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

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.

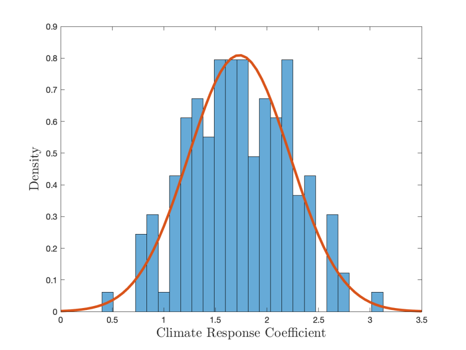
- Matthews *et al* and others have purposefully constructed a simple "approximate" climate model:

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

- 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 β_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).

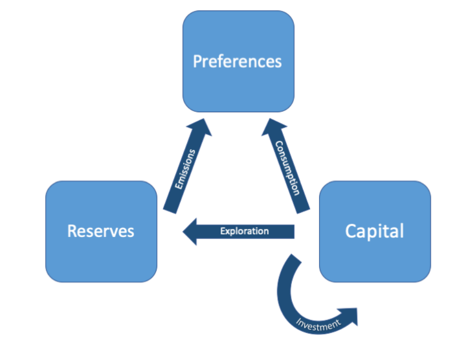
Carbon budgeting

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 penalty added with $F_t \geq \bar{f}$.

- γ_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, γ_1, γ_2) and climate sensitivity (coefficient β_f) multiplies!

Damages in Preference

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

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

  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

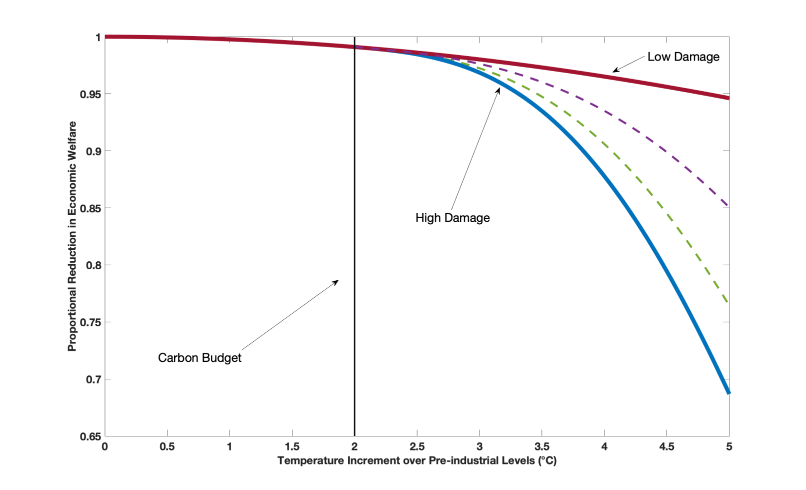
Climate change diminishes growth in the capital evolution:

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

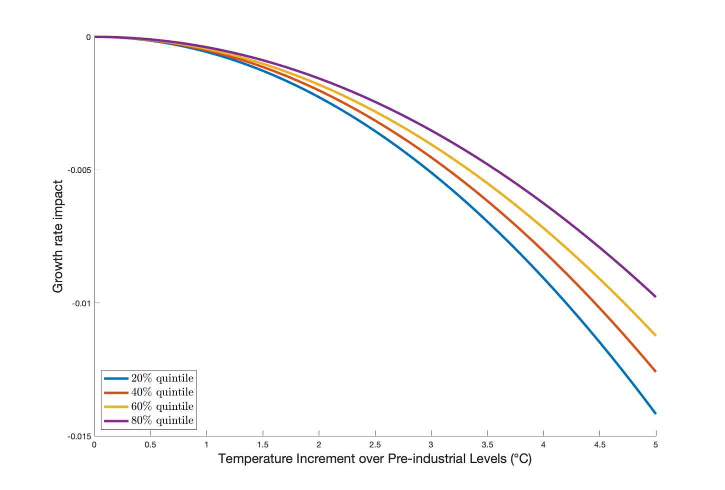
Measurement challenges

- 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.

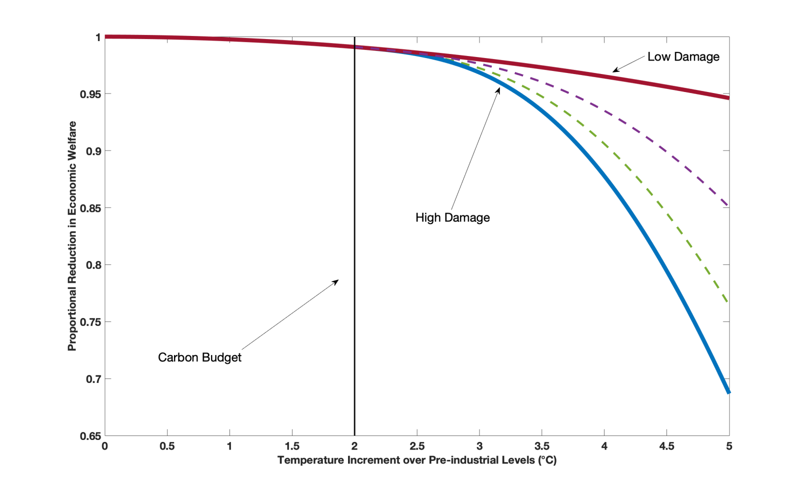
Hansen-Sargent (2019) combine these approaches.

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).

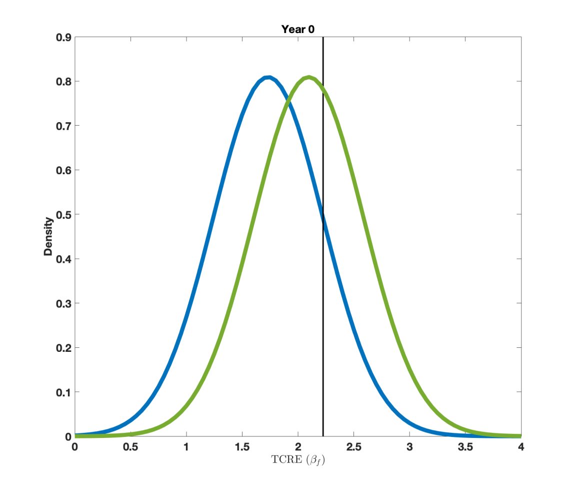
- ambiguity about local mean specification in the state dynamics
- axiomatic defense justifies a differential aversion to ambiguity over models
- equivalence between the smooth ambiguity and recursive robust choice of priors (Hansen-Sargent, 2007)
- additional adjustment for potential model misspecification

Proportional Damage Uncertainty: Reconsidered



Ambiguity Adjusted Probabilities

Time = Year 0. Baseline weights equal for both models.

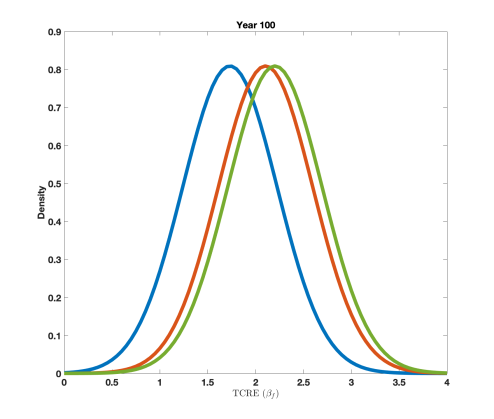


Blue = Baseline and Green = Adjusted.

Adjusted weights: equal for low and high.

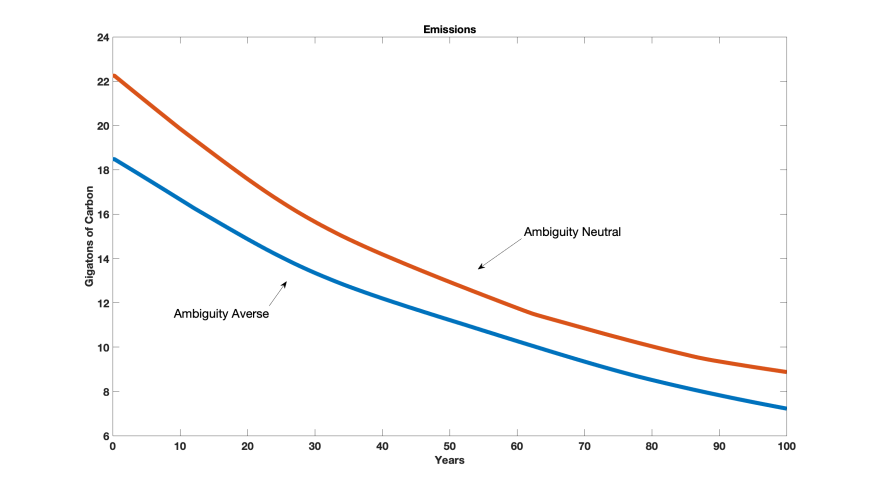
Ambiguity Adjusted Probabilities

Time = Year 100. Baseline weights equal for both models.



Blue = Baseline, Red = Low Damage, Green = High Damage.
Adjusted weights = .37 for low and .63 for high.

Ambiguity Aversion: Impact



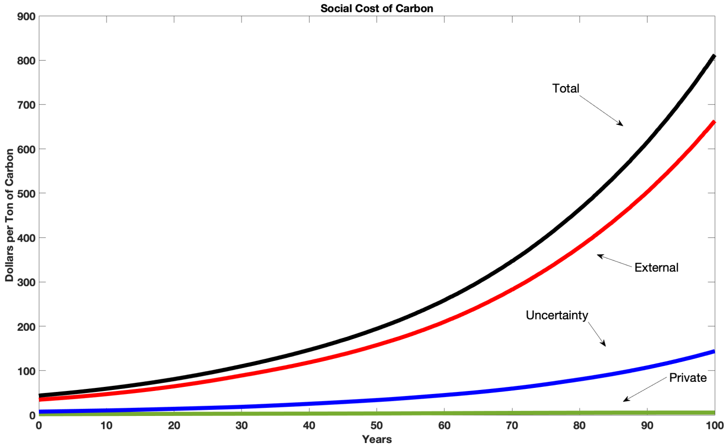
Preference comparison. Average trajectories over simulated paths.

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.

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
  - compare the impact of climate damage uncertainty with other sources of growth uncertainty

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 layers of uncertainty.