UNCERTAIN OUTCOMES AND CLIMATE CHANGE POLICY

Robert S. Pindyck

Massachusetts Institute of Technology

FEEM
June 3, 2010

Introduction

- Uncertainty is at the heart of climate change policy:

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.
  - Uncertainty over technological changes that might reduce impacts or costs of abatement.

Introduction

- Uncertainty is at the heart of climate change policy:
    - Uncertainty over underlying physical/ecological processes.
    - Uncertainty over economic impact of climate change, including possible adaptation.
    - Uncertainty over technological changes that might reduce impacts or costs of abatement.
- Important irreversibilities, raising issues of waiting/learning.

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.
  - Uncertainty over technological changes that might reduce impacts or costs of abatement.
- Important irreversibilities, raising issues of waiting/learning.
  - GHG concentrations decay very slowly.

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.
  - Uncertainty over technological changes that might reduce impacts or costs of abatement.
- Important irreversibilities, raising issues of waiting/learning.
  - GHG concentrations decay very slowly.
  - Abatement policy imposes sunk costs.

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.
  - Uncertainty over technological changes that might reduce impacts or costs of abatement.
- Important irreversibilities, raising issues of waiting/learning.
  - GHG concentrations decay very slowly.
  - Abatement policy imposes sunk costs.
- Long time horizon – around 100 years. How to discount?

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.
  - Uncertainty over technological changes that might reduce impacts or costs of abatement.
- Important irreversibilities, raising issues of waiting/learning.
  - GHG concentrations decay very slowly.
  - Abatement policy imposes sunk costs.
- Long time horizon – around 100 years. How to discount?
- What does uncertainty, and especially low-probability extreme outcomes, imply for climate change policy?

Introduction

- Uncertainty is at the heart of climate change policy:
  - Uncertainty over underlying physical/ecological processes.
  - Uncertainty over economic impact of climate change, including possible adaptation.
  - Uncertainty over technological changes that might reduce impacts or costs of abatement.
- Important irreversibilities, raising issues of waiting/learning.
  - GHG concentrations decay very slowly.
  - Abatement policy imposes sunk costs.
- Long time horizon – around 100 years. How to discount?
- What does uncertainty, and especially low-probability extreme outcomes, imply for climate change policy?
- Willingness to Pay (WTP): What fraction of current and future consumption would society give up to keep ΔT low?

Introduction (Con't)

- Weitzman (2009): Thick tails.

Introduction (Con't)

- Weitzman (2009): Thick tails.

Introduction (Con't)

- Weitzman (2009): Thick tails.
  - Suppose ΔT has a some distribution with unknown variance.

Introduction (Con't)

- Weitzman (2009): Thick tails.
  - Suppose ΔT has a some distribution with unknown variance.
  - Bayesian updating of variance estimate.

Introduction (Con't)

- Weitzman (2009): Thick tails.
  - Suppose ΔT has a some distribution with unknown variance.
  - Bayesian updating of variance estimate.
  - Then posterior-predictive distribution has thick tails. (No MGF, tails $\rightarrow 0$ more slowly than exponentially.)

Introduction (Con't)

- Weitzman (2009): Thick tails.
  - Suppose ΔT has a some distribution with unknown variance.
  - Bayesian updating of variance estimate.
  - Then posterior-predictive distribution has thick tails. (No MGF, tails $\rightarrow 0$ more slowly than exponentially.)
  - With power utility function (e.g., CRRA), marginal utility of consumption $\rightarrow \infty$ as $C \rightarrow 0$. Implies WTP is 100%.

Introduction (Con't)

- Weitzman (2009): Thick tails.
  - Suppose ΔT has a some distribution with unknown variance.
  - Bayesian updating of variance estimate.
  - Then posterior-predictive distribution has thick tails. (No MGF, tails $\rightarrow 0$ more slowly than exponentially.)
  - With power utility function (e.g., CRRA), marginal utility of consumption $\rightarrow \infty$ as C $\rightarrow 0$. Implies WTP is 100%.
- Shows limitations of expected cost-benefit analysis, but not much guidance for policy.

Introduction (Con't)

- Weitzman (2009): Thick tails.
  - Suppose ΔT has a some distribution with unknown variance.
  - Bayesian updating of variance estimate.
  - Then posterior-predictive distribution has thick tails. (No MGF, tails $\to 0$ more slowly than exponentially.)
  - With power utility function (e.g., CRRA), marginal utility of consumption $\to \infty$ as C $\to 0$. Implies WTP is 100%.
- Shows limitations of expected cost-benefit analysis, but not much guidance for policy.
- Integrated Assessment Models (IAMs): use ad hoc loss functions and focus on "most likely" scenarios.

This Study

- Uncertainty over ΔT and economic impact of ΔT.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.
- Displaced gamma distribution for ΔT. Fit to IPCC (2007) summary of studies.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.
- Displaced gamma distribution for ΔT. Fit to IPCC (2007) summary of studies.
- Unlike IAMs, I relate ΔT to growth rate, not level, of real GDP.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.
- Displaced gamma distribution for ΔT. Fit to IPCC (2007) summary of studies.
- Unlike IAMs, I relate ΔT to growth rate, not level, of real GDP.
- I make loss function stochastic. Key parameter unknown.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.
- Displaced gamma distribution for ΔT. Fit to IPCC (2007) summary of studies.
- Unlike IAMs, I relate ΔT to growth rate, not level, of real GDP.
- I make loss function stochastic. Key parameter unknown.
    - Treat this the same way as climate sensitivity.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.
- Displaced gamma distribution for ΔT. Fit to IPCC (2007) summary of studies.
- Unlike IAMs, I relate ΔT to growth rate, not level, of real GDP.
- I make loss function stochastic. Key parameter unknown.
  - Treat this the same way as climate sensitivity.
  - As with ΔT, displaced gamma distribution. Use recent economic impact studies (IAMs) to calibrate.

This Study

- Uncertainty over ΔT and economic impact of ΔT.
- I use current "state of knowledge" for distributions of ΔT and its impact.
- Displaced gamma distribution for ΔT. Fit to IPCC (2007) summary of studies.
- Unlike IAMs, I relate ΔT to growth rate, not level, of real GDP.
- I make loss function stochastic. Key parameter unknown.
  - Treat this the same way as climate sensitivity.
  - As with ΔT, displaced gamma distribution. Use recent economic impact studies (IAMs) to calibrate.
- I ignore irreversibilities. Companion study.

Plan for Talk

- Background and overview of methodology.
- Uncertainty over climate sensitivity, use of gamma distribution.
- Economic impact of ΔT.
  - Choice of loss function.
  - Treatment of uncertainty.
- Willingness to pay to keep (uncertain) $\Delta T \leq \tau$.
  - General formulation.
  - No uncertainty.
  - Only uncertainty over ΔT.
- Policy implications and conclusions.

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:
  1. Project future emissions (of CO_2e composite or individual GHGs) under BAU and abatement scenarios, and resulting atmospheric CO_2e.

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:
  1. Project future emissions (of CO_2e composite or individual GHGs) under BAU and abatement scenarios, and resulting atmospheric CO_2e.
  2. Project resulting ΔT over time (globally or regionally).

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:
  1. Project future emissions (of CO_2e composite or individual GHGs) under BAU and abatement scenarios, and resulting atmospheric CO_2e.
  2. Project resulting ΔT over time (globally or regionally).
  3. Translate ΔT into lost GDP and consumption (globally or regionally). This is most speculative part, because hard to estimate potential adaptation.

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:
  1. Project future emissions (of CO_2e composite or individual GHGs) under BAU and abatement scenarios, and resulting atmospheric CO_2e.
  2. Project resulting ΔT over time (globally or regionally).
  3. Translate ΔT into lost GDP and consumption (globally or regionally). This is most speculative part, because hard to estimate potential adaptation.
  4. Estimate current and future costs of abating GHG emissions by various amounts.

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:
  1. Project future emissions (of CO_2e composite or individual GHGs) under BAU and abatement scenarios, and resulting atmospheric CO_2e.
  2. Project resulting ΔT over time (globally or regionally).
  3. Translate ΔT into lost GDP and consumption (globally or regionally). This is most speculative part, because hard to estimate potential adaptation.
  4. Estimate current and future costs of abating GHG emissions by various amounts.
  5. Assumptions about social utility, pure rate of time preference, and but-for growth, for intertemporal comparisons.

Standard IAM Policy Analysis

- Economic analyses usually built around 5 elements:
  1. Project future emissions (of CO_2e composite or individual GHGs) under BAU and abatement scenarios, and resulting atmospheric CO_2e.
  2. Project resulting ΔT over time (globally or regionally).
  3. Translate ΔT into lost GDP and consumption (globally or regionally). This is most speculative part, because hard to estimate potential adaptation.
  4. Estimate current and future costs of abating GHG emissions by various amounts.
  5. Assumptions about social utility, pure rate of time preference, and but-for growth, for intertemporal comparisons.
- For each step, substantial uncertainty.

IAM Analyses (Con't)

- Apart from *Stern Review* (low discount rate, low abatement costs, high economic impact), most studies suggest low to moderate abatement now (or waiting).

IAM Analyses (Con't)

- Apart from *Stern Review* (low discount rate, low abatement costs, high economic impact), most studies suggest low to moderate abatement now (or waiting).
- Increasing rate of abatement is dynamically efficient, allows for learning about ΔT and its impact, and allows for technological change (e.g., lower abatement costs).

IAM Analyses (Con't)

- Apart from *Stern Review* (low discount rate, low abatement costs, high economic impact), most studies suggest low to moderate abatement now (or waiting).
- Increasing rate of abatement is dynamically efficient, allows for learning about ΔT and its impact, and allows for technological change (e.g., lower abatement costs).
- If you believe ΔT is within IPCC's 90% confidence interval, hard to justify stringent abatement now.

IAM Analyses (Con't)

- Apart from *Stern Review* (low discount rate, low abatement costs, high economic impact), most studies suggest low to moderate abatement now (or waiting).
- Increasing rate of abatement is dynamically efficient, allows for learning about ΔT and its impact, and allows for technological change (e.g., lower abatement costs).
- If you believe ΔT is within IPCC's 90% confidence interval, hard to justify stringent abatement now.
- Maybe not: Might tails of the distributions for ΔT and/or impact — possibility of extreme outcomes — support stringent abatement?

Methodology

- I avoid dealing with abatement costs and GHG emissions and accumulation by estimating WTP, and focusing on uncertainty over ΔT and economic impact.

Methodology

- I avoid dealing with abatement costs and GHG emissions and accumulation by estimating WTP, and focusing on uncertainty over ΔT and economic impact.
- Temperature Change. Use IPCC survey of 22 studies of climate sensitivity.

Methodology

- I avoid dealing with abatement costs and GHG emissions and accumulation by estimating WTP, and focusing on uncertainty over ΔT and economic impact.
- Temperature Change. Use IPCC survey of 22 studies of climate sensitivity.
  - Fit displaced gamma distribution for ΔT_H, $H = 100$ years.

Methodology

- I avoid dealing with abatement costs and GHG emissions and accumulation by estimating WTP, and focusing on uncertainty over ΔT and economic impact.
- Temperature Change. Use IPCC survey of 22 studies of climate sensitivity.
  - Fit displaced gamma distribution for ΔT_H, $H = 100$ years.
  - Studies too "conservative?" Can re-fit to subset with larger tails; can change variance or skewness of base distribution.

Methodology

- I avoid dealing with abatement costs and GHG emissions and accumulation by estimating WTP, and focusing on uncertainty over ΔT and economic impact.
- Temperature Change. Use IPCC survey of 22 studies of climate sensitivity.
  - Fit displaced gamma distribution for ΔT_H, $H = 100$ years.
  - Studies too "conservative?" Can re-fit to subset with larger tails; can change variance or skewness of base distribution.
  - I assume *immediate doubling* of GHG concentration, $\Delta T_t \rightarrow 2\Delta T_H$ as t gets large:

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

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t) C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.
    - Impact of ΔT likely to be permanent.

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.
    - Impact of ΔT likely to be permanent.
    - Resources to counter effects (floods, health, etc.) reduce those for R&D and investment.

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.
    - Impact of ΔT likely to be permanent.
    - Resources to counter effects (floods, health, etc.) reduce those for R&D and investment.
    - Empirical support: Dell et al (2008, 2009).

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.
    - Impact of ΔT likely to be permanent.
    - Resources to counter effects (floods, health, etc.) reduce those for R&D and investment.
    - Empirical support: Dell et al (2008, 2009).
  - I use linear relation: $g_t = g_0 - \gamma \Delta T_t$.

Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.
    - Impact of ΔT likely to be permanent.
    - Resources to counter effects (floods, health, etc.) reduce those for R&D and investment.
    - Empirical support: Dell et al (2008, 2009).
  - I use linear relation: $g_t = g_0 - \gamma \Delta T_t$.
  - Use IAMs to get dist. for β in $L(\Delta T) = e^{-\beta(\Delta T)^2}$ at $H = 100$.

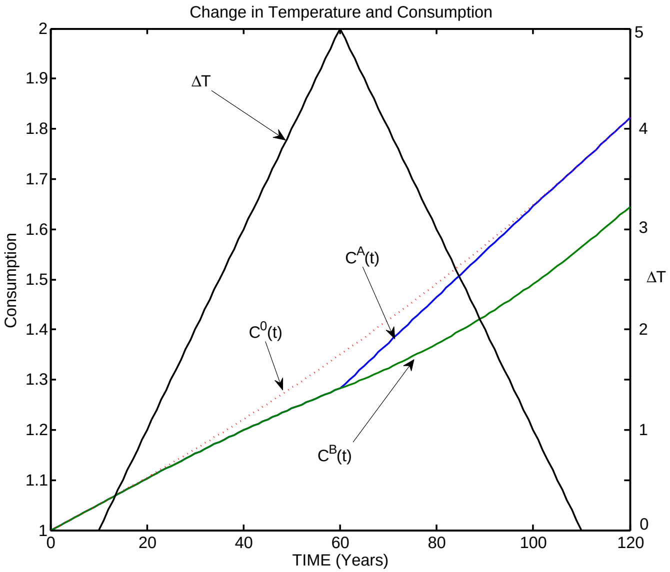
Methodology (Con't)

- Economic Impact. ΔT reduces real growth rate.
  - Existing studies: $C_t = L(\Delta T_t)C_t^*$, where C_t^* is "but-for" C with no warming, $L(0) = 1$, and $L' < 0$.
  - Expect ΔT to reduce *growth rate* of GDP and C, not level.
    - Impact of ΔT likely to be permanent.
    - Resources to counter effects (floods, health, etc.) reduce those for R&D and investment.
    - Empirical support: Dell et al (2008, 2009).
  - I use linear relation: $g_t = g_0 - \gamma \Delta T_t$.
  - Use IAMs to get dist. for β in $L(\Delta T) = e^{-\beta(\Delta T)^2}$ at $H = 100$.
  - Translate into distribution for γ. Normalizing $C_0 = 1$,

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

Then $e^{-\frac{2\gamma H \Delta T_H}{\ln(1/2)} + (g_0 - 2\gamma \Delta T_H)H + \frac{\gamma H \Delta T_H}{\ln(1/2)}} = e^{g_0 H - \beta(\Delta T)^2}$, and $\gamma = 1.79\beta \Delta T_H / H$.

Example of Economic Impact



Willingness to Pay

- Willingness to Pay. Posit CRRA utility (for entire world!):

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

Willingness to Pay

- Willingness to Pay. Posit CRRA utility (for entire world!):

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

- Calculate $w^*(\tau)$: fraction of current and future C_t society would sacrifice to ensure $\Delta T_H \leq \tau$.

Willingness to Pay

- Willingness to Pay. Posit CRRA utility (for entire world!):

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

- Calculate $w^*(\tau)$: fraction of current and future C_t society would sacrifice to ensure $\Delta T_H \leq \tau$.
- If we sacrifice $w(\tau)$ of $\{C_t\}$ so $\Delta T_H \leq \tau$, welfare is:

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

where $\rho = (\eta - 1)(g_0 - 2\gamma \Delta T_H) + \delta$,
$\omega = 2(\eta - 1)\gamma H \Delta T_H / \ln(1/2)$, and $\mathcal{E}_{0,\tau}$ is expectation over ΔT_H and γ conditional on $\Delta T_H \leq \tau$.

Willingness to Pay (Con't)

- If no action is taken, welfare is:

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

where $\mathcal{E}_0$ is expectation with ΔT_H unconstrained.

Willingness to Pay (Con't)

- If no action is taken, welfare is:

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

  where $\mathcal{E}_0$ is expectation with ΔT_H unconstrained.
- WTP is value $w^*(\tau)$ that equates $W_1(\tau)$ and W_2.

Willingness to Pay (Con't)

- If no action is taken, welfare is:

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

  where $\mathcal{E}_0$ is expectation with ΔT_H unconstrained.
- WTP is value $w^*(\tau)$ that equates $W_1(\tau)$ and W_2.
- Question: Do fitted distributions for ΔT_H and γ, along with "reasonable" values for δ, η and g_0, yield $w^*(\tau) > 2$ or 3% for τ around 2 or 3°C?

Distribution for ΔT

- Fit a displaced gamma distribution:

$$f(x; r, \lambda, \theta) = \frac{\lambda^r}{\Gamma(r)} (x - \theta)^2 e^{-\lambda(x-\theta)} \quad , \qquad x \geq \theta$$

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

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

- Here θ is the displacement parameter. Moment generating function is

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

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0°$C.

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:
  - 17% probability of $\Delta T \geq 4.5^\circ$C

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:
  - 17% probability of $\Delta T \geq 4.5^\circ$C
  - 5% probability of $\Delta T \geq 7.0^\circ$C

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:
  - 17% probability of $\Delta T \geq 4.5^\circ$C
  - 5% probability of $\Delta T \geq 7.0^\circ$C
  - 1% probability of $\Delta T \geq 10.0^\circ$C

Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:
  - 17% probability of $\Delta T \geq 4.5^\circ$C
  - 5% probability of $\Delta T \geq 7.0^\circ$C
  - 1% probability of $\Delta T \geq 10.0^\circ$C
- Fitting distribution to mean, 5%, and 1% points gives $r = 3.8$, $\lambda = 0.92$, and $\theta = -1.13$.

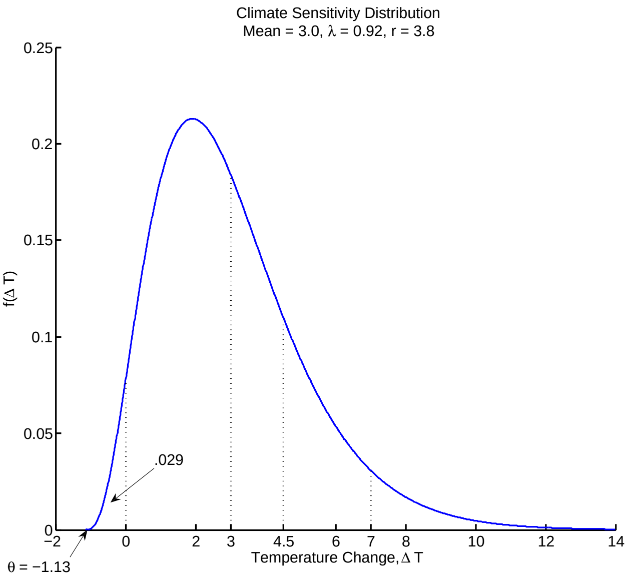
Distribution for ΔT (Con't)

- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:
  - 17% probability of $\Delta T \geq 4.5^\circ$C
  - 5% probability of $\Delta T \geq 7.0^\circ$C
  - 1% probability of $\Delta T \geq 10.0^\circ$C
- Fitting distribution to mean, 5%, and 1% points gives $r = 3.8$, $\lambda = 0.92$, and $\theta = -1.13$.
- Implies 21% probability of $\Delta T \geq 4.5^\circ$C.

Distribution for ΔT (Con't)

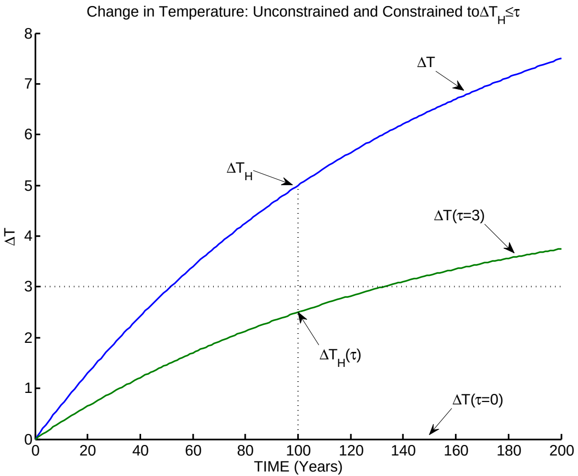
- Want climate sensitivity, i.e., ΔT resulting from doubling of atmospheric CO_2e.
- IPCC (2007) summary of 22 studies puts $\mathcal{E}(\Delta T) = 3.0^\circ$C.
- IPCC puts studies in standardized form. Can infer:
    - 17% probability of $\Delta T \geq 4.5^\circ$C
    - 5% probability of $\Delta T \geq 7.0^\circ$C
    - 1% probability of $\Delta T \geq 10.0^\circ$C
- Fitting distribution to mean, 5%, and 1% points gives $r = 3.8$, $\lambda = 0.92$, and $\theta = -1.13$.
- Implies 21% probability of $\Delta T \geq 4.5^\circ$C.
- Implies 2.9% probability of *negative* ΔT, consistent with scientific studies.

Fitted Distribution for ΔT_H



ΔT_t: Unconstrained and Constrained so $\Delta T_H \leq \tau$

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



Uncertainty Over Economic Impact

- How bad would be a $\Delta T \geq 5°C$?

Uncertainty Over Economic Impact

- How bad would be a $\Delta T \geq 5^{\circ}$C?
- Might argue we do not — and cannot — know. Outside of our experience and models.

Uncertainty Over Economic Impact

- How bad would be a $\Delta T \geq 5^\circ$C?
- Might argue we do not — and cannot — know. Outside of our experience and models.
- Could say same thing about probabilities of ΔT beyond 5°C; outside of experience and range of climate science models.

Uncertainty Over Economic Impact

- How bad would be a $\Delta T \geq 5^\circ$C?
- Might argue we do not — and cannot — know. Outside of our experience and models.
- Could say same thing about probabilities of ΔT beyond 5°C; outside of experience and range of climate science models.
- Alternative: treat IAMs and related models analogously to climate science models.

Uncertainty Over Economic Impact

- How bad would be a $\Delta T \geq 5^\circ$C?
- Might argue we do not — and cannot — know. Outside of our experience and models.
- Could say same thing about probabilities of ΔT beyond 5°C; outside of experience and range of climate science models.
- Alternative: treat IAMs and related models analogously to climate science models.
- IAMs give range (and confidence points) of lost GDP for 4°C and 5°C ΔT.

Uncertainty Over Economic Impact

- How bad would be a $\Delta T \geq 5^{\circ}$C?
- Might argue we do not — and cannot — know. Outside of our experience and models.
- Could say same thing about probabilities of ΔT beyond 5°C; outside of experience and range of climate science models.
- Alternative: treat IAMs and related models analogously to climate science models.
- IAMs give range (and confidence points) of lost GDP for 4°C and 5°C ΔT.
- Can use this information to get probability distribution for economic impact.

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$
- Treat β as stochastic.

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$
- Treat β as stochastic.
- DG distribution, $g(\beta)$; β and ΔT independently distributed.

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$
- Treat β as stochastic.
- DG distribution, $g(\beta)$; β and ΔT independently distributed.
- Calibrate parameters of distribution for β using:

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$
- Treat β as stochastic.
- DG distribution, $g(\beta)$; β and ΔT independently distributed.
- Calibrate parameters of distribution for β using:
  - IPCC (2007) — for $\Delta T = 4^\circ$C, global mean loss " most likely" in range of 1% to 5% of GDP.

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$
- Treat β as stochastic.
- DG distribution, $g(\beta)$; β and ΔT independently distributed.
- Calibrate parameters of distribution for β using:
  - IPCC (2007) — for $\Delta T = 4°$C, global mean loss " most likely" in range of 1% to 5% of GDP.
  - "Most likely" $=$ 66% to 90% confidence interval.

Economic Impact

- Begin with exponential-quadratic: $L(\Delta T) = \exp[-\beta(\Delta T)^2]$
- Treat β as stochastic.
- DG distribution, $g(\beta)$; β and ΔT independently distributed.
- Calibrate parameters of distribution for β using:
  - IPCC (2007) — for $\Delta T = 4°$C, global mean loss " most likely" in range of 1% to 5% of GDP.
  - "Most likely" $=$ 66% to 90% confidence interval.
  - Dietz and Stern (2008) graphical summary of IAM damage estimates shows 0.5% to 2% of lost GDP for $\Delta T = 3°$C, and 1% to 8% of GDP for $\Delta T = 5°$C.

Economic Impact (Con't)

- Want distribution for γ in $g_t = g_0 - \gamma \Delta T_t$. Use $\gamma = 1.79 \beta \Delta T / H$.

Economic Impact (Con't)

- Want distribution for γ in $g_t = g_0 - \gamma \Delta T_t$. Use $\gamma = 1.79\beta\Delta T/H$.
- Using IPCC range, I take mean loss for $\Delta T = 4°$C to be 3% of GDP, and 5% and 95% points (or 17% and 83% points) to be 1% of GDP and 5% of GDP. Results consistent with summary numbers in Dietz and Stern.

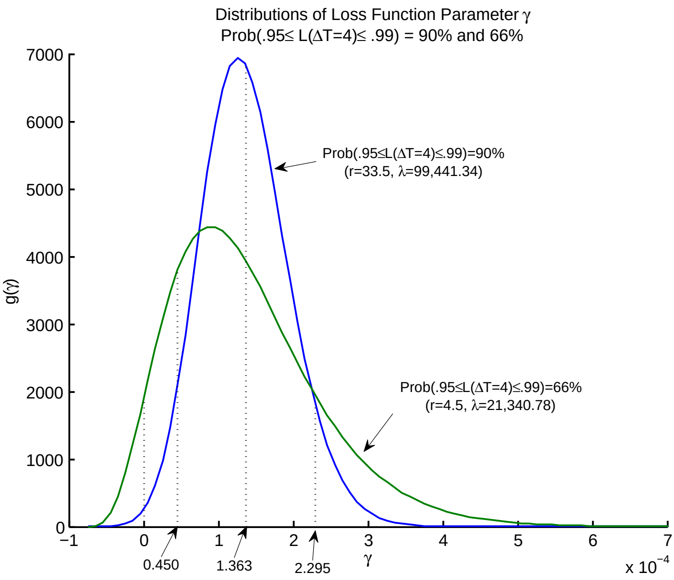
Economic Impact (Con't)

- Want distribution for γ in $g_t = g_0 - \gamma \Delta T_t$. Use $\gamma = 1.79\beta\Delta T / H$.
- Using IPCC range, I take mean loss for $\Delta T = 4°$C to be 3% of GDP, and 5% and 95% points (or 17% and 83% points) to be 1% of GDP and 5% of GDP. Results consistent with summary numbers in Dietz and Stern.
- Implies that mean, 5% and 95% (or 17% and 83%) values for γ are $\gamma_0 = .0001363$, $\gamma_1 = .0000450$, and $\gamma_2 = .0002295$.

Economic Impact (Con't)

- Want distribution for γ in $g_t = g_0 - \gamma \Delta T_t$. Use $\gamma = 1.79\beta\Delta T / H$.
- Using IPCC range, I take mean loss for $\Delta T = 4°$C to be 3% of GDP, and 5% and 95% points (or 17% and 83% points) to be 1% of GDP and 5% of GDP. Results consistent with summary numbers in Dietz and Stern.
- Implies that mean, 5% and 95% (or 17% and 83%) values for γ are $\gamma_0 = .0001363$, $\gamma_1 = .0000450$, and $\gamma_2 = .0002295$.
- I fit DGD to these numbers, and use higher-variance version for WTP calculations.

Distributions for Loss Function Parameter γ



Willingness to Pay

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

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

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

where θ_T and θ_γ are lower limits on distributions for ΔT and γ, and $F(\tau) = \int_{\theta_T}^{\tau} f(\Delta T) d\Delta T$.

Willingness to Pay

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

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

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

where θ_T and θ_γ are lower limits on distributions for ΔT and γ, and $F(\tau) = \int_{\theta_T}^{\tau} f(\Delta T) d\Delta T$.

- Thus $W_1(\tau)$ (abatement) and W_2 (no abatement) are:

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

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

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

$$w^*(\tau) = 1 - \left[G_\infty / \; G_\tau\right]^{\frac{1}{1-\eta}}$$

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.
- Translation: want "small" δ, η, and g_0.

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.
- Translation: want "small" δ, η, and g_0.
  - In finance and macro literature, δ usually .01 to .04.

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.
- Translation: want "small" δ, η, and g_0.
  - In finance and macro literature, δ usually .01 to .04.
  - Can argue (value judgment) for intergenerational comparisons, δ should be close to 0.

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.
- Translation: want "small" δ, η, and g_0.
  - In finance and macro literature, δ usually .01 to .04.
  - Can argue (value judgment) for intergenerational comparisons, δ should be close to 0.
  - In finance and macro literature, η usually 1.5 to 4.

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.
- Translation: want "small" δ, η, and g_0.
  - In finance and macro literature, δ usually .01 to .04.
  - Can argue (value judgment) for intergenerational comparisons, δ should be close to 0.
  - In finance and macro literature, η usually 1.5 to 4.
  - Actual g_0 around .02 to .025.

Willingness to Pay (Con't)

- Setting $W_1(\tau) = W_2$, WTP is

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

- Parameter Values. Want "reasonable" numbers for δ, η, and g_0, but skewed to high WTP.
- Translation: want "small" δ, η, and g_0.
  - In finance and macro literature, δ usually .01 to .04.
  - Can argue (value judgment) for intergenerational comparisons, δ should be close to 0.
  - In finance and macro literature, η usually 1.5 to 4.
  - Actual g_0 around .02 to .025.
- I will use $\delta = 0$, $\eta \approx 2$, and g_0 from .015 to .025.

No Uncertainty

- Removing uncertainty provides intuition for WTP.

No Uncertainty

- Removing uncertainty provides intuition for WTP.
- With no uncertainty:

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

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

where $\omega = 2(\eta - 1)\gamma_0 H \Delta T_H / \ln(1/2)$ and $\omega_\tau = 2(\eta - 1)\gamma_0 \tau / \ln(1/2)$. (I use mean value, γ_0, as certainty-equivalent γ.)

No Uncertainty

- Removing uncertainty provides intuition for WTP.
- With no uncertainty:

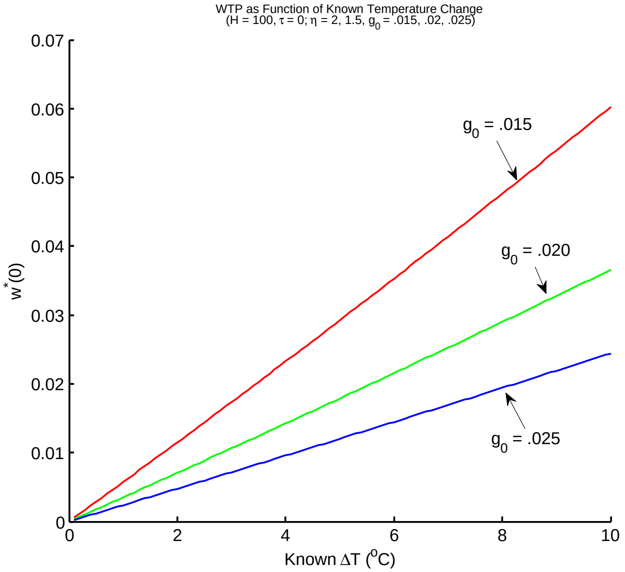
$$W_1(\tau) = \frac{[1 - w(\tau)]^{1-\eta}}{1-\eta} \int_0^N e^{\omega_\tau - \rho t - \omega_\tau (1/2)^{t/H}} dt$$

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

where $\omega = 2(\eta - 1)\gamma_0 H \Delta T_H / \ln(1/2)$ and $\omega_\tau = 2(\eta - 1)\gamma_0 \tau / \ln(1/2)$. (I use mean value, γ_0, as certainty-equivalent γ.)

- Figure shows $w^*(0)$ for range of ΔT_H, with $\eta = 2$, $\delta = 0$, and $g = .015, .020, .025$.

WTP for Known ΔT_H $(\tau = 0)$



Both ΔT and γ Uncertain

- Both ΔT and the impact parameter γ are uncertain.

Both ΔT and γ Uncertain

- Both ΔT and the impact parameter γ are uncertain.
- Figure shows $w^*(\tau)$ for $\delta = 0$, $\eta = 2$ and 1.5, and $g_0 = .015$, .020, and .025.

Both ΔT and γ Uncertain

- Both ΔT and the impact parameter γ are uncertain.
- Figure shows $w^*(\tau)$ for $\delta = 0$, $\eta = 2$ and 1.5, and $g_0 = .015$, .020, and .025.
- To get WTP above 2%, even for $\tau = 0$, need $\eta = 1.5$ or $g_0 = .015$ if $\eta = 2$.

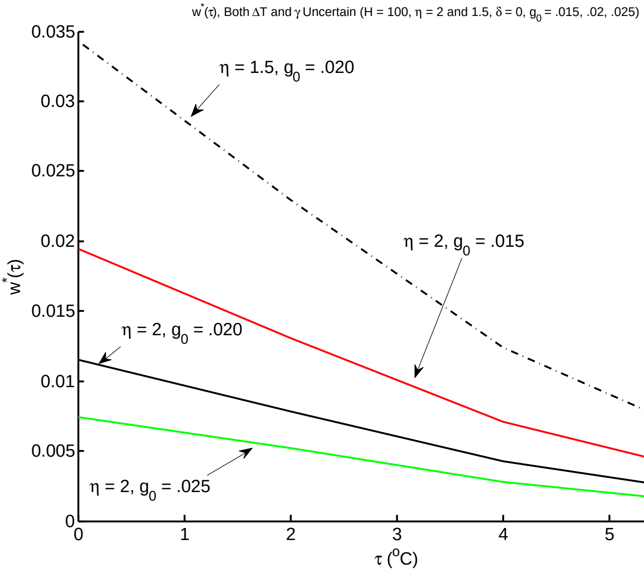
Both ΔT and γ Uncertain

- Both ΔT and the impact parameter γ are uncertain.
- Figure shows $w^*(\tau)$ for $\delta = 0$, $\eta = 2$ and 1.5, and $g_0 = .015$, .020, and .025.
- To get WTP above 2%, even for $\tau = 0$, need $\eta = 1.5$ or $g_0 = .015$ if $\eta = 2$.
- Next figure shows $w^*(3)$ as function of η for $g_0 = .02$. For $\delta = 0$, can get $w^*(3) > .05$ if η close to 1.

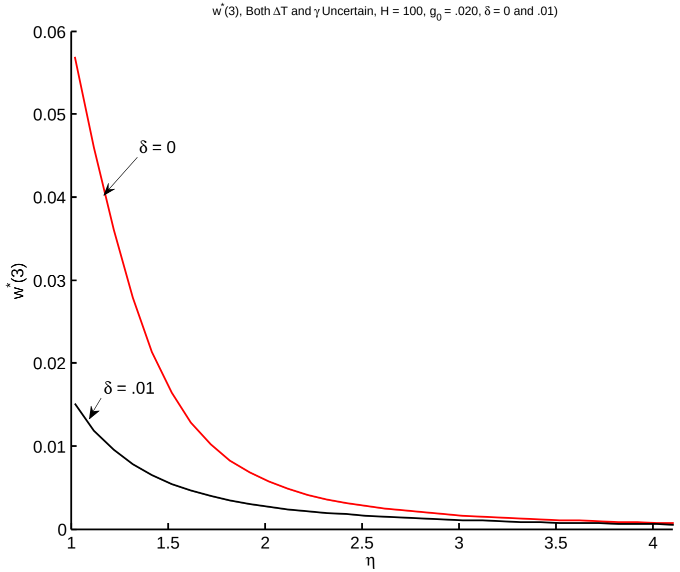
Both ΔT and γ Uncertain

- Both ΔT and the impact parameter γ are uncertain.
- Figure shows $w^*(\tau)$ for $\delta = 0$, $\eta = 2$ and 1.5, and $g_0 = .015$, .020, and .025.
- To get WTP above 2%, even for $\tau = 0$, need $\eta = 1.5$ or $g_0 = .015$ if $\eta = 2$.
- Next figure shows $w^*(3)$ as function of η for $g_0 = .02$. For $\delta = 0$, can get $w^*(3) > .05$ if η close to 1.
- If $\delta = .01$, $w^*(3) < .02$ for any η.

WTP for ΔT and γ Uncertain, $\delta = 0$, $\eta = 2, 1.5$



WTP Versus η for $\tau = 3$.



Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.

Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.

Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.

Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.
- Figure shows $w^*(3)$ versus η for $H = 75$ years.

Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.
- Figure shows $w^*(3)$ versus η for $H = 75$ years.
    - Now if $\delta = 0$ and η close to 1, $w^*(3)$ close to .08.

Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.
- Figure shows $w^*(3)$ versus η for $H = 75$ years.
  - Now if $\delta = 0$ and η close to 1, $w^*(3)$ close to .08.
  - If $\delta = .01$, $w^*(3) < .03$ for all η.

Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.
- Figure shows $w^*(3)$ versus η for $H = 75$ years.
  - Now if $\delta = 0$ and η close to 1, $w^*(3)$ close to .08.
  - If $\delta = .01$, $w^*(3) < .03$ for all η.
- Next figure shows $w^*(3)$ for $H = 100$ but $\mathcal{E}(\Delta T_{100}) = 5°C$.

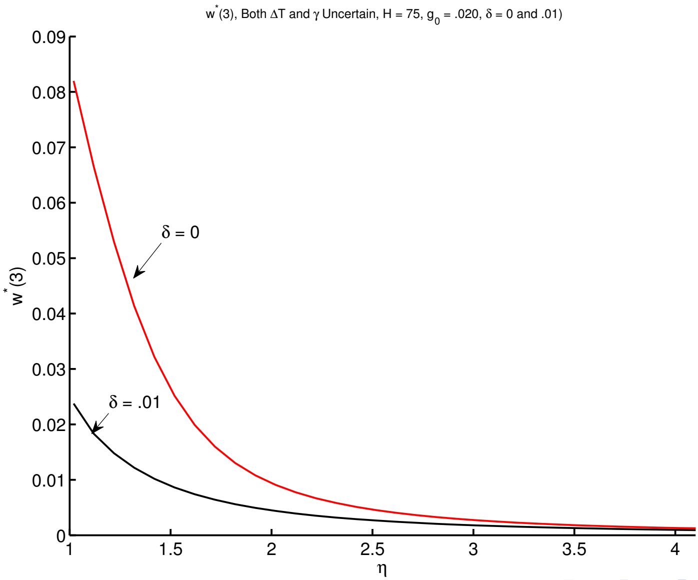
Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.
- Figure shows $w^*(3)$ versus η for $H = 75$ years.
  - Now if $\delta = 0$ and η close to 1, $w^*(3)$ close to .08.
  - If $\delta = .01$, $w^*(3) < .03$ for all η.
- Next figure shows $w^*(3)$ for $H = 100$ but $\mathcal{E}(\Delta T_{100}) = 5°C$.
  - Now if η near 1, $w^*(3)$ close to 10%.

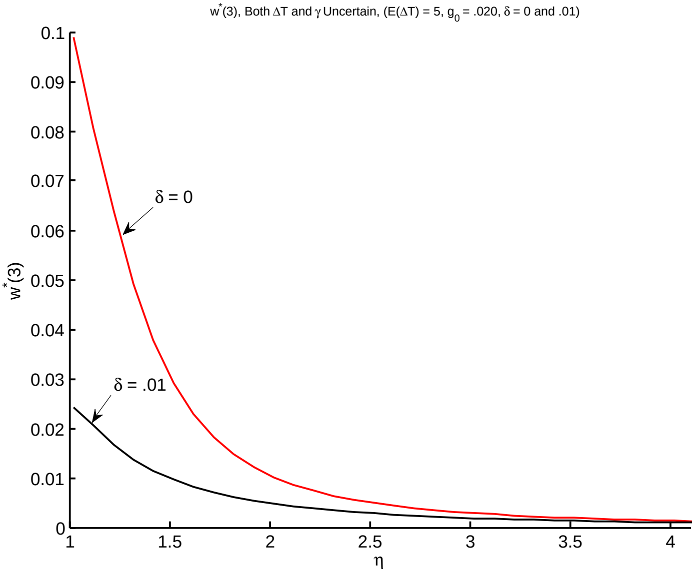
Both ΔT and γ Uncertain (Con't)

- Most parameter values give low WTP, even for small τ.
- But these results based on distributions for ΔT and γ inferred from IPCC (2007) and concurrent economic studies.
- Perhaps "most likely" ΔT in 2100 is higher than IPCC's 1.0°C to 4.5°C range. In Feb. 2009 report, MIT model puts $\mathcal{E}(\Delta T)$ in 2100 at 4°C to 5°C, not 3°C.
- Figure shows $w^*(3)$ versus η for $H = 75$ years.
  - Now if $\delta = 0$ and η close to 1, $w^*(3)$ close to .08.
  - If $\delta = .01$, $w^*(3) < .03$ for all η.
- Next figure shows $w^*(3)$ for $H = 100$ but $\mathcal{E}(\Delta T_{100}) = 5°$C.
  - Now if η near 1, $w^*(3)$ close to 10%.
  - But if $\delta = .01$, $w^*(3)$ again very low for all η.

WTP Versus η for $\tau = 3$, $H = 75$ years.



WTP Versus η for $\tau = 3$, $\mathcal{E}(\Delta T_{100}) = 5°C$.



Policy Implications

- Policy implications are rather stark.

Policy Implications

- Policy implications are rather stark.
  - For temperature and impact distributions based on IPCC and "conservative" parameter values (e.g., $\delta = 0$, $\eta = 2$, $g_0 = .02$), WTP to prevent *any* ΔT is around 2% or less.

Policy Implications

- Policy implications are rather stark.
  - For temperature and impact distributions based on IPCC and "conservative" parameter values (e.g., $\delta = 0$, $\eta = 2$, $g_0 = .02$), WTP to prevent *any* ΔT is around 2% or less.
  - If objective is to keep ΔT in 100 years below 3°C (much more feasible), WTP lower still.

Policy Implications

- Policy implications are rather stark.
  - For temperature and impact distributions based on IPCC and "conservative" parameter values (e.g., $\delta = 0$, $\eta = 2$, $g_0 = .02$), WTP to prevent *any* ΔT is around 2% or less.
  - If objective is to keep ΔT in 100 years below 3°C (much more feasible), WTP lower still.
  - Even if $H = 75$ or $\mathcal{E}(\Delta T) = 5^{\circ}$C, get high WTP only if $\eta < 1.5$.

Policy Implications

- Policy implications are rather stark.
  - For temperature and impact distributions based on IPCC and "conservative" parameter values (e.g., $\delta = 0$, $\eta = 2$, $g_0 = .02$), WTP to prevent *any* ΔT is around 2% or less.
  - If objective is to keep ΔT in 100 years below 3°C (much more feasible), WTP lower still.
  - Even if $H = 75$ or $\mathcal{E}(\Delta T) = 5°\text{C}$, get high WTP only if $\eta < 1.5$.
  - If $\delta = .01$, get low WTP for *all* parameter combinations.

Policy Implications (Con't)

- Two reasons. First, limited weight in tails of distributions for ΔT and γ, consistent with studies surveyed by the IPCC.

Policy Implications (Con't)

- Two reasons. First, limited weight in tails of distributions for ΔT and γ, consistent with studies surveyed by the IPCC.
  - Distribution for ΔT implies 21% probability of $\Delta T \geq 4.5^\circ$C in 100 years, and 5% probability of $\Delta T \geq 7.0^\circ$C.

Policy Implications (Con't)

- Two reasons. First, limited weight in tails of distributions for ΔT and γ, consistent with studies surveyed by the IPCC.
  - Distribution for ΔT implies 21% probability of $\Delta T \geq 4.5^\circ$C in 100 years, and 5% probability of $\Delta T \geq 7.0^\circ$C.
  - Distribution for γ implies a 17% probability of $\gamma \geq .00023$.

Policy Implications (Con't)

- Two reasons. First, limited weight in tails of distributions for ΔT and γ, consistent with studies surveyed by the IPCC.
  - Distribution for ΔT implies 21% probability of $\Delta T \geq 4.5^{\circ}$C in 100 years, and 5% probability of $\Delta T \geq 7.0^{\circ}$C.
  - Distribution for γ implies a 17% probability of $\gamma \geq .00023$.
  - $\Delta T = 4.5^{\circ}$C and $\gamma = .00023$ implies GDP in 100 years 5.7% lower than if $\Delta T = 0$. But Prob($\Delta T \geq 4.5^{\circ}$C *and* $\gamma \geq .00023$) only about 3.6%.

Policy Implications (Con't)

- Two reasons. First, limited weight in tails of distributions for ΔT and γ, consistent with studies surveyed by the IPCC.
  - Distribution for ΔT implies 21% probability of $\Delta T \geq 4.5^{\circ}$C in 100 years, and 5% probability of $\Delta T \geq 7.0^{\circ}$C.
  - Distribution for γ implies a 17% probability of $\gamma \geq .00023$.
  - $\Delta T = 4.5^{\circ}$C and $\gamma = .00023$ implies GDP in 100 years 5.7% lower than if $\Delta T = 0$. But Prob($\Delta T \geq 4.5^{\circ}$C *and* $\gamma \geq .00023$) only about 3.6%.
  - $\Delta T = 7^{\circ}$C (and $\gamma = .00023$) implies GDP in 100 years 9% lower, but probability only 0.9%.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.
  - Initial consumption discount rate is ηg_0, at least .03 if $\eta = 2$.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.
  - Initial consumption discount rate is ηg_0, at least .03 if $\eta = 2$.
  - And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve much smaller losses in earlier years.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.
    - Initial consumption discount rate is ηg_0, at least .03 if $\eta = 2$.
    - And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve much smaller losses in earlier years.
- These results argue against stringent GHG abatement policy, but are consistent with moderate abatement.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.
  - Initial consumption discount rate is ηg_0, at least .03 if $\eta = 2$.
  - And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve much smaller losses in earlier years.
- These results argue against stringent GHG abatement policy, but are consistent with moderate abatement.
- 2% of GDP in range of cost estimates for compliance with Kyoto Protocol.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.
  - Initial consumption discount rate is ηg_0, at least .03 if $\eta = 2$.
  - And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve much smaller losses in earlier years.
- These results argue against stringent GHG abatement policy, but are consistent with moderate abatement.
- 2% of GDP in range of cost estimates for compliance with Kyoto Protocol.
- Taking U.S. in isolation, WTP of 2% implies $300 billion per year for GHG abatement.

Policy Implications (Con't)

- Second, even with $\delta = 0$, implicit discounting of consumption is significant.
  - Initial consumption discount rate is ηg_0, at least .03 if $\eta = 2$.
  - And a (low-probability) 5.7 or 9 percent loss of GDP in 100 years would involve much smaller losses in earlier years.
- These results argue against stringent GHG abatement policy, but are consistent with moderate abatement.
- 2% of GDP in range of cost estimates for compliance with Kyoto Protocol.
- Taking U.S. in isolation, WTP of 2% implies \$300 billion per year for GHG abatement.
- And if $w^*(3) = .01$, would justify \$150 billion per year if abatement would limit ΔT to 3°C.

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.
- How different would the result be if I assumed a direct impact on GDP, as do most IAMs?

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.
- How different would the result be if I assumed a direct impact on GDP, as do most IAMs?
- Companion paper compares two alternative loss functions.

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.
- How different would the result be if I assumed a direct impact on GDP, as do most IAMs?
- Companion paper compares two alternative loss functions.
- Direct impact:

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.
- How different would the result be if I assumed a direct impact on GDP, as do most IAMs?
- Companion paper compares two alternative loss functions.
- Direct impact:
    - $L(\Delta T) = e^{-\beta(\Delta T)^2}$

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.
- How different would the result be if I assumed a direct impact on GDP, as do most IAMs?
- Companion paper compares two alternative loss functions.
- Direct impact:
  - $L(\Delta T) = e^{-\beta(\Delta T)^2}$
  - Recall $\gamma = 1.79\beta\Delta T_H / H$.

The Loss Function

- I argued that ΔT should reduce the *growth rate* of GDP, not the level.
- How different would the result be if I assumed a direct impact on GDP, as do most IAMs?
- Companion paper compares two alternative loss functions.
- Direct impact:
  - $L(\Delta T) = e^{-\beta(\Delta T)^2}$
  - Recall $\gamma = 1.79\beta\Delta T_H / H$.
- Can get WTP by similar steps.

The Loss Function (Con't)

- Let $w_c^*(\tau)$ denote WTP for direct impact on GDP and consumption, $w_g^*(\tau)$ denote growth rate impact.

The Loss Function (Con't)

- Let $w_c^*(\tau)$ denote WTP for direct impact on GDP and consumption, $w_g^*(\tau)$ denote growth rate impact.
- With direct impact, consumption loss is greater at short horizons, but smaller at long horizons.

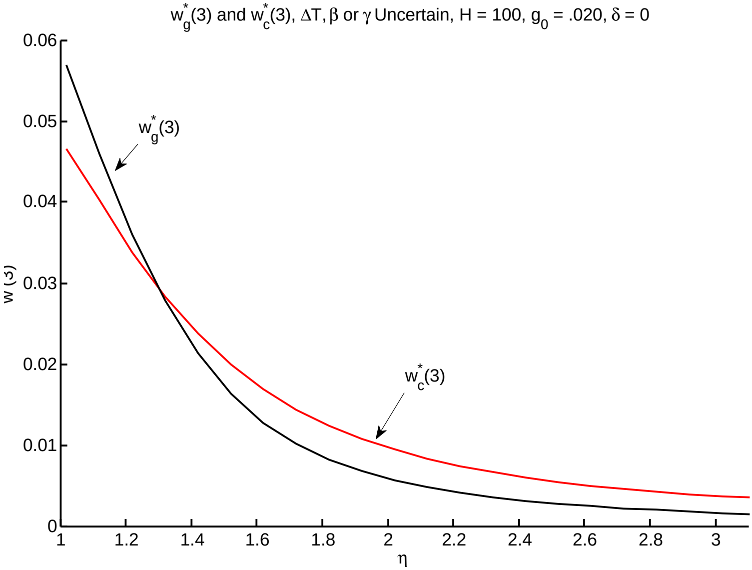
The Loss Function (Con't)

- Let $w_c^*(\tau)$ denote WTP for direct impact on GDP and consumption, $w_g^*(\tau)$ denote growth rate impact.
- With direct impact, consumption loss is greater at short horizons, but smaller at long horizons.
- $w_c^*(\tau) < w_g^*(\tau)$ for low values of η because low η implies low consumption discount rate.

The Loss Function (Con't)

- Let $w_c^*(\tau)$ denote WTP for direct impact on GDP and consumption, $w_g^*(\tau)$ denote growth rate impact.
- With direct impact, consumption loss is greater at short horizons, but smaller at long horizons.
- $w_c^*(\tau) < w_g^*(\tau)$ for low values of η because low η implies low consumption discount rate.
- Overall, differences are small, and basic results hold.

$w_c^*(3)$ and $w_g^*(3)$, $H = 100$, $g_0 = .020$, $\delta = 0$



Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.
- Dynamically efficient, accounts for technological change that reduces abatement costs, and allows for learning.

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.
- Dynamically efficient, accounts for technological change that reduces abatement costs, and allows for learning.
- Caveats are in order:

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.
- Dynamically efficient, accounts for technological change that reduces abatement costs, and allows for learning.
- Caveats are in order:
  - I used current consensus on the distributions for ΔT and its impact. Maybe consensus is wrong, especially about tails.

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.
- Dynamically efficient, accounts for technological change that reduces abatement costs, and allows for learning.
- Caveats are in order:
  - I used current consensus on the distributions for ΔT and its impact. Maybe consensus is wrong, especially about tails.
  - We have very little data to assess, e.g., likelihood of $\Delta T > 5^\circ$C, never mind its economic impact.

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.
- Dynamically efficient, accounts for technological change that reduces abatement costs, and allows for learning.
- Caveats are in order:
  - I used current consensus on the distributions for ΔT and its impact. Maybe consensus is wrong, especially about tails.
  - We have very little data to assess, e.g., likelihood of $\Delta T > 5^\circ$C, never mind its economic impact.
  - I used linear loss function, but maybe convex relationship between ΔT and the growth rate g_t is more realistic.

Conclusions and Caveats

- Debate among economists is not whether to abate, but whether a stringent policy is needed now, or instead begin slowly.
- My results support a "begin slowly" policy.
- Dynamically efficient, accounts for technological change that reduces abatement costs, and allows for learning.
- Caveats are in order:
  - I used current consensus on the distributions for ΔT and its impact. Maybe consensus is wrong, especially about tails.
  - We have very little data to assess, e.g., likelihood of $\Delta T > 5^\circ$C, never mind its economic impact.
  - I used linear loss function, but maybe convex relationship between ΔT and the growth rate g_t is more realistic.
- Results also imply: Keep research focus on the tails.