A GLOBAL EQUILIBRIUM MODEL OF ECONOMY-CLIMATE INTERACTIONS

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July 2009

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:

$$\begin{aligned} T_{A,t+1} &= a_1 T_{At} + a_2(T_{At} - T_{Lt}) + a_3 F_{t+1} \\ T_{L,t+1} &= T_{Lt} + a_4(T_{At} - T_{Lt}) \end{aligned}$$

- 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:

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

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):

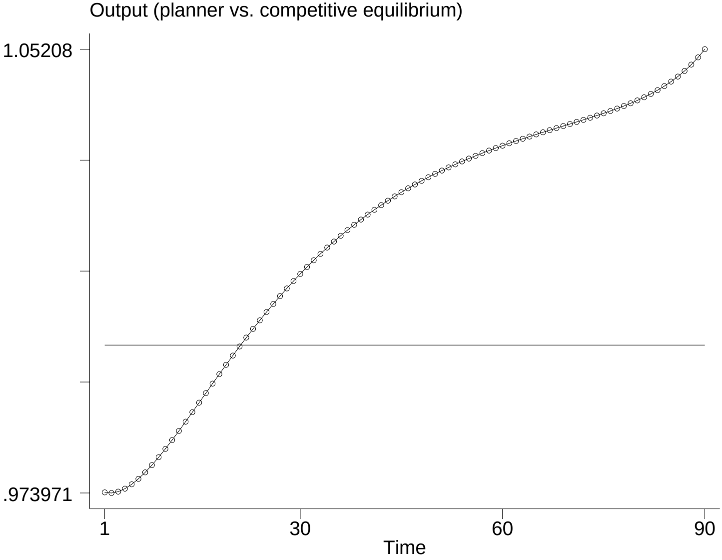
$$-U_C F_E + \beta U'_C F'_E + \gamma - \beta \gamma' = 0$$

- Climate externality:

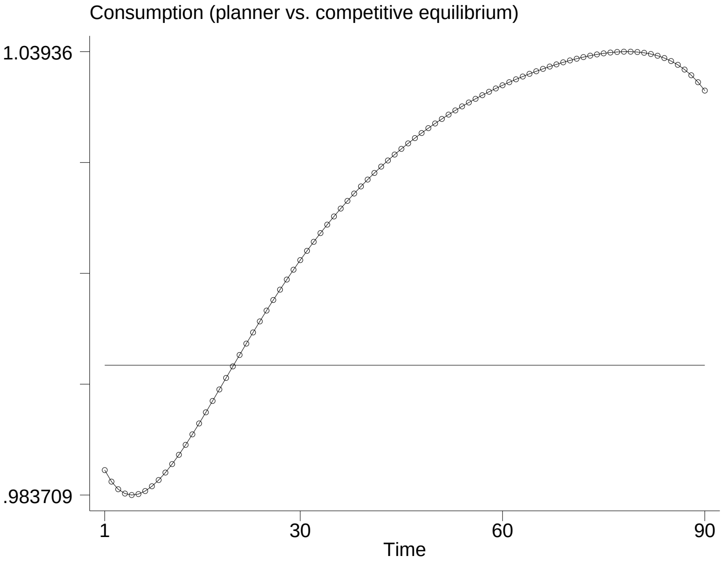
$$\beta U'_C F'_M + \gamma - \beta \rho \gamma' = 0$$

Shooting algorithm

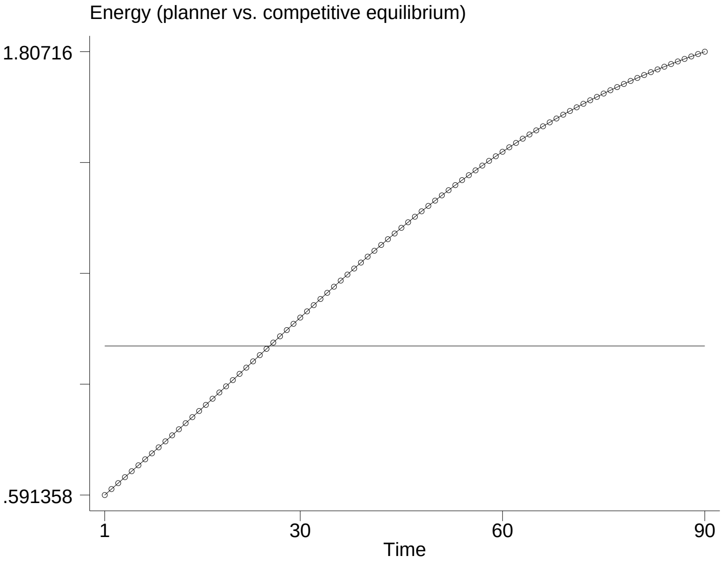
- Assume a finite horizon T.
- Guess on an energy sequence that hits the balanced-growth path at T .
- Use the consumption-savings condition to "shoot" a path for capital that hits the balanced-growth path at T.
- Use the climate externality condition to determine a sequence of multipliers.
- Use the energy choice condition to "shoot" a path for energy that hits the balanced-growth path at T.
- Rinse. Lather. Repeat.



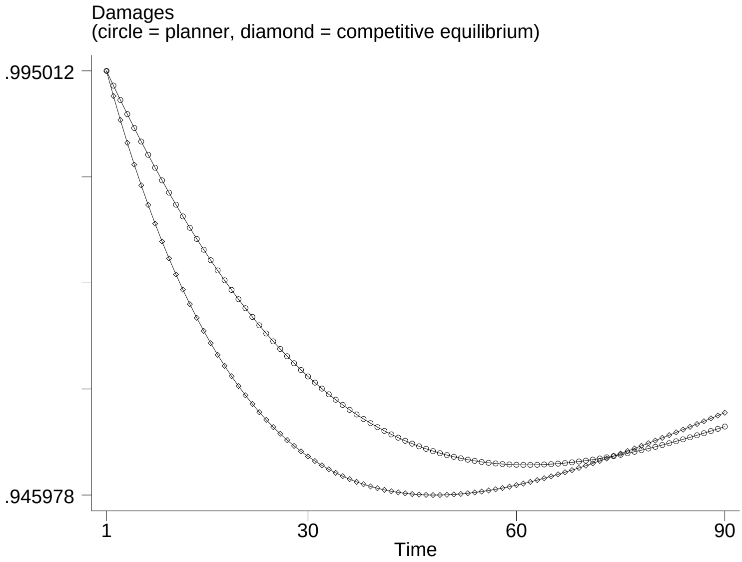
Output (planner vs. competitive equilibrium)
1.05208
.973971
1
30
60
90
Time



Consumption (planner vs. competitive equilibrium)
1.03936
.983709
1
30
60
90
Time



Energy (planner vs. competitive equilibrium)
1.80716
.591358
1
30
60
90
Time


Damages
(circle = planner, diamond = competitive equilibrium)
.995012
.945978
1
30
60
90
Time

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 $b_i = B_i$):

$$-U_C(B_0 - B_1) + \beta V_C(B_1, M_1) = 0.$$

- Planner's f.o.c. (internalizes externality):

$$-U_C(B_0 - B_1) + \beta V_C(B_1, M_1) - \beta V_M(B_1, M_1) = 0.$$

- 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).