

# Pricing Uncertainty Induced by Climate Change

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# Climate Science and Uncertainty

*... the eventual equilibrium global mean temperature associated with a given stabilization level of atmospheric greenhouse gas concentrations remains **uncertain**, **complicating** the setting of stabilization targets to avoid potentially dangerous levels of global warming.*

Citation: Allen *et al.*: 2009

# Approach Taken

- ▷ Posit a **social planning** decision problem
- ▷ Include two interacting dynamic channels:
  - economic activity (e.g.  $CO_2$  emissions) alters the climate (e.g temperature)
  - climate change alters economic opportunities (e.g. damages)
- ▷ Adopt a **broad notion** of uncertainty with multiple layers
- ▷ Explore how uncertainty operates through these two **channels**
- ▷ Deduce the **social cost of carbon** as a marginal rate of substitution between consumption and emissions - Pigouvian tax
- ▷ Interpret the cost attributed to the **externality** using **asset pricing** methods

# Why Asset Pricing

## Asset pricing methods

- ▷ embrace uncertainty - a market compensates investors for being exposed to uncertainty
- ▷ provide compensations over alternative horizons - equity prices reflect cash flows of enterprises in current and future time periods

## In this investigation we use:

- ▷ social valuation rather than private valuation
- ▷ climate change and the subsequent societal damages induced by economic activity as the “cash flow” to be valued

**Approach:** Construct a **probability measure** that adjusts conveniently for **uncertainty**, broadly conceived!

# Two sources of uncertainty

- ▷ climate (temperature) consequences of  $CO_2$  emissions
- ▷ economic consequences of temperature changes

## Observations:

- ▷ measurement or quantification research in geophysics focuses on the first and economics on the latter.
- ▷ each is dynamic.

We study the “multiplicative” or “compound” interactions.

- ▷ When **both** happen to be **small**, then their product is **tiny**.
- ▷ When **both** happen to be **large**, then their product is **huge**.

# Climate Impacts

Climate literature suggests an approximation that simplifies discussions of uncertainty and its impact.

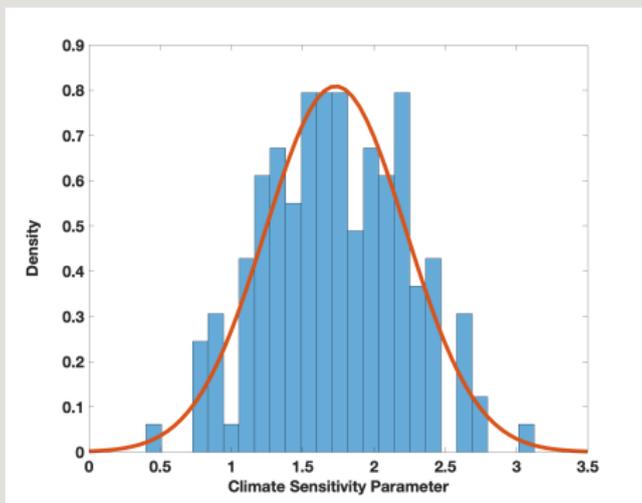
- ▷ Matthews *et al* and others have purposefully constructed a simple “**approximate**” climate model:

$$T_t - T_0 \approx \beta_f \int_0^t E_\tau d\tau \doteq F_t.$$

- ▷  $F$  cumulates (adds up) the emissions over time.
- ▷ Abstract from transient changes in temperature.

Emissions today have a **permanent impact** on temperature in the future where  $\beta_f$  is a **climate sensitivity parameter**.

# Climate Sensitivity Uncertainty



Histograms and density for the climate sensitivity parameter across models. Evidence is from MacDougall-Swart-Knutti (2017).

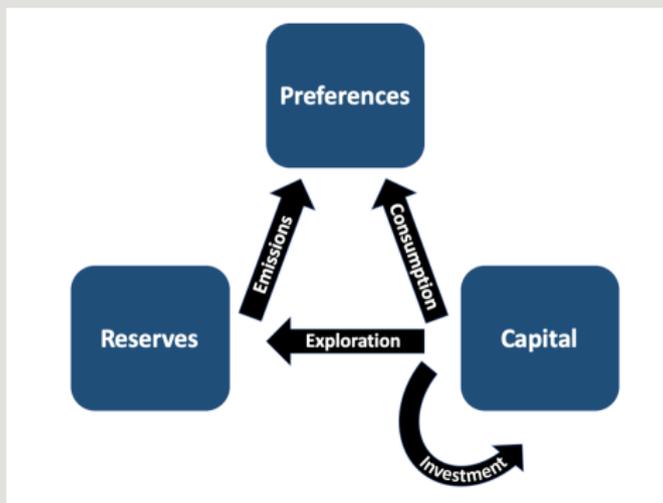
# Carbon budgeting

Some in the climate science community argue for a **carbon budgeting approach** as a simplified way to frame the discussion of environmental damages.

- ▷ exploit the Matthews approximation linking emissions to temperature
- ▷ design policy to enforce a Hotelling-like restriction on cumulative carbon emissions because of climate impact

Still must **confront uncertainty** as to what the constraint should be because it depends on the climate sensitivity parameter.

# Baseline Economic Model



Formally we introduce Brownian increment shocks, adjustment costs in capital accumulation and curvature in the mapping from exploration to reserves.

# Economic Environment: Information

- ▷  $W \doteq \{W_t : t \geq 0\}$  is a multivariate standard **Brownian motion** and  $\mathcal{F} \doteq \{\mathfrak{F}_t : t \geq 0\}$  is the corresponding Brownian filtration with  $\mathfrak{F}_t$  generated by the Brownian motion between dates zero and  $t$ .
- ▷ Let  $Z \doteq \{Z_t : t \geq 0\}$  be a stochastically stable, multivariate **forcing process** with evolution:

$$dZ_t = \mu_z(Z_t)dt + \sigma_z(Z_t)dW_t.$$

# Economic Environment: Production

AK model with adjustment costs

▷ Evolution of capital  $K$

$$dK_t = K_t \left[ \mu_k(Z_t)dt + \phi_0 \log \left( 1 + \phi_1 \frac{I_t}{K_t} \right) dt + \sigma_k \cdot dW_t \right].$$

where  $I_t$  is investment and  $0 < \phi_0 < 1$  and  $\phi_1 > 1$ .

▷ Production

$$C_t + I_t + J_t = \alpha K_t$$

where  $C_t$  is consumption and  $J_t$  is investment in new fossil fuel reserves.

# Economic Environment: Reserves

- ▷ **Reserve stock**,  $R$ , evolves according to:

$$dR_t = -E_t dt + \psi_0 (R_t)^{1-\psi_1} (J_t)^{\psi_1} + R_t \sigma_R \cdot dW_t$$

where  $\psi_0 > 0$  and  $0 < \psi_1 \leq 1$  and  $E_t$  is the emission of carbon.

- ▷ **Hotelling** fixed stock of reserves is a special case with  $\psi_0 = 0$ .

# Economic Impacts of Climate Change

Explore three specifications:

- i) adverse impact on **societal preferences**
- ii) adverse impact on **production possibilities**
- iii) adverse impact on the **growth potential**

# Damage Specification

Posit a **damage process**,  $D$ , to capture **negative externalities** on society imposed by carbon emissions. Evolution for  $\log D_t$ :

$$d \log D_t = (\gamma_1 + \gamma_2 F_t) E_t \beta_f dt + d\nu_d(Z_t) + E_t \sigma_d \cdot dW_t$$

for  $F_t \leq \bar{f}$  with an additional quadratic penalty:

$$\gamma_3 (F_t - \bar{f})^2$$

when  $F_t > \bar{f}$

- ▷  $\gamma_2$  gives a **nonlinear damage** adjustment
- ▷ additional penalty gives a smooth alternative to **carbon budget**
- ▷  $\sigma_d \cdot dW_t$  captures one form of **coefficient uncertainty** in damage/climate sensitivity

**Uncertainty** in the **economic damages** (coefficients,  $\gamma_1, \gamma_2, \gamma_3$ ) and **climate sensitivity** (coefficient  $\beta_f$ ) **multiplies!**

# Damages in Preference

- ▷ the per period (instantaneous) contribution to preferences is:

$$\delta(1 - \kappa) (\log C_t - \log D_t) + \delta\kappa \log E_t$$

where  $\delta > 0$  is the subjective rate of discount and  $0 < \kappa < 1$  is a preference parameter that determines the relative importance of emissions in the instantaneous utility function.

- ▷ we may “**equivalently**” think of this as a model with proportional damages to consumption and or production.

# Damages to Growth

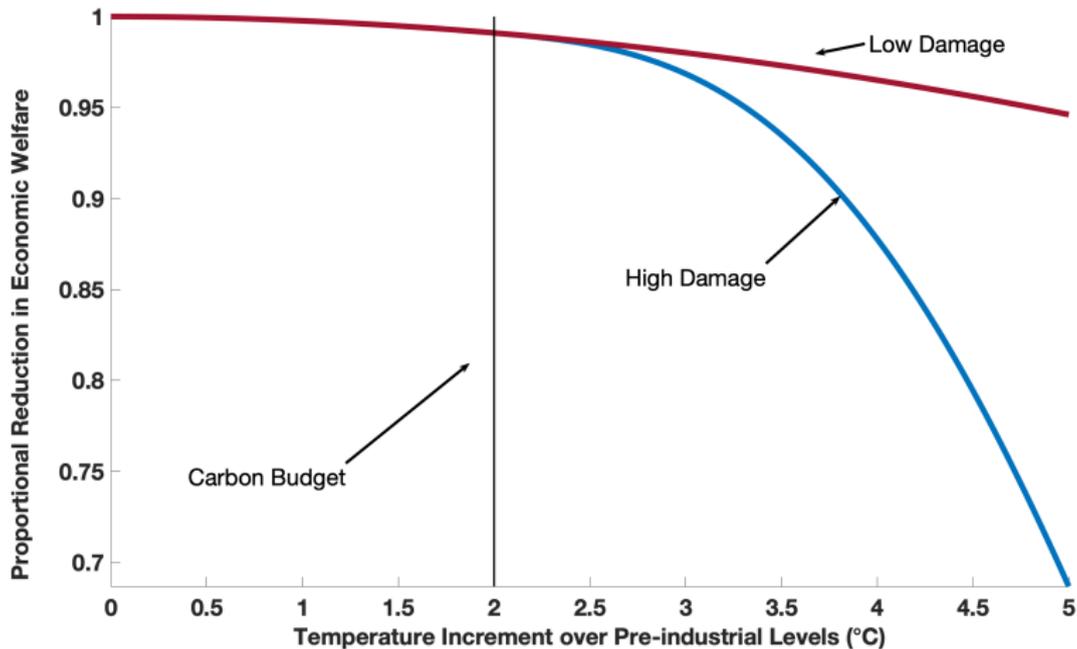
Climate change diminishes growth in the capital evolution:

$$dK_t = K_t \left[ \mu_k(Z_t)dt - \log D_t dt + \phi_0 \log \left( 1 + \phi_1 \frac{I_t}{K_t} \right) dt + \sigma_k \cdot dW_t \right]$$

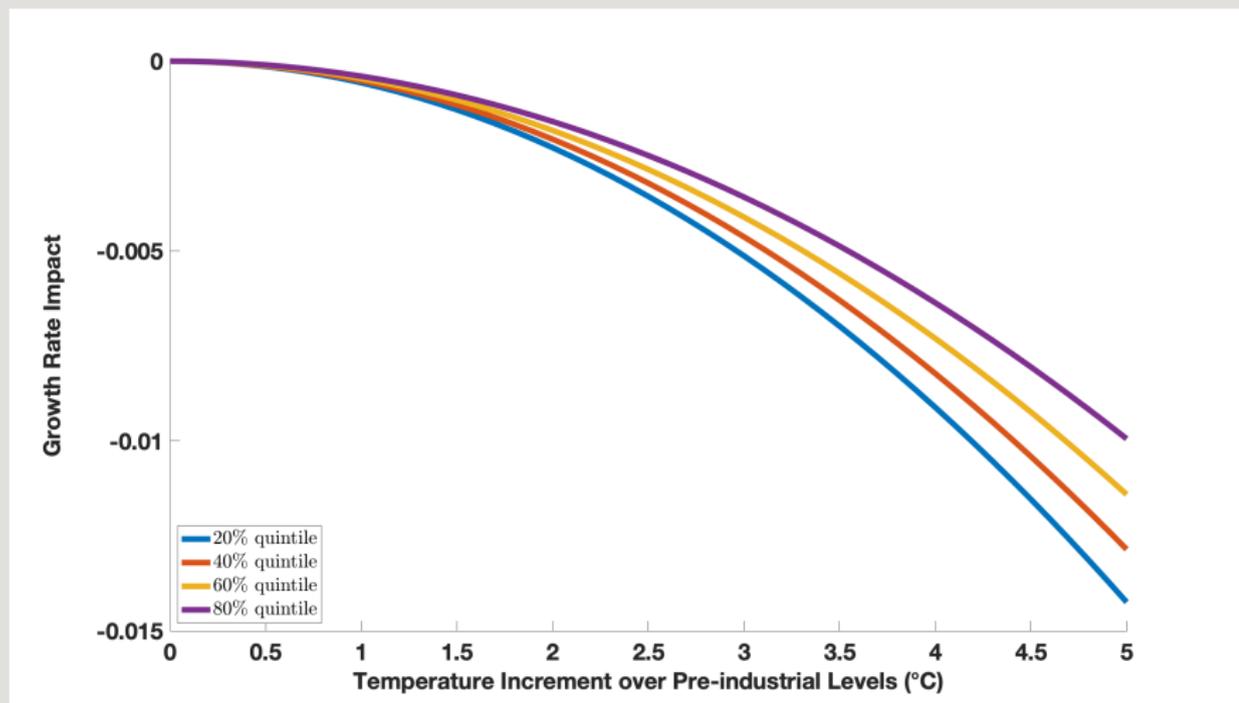
# Measurement challenges

- ▷ little historical experience to draw upon
- ▷ impacts are likely different for regions of the world that are differentially exposed to climate change
- ▷ potentially big differences between long-run and short-run consequences because of adaptation

# Proportional Damage Uncertainty



# Growth-Rate Damage Uncertainty



Evidence from Burke et al (2018).

# Uncertainty in Decision Making

Explore three components to uncertainty:

- ▷ **risk** - uncertainty *within* a model: uncertain outcomes with known probabilities
- ▷ **ambiguity** - uncertainty *across* models: unknown weights for alternative possible models
- ▷ **misspecification** - uncertainty *about* models: unknown flaws of approximating models

Impact how we pose the social planning problem and solve the planning problem and the appropriate stochastic discount factor.

# Navigating Uncertainty

Statistical models we use in practice are **misspecified**, and there is **ambiguity** as to which model among multiple ones is the best one.

- Aim of **robust** approaches:
  - ▷ use models in **sensible ways** rather than discard them
  - ▷ use probability and statistics to provide tools for limiting the type and amount of uncertainty that is entertained
- Uncertainty aversion - **dislike** uncertainty about probabilities over future events
- Outcome - **target** the uncertainty components with the **most adverse consequences** for the decision maker

Robust decisions may differ from risk averse decisions but they **do NOT** necessarily imply **inaction!**

# Decision Theory I

Ambiguity over alternative (structured) models and concerns about model misspecification. Hansen-Sargent (2019) show how to combine two approaches:

- ▷ Chen- Epstein (2002) recursive implementation of max-min utility model axiomatized by Gilboa-Schmeidler(1989). Confront **structured model uncertainty**.
- ▷ Hansen-Sargent (2001) a recursive penalization used to explore model misspecification building on robust control theory.

Hansen-Sargent (2019) combine these approaches.

# Decision Theory II

Hansen-Miao (2018) propose a recursive implementation of the smooth ambiguity model in continuous time. Discrete time version originally axiomatized by Klibanoff-Marinacci-Mukerji (2005).

- ▷ ambiguity about **local mean specification** in the state dynamics
- ▷ axiomatic defense justifies a **differential aversion** to ambiguity over models
- ▷ **equivalence** between the **smooth ambiguity** and **recursive robust choice of priors** (Hansen-Sargent, 2007)
- ▷ additional adjustment for potential model misspecification

# Social Cost of Carbon as an Asset Price

- ▷ Interpret the outcome of a robust social planner's problem
- ▷ Discounting is **stochastic** and adjusted to accommodate concerns for ambiguity and model misspecification
- ▷ Shadow prices are computed using an **efficient allocation** and not necessarily what is observed in competitive markets

Construct a **decomposition** of the SCC in terms of **economically meaningful** components.

# An Uncertainty Adjustment for Valuation

- ▷ Deduce **ambiguity-adjusted** probabilities via a max-min problem.
- ▷ Consider a **social** cash flow (proportional damages)

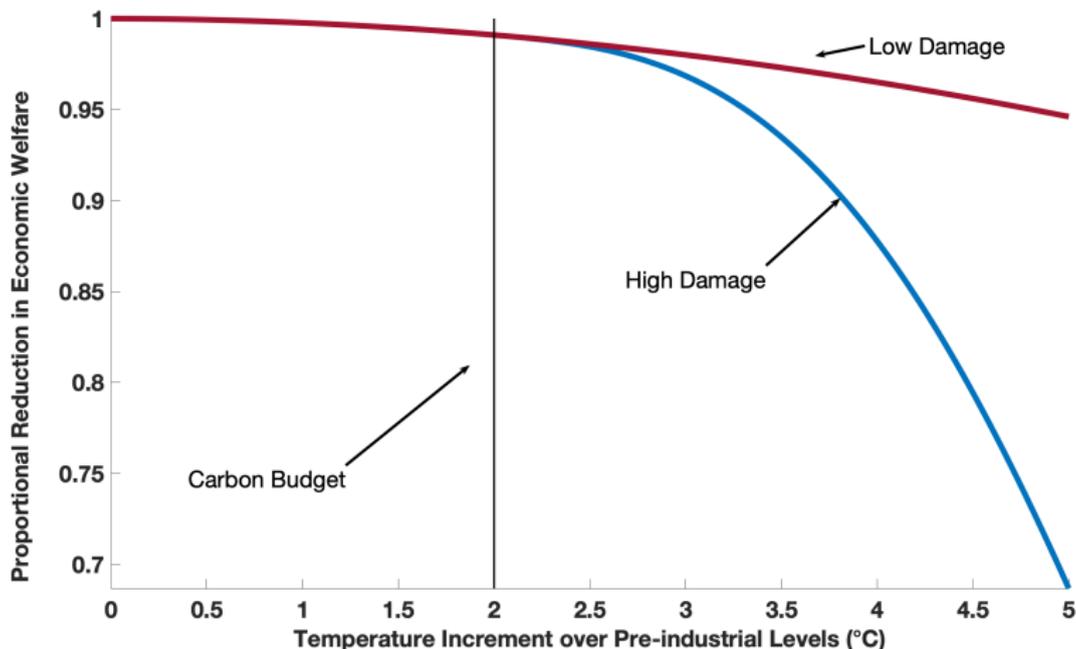
$$\begin{aligned} & \delta(\kappa - 1)\beta_f(\gamma_1 + \gamma_2 F_{t+\tau}) & F_t \leq \bar{f} \\ \delta(\kappa - 1)\beta_f \left[ \gamma_1 + \gamma_2 F_{t+\tau} + \gamma_3 (F_{t+\tau} - \bar{f})^2 \right] & F_t > \bar{f} \end{aligned}$$

scaled by the marginal utility of consumption at date  $t + \tau$ .

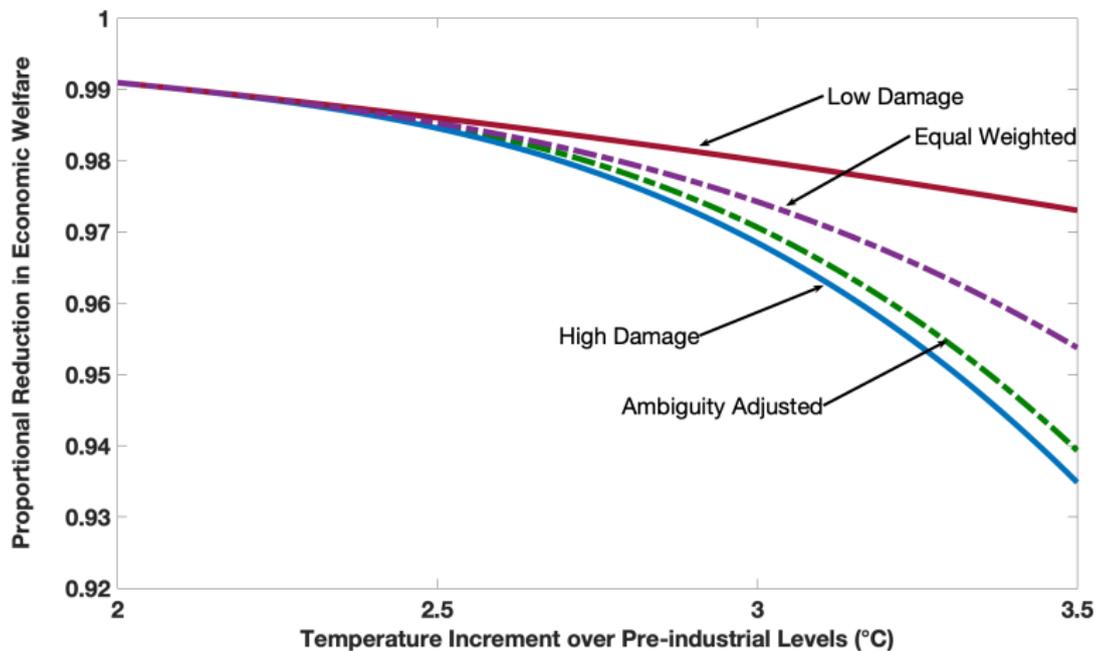
- ▷ Form discounted expected value using two measures.
  - One **integrates** over the uncertainty. Compute by solving a Feynman-Kac equation
  - Another used **ambiguity-adjusted** probabilities. Extract directly from the Hamilton-Jacobi-Bellman equation of the planner

We use the **difference** to quantify the impact of **uncertainty** on the SCC (social cost of carbon).

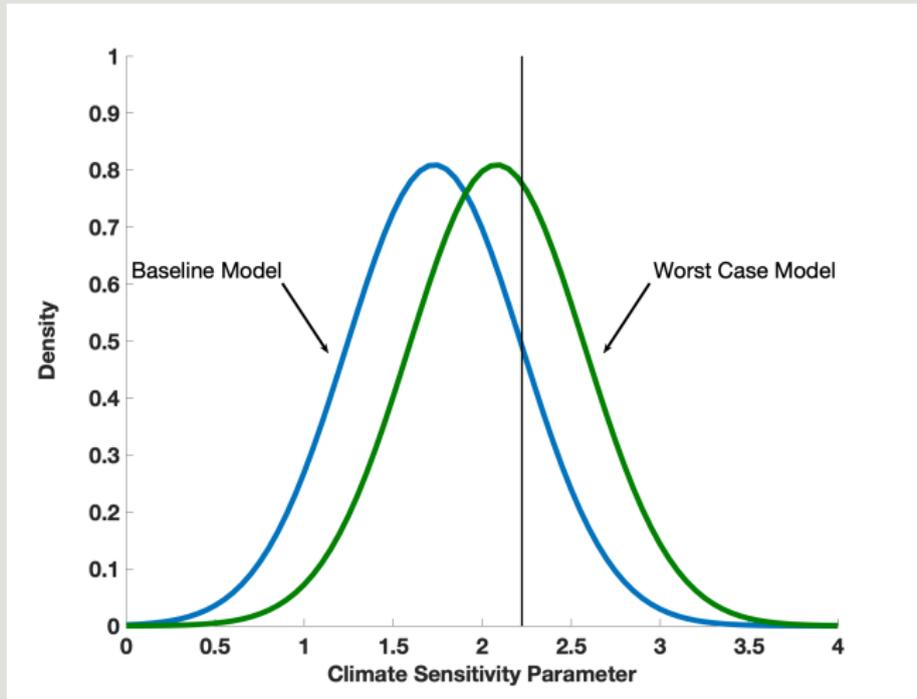
# Proportional Damage Uncertainty: Reconsidered



# Ambiguity Adjusted Weights for Damages

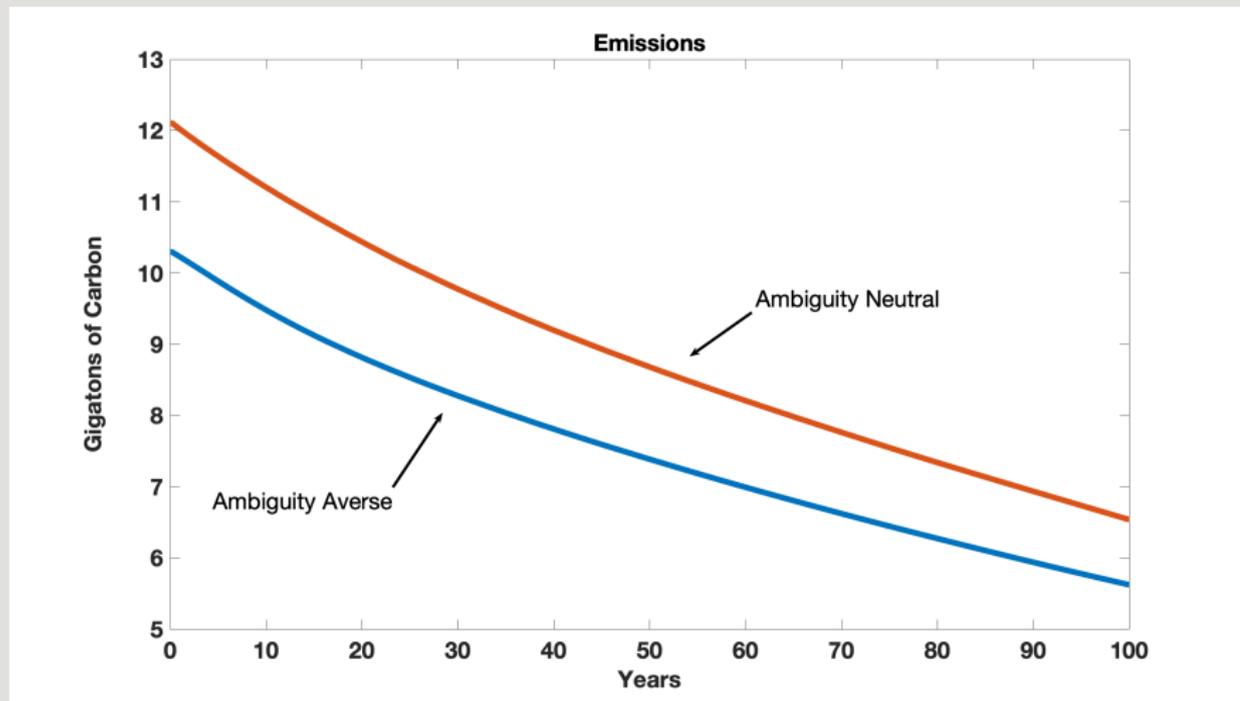


# Ambiguity Adjusted Probabilities for Climate Sensitivity



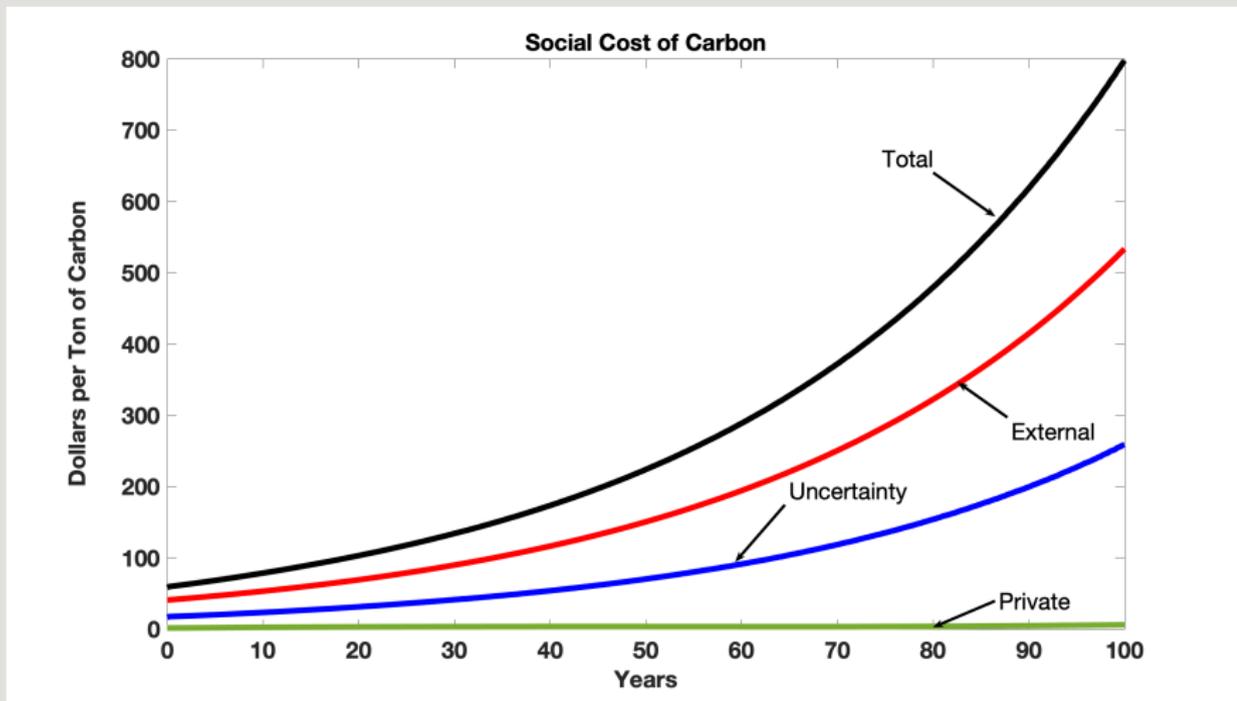
Blue = Baseline and Green = Adjusted.

# Ambiguity Aversion: Impact



Preference comparison. Average trajectories over simulated paths.

# Social Costs of Carbon



Cost decomposition. Average trajectories over simulated paths.

# Where We Stand

## ▷ Social cost of carbon

- cost **can increase** substantially by incorporating broader notions of uncertainty
- important **interaction** between damage uncertainty and climate impact uncertainty

## ▷ Extensions

- explore with climate scientists **more ambitious** climate model inputs
- assess **other potential policies** including green energy subsidies and publicly funded R and D for mitigation
- introduce explicitly **adaptation** to the specification of damages
- investigate the potential impact of **learning** as consequences become all the more evident

# Conclusions

- ▷ Decision theory under a broad umbrella of uncertainty **does not** imply **inaction**.
- ▷ Asset pricing and decision theory tools help in **navigating** through the **multiple components** of uncertainty.

# Complementary References

- ▷ Cai, Judd, and Longtzek (2017), *The Social Cost of Carbon with Climate Risk*
- ▷ Hambel, Kraft, and Schwartz (2018), *Optimal Carbon Abatement in a Stochastic Equilibrium Model with Climate Change*
- ▷ Lemoine and Traeger (2016), *Ambiguous Tipping Points*
- ▷ Millner, Dietz, and Heal (2013), *Scientific Ambiguity and Climate Policy*
- ▷ Nordhaus (2018), *Projections and Uncertainties About Climate Change in an Era of Minimal Climate Policies*
- ▷ Weitzman (2012), *GHG Targets as Insurance Against Catastrophic Climate Damages*