Responses to Climate Change in a Dynamic Stochastic Economy[1]

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[1] Presentation for Blue Waters project (PI: Yongyang Cai (OSU); Team members: Kenneth Judd (Hoover), William Brock (UW), Thomas Hertel (Purdue), Simon Scheidegger (Zurich), Carlos Rangel (PSU), TJ Canann (UMinn). The presentation is mainly based on our recent working paper, "Climate Policy under Cooperation and Competition between Regions with Spatial Heat Transport", written by Cai, Brock, Xepapadeas and Judd.

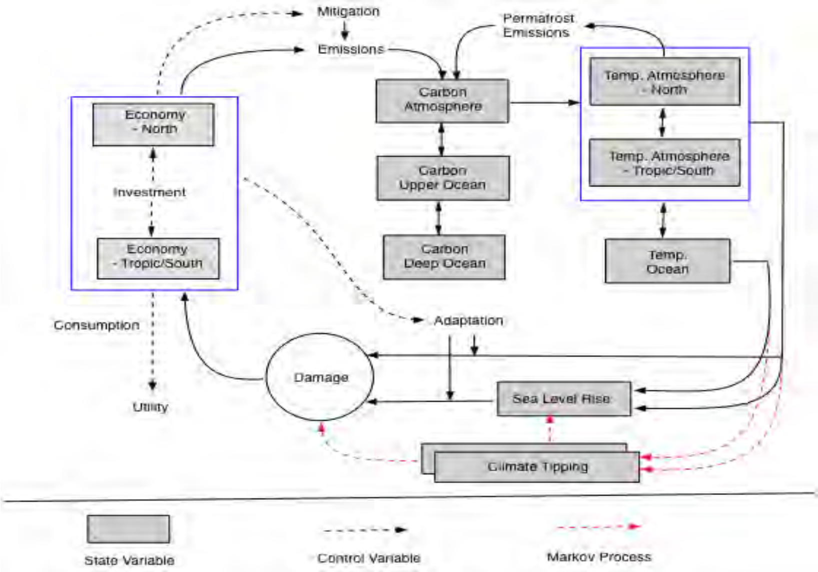
Polar Amplification

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

DIRESCU Model

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



Climate Tipping Point

- Uncertain tipping time with tipping probability

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

- Transition matrix

$$\left[\begin{array}{cc} 1 - p_t & p_t \\ 0 & 1 \end{array}\right]$$

- Duration: $\mathcal{D}$ years
- transition law of tipping state J_t:

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

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

Output

- Net Output at time t in region i

$$Y_{t,i} \equiv \frac{(1 - J_t)\mathcal{Y}_{t,i}}{1 + (1 - P_{t,i})\left(D^{\mathrm{S}}_{t,i} + D^{\mathrm{T}}_{t,i}\right)}. \tag{2}$$

  - $\mathcal{Y}_{t,i}$: gross output
  - $P_{t,i}$: adaptation
  - $D^{\mathrm{S}}_{t,i}$: damage from sea level rise
  - $D^{\mathrm{T}}_{t,i}$: damage directly from temperature increase

Epstein–Zin preference

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

$$V_t(\mathbf{x}_t) = \max_{\mathbf{a}_t} \sum_{i=1}^{2} \left\{ \tau_{t,i} u(c_{t,i}) L_{t,i} + \frac{\beta}{\widehat{\psi}} \left[\mathbb{E}_t \left(\left(\widehat{\psi} V_{t+1}(\mathbf{x}_{t+1}) \right)^{\Theta} \right) \right]^{1/\Theta} \right\}, \tag{3}$$

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

- Parallel Value Function Iteration
  - Terminal condition: estimate $V_T(\mathbf{x})$ for time T
  - Backward induction:

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

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

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

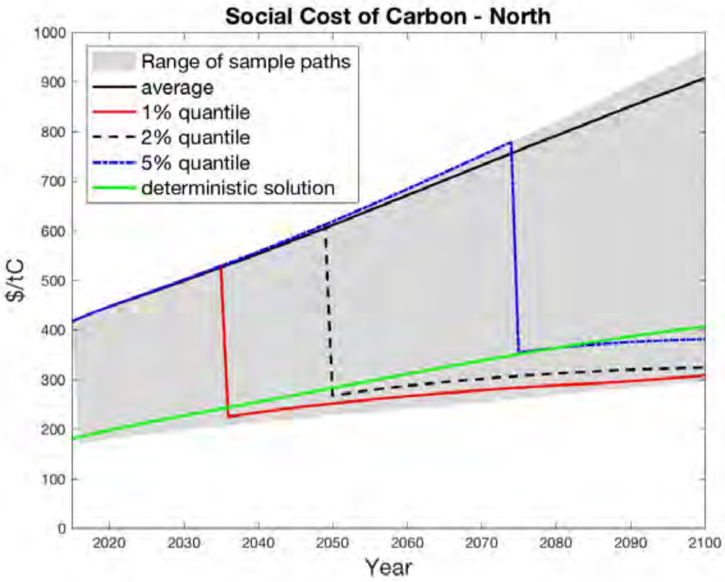
      for each approximation node $\mathbf{x}_{t,i}$ *(#node:* $5^9 \times 2 = 3.9$ *million)*
    - *Step **2.** Fitting step. Using an appropriate approximation (complete Chebyshev polynomial #term:* $\begin{pmatrix} 9+4 \\ 4 \end{pmatrix} \times 2 = 1430$*) method*

      $\widehat{V}_t(\mathbf{x}_{t,i}; \mathbf{b}_t) \approx v_{t,i}$

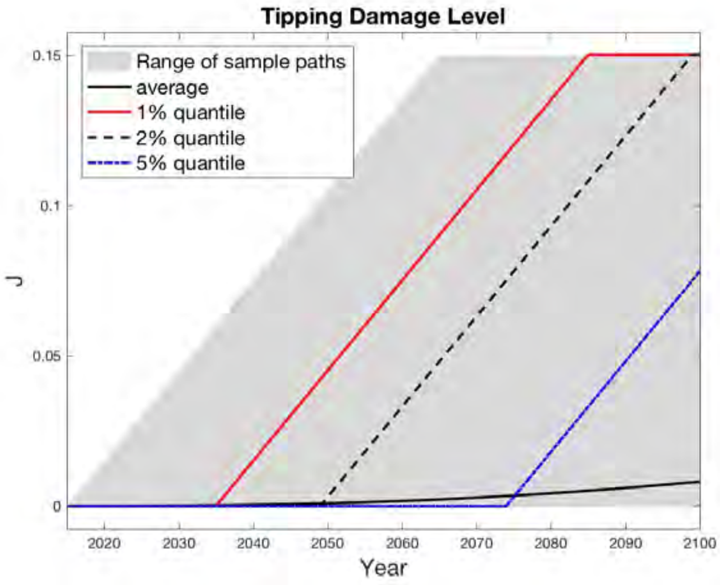
Parallelization

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

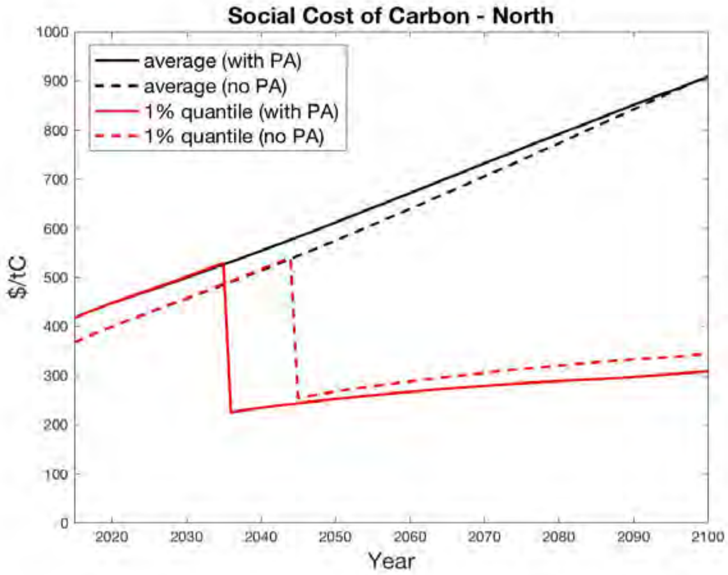
Results from the Stochastic Model



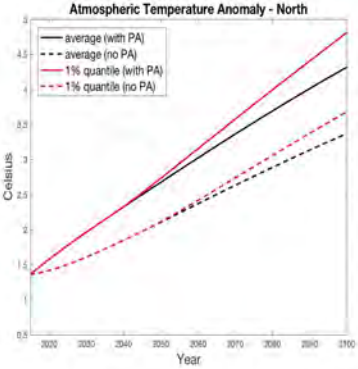
Results from the Stochastic Model

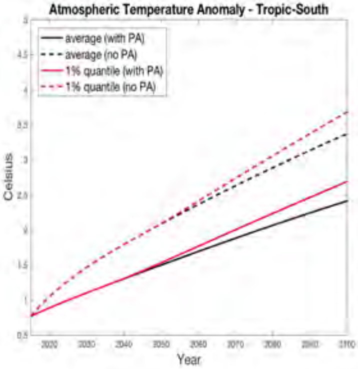


Bias from ignoring PA

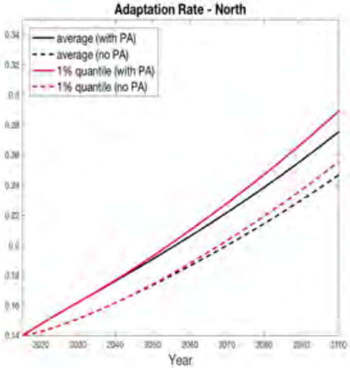


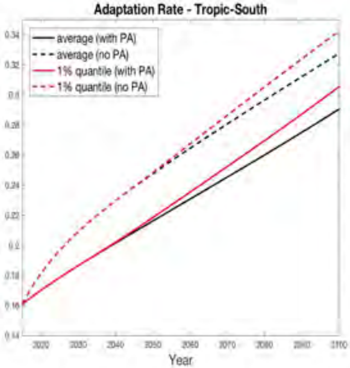
Bias from ignoring PA


Atmospheric Temperature Anomaly - North


Atmospheric Temperature Anomaly - Tropic-South

Bias from ignoring PA





Sensitivity on the IES, RA and Welfare Criterion

IES (ψ)	λ	Deterministic		Stochastic			
		North	Tropic -South	North		Tropic-South	
				$\gamma = 3.066$	$\gamma = 10$	$\gamma = 3.066$	$\gamma = 10$
0.69	0	59	35	111	130	68	79
	0.4	55	39	104	121	75	88
	0.6	53	42	101	118	81	94
	1	50	50	96	112	97	114
1.5	0	193	135	446	510	316	361
	0.4	180	144	416	477	339	387
	0.6	174	150	403	460	352	402
	1	163	163	378	431	384	438

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 (2018). Climate Policy under Cooperation and Competition between Regions with Spatial Heat Transport. NBER working paper 24473, under review in *The Review of Economic Studies*.
- Cai, Y., J. Steinbuks, J.W. Elliott, and T.W. Hertel (2018). Modeling Uncertainty in Large Scale Multi Sectoral Land Use Problems. Under review in *Journal of the Association of Environmental and Resource Economists*.
- Cai, Y., K.L. Judd, and R. Xu (2018). Numerical solution of dynamic portfolio optimization with transaction costs. NBER working paper 18709, under review in *Operations Research*.
- Cai, Y., and K.L. Judd (2018). Numerical dynamic programming with error control: an application to climate policy.

Impact

- 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
- 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

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Summary

- The regional SCC stochastic processes are derived and various uncertainty fan charts with and without tipping points are presented and compared with and without heat and moisture transport as well as for a range of risk aversion, IESs and welfare weights
- Neglecting heat and moisture transport leads to many biases
  - inaccurate forecasting of the first time of arrival of potential tipping points located in the high latitudes of the Northern Hemisphere
  - solutions without heat transport will underestimate what actual heat-related damage there is in the North, and overestimate the actual heat-related damage in the Tropic-South
  - Without heat transport, the adaptation rates in the North will be underestimated as its corresponding atmospheric temperature anomaly is underestimated, and the adaptation rates in the Tropic-South will be overestimated as its corresponding atmospheric temperature anomaly is overestimated

Summary

- Endogenous SLR is an important new contribution of our modeling
- When welfare weights are more egalitarian, the SCC of the North increases relative to the Tropic-South and investments from the North to the Tropic-South are larger compared to the non-egalitarian Negishi weights case (i.e., competitive equilibrium)
- SCCs for both regions tend to be larger for larger IES values for climate tipping risks.
- Optimal SCC paths for both regions from ignoring heat transport are higher than those with heat transport in the deterministic model. However, if we allow for stochastic tipping points, ignoring PA leads to underestimation of the SCC in both regions.