A GLOBAL EQUILIBRIUM MODEL OF ECONOMY-CLIMATE INTERACTIONS

Per Krusell

*Institute for International Economic Studies*

and

Tony Smith

*Yale University*

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Goals of the project

1. Push out the frontier in “integrated-assessment” modelling.
2. Build a quantitative model of economic-climate interactions featuring:
   - a full microfoundation to permit standard welfare analysis;
   - a very large number of regions;
   - uncertainty about climatic, meteorological, and other shocks;
   - a high degree of region-specific detail; and
   - rich economic interactions between regions (e.g., insurance).
3. Use the model to provide quantitative evaluations of the distributional effects of climate-related policies.
4. Long-run agenda: study the international climate-policy game.
The climate system

- Three stocks of carbon: $M_A$ (atmosphere), $M_U$ (upper ocean), $M_L$ (lower ocean).
- Two global temperatures: $T_A$ and $T_L$.
- A simple dynamic system for the three deposits:

$$
\begin{bmatrix}
M_{A,t+1} \\
M_{U,t+1} \\
M_{L,t+1}
\end{bmatrix} =
\begin{bmatrix}
\phi_{11} & \phi_{21} & 0 \\
1 - \phi_{11} & 1 - \phi_{21} - \phi_{23} & \phi_{32} \\
0 & \phi_{23} & 1 - \phi_{32}
\end{bmatrix}
\begin{bmatrix}
M_{At} \\
M_{Ut} \\
M_{Lt}
\end{bmatrix} +
\begin{bmatrix}
E_t \\
0 \\
0
\end{bmatrix}
$$

- A simple dynamic system for temperature:

$$
T_{A,t+1} = a_1 T_{At} + a_2 (T_{At} - T_{Lt}) + a_3 F_{t+1}
$$

$$
T_{L,t+1} = T_{Lt} + a_4 (T_{At} - T_{Lt})
$$

- Radiative forcing:

$$
F_{t+1} = a_5 \log(a_6 M_{A,t+1}) + O_{t+1}
$$
A baseline model

- The climate system is embedded in a global macroeconomic model that builds on:
  1. Nordhaus et al: RICE model;
  2. Bewley-Huggett-Aiyagari: a continuum of “regions”, or points on the globe, hit by shocks and interacting in limited financial markets; and
  3. Castro-Covas-Angeletos: each region is an “entrepreneur” endowed with a (region-specific) production technology.

- Preferences: \[ E_0 \sum_{t=0}^{\infty} \beta^t U(c_t). \]
- Technology: \[ y_t = a_t z_{1t} F(z_{2t}, k_t, h_t, e_t), \text{ } F \text{ Cobb-Douglas}. \]
- Markov process for TFP shocks: \[ G_1(z_{1t}, x) \equiv P(z_{1,t+1} \leq x). \]
- Markov process for climate shocks:
  \[ G_2(z_{2t}, x, T_{A,t+1}) \equiv P(z_{2,t+1} \leq x). \]
- No aggregate uncertainty.
- Ex-ante heterogeneity easy to introduce.
Markets

- Carbon energy, a non-renewable resource, is produced (extracted) by competitive risk-neutral “energy” firms and bought and sold in a worldwide competitive market.
- No extraction costs.
- No international markets for physical capital; installed capital is immobile.
- Labor supply is fixed.
- Regions can buy and sell shares in energy firms in a competitive worldwide market (equivalent to trading a risk-free bond). Each share yields a dividend equal to the market value of (newly extracted) carbon energy.
- Each region has a non-trivial portfolio problem: invest in its own physical capital and/or take a position in the worldwide bond market.
Definition of equilibrium

- Individual state variables: wealth ($\omega$) and shocks $z = (z_1, z_2)$.

- Aggregate state variables:
  1. Climate (stocks of carbon and current global temperatures);
  2. Trend in TFP (common across regions);
  3. Worldwide stock of carbon energy; and
  4. Distribution over ($\omega, z$).

- Aggregate functions: $H$ (law of motion for aggregate state), $P$ (price of energy), $\Pi$ (price of shares in energy firm), and $E$ (worldwide energy use).

- Equilibrium conditions: regions behave optimally given ($H, P, \Pi, E$); $H$ is consistent with individual decision rules; market for energy clears; market for shares clears; Hotelling condition holds (energy firms indifferent to timing of extraction).
Special cases

- Eliminate shocks and the climate externality: an endogenous growth model as in Dasgupta and Heal (1974). Energy extraction and the stock of energy decline at a constant rate; output, consumption, and capital grow at a constant rate (if TFP growth is high enough).

- Retain climate externality, but eliminate shocks and international borrowing and lending, impose a finite horizon, and replace the continuum with a (small) finite number of regions: decentralized version of the RICE model.

- Eliminate climate externality but retain shocks and study a steady state: Bewley-Huggett-Aiyagari with a non-renewable resource. Distribution replicates itself; endogenous growth rates close to those with complete markets in quantitative examples.
Eventually all carbon energy is extracted and the long-run stocks of carbon reach a steady state.

So it’s all about transition to the (very) long-run balanced growth path!

Need computational methods that can track evolution of the equilibrium distribution (far) away from steady state (see, e.g., Krusell, Mukoyama, Şahin, and Smith).
First steps

- Perform an exercise analogous to the one in Chatterjee.
- Assume **complete markets** against shocks.
- Assume **free mobility of physical capital** across regions. Capital moves to equalize marginal products, so (in effect) there is a (global) representative firm.
- Competitive regions take the climate externality as given: with CRRA preferences the economy aggregates (savings for each region are affine in the region’s present-value wealth).
- Can solve a representative-agent problem to find the competitive equilibrium behavior of the aggregates. The representative-agent **ignores** his effect on climate variables.
- Each region gets a constant share of aggregate consumption, depending on its initial wealth.
The planning problem with complete markets

The social planner internalizes the climate externality, maximizes the lifetime utility of a representative agent, and splits the “pie” across the regions according to some weights:

\[
V(A, K, R, M) = \max_{K', R'} \left[ U(F(A, K, R - R', M) - K') + \beta V(A', K', R', M') \right]
\]

subject to: \( M' = \rho M + R - R' \)
The planner’s first-order conditions

- **Consumption-savings:**
  \[-U_C + \beta U'_C F'_K = 0\]

- **Energy choice** ($\gamma$ is the multiplier on the law of motion for the carbon stock):
  \[-U_C F_E + \beta U'_C F'_E + \gamma - \beta \gamma' = 0\]

- **Climate externality:**
  \[\beta U'_C F'_M + \gamma - \beta \rho \gamma' = 0\]
Shooting algorithm

- Assume a finite horizon $T$.
- Guess on an energy sequence that hits the balanced-growth path at $T$.
- Use the consumption-savings condition to “shoot” a path for capital that hits the balanced-growth path at $T$.
- Use the climate externality condition to determine a sequence of multipliers.
- Use the energy choice condition to “shoot” a path for energy that hits the balanced-growth path at $T$.
- Rinse. Lather. Repeat.
Output (planner vs. competitive equilibrium)

Time

1  30  60  90

.973971

1.05208
Energy (planner vs. competitive equilibrium)
Damages
(circle = planner, diamond = competitive equilibrium)
Intuition: cake-eating with an externality

- Two-period model inspired by Sinclair (1994).
- Continuum of identical consumers, each with a cake of size $b_0$.
- Eating cake generates a stock of “bad stuff” that lowers utility in period 2:

$$U(b_0 - b_1) + \beta V(b_1, M_1),$$

where $M_1 = B_0 - B_1$.
- Competitive f.o.c. (and imposing $b_i = B_i$):

$$-U_C(B_0 - B_1) + \beta V_C(B_1) = 0.$$
- Planner’s f.o.c. (internalizes externality):

$$-U_C(B_0 - B_1) + \beta V_C(B_1) - \beta V_M(M_1) = 0.$$
- Planner wants $B_0 - B_1$ to be smaller than in comp. eq.
Next steps

- **Build tools** for computing transitional dynamics of the world economy with incomplete markets.
- Calibration: greater detail about region-specific damages and/or benefits (see Dell, Olken, and Jones). Incorporate multidimensional climate-related shocks.
- Optimal policy under uncertainty (about the climate system, productivity growth, etc.).
- Endogenize choice of clean vs. dirty energy (see Acemoglu et al on directed technical change to economize on dirty energy).
- Groups of regions with common institutions and/or policies (to study the international policy game).
- Overlapping generations to address issues of intergenerational equity (see Leach).