A Global Economy-Climate Model with High Regional Resolution

Per Krusell
IIES, University of Göteborg, CEPR, NBER

Anthony A. Smith, Jr.
Yale University, NBER

March 2014

WORK-IN-PROGRESS!!!

An increase of two or three degrees wouldn't be so bad for a northern country like Russia. We could spend less on fur coats, and the grain harvest would go up.

VLADIMIR PUTIN, President of Russia, *World Climate Change Conference*, Moscow, 2003

Climate change is going to affect different nations to different degrees and in different ways. Unfashionable though these terms may be, there will be "winners" as well as "losers."

CAROLYN PUMPHREY, Researcher, Strategic Studies Institute, U.S. Army War College, *Global Climate Change: National Security Implications*, 2008

You may agree with — or be provoked by — these statements about climate change.

Several leading studies indicate that the systemic shocks to regional and global economies from climate change will be substantial and will worsen the longer world governments wait to take sufficient policy action.

***Global Investor Statement on Climate Change*, 2010**

Overall goals of the paper

1. Push out the frontier in "integrated-assessment" modelling (beyond Nordhaus's DICE and RICE).
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., trade and insurance).
3. Use the model to provide quantitative evaluations of the distributional effects of climate-related policies.
4. Study the effects of heterogeneous policy (differential carbon taxes or differential tariffs on "carbon content").

Outline

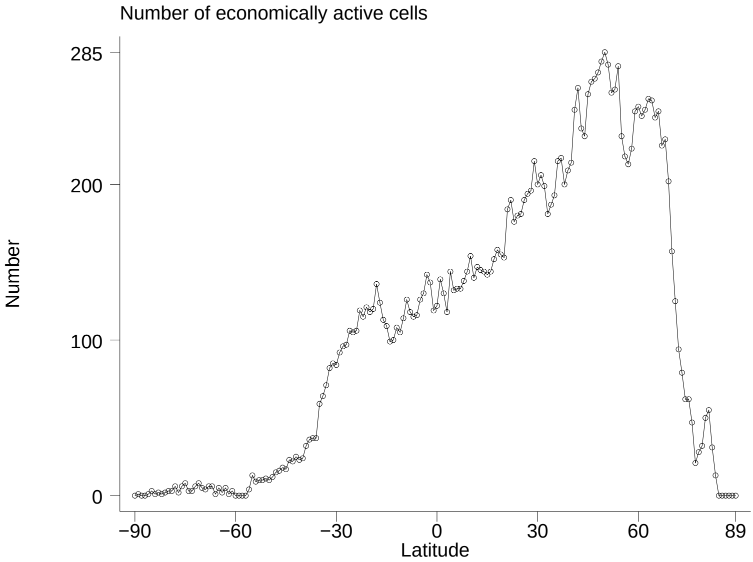
- Regional data on GDP and temperature.
- A baseline model with (exogenous) temperature shocks.
- Calibration and results.
- The model with economy-climate feedback.
- Calibration and results.
- Tax experiments.
- Future steps.

Weather and climate

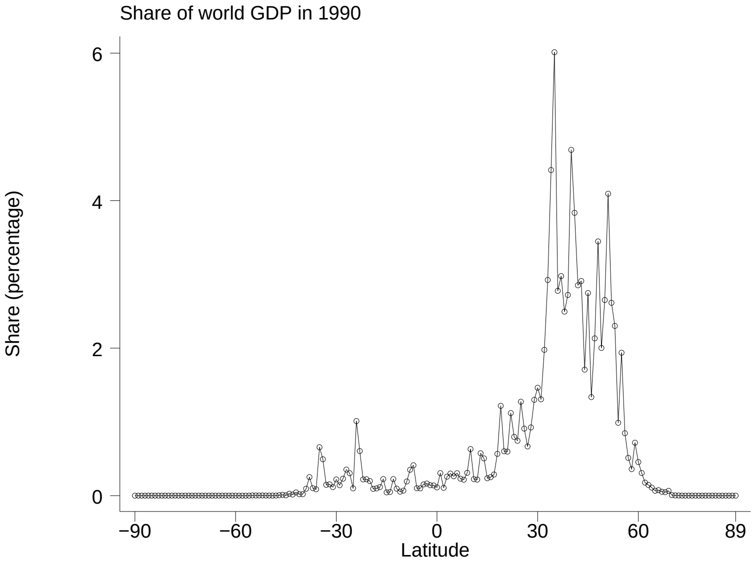
- Weather: stochastic fluctuations in temperature around a trend.
- Climate: the average of weather.
- Secular trends in climate stemming from carbon emissions.
- Cyclical and secular movements in temperature both affect economic outcomes (via changes in total factor productivity, or TFP).
- First incorporate weather, then add climate.
- To be completed: secular trend in the *variance* of shocks to temperature.

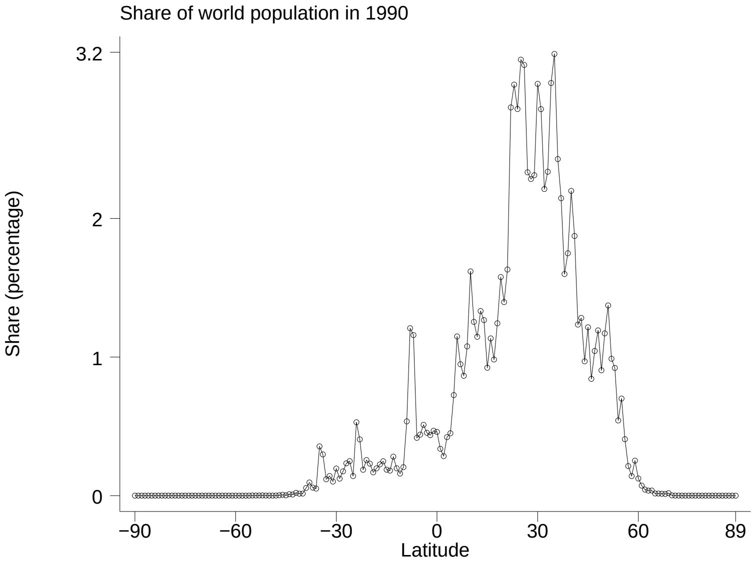
Geographical structure

- Nordhaus's G-Econ database: GDP and population for all such cells in 1990, 1995, 2000, and 2005.
- $\sim 17,000$ cells are economically active and $\sim 2,000$ of these include more than one country. The economic model then has $\sim 19,000$ "regions" (or cell-countries).
- The unit of analysis is a $1^\circ \times 1^\circ$ cell containing land.
- Matsuura and Willmott: gridded $(0.5^\circ \times 0.5^\circ)$ annual terrestrial temperature data for 1900–2008, aggregated to $\sim 25,000$ $1^\circ \times 1^\circ$ cells.

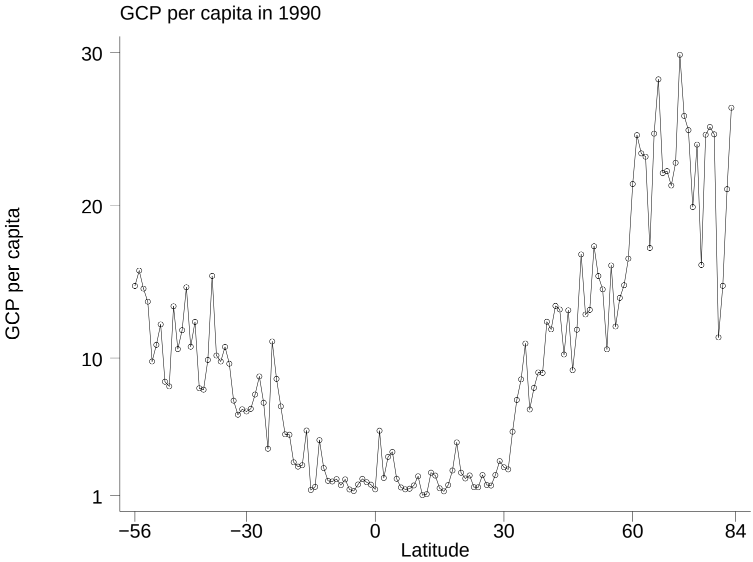


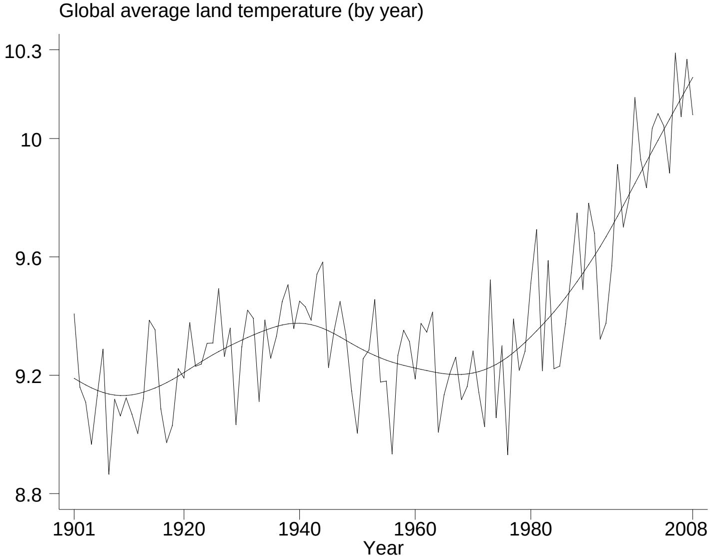
Number of economically active cells
Number
285
200
100
0
−90
−60
−30
0
30
60
89
Latitude


Share of world GDP in 1990
Share (percentage)
6
4
2
0
−90
−60
−30
0
30
60
89
Latitude



Share of world population in 1990
Share (percentage)
3.2
2
1
0
−90
−60
−30
0
30
60
89
Latitude


GCP per capita in 1990
GCP per capita
30
20
10
1
−56
−30
0
30
60
84
Latitude



Global average land temperature (by year)
10.3
10
9.6
9.2
8.8
1901
1920
1940
1960
1980
2008
Year

Regional GDP and temperature: panel evidence

- Follow Dell, Jones, and Olken (2009), but use cells rather than countries as the unit of analysis:

$$\begin{aligned} y_{it} &= \phi_1 T_{it} + \log(A_{it}) \\ \Delta \log(A_{it}) &= g_i + \phi_2 T_{it} + \text{time fixed effects} + \text{error} \end{aligned}$$

- Main Dell et al regression:

$$g_{it} = g_i + \phi_1 \cdot \frac{T_{it} - T_{i,t-5}}{5} + \phi_2 \cdot 5^{-1} \sum_{j=0}^{4} T_{i,t-j} + \text{stuff},$$

  where g_{it} is average annual growth rate in GDP per capita over the last 5 years.
- ϕ_1 is a "level" effect and ϕ_2 is a "growth-rate" effect.
- Captures effects of temperature "shocks", not changing climate.

Panel results

	$\hat{\phi}_1$	$\hat{\phi}_2$	# cells
All cells	-1.65 (0.11)	-0.09 (0.07)	17181
Pop. $>$ 50K in 1990	-1.79 (0.24)	0.35 (0.13)	6665
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

A global equilibrium model with shocks to temperature

- Temperature shocks are embedded in a global macroeconomic model that builds on:
  1. Bewley-Huggett-Aiyagari: a continuum of "regions", or points on the globe, hit by shocks and interacting in limited financial markets; and
  2. Castro-Covas-Angeletos: each region is an "entrepreneur" endowed with a (region-specific) production technology.
- Preferences of the consumer/entrepreneur in region i: $\mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t U(c_{it})$, where c_{it} is consumption expenditures.
- Technology: $y_{it} = \exp(-\theta z_{it}) F(k_{it}, A_{it} L_{it}, e_{it})$, where: y_{it} is GDP; k_{it} is the physical capital stock; e_{it} is (carbon) energy in coal equivalents; and A_{it} is labor productivity.
- θ captures economic "damages" caused by deviations, z_{it}, of regional temperature from its expected value.
- A_{it} grows at a constant rate; the vector $\{z_{it}\}$ is stochastic.

Markets

- Capital flows with a one-year lag subject to (regional) restrictions on borrowing.
- Labor supply is fixed and immobile.
- No equity or insurance markets, but regions can self-insure by trading a risk-free bond in a global market.
- Each region has a nontrivial portfolio problem: invest in its own physical capital and/or take a position in the bond market.
- Energy is produced at a constant marginal cost, which equals the price of energy in a perfectly competitive global energy market.
- *Remark*: The model allows for adaptation in the form of movements of resources in response to productivity differences across regions (and it allows for "leakage" in response to differential carbon policy).

Dynamic program of a typical region

- *Region-specific* state variables: wealth, ω; trend in productivity, A; regional temperature shock, z. *Aggregate* state variables: global capital, $\bar{k}$; (weighted) average temperature shock, $\bar{z}$.
- $v(\omega, z, A, \bar{k}, \bar{z}) =$
  $\max_{k',b'} \left[U(c) + \beta \mathbf{E}_{z',\bar{z}'|z,\bar{z}}\, v(\omega', z', A', \bar{k}', \bar{z}')\right]$, subject to:

$$
\begin{aligned}
c &= \omega - k' - q(\bar{k}, \bar{z})b' \\
\omega' &= \max_{e'} \left[\exp(-\theta z')\, F(k', A', e') - pe')\right] + (1-\delta)k' + b' \\
A' &= (1+g)A \\
b' &\geq \underline{b}(k') \\
\bar{k}' &= H(\bar{k}, \bar{z})
\end{aligned}
$$

and a conditional distribution for $(z', \bar{z}')$ given $(z, \bar{z})$.

Approximate aggregation

- Definition of equilibrium: the bond-pricing function q clears the bond market and the optimal decisions of the regions generate H and the density $f(\bar{z}'|\bar{z})$.
- Use global capital and (weighted) average shock as state variables rather than full joint distribution over capital and shocks.
- Use algorithm from Krusell and Smith (1997): guess on (q, H, f); solve for decision rules; simulate evolution of the distribution, allowing the bond price to deviate in each period from the bond pricing function so as to clear the bond market; update guesses for (q, H, f).
- In the calibrated economy, regions can make very accurate forecasts of current and future interest rates (and global energy emissions) using the limited set of state variables.

Calibration

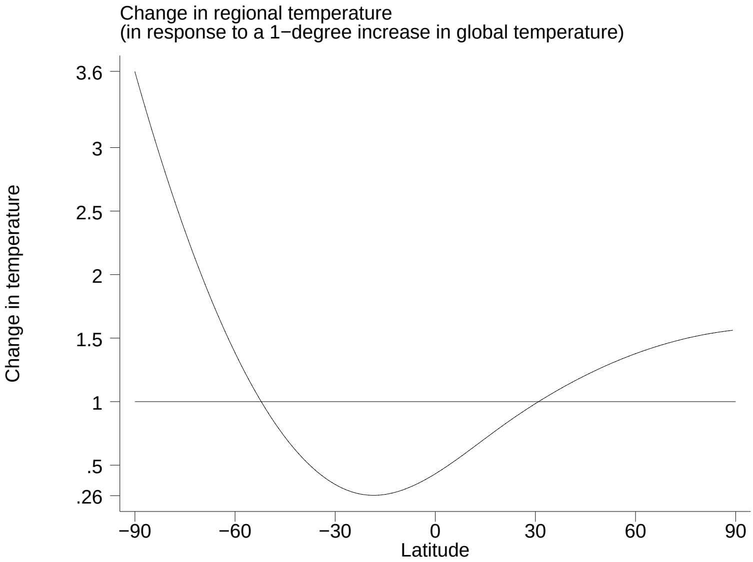
- Annual model with log period utility.
- Discount factor of 0.985 and annual depreciation rate of 10%.
- Can borrow up to $\underline{b}(k') = \gamma(\delta - 1)k'$; set $\gamma = 0.1$.
- Production function is CES in $k^{\alpha}(AL)^{1-\alpha}$ and Be, with elasticity 0.1.
- Annual growth rate of labor-augmenting productivity is 1%.
- Initial distribution of region-specific capital and level of productivity chosen to: (1) match regional GDP per capita in 1990 and; (2) equalize the marginal product of capital across regions.
- Price of "coal" and B chosen to match: (1) total carbon emissions in 1990; and (2) energy share of 5% along a balanced growth path.

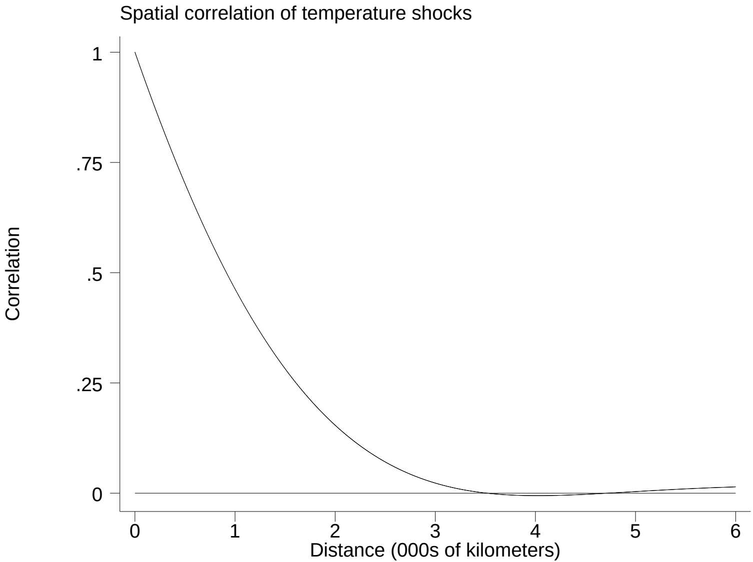
A stochastic process for regional temperature

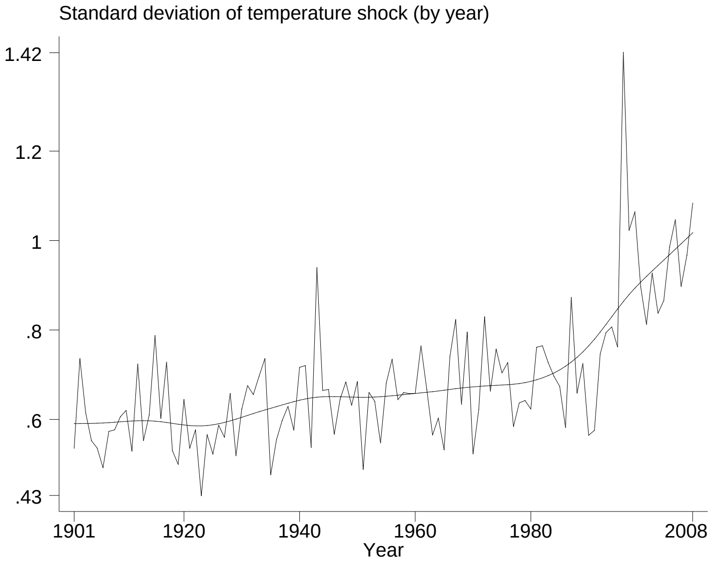
- Use gridded temperature data to estimate a stochastic process for regional temperature.
- An exercise in (empirical) statistical downscaling.
- The downscaling model:

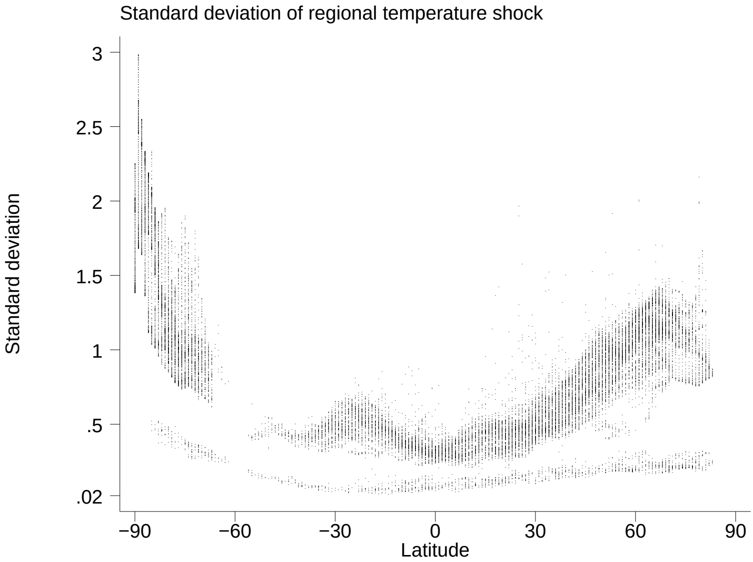
$$
\begin{aligned}
T_{it} &= \bar{T}_i + f(\ell_i; \psi_1) T_t + z_{it} \\
z_{it} &= \rho z_{i,t-1} + \nu_{it} \\
\mathrm{var}(\nu_{it}) &= \sigma_\nu^2 \\
\mathrm{corr}(\nu_{it}, \nu_{jt}) &= g(d(i,j); \psi_2)
\end{aligned}
$$

- Allows for: (i) region-specific dependence of regional temperature on global temperature; (ii) autocorrelation; and (iii) spatial correlation.
- Estimates: $\hat{\rho} = 0.41$, $\hat{\sigma}_\nu = 0.72$.


Change in regional temperature
(in response to a 1−degree increase in global temperature)
Change in temperature
3.6
3
2.5
2
1.5
1
.5
.26
−90
−60
−30
0
30
60
90
Latitude


Spatial correlation of temperature shocks
Correlation
1
.75
.5
.25
0
0
1
2
3
4
5
6
Distance (000s of kilometers)


Standard deviation of temperature shock (by year)
1.42
1.2
1
.8
.6
.43
1901
1920
1940
1960
1980
2008
Year


Standard deviation of regional temperature shock
Standard deviation
3
2.5
2
1.5
1
.5
.02
−90
−60
−30
0
30
60
90
Latitude

Evidence of ARCH in temperature shocks

- In a pooled regression, coefficient on the lagged squared temperature residual in an ARCH(1) model is 0.34.

Calibrating the damage parameter

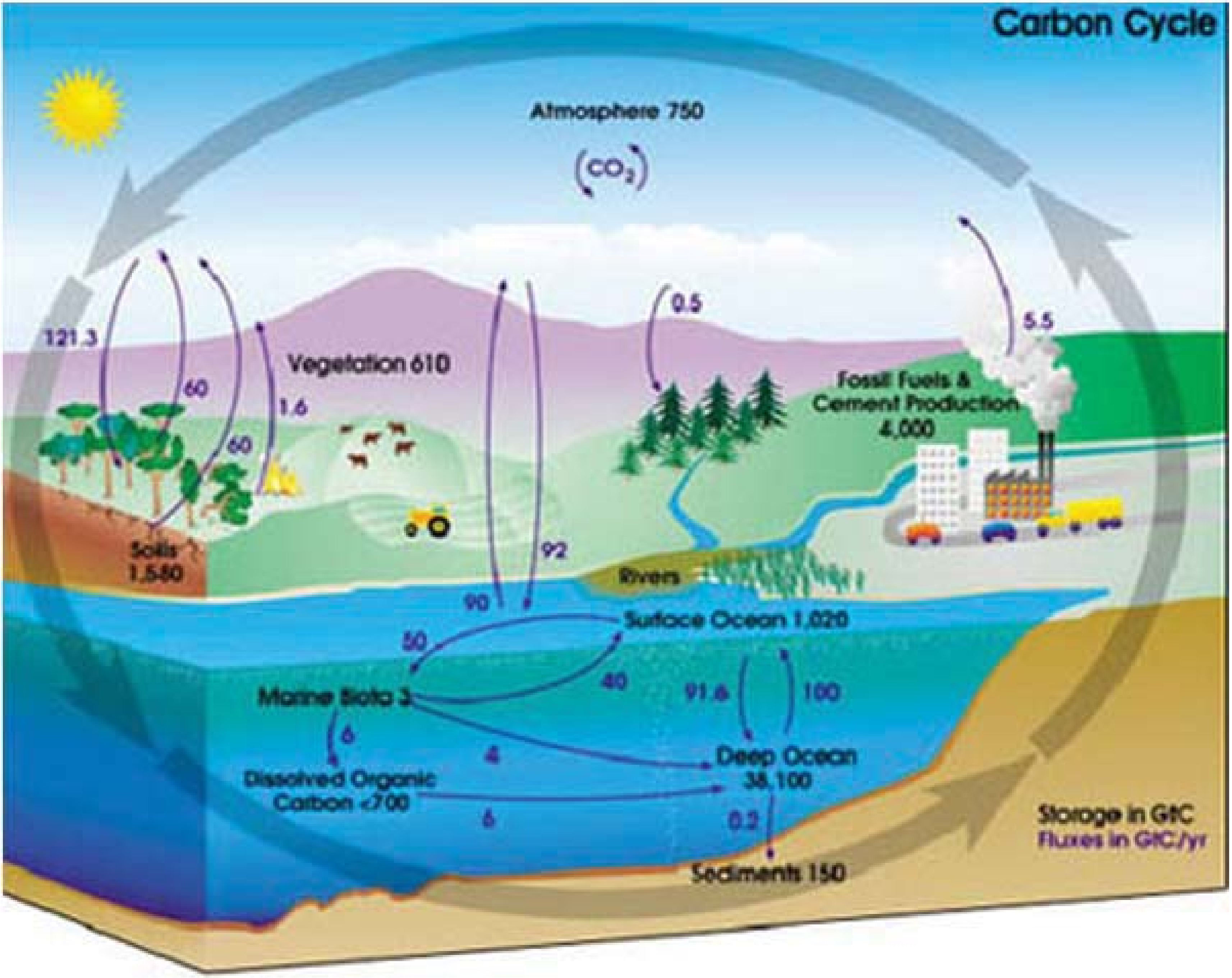
- Use indirect inference (a way of implementing of simulation estimation).
- Choose θ so that simulated data from the equilibrium model replicates the regression coefficients in the panel regressions using the observed data on GDP and temperature at the regional level.
- Result: $\hat{\theta} \approx 0.02$—a 1-degree shock to temperature reduces TFP (temporarily) by 2%.
- Regression coefficients from the model: $\hat{\phi}_1 = -1.72\%$ (level effect), $\hat{\phi}_2 = -0.27\%$ (growth-rate effect); compare to -1.65% and -0.09% in the observed data.
- Future work: allow θ to vary across different types of regions.

Aggregate fluctuations from idiosyncratic shocks

- GDP is highly concentrated spatially: top 1% of regions (192 cells) produce 44% of world GDP; top 15% of regions (2840 cells) produce 90% of world GDP.
- Temperature shocks are correlated in space.
- Implication: using the calibrated damage parameter, regional temperature shocks produce aggregate fluctuations in world GDP (and in the world interest rate): coefficient of variation of world GDP is 0.5%.

The climate-economy model

- Global temperature (as a deviation from preindustrial level) is given by:
$$T = \lambda \frac{\log(S/\bar{S})}{\log 2},$$
where S is the stock of carbon in the atmosphere and λ is "climate sensitivity" (we set $\lambda = 3$).
- Introduce feedback from carbon emissions to economic activity: $S \to T \to$ TFP via a Nordhaus-style "damage" function, $G(T)$:
$$G(T) = \frac{1}{1 + 0.00284\,T^2}.$$
- The stock of carbon evolves according to the physical laws of the carbon cycle. At some known time in the future (140 years), "green" energy replaces carbon energy.


Carbon Cycle
Atmosphere 750
CO2
121.3
60
60
1.6
Vegetation 610
Soils
1,580
90
92
0.5
5.5
Fossil Fuels &
Cement Production
4,000
Rivers
Surface Ocean 1,020
50
40
Marine Biota 3
91.6
100
6
4
Deep Ocean
38,100
Dissolved Organic
Carbon <700
6
0.2
Sediments 150
Storage in GtC
Fluxes in GtC/yr

A simple model of the carbon cycle

- The total stock of atmospheric carbon, S_t, is the sum of a permanent stock, S_{1t}, and a (slowly) depreciating stock, S_{2t}: $S_t = S_{1t} + S_{2t}$.
- $S_{1t} = 0.25E_t + S_{1,t-1}$, where E_t is total carbon emissions.
- $S_{2t} = 0.36(1 - 0.25)E_t + 0.998S_{2,t-1}$.
- Half-life of a freshly-emitted unit of carbon is 30 years; half-life of the depreciating stock (given no new emissions) is 300 years.

Dynamic program of a typical region with feedback

- Two new *aggregate* state variables: current carbon stocks.
- $v_t(\omega, z, A, \bar{k}, \bar{z}, S_1, S_2) =$
  $\max_{k',b'} \left[U(c) + \beta \mathbf{E}_{z',\bar{z}'|z,\bar{z}}\, v_{t+1}(\omega', z', A', \bar{k}', \bar{z}', S_1', S_2')\right]$, s.t.

$$
\begin{aligned}
c &= \omega - k' - q_t(\bar{k}, \bar{z}, S_1, S_2) b' \\
\omega' &= \max_{e'} \left[G(f(\ell) T(S)) \exp(-\theta z')\, F(k', A', e') - pe'\right] + \\
&\quad (1-\delta)k' + b' \\
A' &= (1+g)A \\
b' &\geq \underline{b}(k') \\
\bar{k}' &= H_t(\bar{k}, \bar{z}, S_1, S_2) \\
S_1' &= \phi_1 E_{t+1}(\bar{k}', \bar{z}', S) + S_1 \\
S_2' &= \phi_2 E_{t+1}(\bar{k}', \bar{z}', S) + \phi_3 S_2
\end{aligned}
$$

and a (time-varying) conditional distribution for $(z', \bar{z}')$ given $(z, \bar{z})$.

Hard computational problem

- Heterogeneity + portfolio problem with occasionally binding borrowing constraint + aggregate uncertainty + transition.
- A recursive competitive equilibrium is a fixed point in a set of of *functions* indexed by time: $\{q_t, H_t, E_t\}$.
- Simplification #1: the “constrained” and “unconstrained” problems (nearly) separate and the constrained decision rule is (nearly) linear.
- Simplification #2: the functions $\{q_t, H_t, E_t\}$ are (nearly) linear.
- But fair to say that the computational model goes well beyond what’s been done in macro so far . . .
- . . . and solves problems (stemming from forward-looking behavior) that natural scientists do not have to face!

Imagine how much harder physics would be if electrons had feelings!

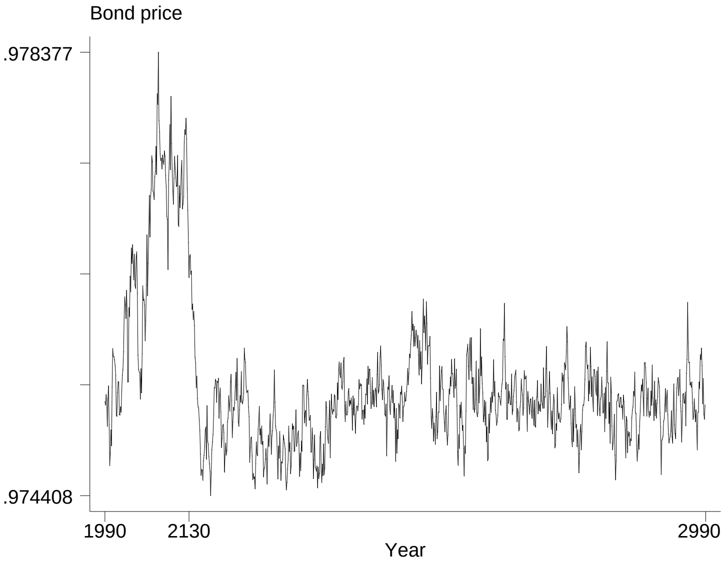
–Richard Feynman

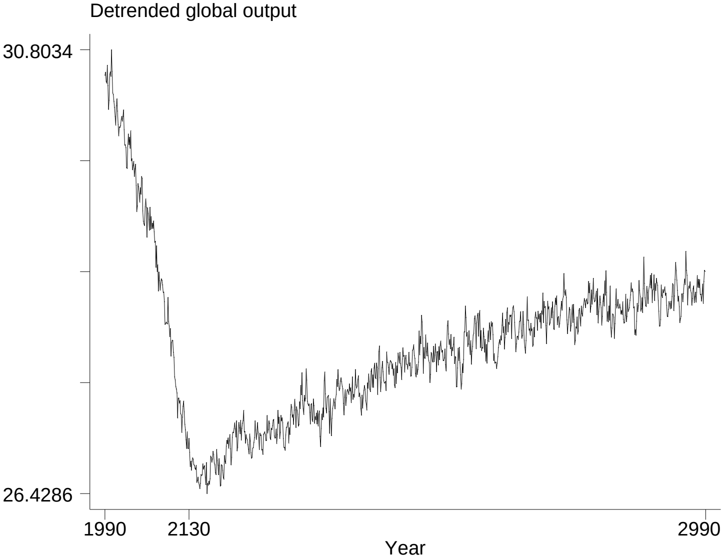
Computational algorithm

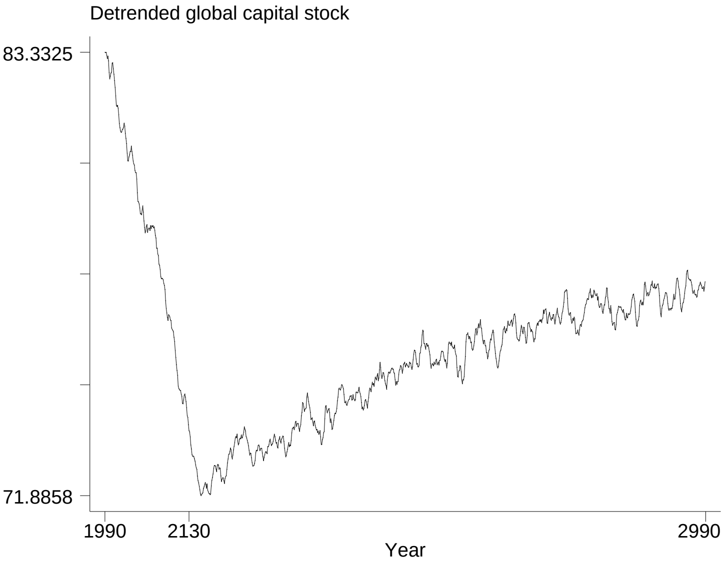
- Solve steady-state problem after total stock of carbon has settled down (at date T).
- Guess on (time-varying) coefficients of aggregate functions.
- Solve a typical's region problem backwards from T, obtaining (time-varying) decision rules.
- Simulate the global economy forwards N times.
- Use simulated data to confirm coefficients. (Perturb the distribution at each point in time to calculate estimates of slope coefficients; "connect" these over time using a spline.)
- Check forecasting accuracy of each function.

Results from computational model

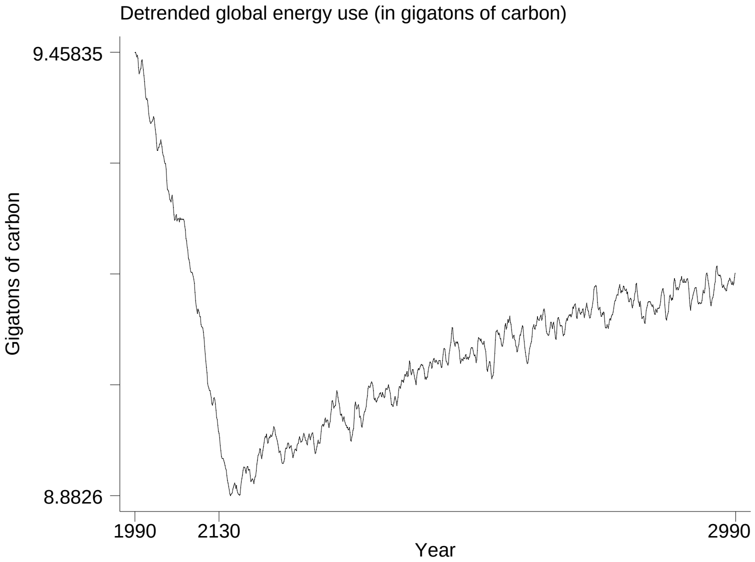
- Comparing equilibrium outcomes: one region vs. many regions.
- Distributions gains/losses in two tax experiments:
  1. All regions impose a tax on carbon emissions.
  2. Only U.S. regions impose a tax.
- To be completed:
  - Distribution of gains/losses from climate change (i.e., compare $\lambda > 0$ to $\lambda = 0$).
  - Graphs of evolution of global resource allocation (i.e., capital) under the various scenarios.


Bond price
.978377
.974408
1990
2130
2990
Year

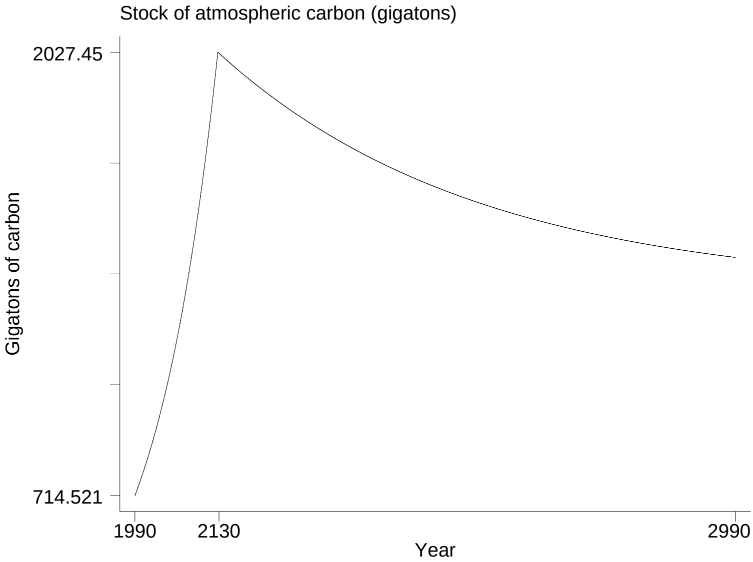

Detrended global output
30.8034
26.4286
1990
2130
2990
Year



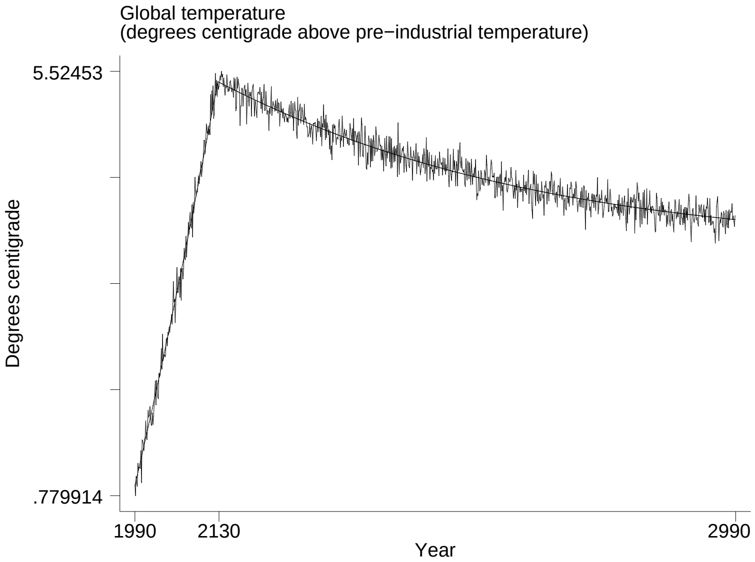
Detrended global capital stock
83.3325
71.8858
1990
2130
2990
Year

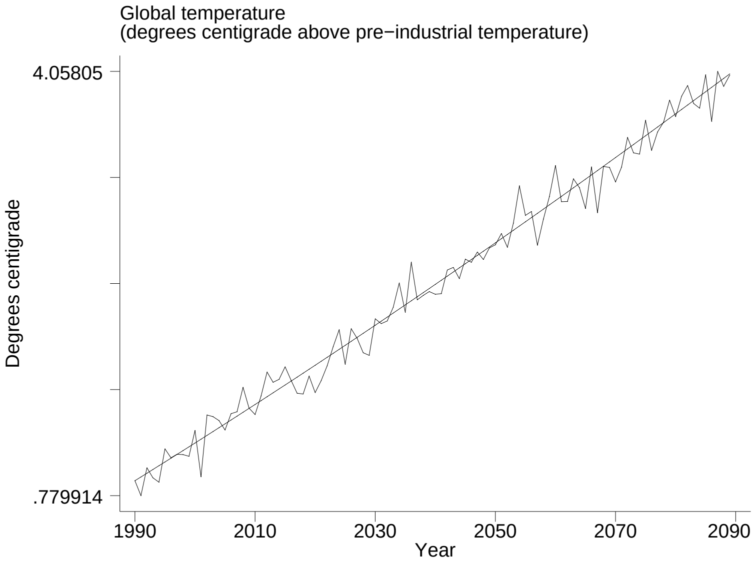


Detrended global energy use (in gigatons of carbon)
9.45835
8.8826
Gigatons of carbon
1990
2130
2990
Year

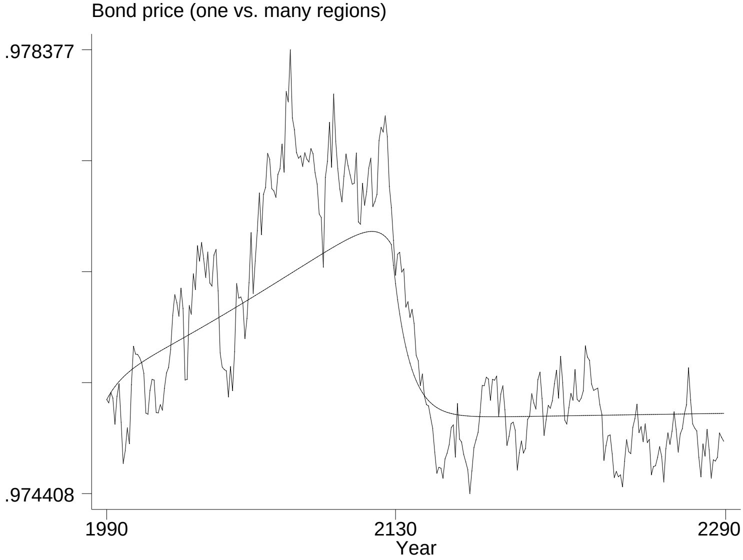


Stock of atmospheric carbon (gigatons)
Gigatons of carbon
2027.45
714.521
1990
2130
2990
Year

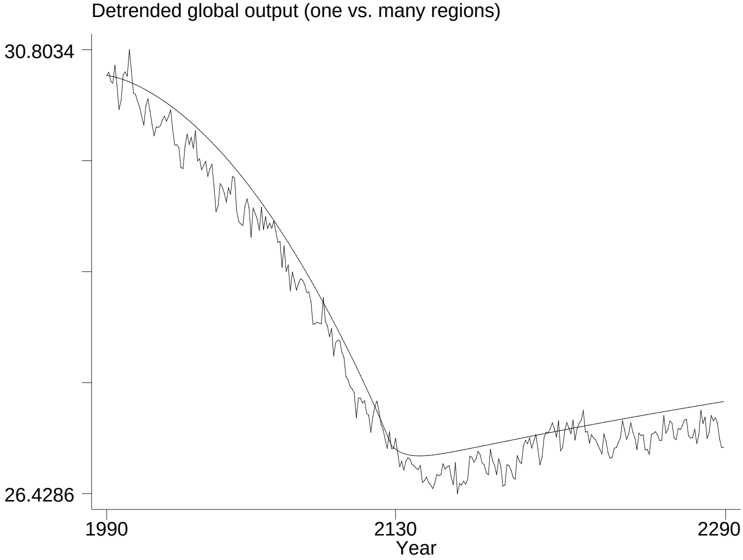

Global temperature
(degrees centigrade above pre−industrial temperature)
5.52453
.779914
Degrees centigrade
1990
2130
2990
Year

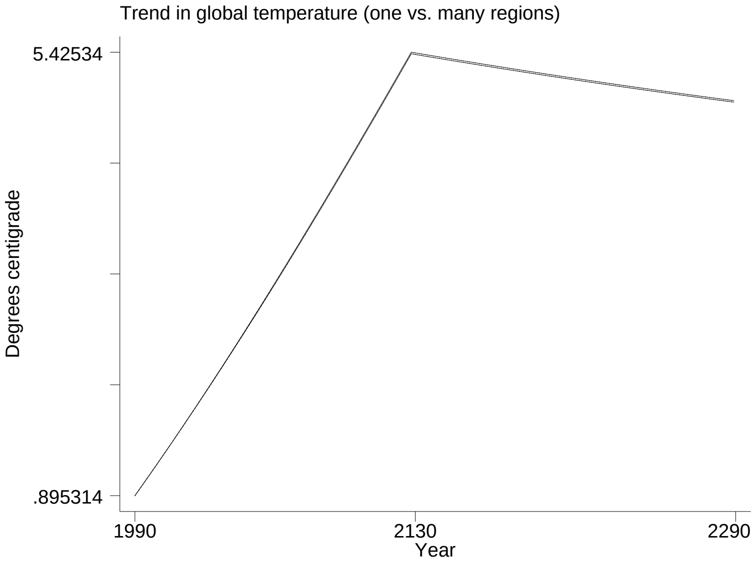


Global temperature
(degrees centigrade above pre−industrial temperature)
4.05805
.779914
Degrees centigrade
1990
2010
2030
2050
2070
2090
Year



Bond price (one vs. many regions)
.978377
.974408
1990
2130
2290
Year


Detrended global output (one vs. many regions)
30.8034
26.4286
1990
2130
2290
Year

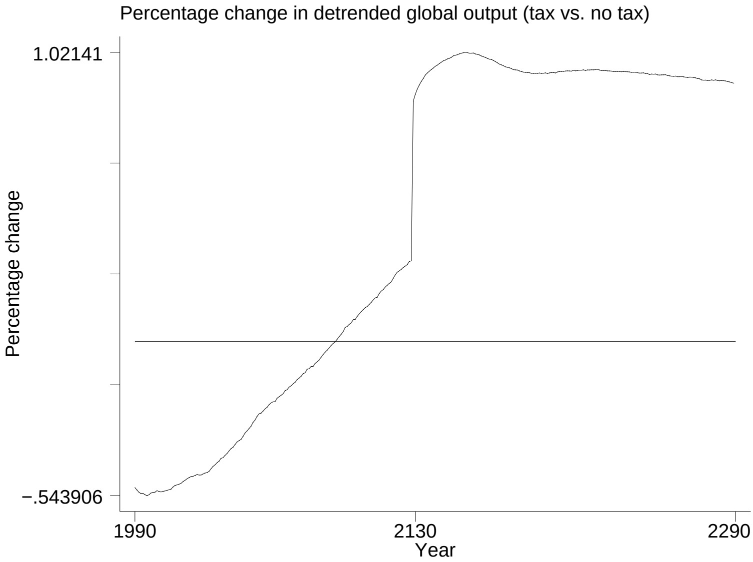

Trend in global temperature (one vs. many regions)
5.42534
.895314
Degrees centigrade
1990
2130
2290
Year

A regional tax on carbon emissions

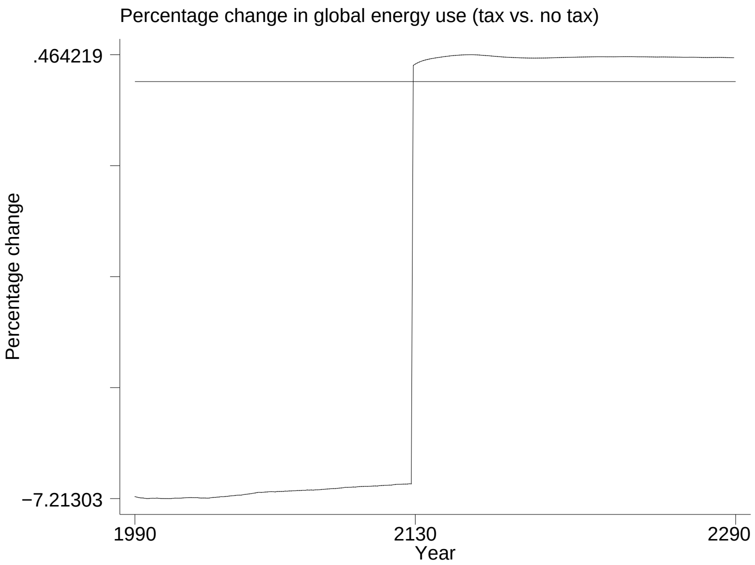
- Next-period wealth given by:

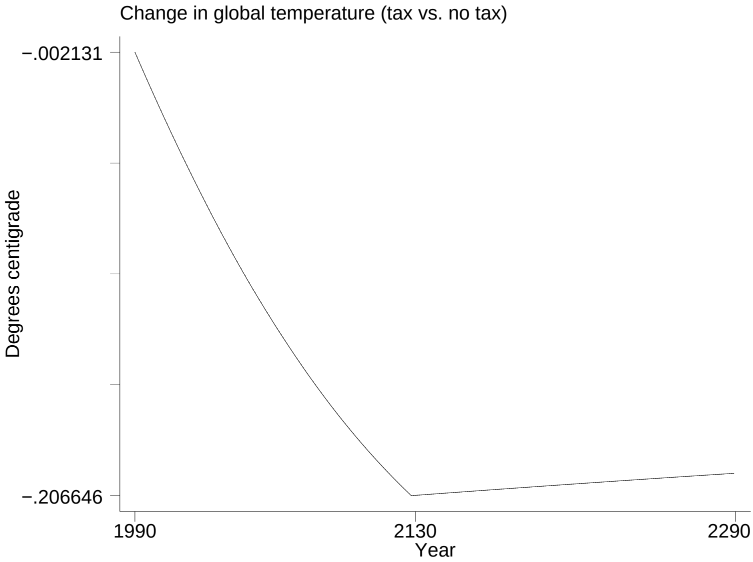
$$\max_{e'} [G(f(\ell)T(S))] \exp(-\theta z') \, F(k', A', e') - p(1+\tau)e')] + (1-\delta)k' + b + D$$

- In equilibrium, the region-specific lump-sum subsidy, D, equals total tax receipts in that region (imagine a continuum of identical entrepreneurs in each region).
- In the experiments, set $\tau = 1$, either for the whole world or just for the U.S.

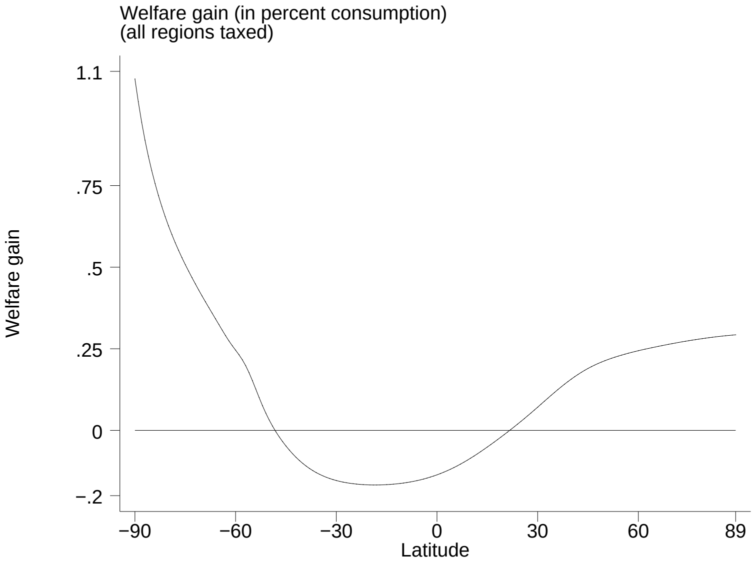


Percentage change in detrended global output (tax vs. no tax)
1.02141
−.543906
Percentage change
1990
2130
2290
Year

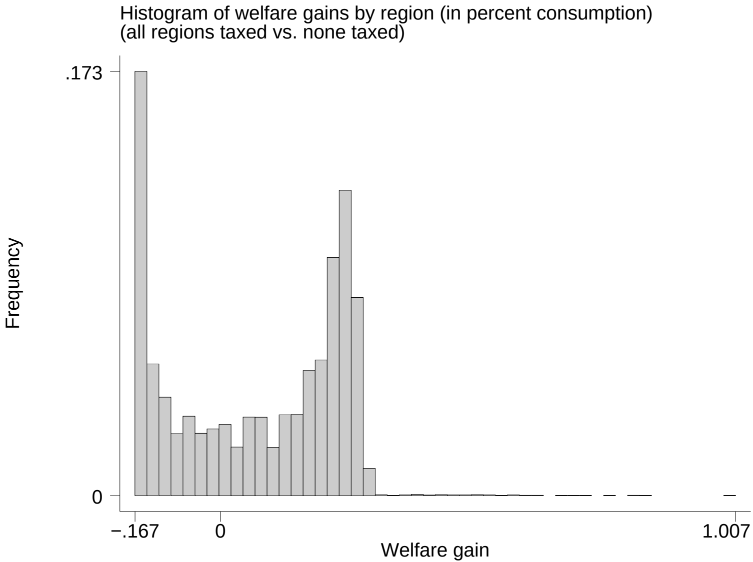

Percentage change in global energy use (tax vs. no tax)
.464219
−7.21303
Percentage change
1990
2130
2290
Year

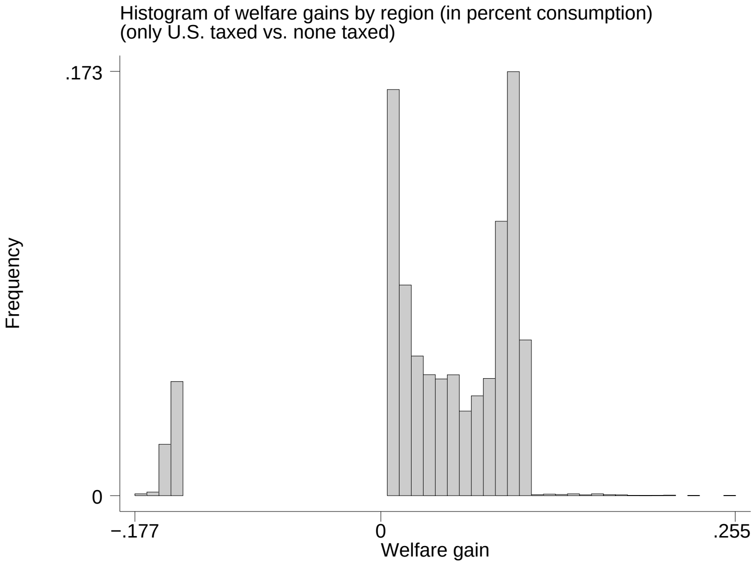


Change in global temperature (tax vs. no tax)
−.002131
−.206646
Degrees centigrade
1990
2130
2290
Year



Welfare gain (in percent consumption)
(all regions taxed)
Welfare gain
1.1
.75
.5
.25
0
−.2
−90
−60
−30
0
30
60
89
Latitude


Histogram of welfare gains by region (in percent consumption)
(all regions taxed vs. none taxed)
.173
0
Frequency
−.167
0
1.007
Welfare gain


Histogram of welfare gains by region (in percent consumption)
(only U.S. taxed vs. none taxed)
.173
0
Frequency
−.177
0
.255
Welfare gain

Summary welfare measures

- Average welfare gain across regions, all taxed vs. none taxed: 0.070%.
- Average welfare gain across regions, only U.S. taxed vs. none taxed: 0.043%.
- Population-weighted welfare gain, all taxed vs. none taxed: 0.039% (compare to 0.1% in one-region world).
- Population-weighted welfare gain, only U.S. taxed vs. none taxed: 0.041%.
- Fraction of world population gaining, all taxed vs. none taxed: 0.66.
- Fraction of world population gaining, only U.S. taxed vs. none taxed: 0.95.
- Fraction of world population gaining, only U.S. taxed vs. all taxed: 0.53

Next steps

- Introduce additional sources of heterogeneity: heteroskedastic shocks, region-specific damage functions. (Easy to parallelize computation of decision rules and simulation of multiple globes.)
- Introduce time-varying variance of temperature shocks.
- Extensions:
  - Precipitation as well as temperature.
  - Additional risk-sharing mechanisms within some groups of regions (within a country, say).
  - Additional interactions between regions: trade, migration.