10</sup> Also, using economic and financial market data for a panel of 147 countries over the period 1950 to 2007, Bansal and Ochoa (2011a, b) show that increases in temperature have a strong negative impact on economic growth.

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:

$$g_t = g_0 - \gamma T_t \quad (2)$$

Thus the growth rate of GDP and consumption falls over time as the temperature increases. 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. I introduce uncertainty into eqn. (2) through the parameter  $\gamma$ . Using information from a number of IAMs, I obtain a distribution for  $\beta$  in the exponential loss function:

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

which applies to the *level* of GDP. I translate this into a distribution for  $\gamma$  using the trajectory for GDP and consumption implied by eqn. (2) for a temperature change-impact combination projected to occur at horizon  $H$ . From eqns. (1) and (2), the growth rate is

$$g_t = g_0 - 2\gamma T_H [1 - (1/2)^{t/H}] .$$

Normalizing initial consumption at 1, this implies:

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

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

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

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<sup>10</sup>“Poor” means below median PPP-adjusted per-capita GDP. Using World Bank data for 209 countries, “poor” 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.

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

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

### 2.3 Willingness to Pay.

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

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

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

Future utility is discounted at the rate  $\delta$ , i.e., the rate of time preference.<sup>12</sup> The “correct” value of  $\delta$  is a subject of debate, with some arguing that  $\delta$  should be zero on ethical grounds (i.e., the welfare of our great grandchildren shouldn’t be valued any less than our own welfare), and others claiming its value should be inferred from market interest rates. Without engaging in that debate, I will generally set  $\delta = 0$  in order to determine whether any combination of “reasonable” parameter values can yield a high WTP.

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

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

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

<sup>12</sup>Using eqns. (2) and (6) and the Ramsey growth model, the *consumption* discount rate is  $R_t = \delta + \eta g_t = \delta + \eta g_0 - 2\eta\gamma T_H [1 - (1/2)^{t/H}]$ . Thus  $R_t$  falls as  $T$  increases, and if  $2\eta\gamma T_H > \delta + \eta g_0$ ,  $R_t$  can become negative. Dasgupta et al (1999) provide a simple example in which climate change results in a 2% annual decline in global consumption, and thus a negative consumption discount rate.

where

$$\rho = (\eta - 1)(g_0 - 2\gamma T_H) + \delta , \quad (8)$$

$$\omega = 2(\eta - 1)\gamma H T_H / \ln(1/2) . \quad (9)$$

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

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \mathcal{E}_{0,\tau} \int_0^\infty e^{\tilde{\omega} - \tilde{\rho}t - \tilde{\omega}(1/2)^{t/H}} dt , \quad (10)$$

where  $\mathcal{E}_{0,\tau}$  denotes the expectation at  $t = 0$  over the distributions of  $T_H$  and  $\gamma$  conditional on  $T_H \leq \tau$ . (I use tildes to denote that  $\rho$  and  $\omega$  are functions of random variables.) To obtain this conditional expectation, I truncate the distribution for  $T$  at  $\tau$  and then renormalize so that it integrates to 1.

If no action is taken to limit warming, social welfare would be:

$$W_2 = \frac{1}{1 - \eta} \mathcal{E}_0 \int_0^\infty e^{\tilde{\omega} - \tilde{\rho}t - \tilde{\omega}(1/2)^{t/H}} dt , \quad (11)$$

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

## 2.4 Policy Implications.

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

I examine whether the fitted distributions for  $T$  and  $\gamma$ , along with “conservative” (in the sense of leading to a higher WTP) parameter assumptions, can yield values of  $w^*(\tau)$  above 2

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<sup>13</sup>As a practical matter, I calculate WTP using a 500-year horizon. After some 200 years we will likely exhaust the economically recoverable stocks of fossil fuels, so GHG concentrations will fall. Also, so many other economic and social changes are likely that the relevance of CRRA expected utility becomes questionable. In any case, I will show that the results are unchanged if I extend the horizon to 1000 years.

or 3% for  $\tau \approx 3^\circ\text{C}$ . I also explore the effects of uncertainty by transforming the distribution for  $T$  to change the mean or variance, and calculating the resulting change in  $w^*(\tau)$ .

### 3 Temperature Change.

The IPCC (2007a) surveyed 22 studies of *climate sensitivity*, the temperature increase that would result from an anthropomorphic doubling of the atmospheric CO<sub>2</sub>e concentration. Given that a doubling (relative to the pre-industrial level) by 2050-60 is the IPCC's consensus prediction, I treat climate sensitivity as a rough proxy for  $T$  a century from now. Each study 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 they could be compared, and estimated that they 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 essentially what Weitzman (2009b) did, and my estimates of the tails from the aggregation of these studies are close to his. To be conservative, I use his estimate of a 17% probability that a doubling of the CO<sub>2</sub>e concentration would lead to a mean temperature increase of 4.5°C or more, a 5% probability of an increase of 7.0°C or more, and a 1% probability of an increase of 10.0°C or more. Thus the 5% and 1% tails of the distribution for  $\Delta T$  clearly represent extreme outcomes; temperature increases of this magnitude are outside the range of human experience.

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

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

where  $\Gamma(r) = \int_0^\infty s^{r-1} e^{-s} ds$  is the Gamma function. The mean, variance and skewness (around the mean) are  $\mathcal{E}(x) = r/\lambda + \theta$ ,  $\mathcal{V}(x) = r/\lambda^2$ , 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 1. 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%) probability of a *reduction* in mean temperature, which 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%.<sup>14</sup>

We can change the mean, variance or skewness, while keeping the other two moments fixed. Denote the scaling factors by  $\alpha_M$ ,  $\alpha_V$ , and  $\alpha_S$  (so setting  $\alpha_M = 1.5$  increases the mean by 50%). Using the equations for the moments, to change the skewness by a factor of  $\alpha_S$  while keeping the mean and variance fixed, replace  $r$ ,  $\lambda$ , and  $\theta$  with  $r_1 = r/\alpha_S^2$ ,  $\lambda_1 = \lambda/\alpha_S$ , and  $\theta_1 = \theta + (1 - 1/\alpha_S)r/\lambda$ . Likewise, to change the variance by a factor  $\alpha_V$ , set  $r_1 = \alpha_V^3 r$ ,  $\lambda_1 = \alpha_V \lambda$ , and  $\theta_1 = \theta + (1 - \alpha_V^2)r/\lambda$ . To change the mean by  $\alpha_M$ , keep  $r$  and  $\lambda$  fixed but set  $\theta_1 = \alpha_M \theta + (\alpha_M - 1)r/\lambda$ , which shifts the distribution to the right or left.

Recall that the distribution for  $T$  pertains to a point in time,  $H$ , and I assume that temperature follows the trajectory of eqn. (1), so that  $T_t \rightarrow 2T_H$  as  $t$  gets large. This is illustrated in Figure 2, which shows a trajectory for  $T_t$  when it is unconstrained (and  $T_H$  happens to equal 5°C), and when it is constrained so that  $T_H \leq \tau = 3^\circ\text{C}$ . Note that even when constrained,  $T_H$  is a random variable and (unless  $\tau = 0$ ) will be less than  $\tau$  with probability 1; in Figure 2 it happens to be 2.5°C. If  $\tau = 0$ , then  $T_t = 0$  for all  $t$ .

## 4 Economic Impact.

What would be the economic impact (broadly construed) of a temperature increase of 7°C or more? One might answer, as Stern (2007, 2008) does, that we simply do not (and cannot) know, because we have had no experience with this much warming, and existing models tell us little about the impact on production, migration, health, etc. 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 surveyed by the IPCC. This is essentially the argument made by Weitzman (2009a), but in terms of underlying “structural uncertainty”

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<sup>14</sup>For comparison, fitting the *fat tailed* distribution of Roe and Baker (2007) to a Bayesian average of 28 PDFs from 21 studies (some different from those in IPCC), Newbold and Daigneault (2010) find a 50% probability of  $T \geq 3.42^\circ\text{C}$  and a 5% probability of  $T \geq 7.45^\circ\text{C}$ .

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 existing models of economic impact at face value and treat them analogously to the climate science models. These models yield a rough consensus regarding likely economic impacts, and provide information about the tails of the distribution for the impact. At issue is the value of  $\gamma$  in eqn. (2). Different IAMs and other economic studies suggest different values for this parameter, and although there are no estimates of confidence intervals (that I am aware of), intervals can be inferred from some of the variation in the suggested values. I therefore treat this parameter as stochastic and distributed as gamma, as in eqn. (12). I further assume that  $\gamma$  and  $T$  are independently distributed, which is realistic given that they are governed by completely different physical/economic processes.

Based on its own survey of impact estimates from four IAMs, the IPCC (2007b) concludes that “global mean losses could be 1–5% of GDP for 4°C of warming.”<sup>15</sup> Also, 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  $T = 3^\circ\text{C}$ , and 1% to 8% of lost GDP for  $T = 5^\circ\text{C}$ . I treat these ranges as “most likely” outcomes, and use the IPCC’s definition of “most likely” to mean a 66 to 90-percent confidence interval. Using the IPCC range and, to be conservative, assuming it applies to a 66-percent confidence interval, I take the mean loss for  $T = 4^\circ\text{C}$  to be 3% of GDP, and the 17-percent and 83-percent points to be 1% and 5% of GDP respectively. These three numbers apply to  $\beta$  in eqn. (3), but are easily translated into corresponding numbers for  $\gamma$  in eqn. (2). From eqn. (5),  $\gamma = 1.79\beta T/H$ . Thus the mean, 17-percent, and 83-percent values for  $\gamma$  are, respectively,  $\bar{\gamma} = .0001363$ ,  $\gamma_1 = .0000450$ , and  $\gamma_2 = .0002295$ .<sup>16</sup>

Using these three numbers to fit a 3-parameter displaced gamma distribution for  $\gamma$  yields  $r_g = 4.5$ ,  $\lambda_g = 21,341$ , and  $\theta_g = \bar{\gamma} - r_g/\lambda_g = -.0000746$ . This distribution is shown in Figure 3. It implies that there is a 5% (1%) probability that  $\gamma \geq .00032$  (.00043), which

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

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

corresponds to  $\beta \geq .0045$  (.0060) and  $L(4^\circ) \leq .931$  (.908).

## 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  $H$ ,  $T_H$  will not exceed  $\tau$ . Specifically, the distribution for  $T$  is cut off at  $\tau$  and rescaled to integrate to 1.<sup>17</sup> Using the CRRA utility function of eqn. (6) and the growth rate of consumption given by eqn. (2),  $w^*(\tau)$  is the *maximum* fraction of consumption society would sacrifice to keep  $T_H \leq \tau$ . As explained in Section 2,  $w^*(\tau)$  is found by equating the social welfare functions  $W_1(\tau)$  and  $W_2$  of eqns. (10) and (11).

Given the distributions  $f(T)$  and  $g(\gamma)$ , let  $M_\tau(t)$  and  $M_\infty(t)$  be the time- $t$  expectations

$$M_\tau(t) = \frac{1}{F(\tau)} \int_{\theta_T}^\tau \int_{\theta_\gamma}^\infty e^{\tilde{\omega} - \tilde{\rho}t - \tilde{\omega}(1/2)^{t/H}} f(T)g(\gamma)dT d\gamma \quad (13)$$

$$M_\infty(t) = \int_{\theta_T}^\infty \int_{\theta_\gamma}^\infty e^{\tilde{\omega} - \tilde{\rho}t - \tilde{\omega}(1/2)^{t/H}} f(T)g(\gamma)dT d\gamma \quad , \quad (14)$$

where  $\tilde{\rho}$  and  $\tilde{\omega}$  are given by eqns. (8) and (9),  $\theta_T$  and  $\theta_\gamma$  are the lower limits on the distributions for  $T$  and  $\gamma$ , and  $F(\tau) = \int_{\theta_T}^\tau f(T)dT$ . Thus  $W_1(\tau)$  and  $W_2$  are:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \int_0^\infty M_\tau(t)dt \equiv \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} G_\tau \quad (15)$$

$$W_2 = \frac{1}{1 - \eta} \int_0^\infty M_\infty(t)dt \equiv \frac{1}{1 - \eta} G_\infty \quad . \quad (16)$$

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

$$w^*(\tau) = 1 - [G_\infty/G_\tau]^{\frac{1}{1-\eta}} \quad . \quad (17)$$

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

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

## 5.1 Parameter Values.

As we will see, WTP depends strongly on the index of relative risk aversion  $\eta$ , the rate of time preference  $\delta$ , and the base level growth rate  $g_0$ . The finance and macroeconomics literatures have estimates of  $\eta$  ranging from 1.5 to 6, and  $\delta$  ranging from .01 to .04. The per capita real growth rate  $g_0$ , measured from historical data, is about .02. It has been argued that for intergenerational comparisons  $\delta$  should be close to zero, on the grounds that society should not value the well-being of our great-grandchildren less than our own. Likewise, while values of  $\eta$  above 4 may be consistent with the (relatively short-horizon) behavior of investors, we might apply lower values to welfare comparisons involving future generations.<sup>18</sup>

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

## 5.2 No Uncertainty.

Removing uncertainty provides intuition for the determinants of WTP and its dependence on some of the parameters. Suppose the trajectory for  $T_t$  its impact on the growth rate were both known with certainty. In particular, suppose that under BAU the temperature will increase to a known value  $T_H$  at time  $H$  (and then continue increasing, asymptotically approaching  $2T_H$ ), but with abatement the temperature will only increase to the level  $\tau$  at time  $H$ . In this case, eqns. (15) and (16) would simplify to:

$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1 - \eta} \int_0^\infty e^{\omega_\tau - \rho t - \omega_\tau (1/2)^{t/H}} dt , \quad (18)$$

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<sup>18</sup>For arguments in favor of low values for  $\eta$  and  $\delta$ , see Heal (2009) and Stern (2008). For opposing views, see Dasgupta (2008), Nordhaus (2007) and Weitzman (2007). As Dasgupta points out, a value of  $\eta$  below 2 is inconsistent with observed savings behavior. In the Ramsey growth model, the optimal savings rate is  $s^* = (R - \delta)/\eta R$ , where  $R$  is the consumption discount rate and return on investment. If  $R = .05$  and  $\delta = .02$ ,  $s^* = .6/\eta$ , suggesting  $\eta$  should be in the range of 2 to 4.

$$W_2 = \frac{1}{1 - \eta} \int_0^\infty e^{\omega - \rho t - \omega(1/2)^{t/H}} dt , \quad (19)$$

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

I calculate the WTP to keep  $T_t$  zero for all time, i.e.,  $w^*(0)$ , over a range of values for  $T_H$  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 4. The graph says that if, for example,  $T_H = 6^\circ\text{C}$  and  $g_0 = .02$ ,  $w^*(0)$  is about  $.022$ , i.e., society should be willing to give up about 2.2% of current and future consumption to keep  $T_H$  at zero instead of  $6^\circ\text{C}$ .<sup>19</sup> Although  $w^*(0)$  is much larger if  $T_H$  is *known* to be  $8^\circ\text{C}$  or more, such temperature outcomes have low probability.

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

### 5.3 Uncertainty Over Temperature and Its Impact.

I now allow for uncertainty over both  $T$  and the impact parameter  $\gamma$ , using the calibrated distributions for each. WTP is given by eqns. (13) to (17). The calculated values of WTP are shown in Figure 5 for  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .015, .020$ , and  $.025$ . Note that if  $g_0$  is  $.02$  or greater, WTP is always less than 1.2%, even for  $\tau = 0$ . To obtain a WTP at or above 2% requires an initial growth rate of only  $.015$  or a lower value of  $\eta$ . The figure also shows that if  $\eta = 1.5$  and  $g_0 = .02$ ,  $w^*(0)$  reaches 3.5%.

Figure 6 shows the dependence of WTP on the index of risk aversion,  $\eta$ . It plots  $w^*(3)$ , i.e., the WTP to ensure  $T_H \leq 3^\circ\text{C}$  at  $H = 100$  years, for  $g_0 = .02$ . Although  $w^*(3)$  is below 2% for moderate values of  $\eta$ , it comes close to 6% if  $\eta$  is reduced to 1 (the value used in Stern (2007)). The reason is that while future utility is not discounted (because  $\delta = 0$ ), future consumption is implicitly discounted at the initial rate  $\eta g_0$ . If  $\eta$  (or  $g_0$ ) is made smaller,

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<sup>19</sup>Remember that the “known  $T$ ” applies only to time  $t = H$ .  $T_t$  follows the trajectory given by eqn. (1).

potential losses of future consumption have a larger impact on WTP. Finally, Figure 6 also shows that discounting future utility, even at a very low rate, considerably reduces WTP. If  $\delta$  is increased to .01,  $w^*(3)$  is again below 2% for all values of  $\eta$ .

I obtained large values of WTP only for fairly extreme combinations of parameter values. However, these results are based on distributions for  $T$  and  $\gamma$  that were calibrated to studies in the IPCC's 2007 report and concurrent economic studies, which were done prior to 2007. Some more recent studies indicate that “most likely” values for  $T$  in 2100 might be higher than the IPCC's 2.0°C to 4.5°C range. For example, a recent report by Sokolov et al (2009) suggests an expected value for  $T$  in 2100 of 4 to 5°C, as opposed to the 3.0°C number I used. Figure 7 duplicates Figure 6 except the mean of  $T_H$  is increased to 5°C — the upper end of the 4 to 5°C range in Sokolov et al (2009) — with the other moments of the distribution unchanged. Now if  $\delta = 0$  and  $\eta$  is below 1.5,  $w^*(3)$  is above 3%, and reaches 10% if  $\eta = 1$ . But once again, these high WTPs are dependent on the assumption that  $\delta = 0$ .

## 5.4 Sensitivity Analysis.

Figures 5, 6 and 7 provide insight into how WTP depends on parameters such as  $\delta$ ,  $\eta$  and  $g_0$ , as well as the mean temperature  $\mathcal{E}(T_H)$ . However, the range of parameter values in those figures is limited. Also, I have used a time horizon of 500 years for all of these calculations, and one might ask whether a longer (or shorter) horizon might affect the results.

Table 1 shows WTP calculations — in particular,  $w^*(0)$  and  $w^*(3)$  — for a wider set of parameter values. As a base case, I set  $\delta = 0$ ,  $\eta = 2$ ,  $g_0 = .020$ ,  $\mathcal{E}(T_H) = 3^\circ\text{C}$ , and  $\mathcal{E}(\gamma) = .0001363$ , with an horizon ( $t_{max}$ ) of 500 years, and obtain  $w^*(0) = .0113$  and  $w^*(3) = .0059$ . (This base case corresponds to the middle solid line in Figure 5.) As can be seen from the next two rows, 500 years is a sufficiently long horizon; increasing it to 1000 years makes no difference (to four decimal places), and shortening it to 300 years reduces  $w^*$ , but only slightly.

The historical per capita real growth rate of world GDP has been around .02, and in Figure 5 I calculated  $w^*(\tau)$  for a lower rate, namely .015. But suppose that for some reason the starting growth rate is substantially lower, e.g., .01 or even 0. As the next three rows of

Table 1: ALTERNATIVE PARAMETER VALUES

Note: Unless otherwise indicated, $\delta = 0$ , $\eta = 2$ , $g_0 = .020$ , $\mathcal{E}(T_H) = 3^\circ\text{C}$ , $\mathcal{E}(\gamma) = .0001363$ , $t_{max}$ (horizon) = 500 years.		
Cases	$w^*(0)$	$w^*(3)$
BASE CASE	.0113	.0059
$t_{max} = 300$	.0110	.0056
$t_{max} = 1000$	.0113	.0059
$g_0 = .010$	.0372	.0190
$g_0 = .005$	.0775	.0407
$g_0 = 0$	.1463	.0791
$\eta = 4$	.0014	.0008
$\eta = 4, g_0 = .010$	.1844	.1820
$\mathcal{E}(T_H) = 5^\circ$	.0189	.0105
$\mathcal{E}(T_H) = 5^\circ, g_0 = .010$	.0599	.0350
$\mathcal{E}(T_H) = 5^\circ, g_0 = .005$	.1232	.0749
$\mathcal{E}(\gamma) = .0002726$	.0243	.0116
$\mathcal{E}(\gamma) = .0002726, g_0 = .015$	.0401	.0198
$\mathcal{E}(T_H) = 5^\circ, \mathcal{E}(\gamma) = .0002726$	.0373	.0211
$g_0 = 0, \delta = .01$	.0372	.0190
$g_0 = 0, \delta = .02$	.0074	.0039
$g_0 = .005, \delta = .01$	.0195	.0098
$\eta = 4, g_0 = .005, \delta = .01$	.0315	.0178
$\mathcal{E}(T_H) = 5^\circ, g_0 = .010, \delta = .01$	.0599	.0350

Table 1 (and Figure 5) show, lowering the growth rate will increase  $w^*$  (because with lower growth the marginal utility of reduced future consumption will be higher). If the starting growth rate is .005,  $w^*(0)$  becomes nearly 8 percent, and if the growth is zero,  $w^*(0)$  reaches almost 15 percent, and  $w^*(3)$  is nearly 8 percent. Thus if one believes that future economic growth — without climate change — is likely to be very low, it becomes easier to justify a stringent GHG abatement policy.

A lower starting growth rate has an even larger impact on  $w^*$  if  $\eta$  is large. As the table (and Figure 6) show, increasing  $\eta$  to 4 but leaving other parameters unchanged pushes  $w^*$  down well below 1 percent, but if  $\eta = 4$  and the starting growth rate is only .010,  $w^*(0)$  is over 18 percent. (The reason is that with  $\delta = 0$ , the consumption discount rate ( $\eta g_t$ )

becomes a large negative number as higher temperatures cause  $g_t$  to fall below zero.)

The next six rows of the table show the effects of increasing the mean of the temperature distribution (to 5°C) and/or the mean of the distribution for the impact parameter  $\gamma$  (to double its base value). Note that just increasing  $\mathcal{E}(T_H)$  to 5°C increases  $w^*$  only slightly (unless, as Figure 7 shows,  $\eta$  is close to 1). But also reducing the starting growth rate to .010 or .005 magnifies the increases in  $w^*$  shown in rows 4 and 5 of the table. Shifting the distribution for the growth rate parameter  $\gamma$  by doubling its mean roughly doubles  $w^*(0)$  and  $w^*(3)$ , and combining the doubling of  $\mathcal{E}(\gamma)$  with the increase in  $\mathcal{E}(T_H)$  increases  $w^*(0)$  to just under 4 percent.

As these results show, one can come up with parameter combinations that yield a relatively high WTP. But all of these results depend on keeping the rate of time preference,  $\delta$ , at zero. As the bottom panel of Table 1 shows, if  $\delta$  is increased, even to just .01, WTP falls sharply. For example, if the starting growth rate is reduced to zero but  $\delta = .01$ ,  $w^*(0)$  is below 4 percent (compared to nearly 15 percent if  $\delta = 0$ ), and if  $\delta = .02$  (a number more consistent with financial market and experimental data),  $w^*(0)$  is below 1 percent. Table 1, along with Figures 6 and 7, confirm that the argument for the immediate adoption of a stringent abatement policy hinges critically on the assumption that  $\delta$  is — or for policy purposes should be — zero.

## 5.5 Risk versus Expected Outcomes.

As Figure 7 shows, increasing the expected value of  $T_H$ , while leaving the variance and skewness of the distribution unchanged, can substantially increase WTP. But how important is outcome *uncertainty* as a driver of WTP? To determine how WTP depends on expected outcomes versus uncertainty over those outcomes, I vary the mean and standard deviation of the temperature distribution. (For simplicity, I focus on the distribution for temperature, and hold  $\gamma$  fixed at its expected value.)

Table 2 shows  $w^*(0)$ , the WTP to prevent *any* increase in temperature, calculated for shifts in the mean and standard deviation of the distribution for  $T$ , with  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .02$ . (The impact parameter  $\gamma$  is set at  $\bar{\gamma} = .0001363$ .) The table also shows the sensitivity

Table 2: WTP, CHANGES IN  $\mathcal{E}(T)$  AND  $\text{SD}(T)$ .

$\mathcal{E}(T)$	$\text{SD}(T)$	$w^*(0)$	$\partial w^*/\partial \mathcal{E}(T)$	$\partial w^*/\partial \text{SD}$	MRS
2.0°C	2.12°C	.0089	.0018	.0039	-2.15
<b>3.0°C</b>	<b>2.12°C</b>	<b>.0113</b>	<b>.0029</b>	<b>.0026</b>	<b>-0.88</b>
5.0°C	2.12°C	.0189	.0031	.0051	-1.65
7.0°C	2.12°C	.0239	.0034	.0058	-1.73
3.0°C	1.40°C	.0054	.0018	.0137	-7.50
<b>3°C</b>	<b>2.12°C</b>	<b>.0113</b>	<b>.0029</b>	<b>.0026</b>	<b>-0.88</b>
3.0°C	3.5°C	.0151	.0021	.0028	-1.30
3.0°C	4.0°C	.0165	.0020	.0028	-1.37
5.0°C	1.68°C	.0138	.0029	.0092	-3.16
4.0°C	2.0°C	.0138	.0029	.0048	-1.69
3.0°C	3.0°C	.0138	.0022	.0028	-1.23
2.0°C	3.7°C	.0138	.0018	.0029	-1.62
1.55°C	4.0°C	.0138	.0016	.0029	-1.77

*Note:* Table shows  $w^*(0)$ , fraction of consumption society would sacrifice to prevent any increase in temperature, corresponding to a particular  $\mathcal{E}(T)$  and  $\text{SD}(T)$  absent abatement.  $H = 100$  years,  $\delta = 0$ ,  $\eta = 2$ ,  $g_0 = .02$ , and  $\gamma = \bar{\gamma} = .000136$ . Bold entries correspond to base case ( $\bar{T} = 3^\circ\text{C}$  and  $\text{SD} = 2.12^\circ\text{C}$ .) The marginal rate of substitution is  $\text{MRS} = -(\partial w^*/\partial \text{SD})/(\partial w^*/\partial \mathcal{E}(T))$ .

of  $w^*$  to changes in the mean and standard deviation, i.e.,  $\partial w^*/\partial \mathcal{E}(T)$  and  $\partial w^*/\partial \text{SD}$ , and the implied marginal rate of substitution,  $\text{MRS} = -(\partial w^*/\partial \text{SD})/(\partial w^*/\partial \mathcal{E}(T))$ , i.e., the local trade-off between risk and expected temperature change that keeps  $w^*(0)$  constant. The first panel shows results of changing the mean while keeping the standard deviation constant, the second panel shows results for the opposite, and the third panel shows combinations of mean and standard deviation for which  $w^*(0)$  is constant at .0138.

Note that except for extreme values of  $\mathcal{E}(T)$  and  $\text{SD}(T)$ ,  $\partial w^*/\partial \mathcal{E}(T)$  is around .002 to .003 and  $\partial w^*/\partial \text{SD}$  is around .003 to .006, so that the MRS is about -1 to -2. Thus WTP is more sensitive to changes in the standard deviation of temperature than to changes in its mean. The third panel essentially maps out an “iso-WTP” curve, i.e., combinations of  $\mathcal{E}(T)$  and  $\text{SD}(T)$  for which  $w^*$  is constant, and corresponds to a policy indifference curve. But unlike an indifference curve for a well-behaved demand system (e.g., for food and clothing), the MRS need not (and does not) change monotonically as we move down the curve from high  $\mathcal{E}(T)$ -low  $\text{SD}(T)$  to low  $\mathcal{E}(T)$ -high  $\text{SD}(T)$ . Instead it declines in magnitude but then

increases slightly as  $\mathcal{E}(T)$  is reduced below 3.5°C.

Figure 8 shows two iso-WTP curves, both for  $\eta = 2$ ,  $g_0 = .02$ , and  $\delta = 0$ . The lower curve corresponds to the base case temperature distribution shown in Figure 1 for which the mean is 3°C and the standard deviation is 2.12°C, and which yields  $w^*(0) = .0113$ . Thus the curve shows the locus of means and standard deviations such that the transformed temperature distribution yields the same  $w^*(0) = .0113$ . Increases in the standard deviation result in substantial increases in WTP, so as  $SD(T)$  approaches 4°C, an expected temperature change *below zero* is needed to keep WTP at .0113. Clearly WTP is strongly driven by uncertainty over warming. For low values of  $SD(T)$  the MRS is large in magnitude, so that large decreases in  $\mathcal{E}(T)$  are welfare-equivalent to small decreases in  $SD(T)$ . (For example, doubling  $\mathcal{E}(T)$  to 6°C while reducing  $SD(T)$  only to 1.4°C results in the same WTP of .0113.) The top curve shows combinations of  $\mathcal{E}(T)$  and  $SD(T)$  for which  $w^*(0) = .0141$ , which is the WTP that results from keeping the standard deviation at 2.12°C but increasing the mean to 4°C. Note that this is welfare-equivalent to a standard deviation of 1.4°C and mean of 7°C.

Discussions of climate change policy often revolve around the implications of differing estimates of expected temperature increases, and uncertainty is treated more as a limit on our ability to predict temperature than a direct determinant of policy. But as these results show, uncertainty over future temperatures can be more important than expectations in welfare terms, and a stronger driver of WTP and thus of policy.

## 5.6 Policy Implications.

We have seen that for temperature and impact distributions based on the IPCC and “conservative” parameter values (e.g.,  $\delta = 0$ ,  $\eta = 2$ , and  $g_0 = .02$ ), WTP to prevent *any* increase in temperature is around 2%. And if the (much more feasible) policy objective is to ensure that  $T$  in 100 years does not exceed its expected value of 3°C, WTP is lower. Higher WTP estimates are obtained for low values of  $\eta$  (near 1) and very low initial GDP growth rates (e.g., 0 to 1 percent). But even these higher WTP estimates depend on setting  $\delta = 0$ . This is problematic, because empirical evidence would put  $\delta$  at .02 or even higher; arguments for  $\delta = 0$  are usually based on ethics, an area that is outside the expertise of most economists.

Why did I obtain low to moderate values of WTP, even with  $\delta = 0$ ? One reason for these results is the limited weight in the tails of the distributions for  $T$  and  $\gamma$ . The distribution calibrated for  $T$  implies a 21% probability of  $T \geq 4.5^\circ\text{C}$  in 100 years, and a 5% probability of  $T \geq 7.0^\circ\text{C}$ , numbers consistent with the studies surveyed by the IPCC. Likewise, the calibrated distribution for  $\gamma$  implies a 17% probability of  $\gamma \geq .00023$ . A realization in which, say,  $T = 4.5^\circ\text{C}$  and  $\gamma = .00023$  would imply that consumption in 100 years would be 5.7 percent lower than with no increase in temperature.<sup>20</sup> However, the probability of  $T \geq 4.5^\circ\text{C}$  and  $\gamma \geq .00023$  is only about 3.6%. An even more extreme outcome in which  $T = 7^\circ\text{C}$  (and  $\gamma = .00023$ ) would imply about a 9 percent loss of GDP in 100 years, but the probability of an outcome this bad or worse is only 0.9%.

Second, even if  $\delta = 0$ , the implicit discounting of consumption is significant. The initial consumption discount rate is  $\rho_0 = \eta g_0$ , which is .03 if  $\eta = 2$  and  $g_0 = .015$ . And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve smaller losses in earlier years.

Although these estimates of WTP do not support the immediate adoption of a stringent GHG abatement policy, they do not imply that no abatement is optimal. For example, 2% of GDP is in the range of cost estimates for compliance with the Kyoto Protocol.<sup>21</sup> Taking the U.S. in isolation, a WTP of 2% amounts to about \$300 billion per year, a 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  $3^\circ\text{C}$ .

We have also seen that there is considerable value in reducing uncertainty over the extent of future warming. In fact an expected temperature increase of  $6^\circ\text{C}$  but a standard deviation of only  $1.4^\circ\text{C}$  is welfare-equivalent to the IPCC “consensus” of an expected temperature increase of  $3^\circ\text{C}$  with a standard deviation of  $2.12^\circ\text{C}$ . Thus research that might reduce our uncertainty over warming is probably a high-NPV investment.

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

<sup>21</sup>See the survey of cost studies by the Energy Information Administration (1998), and the more recent country cost studies surveyed in IPCC (2007c).

## 6 Concluding Remarks.

I have examined the “demand side” of climate policy by calculating a simple WTP measure: the fraction of consumption  $w^*(\tau)$  that society would sacrifice to ensure that any increase in temperature at a future point is limited to  $\tau$ . This avoids having to make projections of GHG emissions and atmospheric concentrations, or estimate abatement costs. Instead I could focus directly on uncertainties over temperature change and over the economic impact of higher temperatures. 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  $T$  below its expected value of 3°C. Given what we know about the distributions for temperature change and its impact, it is difficult to obtain a large WTP unless  $\eta$  is reduced to 1.5 or less, or  $g_0$  is .010 or less, or we assume that the expected amount of warming is substantially larger than the IPCC projects. There are two reasons for these results: limited weight in the tails of the distributions for  $T$  and  $\gamma$ , and the effect of consumption discounting.

One might argue with these WTP calculations on several grounds. First, the “traditional” approach to climate policy analysis is to posit a direct relationship between temperature and GDP as in eqn. (3), and perhaps the growth rate relationship I have used understates damages. Second, perhaps the use of thin-tailed distributions for  $T$  and  $\gamma$  understates the probability of a catastrophic outcome and thereby understates WTP. And third, although I have incorporated what I believe to be the current “state of knowledge” of the distributions for temperature change and its impact, that “state of knowledge” is evolving, both in terms of expected outcomes and the degree of uncertainty over those outcomes.

In Pindyck (2011a) I compare the WTP implications of direct versus growth rate damage functions. Obviously one can posit a damage function of either type that will yield a higher WTP; e.g., by modifying eqn. (3) so that  $T$  is raised to a power greater than 2, or by modifying eqn. (2) so that  $g_t$  is a convex rather than linear function of  $T$ . (Such modifications might be warranted, although there is little data on which to base specifics.) But as for the direct versus growth rate question, I have shown that the damage functions of eqns. (3) and

(2) yield roughly similar estimates for WTP.

Is the true distribution for temperature fat-tailed? We don't know, and there are no data with which to test alternative distributional hypotheses. But if the distribution *is* fat-tailed, would that mean I have grossly underestimated WTP? If we believe that social welfare is properly measured by the CRRA utility function of eqn. (6), then the answer is yes — WTP would be 100%. However, it makes little sense to apply CRRA utility to extreme events. What does it mean to say that marginal utility becomes infinite as consumption approaches zero? Marginal utility should indeed become very large — after all, zero consumption usually implies death. But “very large” is not infinite. Thus one might argue that marginal utility should be bounded by some maximum, perhaps the value of a statistical life (VSL) or some multiple of VSL. I have shown in Pindyck (2011b) that once marginal utility is bounded, extreme results disappear, and a thin-tailed distribution can yield a higher WTP to pay for abatement than a fat-tailed one. The reason is simple; when calibrated to the same mean, 83% and (say) 95% critical points, the thin-tailed distribution will have more mass at moderate temperatures that yield marginal utility close to the maximum.<sup>22</sup>

Finally, the “state of knowledge” numbers to which I fit distributions for  $T$  and  $\gamma$  might be wrong. In fact, some recent studies suggest a shift towards a higher “most likely” range for  $T$ . As Figure 7 and Tables 1 and 2 show, an increase in the expected temperature change can substantially increase WTP, as can (even more so) an increase in the standard deviation of the temperature change. But the framework presented in this paper allows one to easily evaluate the WTP implications of shifts in (or differences of opinion about) the distributions.

All of this comes back to the issue of uncertainty. This paper explored the implications of the considerable uncertainty that exists over both the extent of future warming and its impact. As part of that exercise, I also calculated the trade-off between the expected value of a temperature increase versus its standard deviation. The trade-off is the marginal rate of substitution along an “iso-WTP curve,” i.e., the locus of combinations of the expected value versus the standard deviation of the change in temperature such that the WTP (e.g.,

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<sup>22</sup>Rather than put a bound on marginal utility, one could instead put a bound on the maximum possible temperature increase, e.g., 30°C. But this simply transforms a fat-tailed distribution into a thin-tailed one.

to prevent any temperature increase) is constant. The results show that uncertainty over temperature change can be a stronger driver of WTP than expectations, and thus should be a major focus of climate change policy.

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. My results are consistent with beginning slowly. In addition, beginning slowly has other virtues. It is dynamically efficient in the same way that a declining rate of consumption of an exhaustible resource is dynamically efficient. (Think of the largest tolerable atmospheric GHG concentration minus the current concentration as the remaining resource reserve.) It is also efficient because of the likelihood that technological change will reduce the cost of abatement over time, and because further research may reduce our uncertainty over climate sensitivity and the impact of warming.

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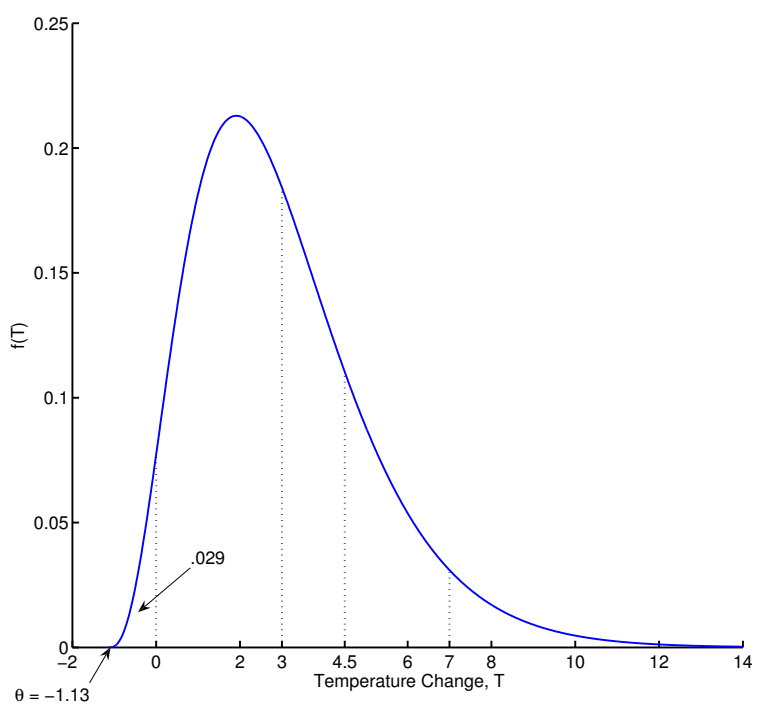


Figure 1: Distribution for Temperature Change. (Mean = 3.0°C,  $\lambda = 0.92$ ,  $r = 3.8$ )

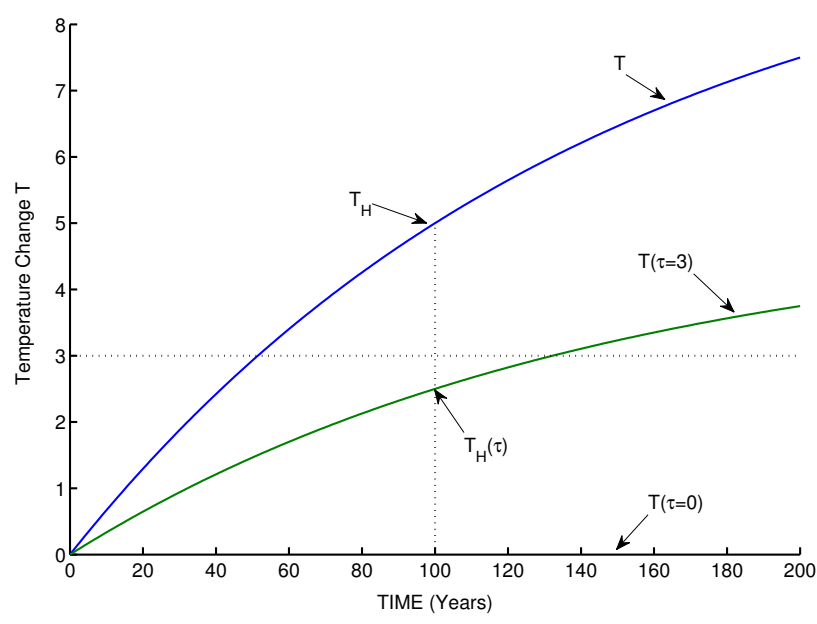


Figure 2: Temperature Change  $T_t$ : Unconstrained and Constrained So  $T_H \leq \tau$

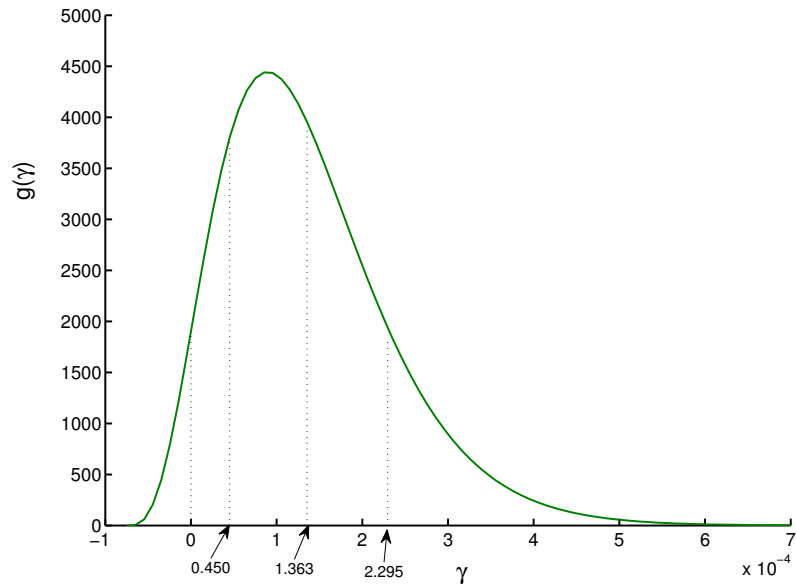


Figure 3: Distribution for Loss Function Parameter  $\gamma$ . ( $\bar{\gamma} = .000136$ ,  $\lambda = 21,341$ ,  $r = 4.5$ )

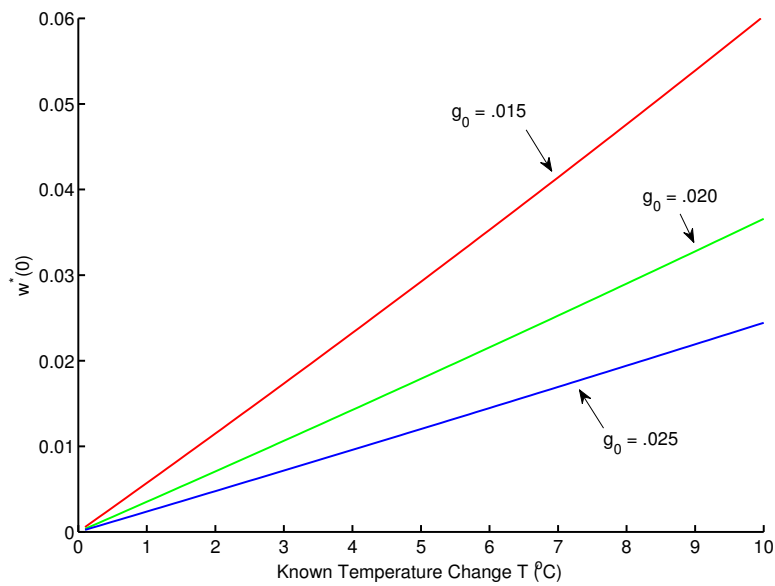


Figure 4: WTP, Known Temperature Change  $T_H$ ,  $\eta = 2$ ,  $g_0 = .015, .020, .025$ , and  $\delta = 0$

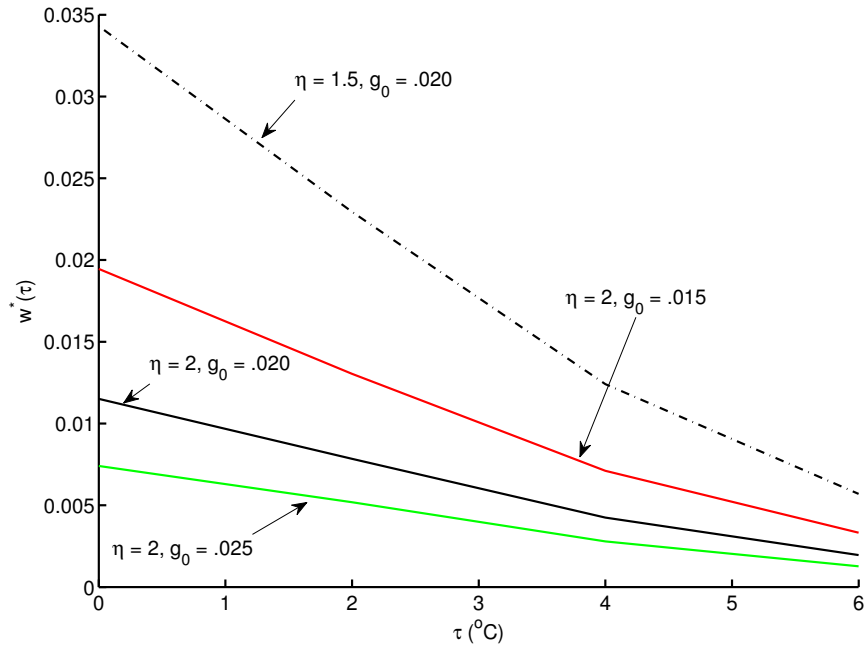


Figure 5:  $w^*(\tau)$ ,  $T$  and  $\gamma$  Uncertain.  $\eta = 2$  and  $1.5$ ,  $g_0 = .015, .020, .025$ , and  $\delta = 0$

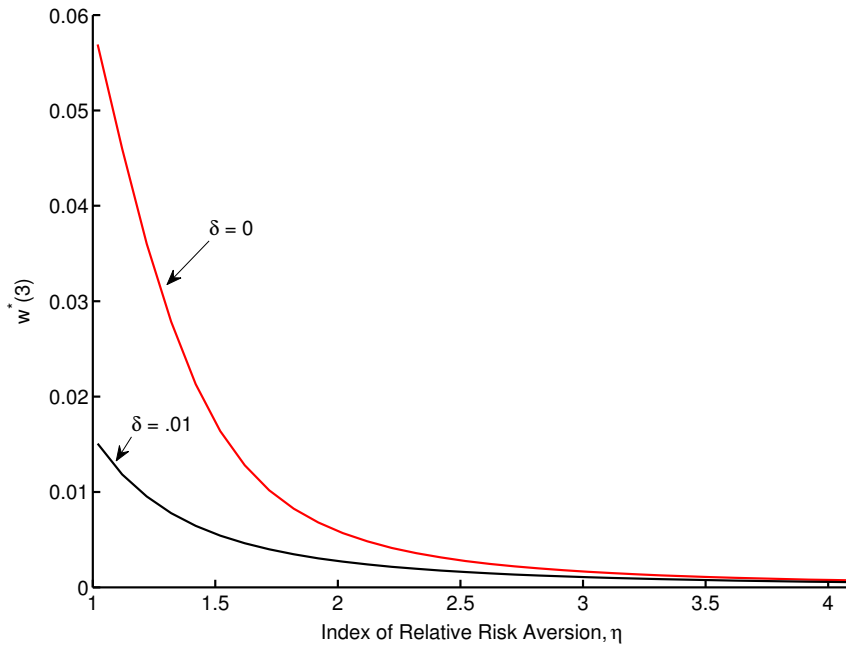


Figure 6: WTP Versus  $\eta$  for  $\tau = 3$ .  $g_0 = .020$  and  $\delta = 0$  and  $.01$

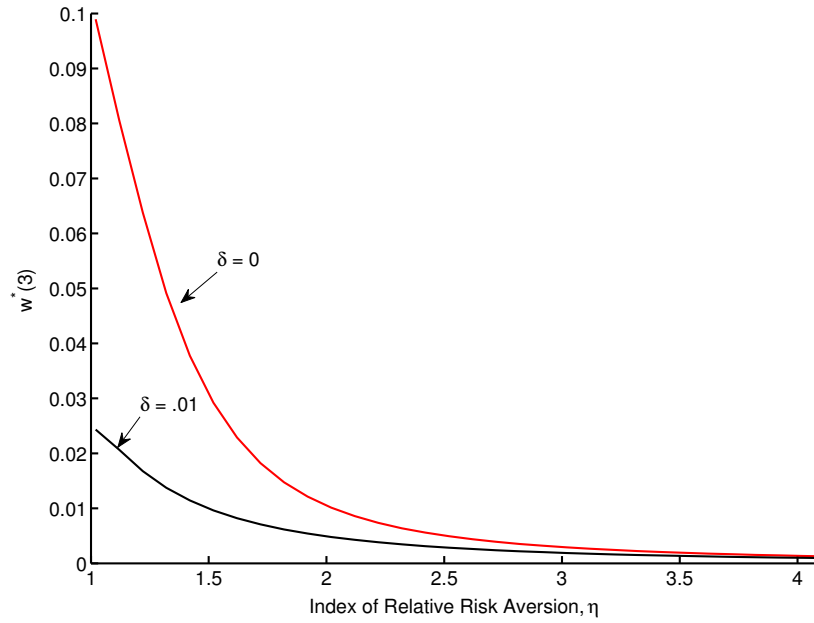


Figure 7: WTP Versus  $\eta$  for  $\tau = 3$ .  $\mathcal{E}(T_H) = 5^\circ\text{C}$ ,  $g_0 = .020$ ,  $\delta = 0$  and  $.01$

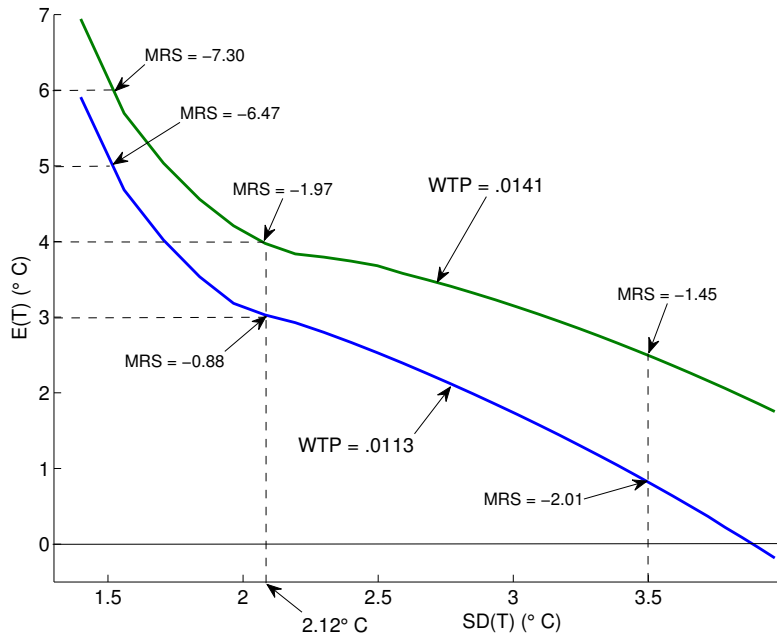


Figure 8: Iso-WTP Curves for  $w^*(0) = .0113$  (Base Case) and  $w^*(0) = .0141$  ( $\mathcal{E}(T) = 4^\circ\text{C}$ );  $\eta = 2$ ,  $g_0 = .020$ , and  $\delta = 0$