Policy Responses to Climate Change in a Dynamic Stochastic Economy\textsuperscript{1}

Kenneth Judd

Hoover Institution, Stanford, CA

May 18, 2017

\textsuperscript{1}Presentation for Blue Waters project (PI: Lars Hansen (UC) Yongyang Cai (OSU); Team members: Kenneth Judd (Hoover, PSU), Simon Scheidegger (Hoover), Carlos Rangel (Hoover, PSU), William Brock (UW), Thomas Hertel (Purdue), TJ Canann (UMinn)
Climate Change Policy Analysis

What should be the policy response to global warming in the face of uncertainty?

- Economists analyze simple stylized models of pieces of the system
  - Deterministic: economic actors know perfectly the economic and climate systems
  - Myopic: ignore known future events (such as WARMING) and policies
  - Bad physics: e.g., CO2 emitted in 2020 causes warming in 2010 (DICE2007, IWG)

- We create dynamic and stochastic integrated models of climate and economy (DSICE)
  - uncertain (random) economic growth
  - parameter uncertainty
  - allow future warming and policies affect decisions today
Economics Is Stuck in the “Stone” (Laptop) Age

- Federal Reserve Models
  - are linear (or nearly so)
  - run on laptops in a few minutes
  - have temporal resolution of three months
  - have spatial resolution greater than 1000 km
  - code authors do not know numerical analysis – no LU, no AD, ...
  - written in Matlab and Eviews: “This allows you solve the problem and graph the results in one program.”

- Federal Reserve economists
  - run the US and world monetary policy
  - I know them; some took my course in numerical methods
  - have no interest in doing better

- We develop computational methods of general value in economics; Climate change policy analysis is an application
Risks

- Economic risks: taste shocks, uncertain technological advances (e.g., quantum computers), financial crisis
- Climate risks: Antarctic and Greenland ice sheet melting (sea level rise, IPCC 2014)
- Two kinds of risk and uncertainty
- Example: Brownian motion
  - We may know the drift and variance parameters
  - We do not know the future position of a particle following a Brownian motion
- In climate change policy work, “uncertainty” usually just means uncertainty about parameters.
- We examine both parameter uncertainty and intrinsic stochasticity
- Economic productivity follows a Brownian motion, its parameters have been estimated by statistical methods, and we incorporate these estimates in our model of the economy and climate.
DSICE Framework

Dynamic Optimization Problem

- Epstein-Zin Preferences: recursive utility function
  - \( u_t(c) = \frac{c^{1-1/\psi}}{1-1/\psi} L_t \): utility flow per period
  - \( \psi \): dynamic consumption flexibility
  - \( \gamma \): risk aversion
  - \( \Gamma = \frac{1-\gamma}{1-1/\psi} \): composite factor

- State: \( S = (K, M, T, J, I) \)
  - ten continuous state variables
  - like 10D parabolic HJB PDE

- Bellman equation

\[
V_t(S) = \mathcal{F}_t V_{t+1}(S^+) \equiv \max_{c, \mu} \left[ u_t(c_t) + \beta \left[ \mathbb{E}_t \left\{ (V_{t+1}(S^+))^\Gamma \right\} \right]^1/\Gamma \right], \\
\text{s.t. } S^+ = F_t(S, c_t, \mu_t, \epsilon_t)
\]
Parallelization of DSICE

- The value function $V_t(S)$ represents system at time $t$ as a function of $S$
- The value function $\hat{V}(S; b^t)$ approximates $V_t(S)$ with polynomials with coefficients $b^t$
- Solve backwards in time, like Hamilton-Jacobi-Bellman PDEs
- For each time $t$, solve the Bellman equation in parallel
  - Step 1. Maximization step: Compute (in parallel)
    \[ v_i = \delta_t \hat{V}(S_i^+; b^{t+1}), \]
    for approximation nodes $S_i$
  - Step 2. Fitting step: compute coefficients $b^t$ such that $\hat{V}(S; b^t)$ fits $(S_i, v_i)$ data.

<table>
<thead>
<tr>
<th>Example</th>
<th># of Optimization problems</th>
<th>#Cores</th>
<th>Wall Clock Time</th>
<th>Total CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>94 billion</td>
<td>10K</td>
<td>3 hours</td>
<td>4 years</td>
</tr>
<tr>
<td>2</td>
<td>372 billion</td>
<td>84K</td>
<td>8 hours</td>
<td>77 years</td>
</tr>
</tbody>
</table>

- Strong scaling: linear over 1K cores to 100K cores
What should the tax ($ per metric ton of C) be in order to limit warming?

Must balance concerns for economic well-being over
  - space
  - time
  - possible evolution of economic productivity
No Target
Two-Degree Target with 82% Success
Two-Degree Target with 100% Success
Application: Range of possible warming

- Climate studies use economic models to predict what could happen if there is no serious mitigation policy.
- DSICE shows that the range is much larger when you include economic uncertainty in analysis.
- The upper tail of potential temperature is of most interest.
- IPCC-style analysis misses the upper tail.
Work in Progress Using Blue Waters

- Spatial-DSICE
  - the polar regions have more warming
  - developing countries (most in the tropical regions) suffer more economic loss from warming
  - sea level rise has different damage in different regions

- DSICE with multiple tipping events


Introduce a new method that can approximately solve up to 400-dimensional dynamic stochastic problems


Impact

A White House (2014) report:

- “The cost of delaying action to stem climate change” is high
- Incorporated our 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)
Summary

- Global warming could have huge and uncertain damage
- DSICE provides a powerful tool with the Blue Waters support for policy analysis in the face of risks and uncertainty
- DSICE shows that the social cost of carbon with risks is significantly higher that the one in the deterministic model
- With the Blue Waters support, our work has made impact to academia, society and government