Climate Change, Growth, and Risk

Ravi Bansal[1] Dana Kiku[2] Marcelo Ochoa[3]

[1]Fuqua School of Business
Duke University & NBER

[2]University of Illinois
at Urbana-Champaign

[3]Federal Reserve Board

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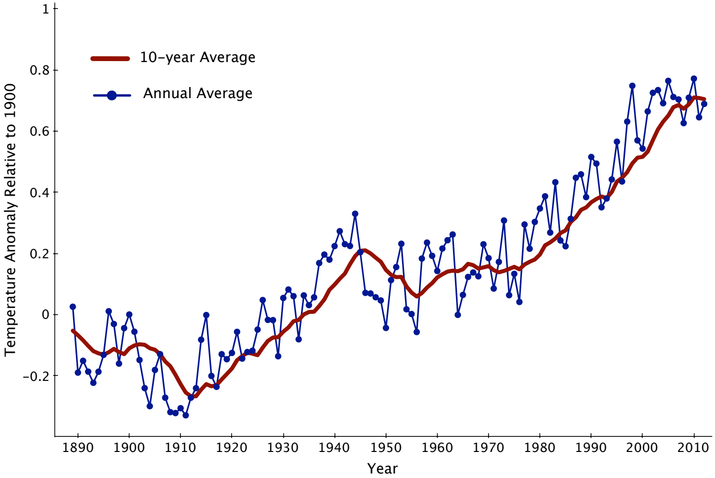
Climate Change and the Economy

- Economic impact of industrial CO_2 emissions:
  - \+ More output & consumption in the short run
  - − Increase in atmospheric concentration of CO_2, leading to global warming and natural disasters in the long run

Global Temperature Anomaly



Source: U.S. National Oceanic and Atmospheric Administration

Economics of Climate Change: Questions

- What is the optimal climate policy?
- How much is society willing to sacrifice today to mitigate future climate change risks?
- What is the Social Cost of Carbon (SCC)?
- Social price of carbon depends critically on:
  - discount rates on consumption strips (Hansen (2012))
  - consumption damage function (cash-flow)

Model Ingredients

- Deterministic DICE/RICE model of Nordhaus (1991, 2010) features prominently in measuring SCC
- Our model:
  - incorporates uncertainty (climate and non-climate risks)
  - planner has preference for timing of resolution of uncertainty
  - features temperature-induced disasters
  - permanent vs. transient output losses (Pindyck (2012))
  - matches key features of consumption and asset return data
    - discount rates consistent with asset markets data

Key Findings

- Sensitivity of utility (and discount rates) to emissions is important for the magnitude of SCC
  - Preference for early resolution of uncertainty induces significant reductions in emissions along the optimal path
  - Power utility agent, even with large disasters, is nonchalant towards climate risks
- Permanent climate-induced disasters lead to sizable SCC, large transient disasters carry small SCC
- Model is consistent with financial markets data
  - Margins that make equity carry a high risk premium also make climate risk important

Climate Module: CO_2 Emissions

- Global CO_2 emissions

$$E_t = Y_t^{\lambda_t}$$

where:

  - Y_t is the total (gross) amount of consumption goods
  - $\lambda_t \geq 0$ is the carbon intensity of consumption

- CO_2 emissions growth rate

$$\Delta e_{t+1} = \lambda_{t+1} \Delta y_{t+1} + \Delta \lambda_{t+1} y_t$$

Climate Module: Global Warming

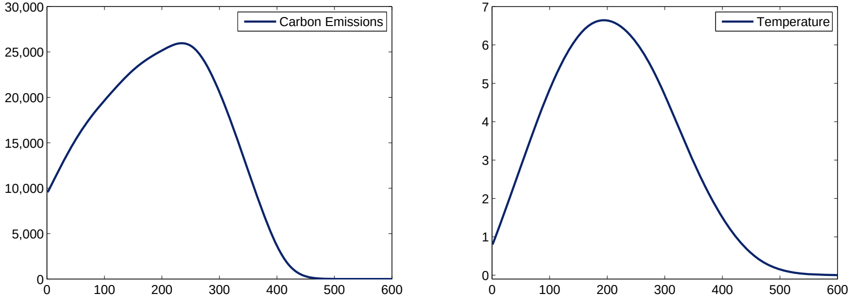
- Accumulation of carbon in the atmosphere leads to global warming
- Geophysical link between CO_2 emissions and global temperature:

$$T_t = \nu T_{t-1} + \chi e_t$$

  - T_t is temperature anomaly (temperature above the pre-industrial level)
  - $e_t \equiv \log E_t$ is the log of CO_2 emissions
  - $\nu \in (0, 1)$ is the rate of carbon retention in the atmosphere
  - $\chi > 0$ is temperature sensitivity to CO_2 emissions

- Consistent with Nordhaus (2008)'s specification

Climate Module: Emissions and Temperature under BAU



- Calibrated to match emission & temperature projections under BAU scenario (Nordhaus (2010))
- Emissions are in millions of metric ton of carbon per annum
- Temperature anomaly (temperature relative to its pre-industrial level) is in Celsius

Climate Module: Global Warming and Natural Disasters

- Climate change due to global warming leads to catastrophic natural disasters that result in a significant reduction in economic growth
- Disasters are triggered when temperature crosses tipping point T^*
- Their impact on consumption growth is modelled using compound Poisson process:

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \zeta_{i,t+1} - d_t \pi_t$$

  - N_{t+1} is a Poisson random variable with intensity π_t
  - $\zeta_{i,t+1} \sim \Gamma(1, d_t)$ are gamma distributed jumps with mean d_t

Climate Module: Global Warming and Natural Disasters

- Frequency of natural disasters and the damage function are increasing in temperature

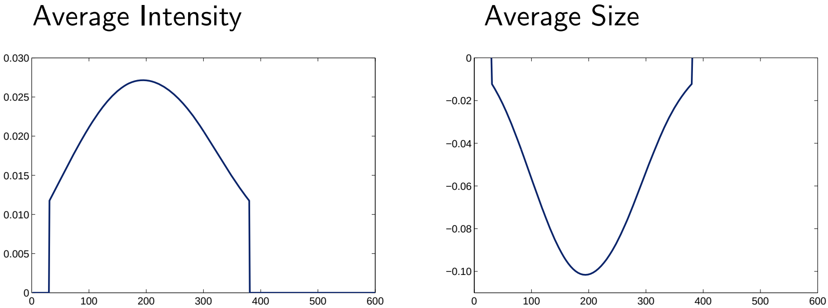
$$\text{Intensity:} \quad \pi_t \equiv E_t[N_{t+1}] = l_0 + l_1 T_t$$

$$\text{Size:} \quad d_t = \begin{cases} q_1 \bar{T}_t + q_2 \bar{T}_t^2 \,, & \text{if} \quad \bar{T}_t > T^* \\ 0 \,, & \text{otherwise} \end{cases}$$

- where $\bar{T} = E_0[T_t]$
- Simplifying, non-critical assumption (since temperature dynamics are dominated by the deterministic trend in emissions)

Climate Module: Global Warming and Natural Disasters

- Disasters under BAU scenario



Economic Module: Growth Dynamics

- Growth dynamics

$$\begin{aligned}
\Delta y_{t+1} &= \mu + x_t + \Delta s_{t+1} + \sigma \eta_{t+1} - \phi_c D_{t+1} \\
x_{t+1} &= \rho_x x_t + \varphi_x \sigma \epsilon_{t+1} - \phi_x D_{t+1} \\
s_{t+1} &= \rho_s s_t + \varphi_s \sigma u_{t+1} - \phi_s D_{t+1}
\end{aligned}$$

where:

  - Δy_t – growth rate of gross consumption
  - x_t – long-run component
  - s_t – transient component
  - D_t – natural disasters

- Industrial emissions (hence, temperature) are driven by output shocks

Alternative Policies

- BAU $\equiv$ Business as usual
  - No abatement, consume all available consumption goods:

$$C_t = Y_t$$

- Implement an abatement policy that limits industrial emissions
  - Benefits: lower frequency and magnitude of disasters
  - Costs: have to sacrifice a fraction of consumption goods to finance abatement policy; hence:

$$C_t = Y_t(1 - \Lambda_t)$$

CO_2 Abatement Policies: Benefits

- Benefit of policy intervention is an acceleration in the development of carbon-free technologies:

$$\begin{aligned} E_t^* &= Y_t^{\lambda_t^*} \\ \Delta\lambda_t^* &= \Delta\lambda_t - \theta_t \end{aligned}$$

  - λ_t^* is the carbon intensity under a given abatement policy
  - λ_t is the intensity under the BAU scenario
  - $\theta_t \geq 0$ is the emission reduction function:

$$\theta_t = \bar{\theta} e^{\alpha t} \ , \quad \text{for } t \in [\tau_0, \tau_1]$$

  - α captures the time schedule of the policy (more earlier vs. more later)
  - $\bar{\theta}$ is the scale of abatement efforts ($\bar{\theta} = 0$ corresponds to BAU)
  - $[\tau_0, \tau_1]$ is the time period when the policy is in effect

CO_2 Abatement Policies: Costs

- Emission reductions cost $\Lambda_t Y_t$ units of consumption goods
- Abatement cost depends on the targeted reduction level (θ_t):

$$\Lambda_t = \xi_t \theta_t^k$$

  - $k > 0$ – more aggressive abatement policies (i.e., larger θ) cost more
  - $\xi_t = \xi_0 e^{-gt}$ declines at rate $g > 0$ (improvement in cost-efficiency)

- Abatement cost function consistent with integrated assessment models (Nordhaus (2010), Anthoff and Tol (2013))

CO_2 Abatement Policies: Benefits vs. Costs

- Net-of-costs consumption dynamics:

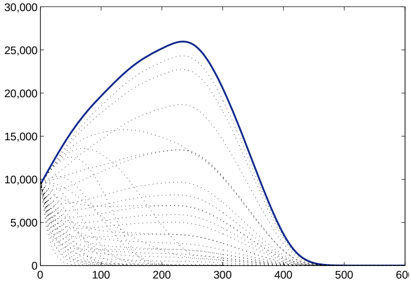
$$\begin{aligned}
C_t &= Y_t(1-\Lambda_t) \\
\Delta c_{t+1} &= \mu - \Delta\Lambda_{t+1} + x_t + \Delta s_{t+1} + \sigma\eta_{t+1} - \phi_c D_{t+1} \\
x_{t+1} &= \rho_x x_t + \varphi_x \sigma \epsilon_{t+1} - \phi_x D_{t+1} \\
s_{t+1} &= \rho_s s_t + \varphi_s \sigma u_{t+1} - \phi_s D_{t+1}
\end{aligned}$$

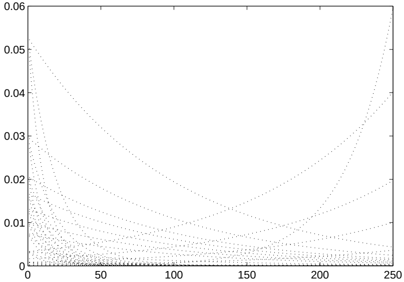
- Cost/Benefit Tradeoff:
  - Lower consumption in the short run
  - Lower risk and costs of natural disasters in the long run

CO_2 Abatement Policies: Benefits and Costs

- Emission reduction function: $\theta_t = \bar{\theta} e^{\alpha t}$, for $t \in [1, 250]$years
- Abatement policies differ in $\alpha \lesseqgtr 0$ and $\bar{\theta} \geq 0$
- Set of available abatement policies allows for a wide range of emission paths

- Emission Path
- Cost (Fraction of Output)





Economic Module: Utility

- Representative agent with Epstein-Zin-Weil recursive preferences:

$$U_t = \left[(1-\delta) C_t^{1-\frac{1}{\psi}} + \delta \left(E_t \left[U_{t+1}^{1-\gamma} \right] \right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{\psi}{\psi-1}}$$

  - δ is subjective discount factor
  - γ is the coefficient of risk aversion
  - ψ the intertemporal elasticity of substitution (IES)

- Life-time utility of the agent:

$$U_t = \left[(1-\delta) WC_t \right]^{\frac{\psi}{\psi-1}} C_t$$

Social Cost of Carbon

- SCC is defined as the marginal utility of carbon emissions (measured in units of consumption goods):

$$SCC = \frac{\partial U_0}{\partial E_0} \bigg/ \frac{\partial U_0}{\partial C_0}$$

- Taking the derivatives, can show that:

$$SCC = \frac{\psi}{\psi - 1} \frac{\partial WC_0 / \partial E_0}{WC_0} C_0$$

- where WC_0 is wealth-to-consumption ratio at time 0

Social Cost of Carbon

- SCC measures the required increase in current consumption to compensate for damages caused by a marginal increase in date-0 emissions
- It incorporates two effects of emissions:
  - Cash-Flow effect – the impact of damages on consumption path
  - Discount-Rate effect – preference to risks and their timing

LRR-C Integrated Model: Solution and Optimization

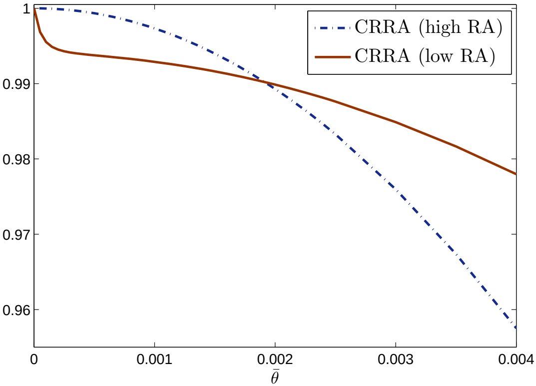
- Calibrate emission/temperature dynamics to match BAU climate scenario (Nordhaus (2010))
- Choose abatement costs consistent with integrated assessment models
- Solve for the optimal abatement policy by maximizing life-time utility
- Solve the model backwards from the long-run steady state along the transition path

Power Utility & ΔC–Disasters

		High-RA	**Low-RA**
β	Time discount factor	0.99	0.99
γ	Risk aversion	5	1/1.5
ψ	IES	1/5	1.5
μ	Mean growth (gross)	0.018	0.018
σ	Vol of iid shock	0.016	0.016
ϕ_c	Disaster impact on Δc	1	1
T^*	Tipping point	2.0°C	2.0°C

- Due to global warming, consumption is subject to permanent disasters
- Long-run and transient components are shut off
- What is utility gain of adopting an abatement policy?

Power Utility & ΔC–Disasters: Utility Gains



Utility gains of alternative abatement policies relative to BAU

- No utility gains from the perspective of power-utility agent
- The plot is constructed for $\alpha = 0$; no utility gains for other values of α

Power Utility & ΔC–Disasters: Intuition

- Pricing implications of power utility

	High-RA	**Low-RA**
Risk-free Rate (%)	9.38	2.20
Risk Premia (%)	0.27	0.03
DR of Cons Strips (%)		
1yr	9.81	2.22
100yr	9.78	2.22
200yr	9.56	2.23
SCC ($US/ton of carbon)	0.02	0

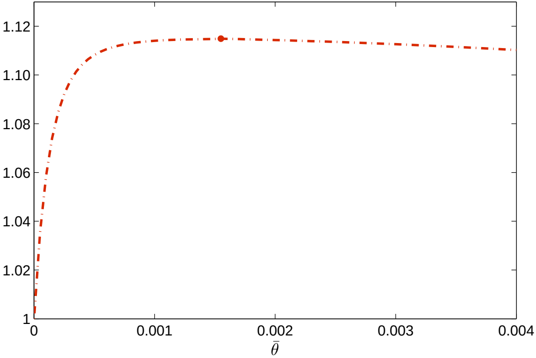
- Climate change is inconsequential due to heavy discounting, or
- Climate change is not perceived as risky

Recursive Preferences & ΔC–Disasters

β	Time discount factor	0.99
γ	Risk aversion	5
ψ	Intertemporal elasticity of substitution	1.5
ϕ_c	Disaster impact on Δc	1
T^*	Tipping point	2.0°C

- Preference for early resolution of uncertainty
- Growth dynamics are kept the same:
  - Disasters have permanent effect on consumption level
  - Long-run and transient components are shut off

EZ & ΔC–Disasters: Utility Gains



Utility gains of alternative abatement policies relative to BAU

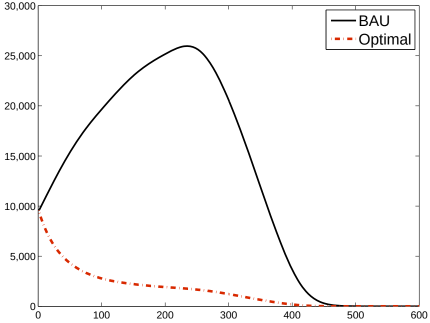
- EZ-agent chooses to implement an abatement policy
- Utility gain under the optimal policy is about 11.5%

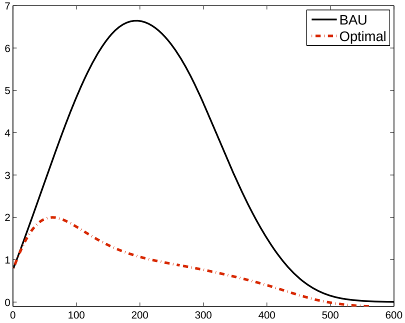
EZ & ΔC–Disasters: Optimal Abatement Policy

- Optimal to implement a stringent abatement policy that prevents future disasters from happening:
  - $\alpha^{opt} = -0.015 < 0$ – more aggressive abatement efforts at the outset (since earlier efforts have long-term emission reduction benefits)
  - $\bar{\theta}^{opt} = 0.00155$ – high enough scale of abatement efforts to prevent temperature anomaly to cross over the 2C^{o} disaster threshold

EZ & ΔC–Disasters: Climate Dynamics

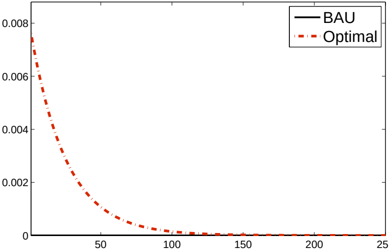
- Emission Path
- Temperature



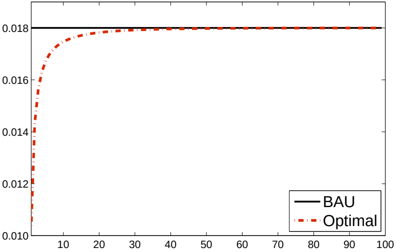


EZ & ΔC–Disasters: Cost of Optimal Policy

- Cost (fraction of output)



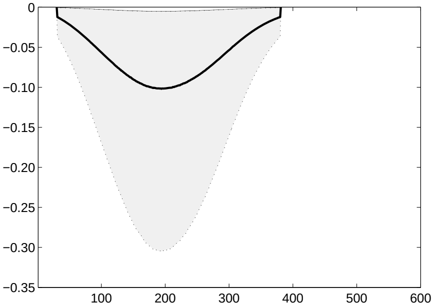
- Cumulative Growth



- Initial cost of the optimal abatement policy is about 0.8% of output

EZ & ΔC–Disasters: Benefits of Optimal Policy

- Distribution of disaster size under BAU scenario



Magnitude of Disasters, [5%, 95%] confidence interval

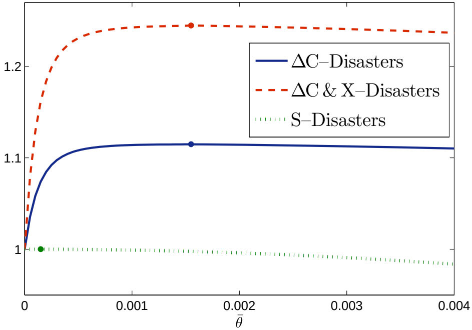
- Under the optimal policy, temperature does not breach 2C^o tipping point
  - ⇒ No climatic disasters under the optimal policy

Alternative Assumptions on Climate Change Risks

Parameter		ΔC & X–Disasters	S–Disasters
ϕ_c	Disaster impact on Δc	1	0
ρ_x	Persistence of long-run growth	0.94	
φ_x	Volatility parameter of long-run growth	0.25	
ϕ_x	Disaster impact on long-run growth	0.04	
ρ_s	Persistence of transient component		0.9
φ_s	Volatility parameter of transient component		0.5
ϕ_s	Disaster impact on transient component		1

- Maintain preferences for early resolution of uncertainty

EZ-Preferences: Utility Gains



Utility gains of optimal abatement policies relative to BAU

- Higher utility gains if climate change risks affect long-run growth
- Less stringent abatement policy and lower gains with S–Disasters

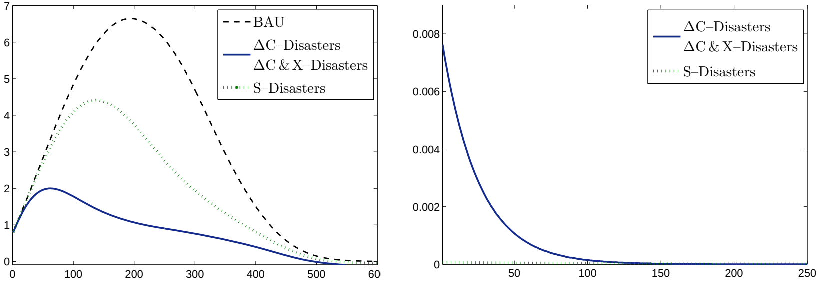
EZ-Preferences: Optimal Policies

	α	$\bar{\theta}$
EZ-Preferences		
ΔC–Disasters	-0.015	0.00155
ΔC & X–Disasters	-0.015	0.00155
S–Disasters	0	0.00015

- If disasters have permanent effect, it is optimal to implement a stringent policy to avert them altogether
- If disasters have only transient impact, the optimal policy is much less stringent and its benefits are smaller

EZ-Preferences: Optimal Policies

- Temperature
- Cost (fraction of output)



Risks, Preferences and Discounting

	Risk Premia (%)	Risk-Free Rate (%)	SCC ($US/ton)
EZ-Preferences			
ΔC–Disasters	0.27	1.98	71
ΔC & X–Disasters	1.26	1.30	168
S–Disasters	0.14	2.10	1.1
CRRA (high-RA)			
ΔC–Disasters	0.27	9.38	0.02
CRRA (low-RA)			
ΔC–Disasters	0.03	2.20	0

- ΔC & X–Disasters specification matches financial market data best:
  - Implied market risk premium is about 4%
  - Risk-free rate is 1.3%

Risks, Preferences and Discounting

- Power Utility:
  - — Elasticity of utility to distant climatic disasters is close to zero
  - ⇒ Zero social cost of carbon
- Preference for Early Resolution of Uncertainty:
  - — Permanent disasters (even in a distant future) have non-trivial effect on current welfare
  - — Elasticity of utility to future disasters that have permanent effect on consumption level and long-run effect on growth is high
  - ⇒ Social cost of carbon is large
  - — Transient disasters matter significantly less

Risk Premia Decomposition

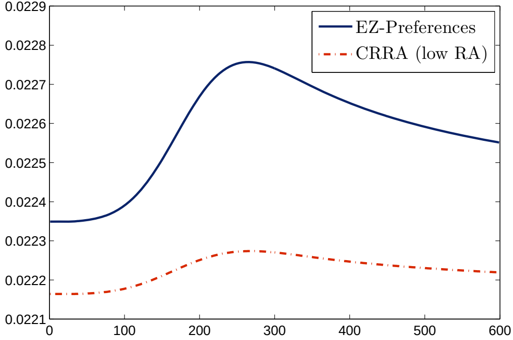
	Risk Premia	Risk Contribution (Fraction of Total)			
	Total	Short-Run	Long-Run	Transient	Jumps
EZ-Preferences					
ΔC–Disasters	0.27%	0.72			0.28
ΔC & X–Disasters	1.26%	0.15	0.61		0.24
S–Disasters	0.14%	0.92		0.03	0.05
CRRA (high-RA)					
ΔC–Disasters	0.27%	0.72			0.28
CRRA (low-RA)					
ΔC–Disasters	0.03%	0.78			0.22

- In ΔC & X–Disasters specification, most premia come from gaussian long-run risks (not the jump components)

Risk Preferences and Discounting

- Compare two specifications:
  1. Preference for Early Resolution of Uncertainty (IES=1.5, RA=5)
  2. Power Utility (IES=1.5, RA=1/IES)
- The same growth dynamics in both specifications
  - ΔC–Disasters
- Have shown:
  1. SCC = \$71 & it is optimal to take actions to reduce emissions
  2. SCC $\approx$ \$0 & abatement policies are sub-optimal relative to BAU

Risk Preferences and Discounting

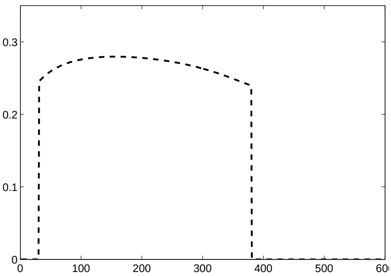


Discount Rates of Consumption Strips

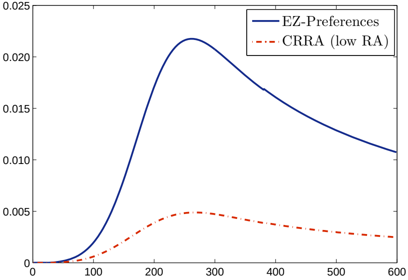
- With preference for early resolution of uncertainty, future is discounted at a higher rate, yet SCC is higher
- What matters is not discounting per se but preferences to timing of risks

Risk Preferences and Discounting

- Consider a marginal increase in emissions at time 0
  - %-Change in Damage Function



  - Elasticity of Discount Rates



- With preference for early resolution of uncertainty, elasticity of utility to emissions is much higher
- Hansen and Scheinkman (2012), Borovička and Hansen (2013) provide analysis of price elasticities

SCC with Smaller Disasters

- Scale down disaster size by half
- Social Cost of Carbon:

	Benchmark	0.5∗Benchmark
EZ-Preferences		
ΔC–Disasters	71	13
ΔC & X–Disasters	168	52
S–Disasters	1.1	0.2
CRRA (high-RA)		
ΔC–Disasters	0.02	0
CRRA (low-RA)		
ΔC–Disasters	0	0

Preference for Robustness

- The economic impact of rapid global warming is highly uncertain
- Incorporate this type of uncertainty in a robust control setting (Hansen and Sargent (2001, 2008, 2010))
- Let P be the probability density of the reference model
- Let Q denote the density associated with an alternative model under which climate-driven cataclysms have worse consequences (larger size of disasters)
- Use entropy to measure model discrepancies:

$$I(P,Q) = E^{P}\left[L\log(L)\right]$$

  - $L = \frac{Q}{P}$ is the likelihood ratio of the two densities

Preference for Robustness

- If the agent is fully confident in the reference specification, entropy is zero
- As the level of confidence declines, the set of plausible alternatives widens and entropy increases
- The degree of model uncertainty can be expressed as an upper bound on relative entropy:

$$I(P,Q) \leq \bar{I}.$$

- With preference for robustness, the agent solves a max-min problem:

$$\max_{\alpha,\bar{\theta}} \min_{Q} \left[(1-\delta) C_t^{1-\frac{1}{\psi}} + \delta \Big(E_t^Q \left[U_{t+1}^{1-\gamma} \right] \Big)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{1}{1-\frac{1}{\psi}}}$$

subject to the budget, the resource allocation and the entropy constraints

Preference for Robustness: Implications

- EZ-preferences and ΔC–Disasters

Entropy Bound ($\bar{I}$)	Utility Gain	SCC
0	1.12	71
0.005	1.15	94
0.010	1.17	105
0.020	1.20	124

- Decisions are made under worst-case scenario among considered alternatives
  - $\bar{I} = 0.005$ – disasters are 10% worse
  - $\bar{I} = 0.01$ – disasters are 15% worse
  - $\bar{I} = 0.02$ – disasters are 21% worse

Conclusions

- Preferences to risks and timing of risks are important for understanding welfare implications of climate change
  - With power utility, distant temperature disasters have little impact on current utility to warrant any (costly) abatement efforts
  - With preferences for early resolution of uncertainty, distant disasters do matter and abatement policies are welfare improving
- Discount rates and their elasticity to climate risks are important determinants of social cost of carbon
  - Important to incorporate equity data as financial markets have a lot to say about discount rates