Pricing an Unknown Climate

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Intro

Equilibrium **climate sensitivity**

- Warming response to a doubling of preindustrial CO_2

IPCC's AR6 guesstimate:

- *Likely* range 2.5-4C
  - translate into hugely different scenarios for life on planet
- Refers to 66% *subjective* probability
- Different methods imply quite different results; paleoclimate data, instrumental records, physical process understanding, "emergent constraints",...

Any temperature level in the 'likely' range (and beyond...)

- far above any recent historic record
- huge extrapolation

↪ Hard uncertainty or **ambiguity**.
(∼ not objectively quantifiable)

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What is our *attitude* to the *subjectivity* of the uncertainty?

- Don't care: Expected Utility
- Do care: Ambiguity Aversion
  1. Capacities - abandon probability distributions
  2. Maximin expected utility - set of probability distributions, pick worst (Gilboa & Schmeidler, 1989)
     - Robust Control (Hansen and Sargent, 2001)
     - Used by most of previous literature on climate ambiguity
  3. Smooth Ambiguity Aversion - subjective second order distribution governed by more aversion(KMM 2005)
     - Recursive smooth ambiguity aversion (KMM 2009) permits anticipated Bayesian learning and time-consistent dynamics
- Should we care?
  - Tomorrow 16:00 room N29 session "Decision Theory": von Neumann-Morgenstern-based 'normative' axiomatization

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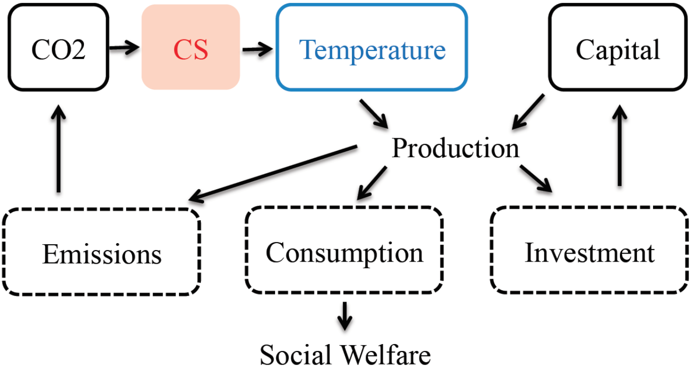
Contribution

1. Social cost of carbon under ambiguity aversion
   - Formula: General climate-economy model
   - Quantitative premium: DICE-based IAM

2. Framework
   - Recursive dynamic programming model
   - Social planner framework with
     - rational foresight and
     - *anticipated* learning

     ↪ Decision maker updates subjective climate sensitivity prior based on temperature observations (Kelly & Kolstad 1999)
   - Klibanoff et al. (2009)'s recursive smooth ambiguity aversion to distinguishes
     - subjective climate sensitivity prior from
     - (objective) temperature stochasticity

Climate-Economy model



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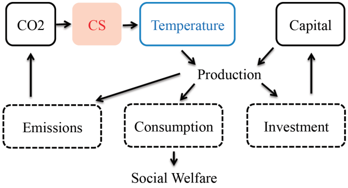
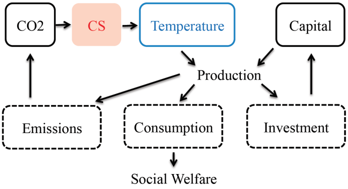


Temperature dynamics:

$$\tilde{T}_{t+1} = \chi_t(M_{t+1})\tilde{s} + \xi_t(T_t) + \tilde{\epsilon}_t$$

$\tilde{s}$: subjectively uncertain climate sensitivity (epistemological)
$\tilde{\epsilon}$: objective temperature shocks (stochastic)

Climate-Economy model - Numerics



Bayesian learning dynamics:

$$\tilde{s}_t \sim N(\mu_{s,t}, \sigma_{s,t}) \quad \& \quad \hat{T}_t \quad \Rightarrow \quad \tilde{s}_{t+1} \sim N(\mu_{s,t+1}, \sigma_{s,t+1})$$

- Conjugate normal prior
- Update to $\mu_{s,t+1}, \sigma_{s,t+1}$ after observing stochastic temperature realization

Preferences

KMM's (2009) smooth ambiguity aversion

- Risk averse to temperature stochasticity,
- Ambiguity averse to climate sensitivity uncertainty,
- Ambiguity and ambiguity aversion disentangled,
- Ambiguity aversion is 'moderate':
  - Limit of infinite ambiguity aversion returns
  - → maximin expected utility (Gilboa & Schmeidler 1989),
  - → and, "thus", robust control (Hansen & Sargent 2001)
- Time consistent
- Decision maker learns (and anticipates to do so!)
- Has normative axiomatic motivation (tomorrow! :-)

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KMM's smooth ambiguity aversion

Bellman equation
with stochasticity, uncertainty, and smooth ambiguity aversion:

$$V_t = \max_{c_t, \mu_t} L_t \, u(c_t) + \beta \times$$
$$f^{-1} \left\{ \int_S f\left(\mathrm{E}_{\epsilon_t} \left[V_{t+1} \right] \right) \mathrm{d}\,\Pi(s,t) \right\}$$

value fct today = current utility + disc future value fct

f: concave function characterizing additional aversion

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Results: Theory

How is the SCC affected by climate sensitivity ambiguity?

Without ambiguity aversion:

$$SCC_0 =$$

$$-\frac{1}{u'(c_0)}\,\mathbf{E}_0^s\mathbf{E}_0^T\left[\sum_{t=1}^{\infty}\sum_{\tau=1}^{t}\prod_{j=1}^{t}\mathcal{R}_j\mathrm{E}_j^s\mathcal{P}_j\mathrm{E}_j^T\; u_t'\,(c_t)\,\frac{\partial F_t}{\partial T_t}\frac{\partial T_t}{\partial CO_{2,\tau}}\frac{\partial CO_{2,\tau}}{\partial E_0}\right]$$

Ambiguity aversion introduces 2 weights:

- Pessimism and
- Prudence

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Ambiguity aversion introduces 2 weights:

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Results: Theory

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Pessimism bias:

$$\mathcal{P}_t = \frac{f'(\cdot)}{\mathbf{E}_t^s\left(f'(\cdot)\right)}$$

- More weight on bad outcomes.
- All else equal, pessimism increases SCC.

$$f'(\cdot) = f'\left(\mathbf{E}^s\left[V_{t+1}(\cdot)\right]\right)$$

Results: Theory

How is the SCC affected by climate sensitivity ambiguity?

Ambiguity prudence:

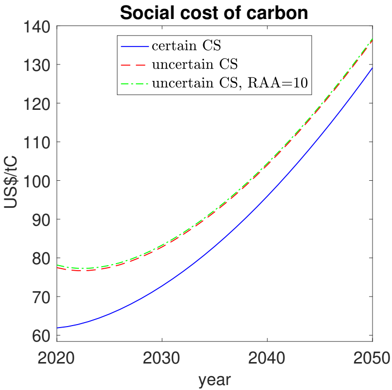
$$\mathcal{R}_t = \frac{\mathbf{E}_t^s\left(f'(\cdot)\right)}{f'\left(f^{-1}(\cdot)\right)}$$

- Prudence = ambiguity aversion decreases in *welfare*.
- Mean-zero shocks to welfare: ambiguity prudence increases SCC.
- But: climate sensitivity uncertainty impact on welfare (highly) non-linear.

Results: Quantitative

How is the SCC affected by climate sensitivity ambiguity?

- *Optimal* emission trajectory
- Expected-draws ($\epsilon_t = 0 \; \forall \; t$)
- Stochastic temperature,
  + Uncertain CS ,
  + Ambiguity aversion
- Ambiguity aversion: **RAA=10**



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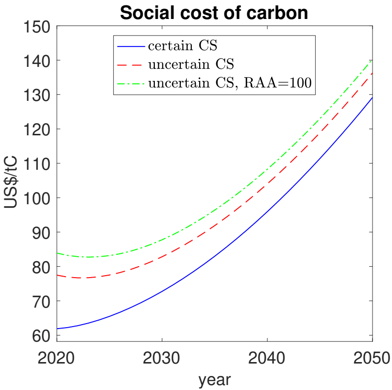
- Extreme ambiguity aversion: **RAA=100**

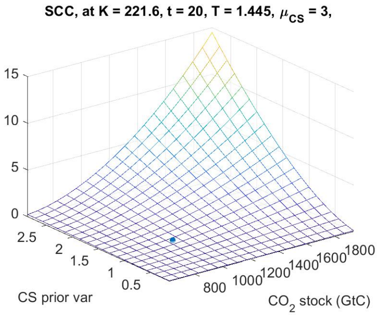


Results: Quantitative

How is the SCC affected by climate sensitivity ambiguity?

Impact *off* optimal trajectory:

- % difference:
  RAA=10 – No AA
- Year 2040
- Subsection of state-space
- Largest effect: high CO_2 & CS prior variance



Note: We show optimal policy after wandering off.

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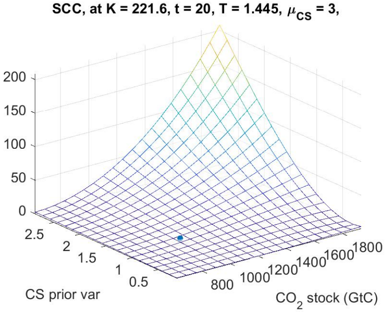

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Related literature

- Lange and Treich (2008)
- Berger et al. (2016), Berger and Marinacci (2020)
- Millner et al. (2013)
- Lemoine and Traeger (2016)
- Xepapadeas & Yannacopoulos (2018), Brock & Xepapadeas (2021)
- Rudik (2020)
- Barnett et al. (2020)

Summing up:

Evaluate climate sensitivity ambiguity in setting that is

- time consistent (possibly rationally/normatively attractive)
- permits moderate ambiguity aversion
- includes anticipated Bayesian learning

Theory:

- introduces two weighting terms into SCC: *pessimism* weighting & *prudence*

Empirics:

- implies only a small positive policy premium of ambiguity

Conclusion for practitioner:

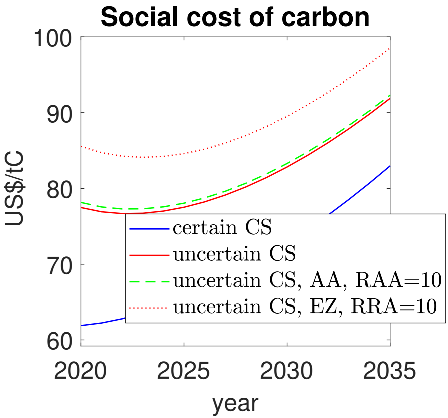
- Error small simply using
  - regular Bayesian expected utility model
  - using best guess prior and neglecting ambiguity

Appendix 1: Epstein-Zin comparison

How is the SCC affected by climate sensitivity ambiguity?

Comparison to Epstein-Zin preferences & according risk aversion:

- *Optimal* emission trajectory
- Moderate ambiguity aversion: **RAA=10**
- Epstein-Zin: **RRA=10**



Appendix 2: Ambiguity premium over Ambiguity Aversion

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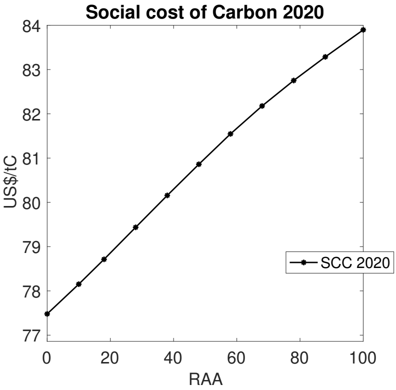

- (Very) moderate effect in optimum $\approx < 1 \; - \; 8\%$
- At least initially almost linear increase

Appendix: IPCC Assessment of Climate Sensitivity

IPCC (AR6): Uncertainty in warming projections *dominated* by climate's sensitivity to additional emissions