

A GLOBAL EQUILIBRIUM MODEL OF ECONOMY-CLIMATE INTERACTIONS

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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: $y_t = a_t z_{1t} F(z_{2t}, k_t, h_t, e_t)$, F 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 (ω) 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 (ω, z) .
- ▶ Aggregate functions: H (law of motion for aggregate state), P (price of energy), Π (price of shares in energy firm), and E (worldwide energy use).
- ▶ Equilibrium conditions: regions behave optimally given (H, P, Π, 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.

Transition

- ▶ *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:

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

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 (γ is the multiplier on the law of motion for the carbon stock):

$$-U_C F_E + \beta U'_C F'_E + \gamma - \beta \gamma' = 0$$

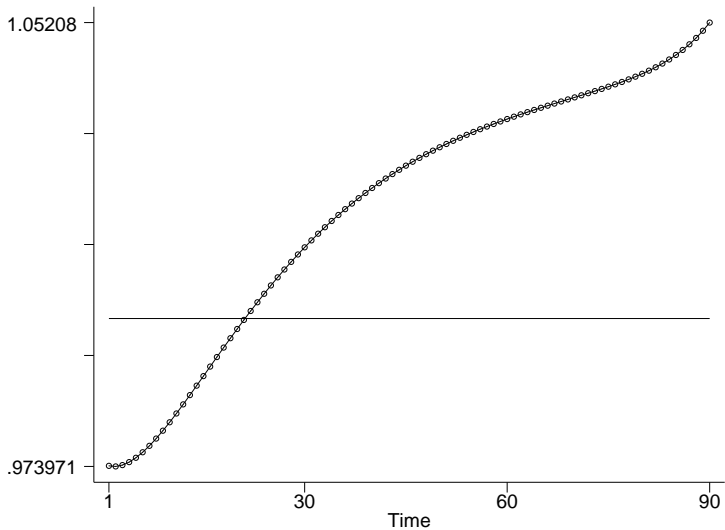
- ▶ Climate externality:

$$\beta U'_C F'_M + \gamma - \beta \rho \gamma' = 0$$

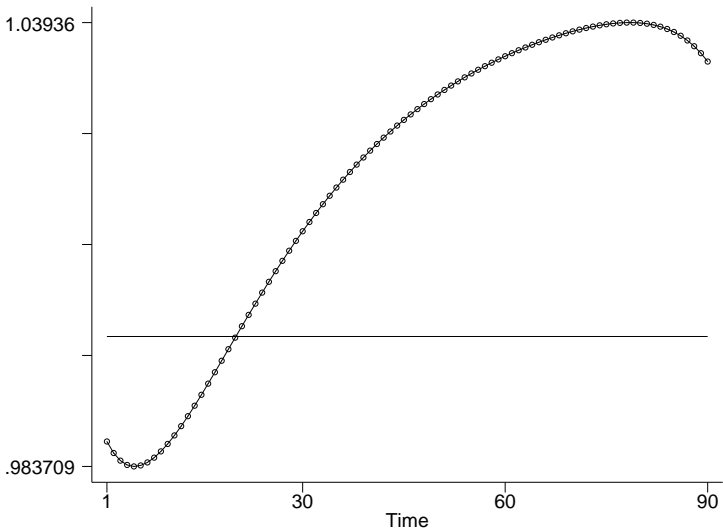
Shooting algorithm

- ▶ 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.

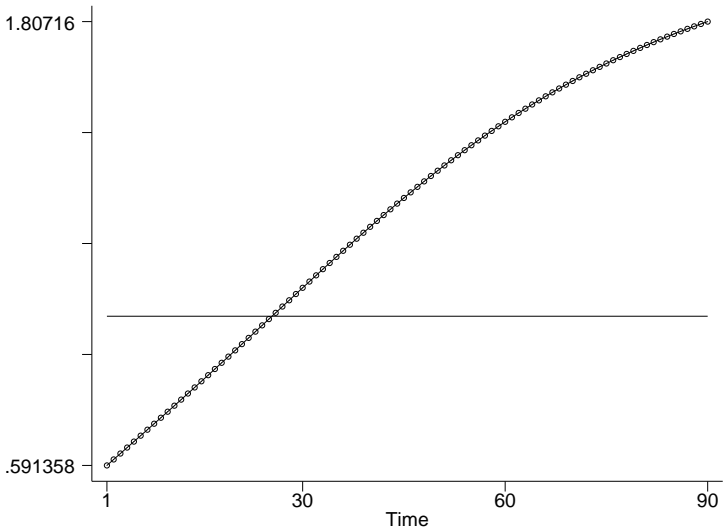
Output (planner vs. competitive equilibrium)



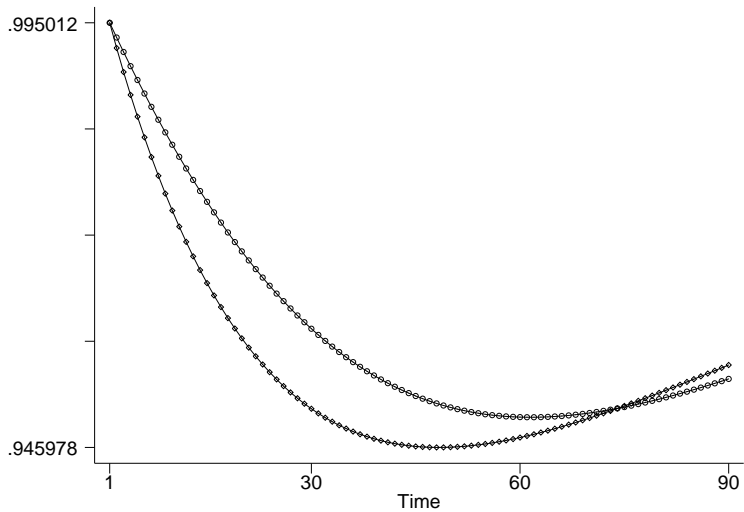
Consumption (planner vs. competitive equilibrium)



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).