Climate Policy in a Dynamic Stochastic Economy[1]

Yongyang Cai
The Ohio State University

June 4, 2019

[1] Presentation for Blue Waters project (PI: Yongyang Cai (OSU); Team members: Kenneth Judd (Hoover), William Brock (UW), Thomas Hertel (Purdue). The presentation is mainly based on the following two working papers: Cai, Brock, Xepapadeas and Judd (2019), "Climate policy under spatial heat transport: cooperative and noncooperative regional outcomes"; Cai and Judd (2019), "Climate policy with carbon capture and storage in the face of economic risks and climate target constraints".

Polar Amplification

Polar Amplification (PA): high latitude regions have higher/faster temperature increases (almost twice that of low latitude regions)

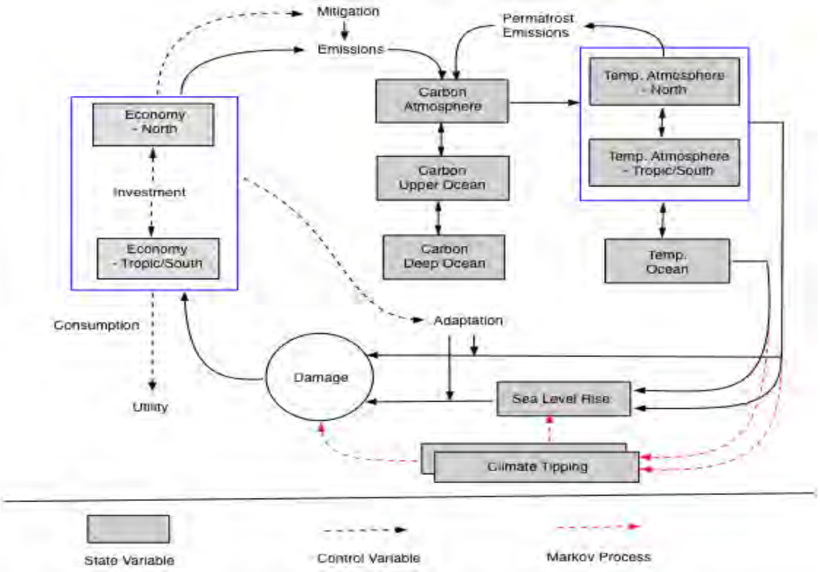
- accelerate the loss of Arctic sea ice
- meltdown of Greenland and West Antarctica ice sheets
- global sea level rise
- thawing of permafrost
  - change in ecosystems
  - infrastructure damage
  - release of greenhouse gases stored in permafrost
- increase frequency of extreme weather events
- tipping points

Contributions

- We develop a Dynamic Integration of Regional Economy and Spatial Climate under Uncertainty (DIRESCU), incorporating
  - an endogenous SLR module
  - an endogenous permafrost melt module
  - the more realistic geophysics of spatial heat and moisture transport from low latitudes to high latitudes
  - use recursive preferences
  - allow for adaptation to regional damage from SLR and temperature increase.
- Calibrate our parameter values to match history as well as to fit the representative concentration pathway (RCP) scenarios
- Solve a dynamic stochastic feedback Nash equilibrium of DIRSCUE
- Climate policy:
  - ignoring PA, SLR, or adapation leads to serious bias
  - non-cooperation leads to much smaller carbon tax than cooperation
  - the North has higher carbon taxes than the Tropic-South

DIRESCU Model

Dynamic Integration of Regional Economy and Spatial Climate under Uncertainty (DIRESCU)



Climate Tipping Point

- Uncertain tipping time with tipping probability

$$p_t = 1 - \exp\left(-\varrho \max\left(0, T^{\mathrm{AT}}_{t,1} - 1\right)\right),$$

- Transition matrix

$$\begin{bmatrix} 1 - p_t & p_t \\ 0 & 1 \end{bmatrix}$$

- Duration: D years
- transition law of tipping state J_t:

$$J_{t+1} = \min(\overline{J}, J_t + \Delta)\chi_t \tag{1}$$

  - χ_t: indicator for tipping's occurrence
  - $\overline{J}$: final damage level
  - $\Delta = \overline{J}/D$: annual increment of damage level after tipping
- We use Atlantic Meridional Overturning Circulation (AMOC) as a representative tipping element ($D = 50$ years, $\overline{J} = 0.15$, $\lambda = 0.00063$)

Social Planner's Deterministic Problem

- Social planner's problem in the cooperative determistic case

$$\max_{I_{t,i}, c_{t,i}, \mu_{t,i}, P_{t,i}} \quad \sum_{t=0}^{\infty} \beta^t \sum_{i=1}^{2} u(c_{t,i}) L_{t,i} \tag{2}$$

  - utility

$$u(c) = \frac{c^{1-\frac{1}{\psi}}}{1-\frac{1}{\psi}}, \tag{3}$$

- Market clearing condition

$$\sum_{i=1}^{2} (I_{t,i} + c_{t,i} L_{t,i} + \Gamma_{t,i}) = \sum_{i=1}^{2} \widehat{Y}_{t,i} \tag{4}$$

Social Planner's Stochastic Problem

- Epstein-Zin preference:
  - γ: risk aversion
  - ψ: intertemporal elasticity of substitution
- Bellman equation:

$$V_t^{\mathrm{Social}}(\mathbf{x}_t) = \max_{\mathbf{a}_t} \left\{ \sum_{i=1}^{2} u(c_{t,i}) L_{t,i} + \frac{\beta}{\widehat{\psi}} \left[\mathbb{E}_t \left(\left(\widehat{\psi} V_{t+1}^{\mathrm{Social}}(\mathbf{x}_{t+1}) \right)^{\Theta} \right) \right]^{1/\Theta} \right\},$$

where $\widehat{\psi} \equiv 1 - \frac{1}{\psi}$ and $\Theta \equiv (1-\gamma)/\widehat{\psi}$

- State variables $\mathbf{x}_t$:

$$\mathbf{x}_t = (K_{t,1}, K_{t,2}, M_t^{\mathrm{AT}}, M_t^{\mathrm{UO}}, M_t^{\mathrm{DO}}, T_{t,1}^{\mathrm{AT}}, T_{t,2}^{\mathrm{AT}}, T_t^{\mathrm{OC}}, S_t, J_t, \chi_t)$$

- Decision variables $\mathbf{a}_t = (I_{t,1}, I_{t,2}, c_{t,1}, c_{t,2}, \mu_{t,1}, \mu_{t,2}, P_{t,1}, P_{t,2})$

Computational Method for Social Planner's Problems

- Parallel Value Function Iteration for Social Planner's Problems
  - Terminal condition: estimate $V_T^{\text{Social}}(\mathbf{x})$ for time T
  - Backward iteration over time t:

$$V_t^{\text{Social}} = \mathfrak{F}_t V_{t+1}^{\text{Social}}$$

    - *Step* ***1.*** *Maximization step (in parallel). Compute*

$$v_{t,j} = (\mathfrak{F}_t \widehat{V}_{t+1}^{\text{Social}})(\mathbf{x}_{t,j})$$

      for each approximation node $\mathbf{x}_{t,j}$ *(#node:* $5^{10} \times 2 = 19.5$ *million)*
    - *Step* ***2.*** *Fitting step. Using an appropriate approximation (complete Chebyshev polynomial #term:* $\binom{10+4}{4} \times 2 = 2002$*) method*

      $\widehat{V}_t^{\text{Social}}(\mathbf{x}_{t,j}; \mathbf{b}_t) \approx v_{t,j}$

Feedback Nash Equilibrium

- Feedback Nash Equilirbium (FBNE), also known as Markov Perfect Equilirbium
  - nocooperation $\Longrightarrow$ no transfer of capital between the regions, so the market clearing condition is

$$I_{t,i} + c_{t,i} L_{t,i} = \widehat{Y}_{t,i} \tag{5}$$

- Bellman equations:

$$V_{t,i}^{\mathrm{FBNE}}(\mathbf{x}_t) = \max_{c_{t,i}, P_{t,i}, \mu_{t,i}} \left\{ u(c_{t,i}) L_{t,i} + \beta \mathcal{G}_{t,i}(\mathbf{x}_{t+1}) \right\}, \tag{6}$$

for $i = 1, 2$, where

$$\mathcal{G}_{t,i}(\mathbf{x}_{t+1}) \equiv \frac{1}{\widehat{\psi}} \left[\mathbb{E}_t \left(\left(\widehat{\psi} V_{t+1,i}^{\mathrm{FBNE}}(\mathbf{x}_{t+1}) \right)^{\Theta} \right) \right]^{1/\Theta}$$

Feedback Nash Equilibrium

- First-order conditions (FOCs) over $c_{t,i}, P_{t,i}, \mu_{t,i}$:

$$
\begin{aligned}
0 &= u'(c_{t,i}) - \beta \frac{\partial \mathcal{G}_{t,i}(\mathbf{x}_{t+1})}{\partial K_{t+1,i}}, && (7) \\
0 &= \frac{\partial \widehat{Y}_{t,i}}{\partial P_{t,i}} && (8) \\
0 &= \frac{\partial \mathcal{G}_{t,i}(\mathbf{x}_{t+1})}{\partial K_{t+1,i}} \frac{\partial \widehat{Y}_{t,i}}{\partial \mu_{t,i}} + \frac{\partial \mathcal{G}_{t,i}(\mathbf{x}_{t+1})}{\partial M_{t+1}^{\mathrm{AT}}} \frac{\partial E_{t,i}^{\mathrm{Ind}}}{\partial \mu_{t,i}} && (9)
\end{aligned}
$$

- Use the solution of the FOCs and the transition laws to compute

$$
V_{t,i}^{\mathrm{FBNE}}(\mathbf{x}_t) = u(c_{t,i}) L_{t,i} + \beta \mathcal{G}_{t,i}(\mathbf{x}_{t+1})
$$

Computational Method for Feedback Nash Equilibrium

- Parallel Value Function Iteration for Feedback Nash Equilirbium
  - Terminal condition: estimate $V_{T,i}^{\mathrm{FBNE}}(\mathbf{x})$ for the terminal time T and $i = 1, 2$
  - Backward iteration over time t:

$$V_{t,i}^{\mathrm{FBNE}} = \mathfrak{F}_{t,i}\mathbf{V}_{t+1}^{\mathrm{FBNE}}, \quad i = 1, 2$$

    - *Step 1 (in parallel). For each approximation node $\mathbf{x}_{t,j}$ (#node: $m = 5^{10} \times 2 = 19.5$ million), compute the feasible action $(\mathbf{a}_{t,1,j}, \mathbf{a}_{t,2,j})$ for both regions that satisfies the FOCs and the* transition laws, and then comptute

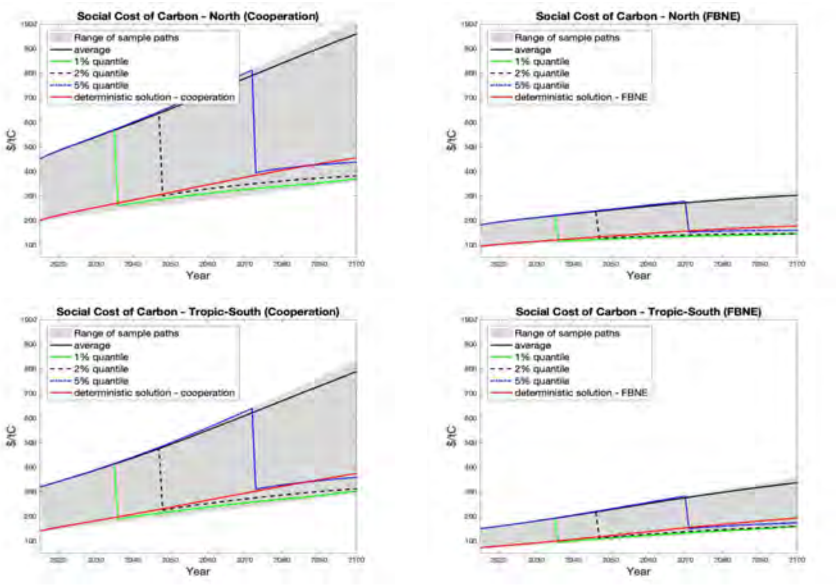
$$v_{t,i,j} = u(c_{t,i,j})L_{t,i} + \beta\mathcal{G}_{t,i}(\mathbf{x}_{t+1,j})$$

      for $i = 1, 2$ and $j = 1, ..., m$.
    - *Step **2.** Fitting step. Using an appropriate approximation (complete Chebyshev polynomial #term: $\begin{pmatrix} 10+4 \\ 4 \end{pmatrix} \times 2 = 2002$) method such that $\widehat{V}_{t,i}^{\mathrm{FBNE}}(\mathbf{x}_{t,j}; \mathbf{b}_{t,i}) \approx v_{t,i,j}$, for $i = 1, 2$ and $j = 1, ..., m$.*

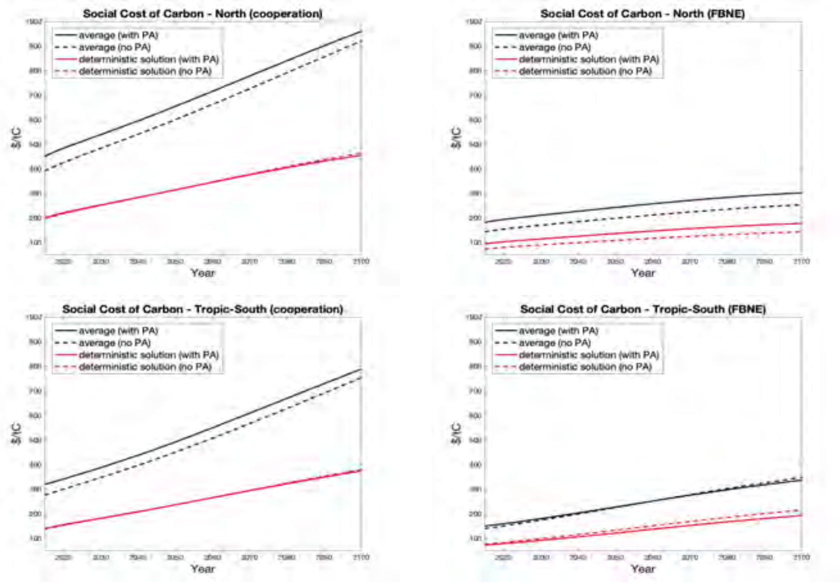
Parallelization

Example	# of Optimization problems	#Cores	Wall Clock Time	Total CPU Time
1	2 billion	3K	3.4 hours	1.2 years
2	372 billion	84K	8 hours	77 years

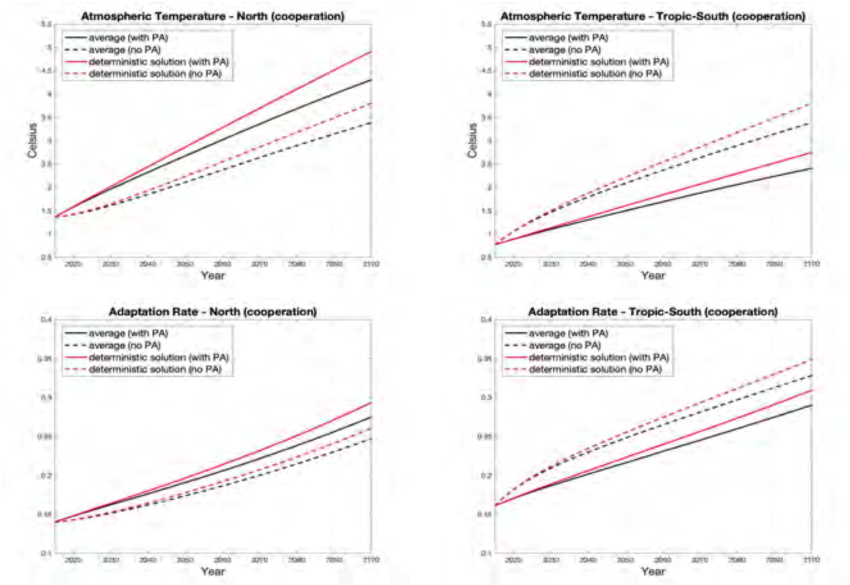
Results of the Benchmark Case



Bias from Ignoring PA



Bias from Ignoring PA



Bias from Ignoring SLR, Adaptation, and Transfer of Capital

Table: Initial carbon tax from ignoring elements

Ignored Element	Model	Deterministic		Stochastic	
		North	Tropic-South	North	Tropic-South
SLR	Coop.	84	58	294	207
	FBNE	32	33	116	109
Adaptation	Coop.	553	384	855	601
	FBNE	355	214	400	299
Capital Transfer	Coop.	236	118	540	275

Sensitivity on the IES and Risk Aversion

Table: Initial carbon tax under various IESs (ψ) and risk aversion (γ)

IES (ψ)	Model	Deterministic		Stochastic			
		North	Tropic -South	North		Tropic-South	
				$\gamma = 3.066$	$\gamma = 10$	$\gamma = 3.066$	$\gamma = 10$
0.69	Coop.	58	35	114	132	69	80
	FBNE	29	17	55	63	32	38
1.5	Coop.	198	137	454	519	318	363
	FBNE	90	67	185	208	152	174

Summary

- The North has higher carbon taxes than the Tropic-South in a cooperative or noncooperative world
- Noncooperation leads to much lower carbon taxes than the social planner's model with economic interactions between the regions
- Closed economy has higher carbon taxes than (semi-)open economy
- Ignoring PA leads to many biases in carbon tax, adaptation, & temperature
- Ignoring SLR underestimates carbon taxes significantly
- Ignoring adaptation overestimates carbon taxes significantly
- For climate tipping risks, larger IES values imply larger carbon taxes in a cooperative or non-cooperative world

Carbon Capture and Storage

- Capital transition law

$$K_{t+1} = (1-\delta)K_t + \widehat{Y}_t - C_t - p_t R_t - \Gamma_t(R_{t-1}, R_t)$$

  - p_t: cost in directly removing a unit of carbon from the atmosphere
  - R_t: removed carbon amount
  - $\Gamma_t(R_{t-1}, R_t)$: adjustment cost
- The carbon cycle is

$$\mathbf{M}_{t+1} = \Phi_M \mathbf{M}_t + (E_t - R_t, 0, 0)^\top, \tag{10}$$

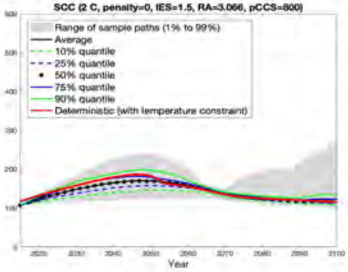
Economic Risk

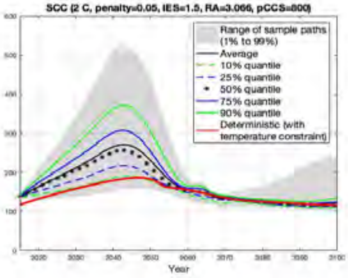
- stochastic productivity, $\widetilde{A}_t \equiv \zeta_t A_t$
  - A_t: deterministic trend
  - ζ_t: productivity shock with long-run risk

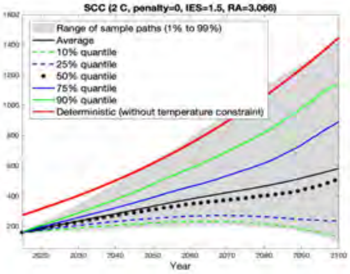
$$\log\left(\zeta_{t+1}\right) = \log\left(\zeta_t\right) + \chi_t + \varrho\omega_{\zeta,t}$$

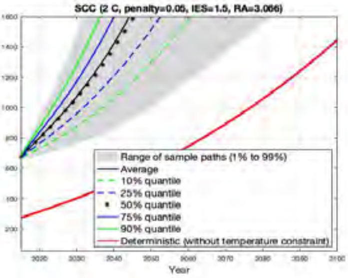
$$\chi_{t+1} = r\chi_t + \varsigma\omega_{\chi,t}$$

Results with/without CCS or 2°C target

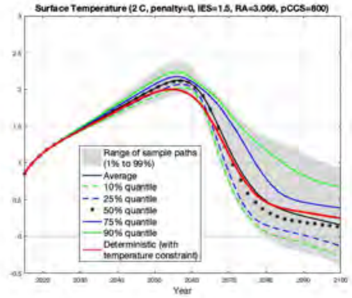


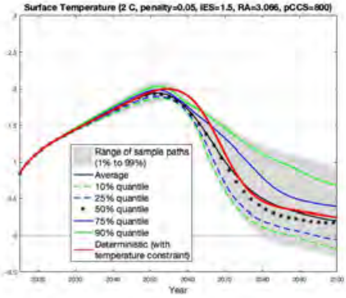


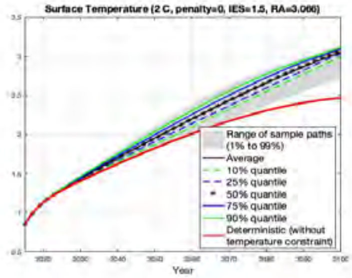


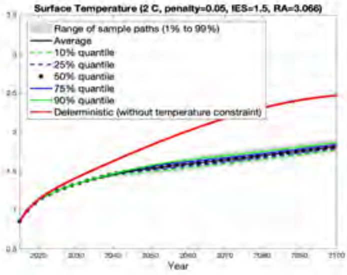


Results with/without CCS or 2°C target









Publications Using Blue Waters

- Cai, Y., and T.S. Lontzek (2018). The social cost of carbon with economic and climate risks. *Journal of Political Economy*, forthcoming.
- Cai, Y., K.L. Judd, and J. Steinbuks (2017). A nonlinear certainty equivalent approximation method for stochastic dynamic problems. *Quantitative Economics*, 8(1), 117–147.
- Yeltekin, S., Y. Cai, and K.L. Judd (2017). Computing equilibria of dynamic games. *Operations Research*, 65(2): 337–356
- Cai, Y., T.M. Lenton, and T.S. Lontzek (2016). Risk of multiple climate tipping points should trigger a rapid reduction in CO2 emissions. *Nature Climate Change* 6, 520–525.
- Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton (2015). Stochastic integrated assessment of climate tipping points calls for strict climate policy. *Nature Climate Change* 5, 441–444.
- Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita (2015). Risk to ecosystem services could significantly affect the cost-benefit assessments of climate change policies. *Proceedings of the National Academy of Sciences*, 112(15), 4606–4611.

Working Papers Using Blue Waters

- Cai, Y., W. Brock, A. Xepapadeas, and K.L. Judd, "Climate policy under spatial heat transport: cooperative and noncooperative regional outcomes."
- Cai, Y. and K.L. Judd, "Climate policy with carbon capture and storage in the face of economic risks and climate target constraints."
- Cai, Y., K.L. Judd, and R. Xu (2019). Numerical solution of dynamic portfolio optimization with transaction costs. R&R in *Operations Research*.
- Cai, Y., J. Steinbuks, K.L. Judd, J. Elliott, and T.W. Hertel (2019). Modeling Uncertainty in Large Scale Multi Sectoral Land Use Problems. Working paper.
- Cai, Y., and K.L. Judd (2018). Numerical dynamic programming with error control: an application to climate policy. Working paper.

Impact

- The 2018 Nobel Committee's scientific report, titled with "Economic Growth, Technological Change, and Climate Change", cited our NCC (2015) paper for supporting the award of the Nobel Prize in Economics to William Nordhaus.
- A 2017 joint report of The National Academies of Science, Engineering, and Medicine, "*Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*"
  - Incorporated our NCC (2016) paper's discussion about uncertainty in the damage function
- A White House (2014) report, "*The cost of delaying action to stem climate change*"
  - Incorporated our JPE paper's conclusion that high SCC can be justified without assuming the possibility of catastrophic events

Acknowledgement

- We thank Blue Waters for making this research possible to do
- We thank the Blue Waters Support team for their always fast and helpful responses
- We thank the support by NSF (SES-0951576 and SES-146364)