A Global Economy-Climate Model with High Regional Resolution

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WORK-IN-PROGRESS!!!

Goals of the project

1. Push out the frontier in “integrated-assessment” modelling.
2. Build a quantitative model of global economy-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.

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 of the consumer/entrepreneur in region i: $E_0 \sum_{t=0}^{\infty} \beta^t U(c_{it})$, where c_{it} is consumption expenditures.
- Technology: $y_{it} = a_{it} \cdot z_{it} \cdot (1 - G_i(T_{it})) \cdot F(k_{it}, e_{it})$, where: y_{it} is regional GDP; k_{it} is the physical capital stock; e_{it} is energy; a_{it} is the long-run trend in total factor productivity (TFP); and z_{it} is an idiosyncratic shock to TFP.
- $G_i(T_{it})$ captures economic "damages" associated with regional (atmospheric) temperature T_{it}.

The climate system

- Following Nordhaus, there are 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:

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

Markets

- Carbon energy, a non-renewable resource, is produced (extracted) by competitive risk-neutral firms and bought and sold in a worldwide competitive market.
- No extraction costs (for simplicity).
- No international markets for physical capital; installed capital is immobile.
- Labor supply is fixed.
- Intertemporal trade: regions are endowed with shares in energy firms which they can trade in a competitive worldwide market (equivalent to trading a risk-free bond).
- Each region has a nontrivial portfolio problem: invest in its own physical capital and/or take a position in the worldwide bond market (subject to a region-specific borrowing constraint).

Government

- Each region belongs to a “country” (or larger political unit).
- The government of each country imposes a (country-specific) tax on regional GDP and rebates the aggregate revenues in a lump sum to balance its budget.
- The government thereby provides (incomplete) insurance against weather (and other) shocks.
- Straightforward to introduce other government policies, such as carbon taxes or cap-and-trade markets for carbon emissions.

Dynamic program of a typical region

- Region-specific state variables: wealth ω and TFP (a and z).
- $\Lambda \equiv (M_A, M_U, M_L, T_A, T_S, \Gamma, R)$, where R is the stock of energy and Γ is the (worldwide) distribution over (ω, a, z).
- $v(\omega, z, \Lambda) = \max_{k', s'} \left[U(c) + \beta E_{T', z' | \Lambda, z} \, v(\omega', z', \Lambda') \right]$, s.t.

$$
\begin{aligned}
c &= \omega - k' - s' \, \Pi \\
\omega' &= (1 - \tau) \max_{e'} \left[a' \, z' \, (1 - G(T')) F(k', e') - P' e' \right] + \\
&\quad (1 - \delta) k' + s' (\Pi' + P' E') + X' \\
s' &\geq \underline{s} \\
\Lambda' &= H(\Lambda)
\end{aligned}
$$

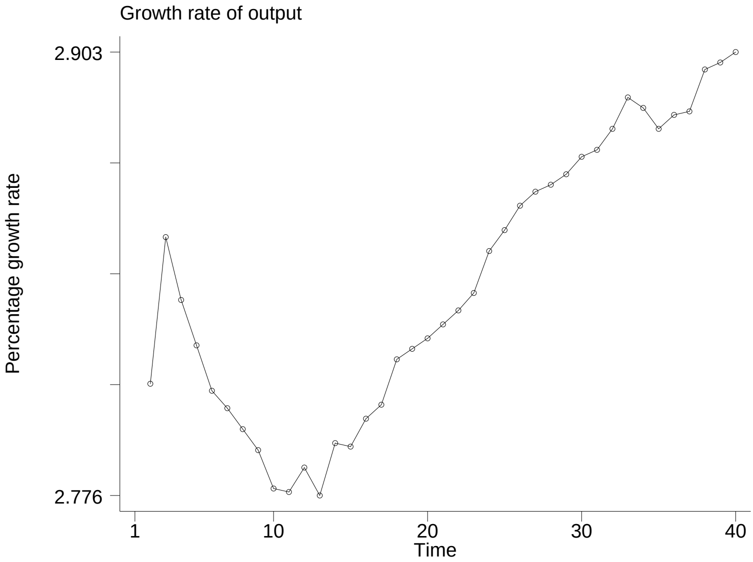
and stochastic processes for T' and z'.

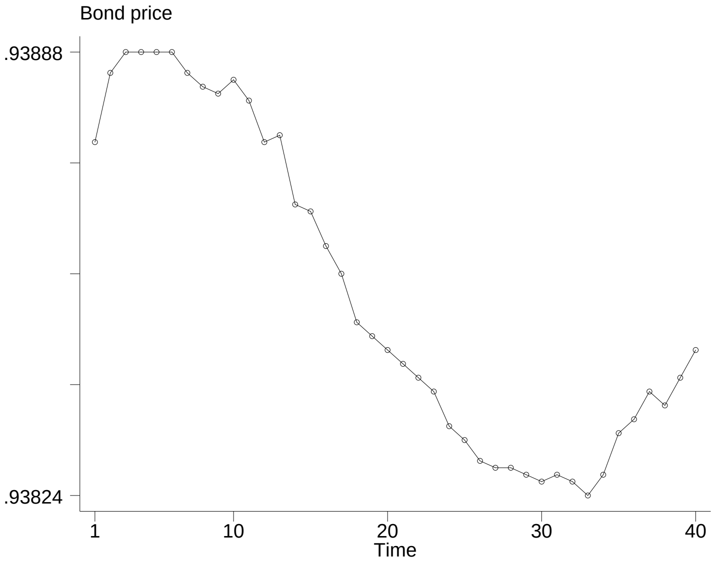
Test case

- Ex-ante identical regions with Cobb-Douglas production.
- TFP shocks only (no weather shocks); shocks uncorrelated across regions.
- Long-run trend in TFP is common across all regions.
- Single stock of (atmospheric) carbon that "depreciates" at a constant rate.
- Damage function depends directly on stock of carbon.
- No government.
- Dasgupta-Heal meets Castro-Covas-Angeletos: if the rate of technological progress is large enough, the global economy converges to a steady state (a balanced-growth path) in which output (GDP) and consumption grow at a constant rate, energy use shrinks at a constant rate, and the distribution over regions replicates itself.
- Goal: compute equilibrium transition path.

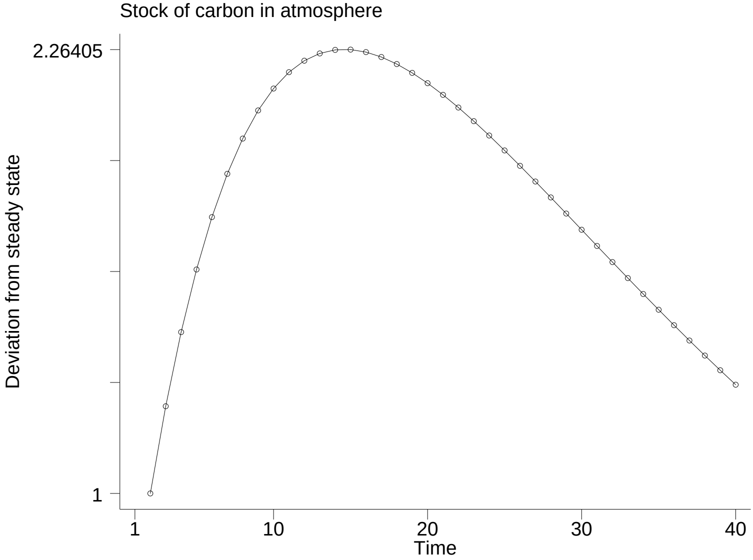
The computational algorithm (we can do it!)

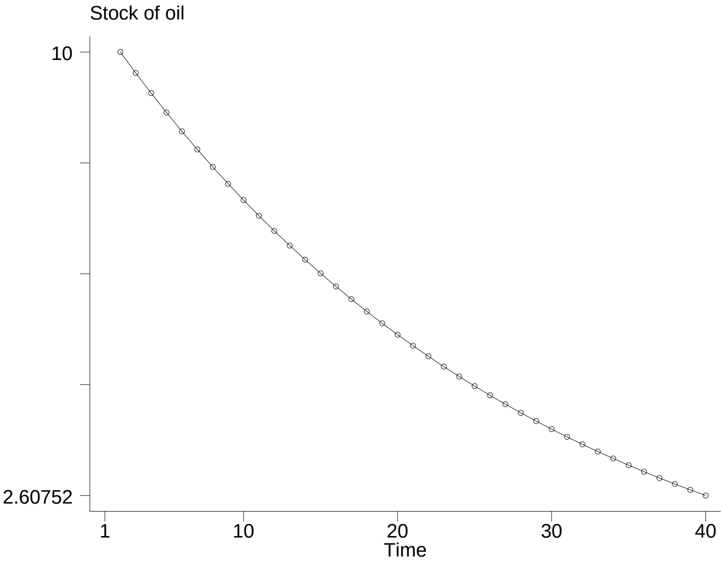
1. Pick a horizon T beyond which the economy is on the balanced-growth path with negligible damages from climate.
2. Guess on $\tilde{P}_0$, where $\tilde{P}_t$ is the value of the stock of energy as a fraction of total wealth in period t.
3. Guess on sequences for the growth rate of output, the interest rate, and energy use as a fraction of the stock of energy.
4. Use the Hotelling condition to get the energy price sequence and the climate system to generate the carbon stock sequence.
5. Compute (time-varying) decision rules backwards from T.
6. Simulate the distribution over regions forwards, adjusting the interest rate to clear the market for shares at each t.
7. Update sequences from step 3 and iterate to convergence.
8. Check that energy use in period T is on the balanced growth path; if not, update $\tilde{P}_0$.

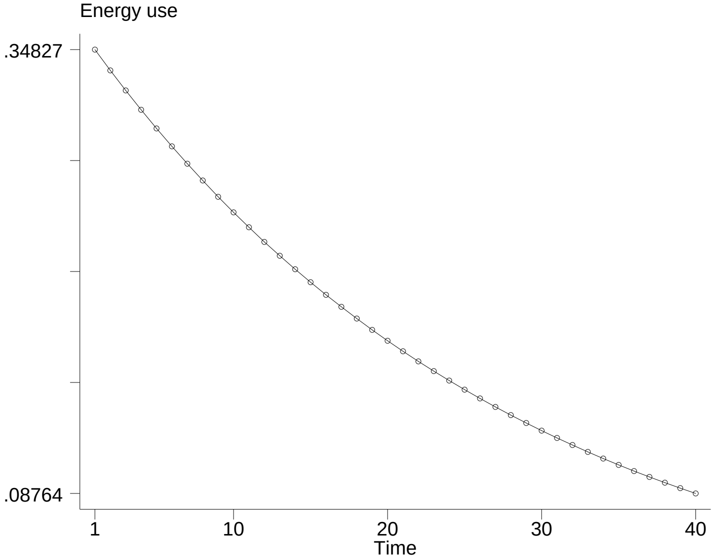

Growth rate of output
2.903
2.776
Percentage growth rate
1
10
20
30
40
Time

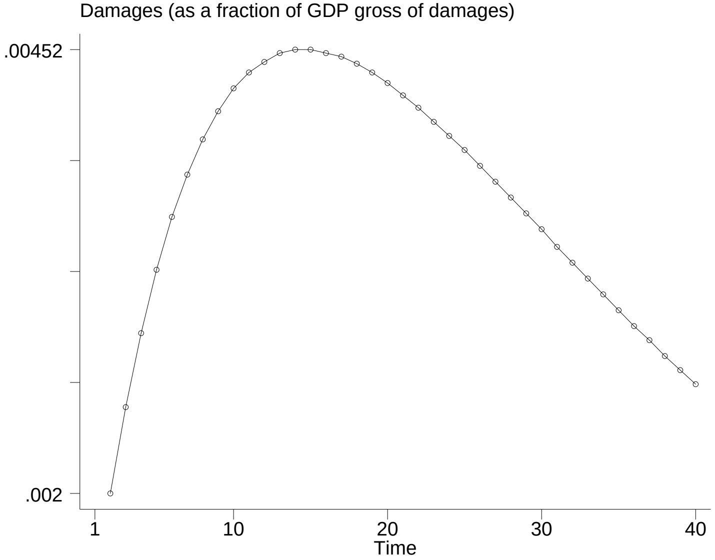


Bond price
.93888
.93824
1
10
20
30
40
Time


Stock of carbon in atmosphere
Deviation from steady state
2.26405
1
1
10
20
30
40
Time


Stock of oil
10
2.60752
1
10
20
30
40
Time


Energy use
.34827
.08764
1
10
20
30
40
Time



Damages (as a fraction of GDP gross of damages)
.00452
.002
1
10
20
30
40
Time

Regional detail: calibration

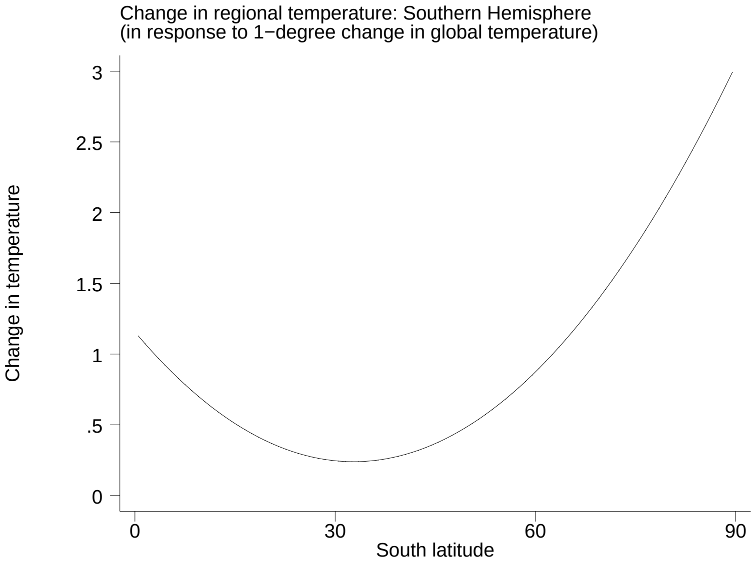
- Geographical structure: $\sim 20,000$ "regions" defined by $(1^\circ \times 1^\circ)$ cells superimposed on the (terrestrial parts of the) globe.
- First task: characterize relationship between regional and global temperature. Use Matsuura and Willmott gridded $(0.5^\circ \times 0.5^\circ)$ annual terrestrial temperature data for 1900–2008.
- Second task: characterize relationship between regional GDP and regional temperature. Use Nordhaus's G-Econ database (gross cell product, or GCP, and population for 1990, 1995, 2000, and 2005).
- Third task: calibrate damage function so that the regional model replicates the relationship between GCP and temperature, given a realistic process for evolution of regional temperature.

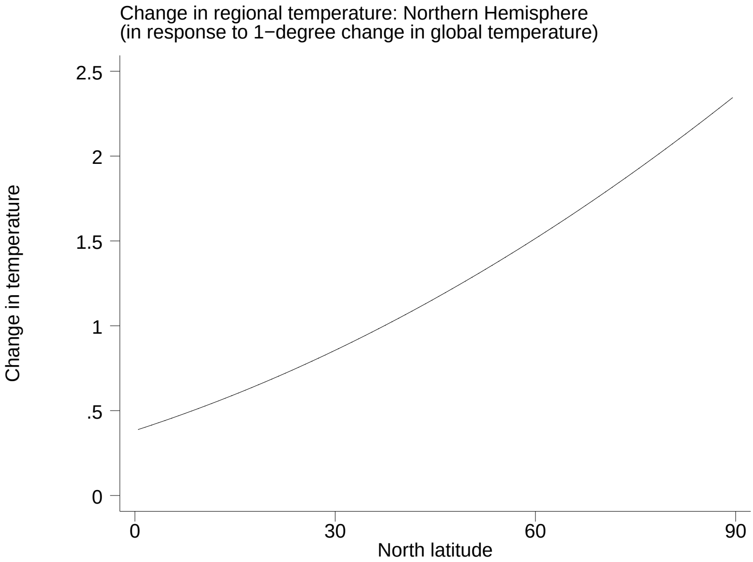
A stochastic process for regional temperature

- An exercise in (empirical) statistical downscaling.
- The downscaling model:

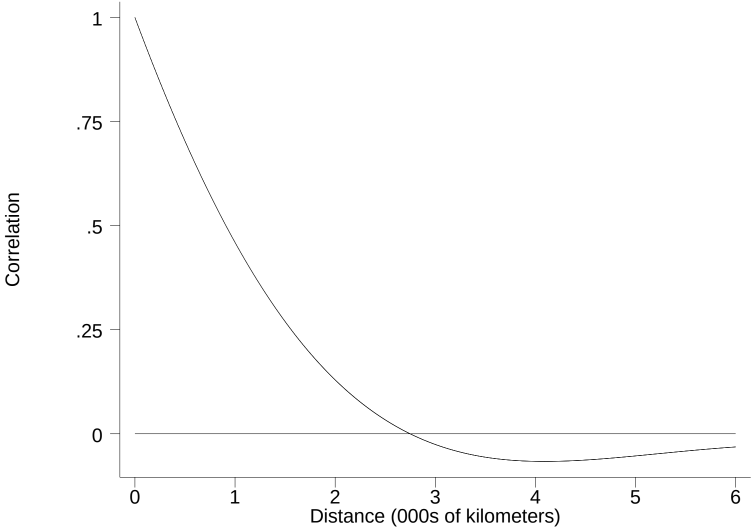
$$\begin{aligned} T_{it} &= \alpha_i + f(\ell_i; \beta) T_t + \epsilon_{it} \\ \epsilon_{it} &= \rho \epsilon_{i,t-1} + \nu_{it} \\ \text{corr}(\nu_{it}, \nu_{jt}) &= g(d(\ell_i, \ell_j); \gamma) \\ \text{var}(\nu_{it}) &= h(\ell_i; \lambda) \end{aligned}$$

- Allows for: (i) region-specific dependence of regional temperature on global temperature; (ii) autocorrelation; (iii) spatial correlation; and (iv) region-specific heteroskedasticity.
- Estimates: $\hat{\rho} = 0.42$, $\hat{\sigma}_\nu = 0.70$.


Change in regional temperature: Southern Hemisphere
(in response to 1−degree change in global temperature)
Change in temperature
3
2.5
2
1.5
1
.5
0
0
30
60
90
South latitude


Change in regional temperature: Northern Hemisphere
(in response to 1−degree change in global temperature)
Change in temperature
2.5
2
1.5
1
.5
0
0
30
60
90
North latitude

Spatial correlation of temperature shocks



Ongoing: out-of-sample process for regional temperature

- Ultimate purpose of project: assess region-specific costs/benefits of global climate change far into the future.
- How does regional temperature vary with global temperature outside of the observed historical ranges?
- One possibility: simply extrapolate.
- Another possibility: use output from climate projection models (MAGICC/SCENGEN, climateprediction.net, PCMDI at LLNL).
- Will need (ideally) thousands of runs to estimate stochastic structure of errors.

Calibrating the damage function

- Focus on economic (market) damages for now.
- Let damages be $G(T_i, \theta)$, where θ is a vector of parameters.
- Basic approach: pick θ so that the economic model reproduces both time-series (short-run) and cross-section (long-run) evidence on the relationship between regional temperature and GDP.
- Basic model allows for adaptation through reallocation of capital across regions over time: borrowing and lending across regions (subject to borrowing constraints) provides a channel for aligning expected marginal products of capital across regions.
- First pass on calibrating the model: do not endogenize global temperature but instead simply use a path "predicted" by a climate projection model (also omit energy as an explicit factor of production).

Cross-sectional evidence

- Regress log GCP per capita on average regional temperature for previous decade:

$$
\begin{aligned}
y_{ij} &= y_j + \beta \bar{T}_{ij} + \text{error} \\
y_{ij} - \bar{y}_j &= \beta(\bar{T}_{ij} - \bar{\bar{T}}_j) + \text{error}
\end{aligned}
$$

- Decadal average temperature controls for climate (not just weather): in the spirit of Mendelsohn and Nordhaus's "Ricardian" approach; see also Nordhaus (2010).

	1990	1995	2000	2005
$\hat{\beta}$	-2.33	-2.03	-1.97	-2.09
s.e.	(0.05)	(0.05)	(0.05)	(0.05)
N	18679	17543	17597	17322
# countries	143	128	131	130

Panel evidence

- Follow Dell, Jones, and Olken (2009), but use $1^\circ \times 1^\circ$ cells as the unit of analysis:

$$\begin{aligned} y_{it} &= \beta T_{it} + \log(A_{it}) \\ \Delta \log(A_{it}) &= g_i + \gamma T_{it} + \text{time fixed effects} + \text{error} \end{aligned}$$

- Main Dell et al regression:

$$g_{it} = g_i + \beta \cdot \frac{T_{it} - T_{i,t-5}}{5} + \gamma \cdot 5^{-1} \sum_{j=0}^{4} T_{i,t-j} + \text{stuff},$$

  where g_{it} is average annual growth rate in GCP per capita over the last 5 years, β is a "level" effect, and γ is a "growth rate" effect.
- Captures effects of temperature "shocks".

Panel results

	$\hat{\beta}$	$\hat{\gamma}$	# cells
All cells	-1.65 (0.11)	-0.09 (0.07)	17161
Pop. $>$ 50K in 1990	-1.79 (0.24)	0.35 (0.13)	6665
Pop. $>$ 10K in 1990	-1.75 (0.19)	0.24 (0.11)	9736
High income in 1990	-1.81 (0.12)	-0.13 (0.08)	8580
Low income in 1990	-0.58 (0.21)	1.37 (0.14)	8581
High income, pop. $>$ 50K	-3.62 (0.41)	0.42 (0.20)	2151
Low income, pop. $>$ 50K	-0.58 (0.28)	0.47 (0.18)	4514
High income, pop. $>$ 10K	-3.37 (0.29)	-0.11 (0.14)	3468
Low income, pop. $>$ 10K	-0.43 (0.24)	0.95 (0.16)	6268

Summary

- Next step (in progress!): merge model with cross-section and panel evidence.
- Start with global model in which global temperature is exogenous; then add economy-climate feedback.
- Important unresolved issue: modelling the long-run evolution of the distribution of regional TFP (for now calibrate TFP to replicate cross-sectional distribution of GCP per capita)
- Then policy experiments and more. Incorporate:
  - non-market damages;
  - additional adaptation mechanisms: migration, choice of clean vs. dirty energy;
  - political economy issues (sub-global climate-policy agreements, leakage).