A Global Economy-Climate Model with High Regional Resolution

Per Krusell
IIES (Stockholm), CEPR, NBER

Anthony A. Smith, Jr.
Yale University, NBER

March 2013

Overall 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., 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 of today's presentation

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

Geographical structure

- 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.
- 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).

Regional GDP and climate: cross-sectional evidence

- y_{ij} is log GDP per capita in a given year for region i in country j and $\bar{T}_{ij}$ is average temperature (over the past decade) in this region.
- Estimate $y_{ij} = \lambda \bar{T}_{ij} +$ country fixed effects $+$ error.
- Results (see also Nordhaus 2006):

	1990	1995	2000	2005
$\hat{\lambda}$	−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

- Central America (−1.9), Central Africa (−6.7), Central Europe (1.5), *China* (−0.1), East Africa (0.9), East Asia (−0.8), *India* (0.5), Middle East (0.4), North America (−2.5), North Africa (−1.9), *Russia* (−4.8), South America (−2.1), *South Africa* (−5.6), Southern Europe (5.5), Southeast Asia (0.9), West Africa (−0.6), Western Europe (−1.5).

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: $E_0 \sum_{t=0}^{\infty} \beta^t U(c_{it})$, 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

- No international markets for physical capital; installed capital is immobile. Labor supply is fixed.
- No state-contingent insurance markets, but regions can self-insure by trading a risk-free bond in a competitive worldwide market.
- 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 borrowing constraint).
- 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, $\bar{z}$.
- $v(\omega, z, A, \bar{k}, \bar{z}) =$
  $\max_{k',b'} \left[U(c) + \beta E_{z',\bar{z}'|z,\bar{z}}\, v(\omega', z', A', \bar{k}', \bar{z}')\right]$, subject to:

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

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

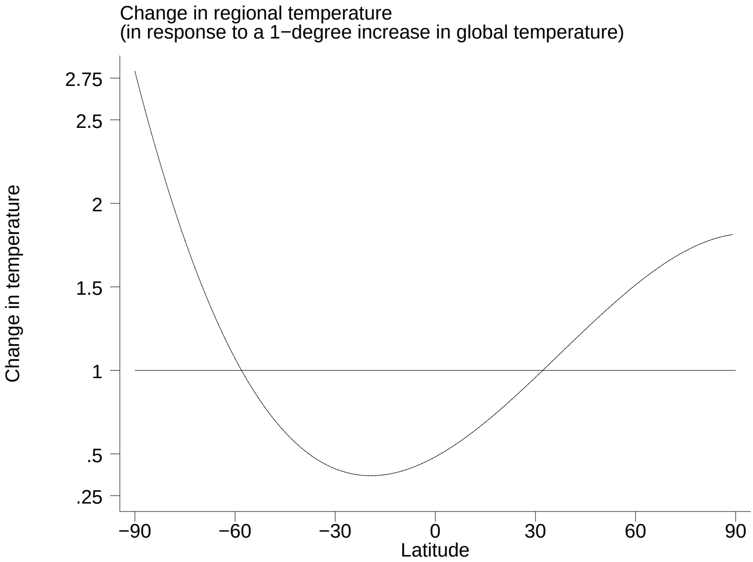
- Annual model with log period utility.
- Discount factor of 0.985 and annual depreciation rate of 10%.
- Can borrow up to $\underline{b}(k') = \gamma(\delta - 1)k'$; set $\gamma = 0.1$.
- Production function is CES in $k^{\alpha}(AL)^{1-\alpha}$ and Be, with elasticity 0.1.
- Annual growth rate of labor-augmenting 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

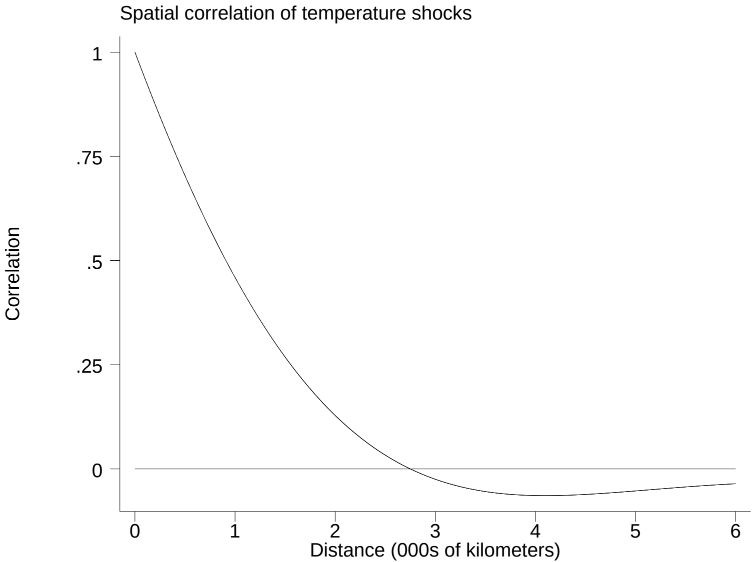
- Use gridded temperature data to estimate a stochastic process for regional temperature.
- An exercise in (empirical) statistical downscaling.
- The downscaling model:

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

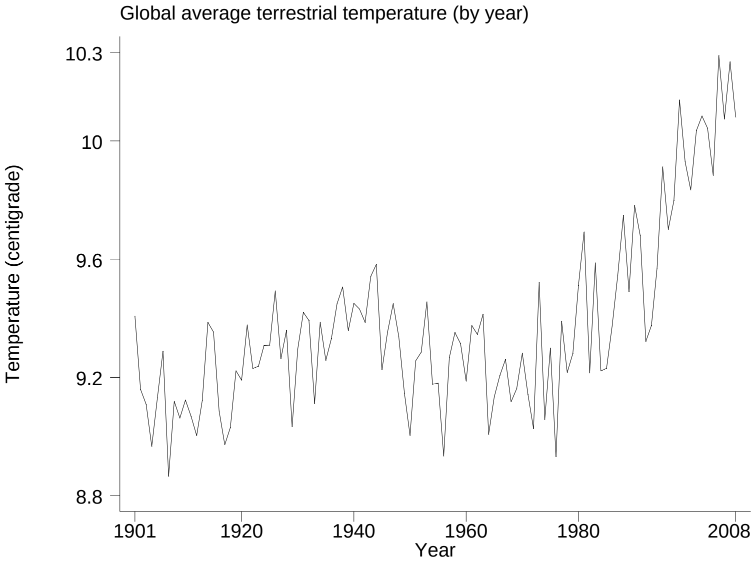
- Allows for: (i) region-specific dependence of regional temperature on global temperature; (ii) autocorrelation; and (iii) spatial correlation.
- Estimates: $\hat{\rho} = 0.42$, $\hat{\sigma}_\nu = 0.70$.

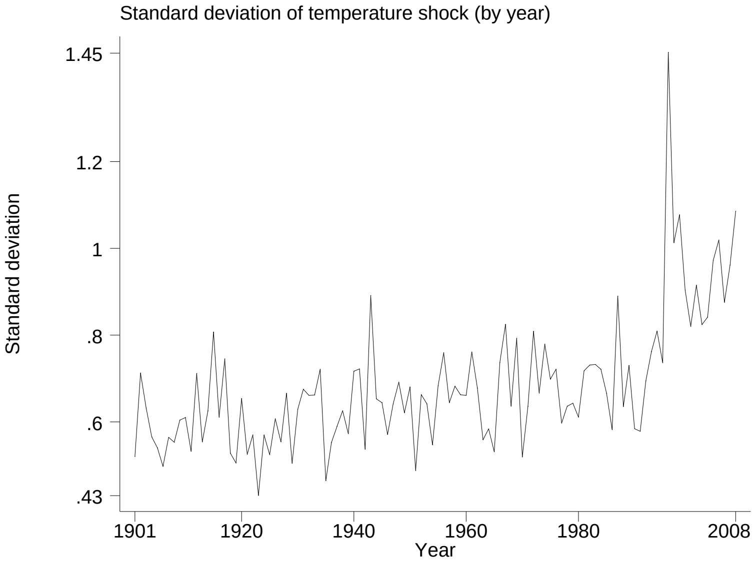


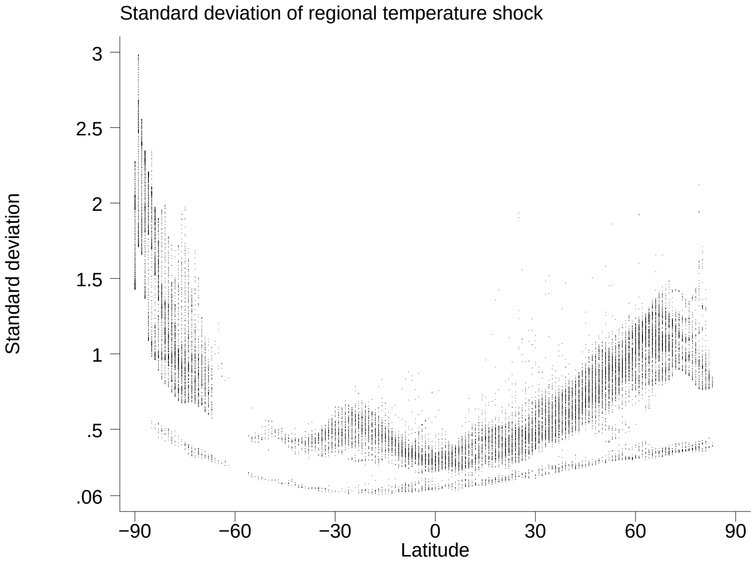
Change in regional temperature
(in response to a 1−degree increase in global temperature)
Change in temperature
2.75
2.5
2
1.5
1
.5
.25
−90
−60
−30
0
30
60
90
Latitude



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


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


Standard deviation of temperature shock (by year)
Standard deviation
1.45
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
.06
−90
−60
−30
0
30
60
90
Latitude

Evidence of ARCH in temperature shocks

- In a polled regression, coefficient on the lagged squared temperature residual in an ARCH(1) model is 0.32.

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; allow global temperature to increase over time, leading to differential regional temperature changes.

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 0.4%.

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".

- Introduce feedback from carbon emissions to economic activity: $S \rightarrow T \rightarrow$ 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.

A simple model of the carbon cycle

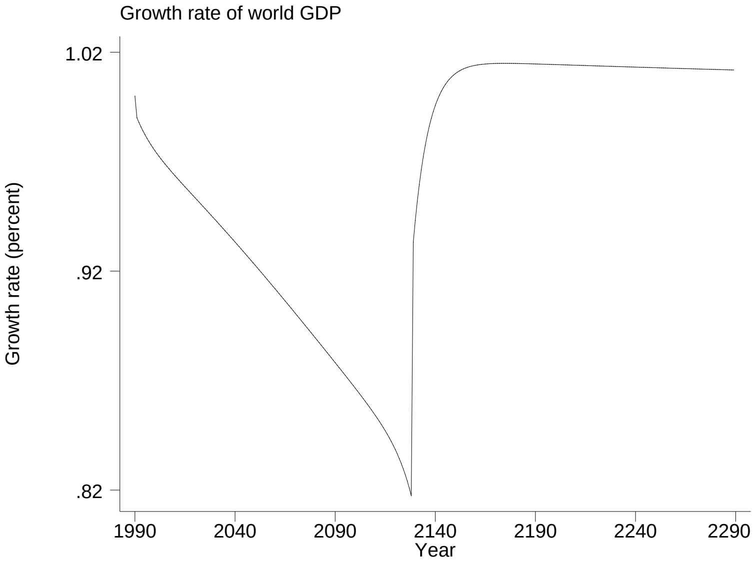
- The total stock of atmospheric carbon, S_t, is the sum of a permanent stock, S_{1t}, and a (slowly) depreciating stock, S_{2t}: $S_t = S_{1t} + S_{2t}$.
- $S_{1t} = 0.25E_t + S_{1,t-1}$, where E_t is total carbon emissions.
- $S_{2t} = 0.36(1 - 0.25)E_t + 0.998S_{2,t-1}$.
- Half-life of a freshly-emitted 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

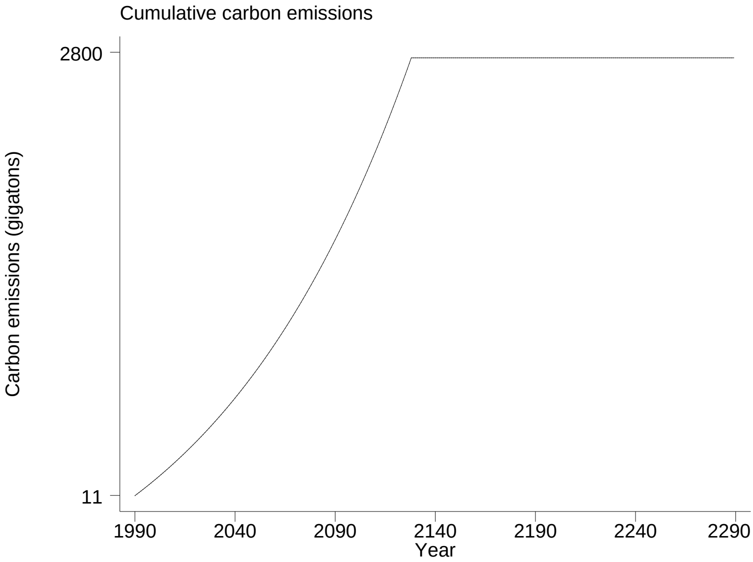
- Two new *aggregate* state variables: current carbon stocks.
- $v_t(\omega, z, A, \bar{k}, \bar{z}, S_1, S_2) =$
  $\max_{k',b'} \left[U(c) + \beta E_{z',\bar{z}'|z,\bar{z}}\, v_{t+1}(\omega', z', A', \bar{k}', \bar{z}', S_1', S_2')\right]$, s.t.

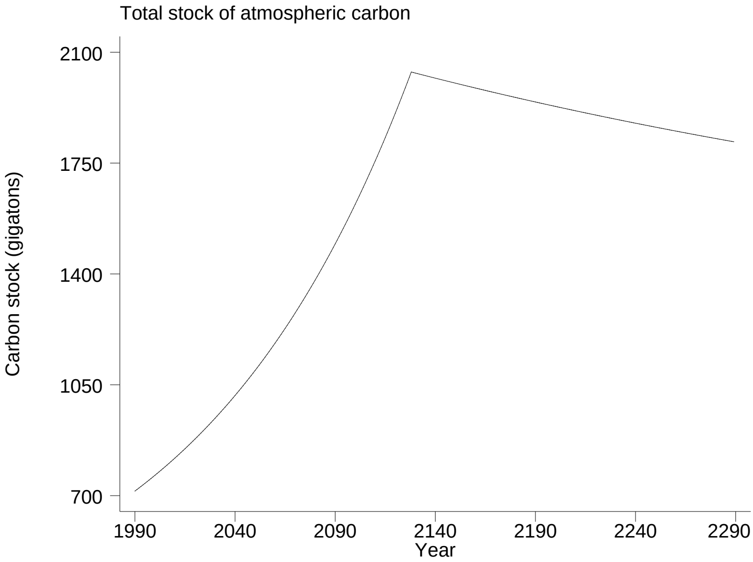
$$
\begin{aligned}
c &= \omega - k' - q_t(\bar{k}, \bar{z}, S_1, S_2) b' \\
\omega' &= \max_{e'} \left[G(T(S'))\exp(-\theta z')\, F(k', a', e') - pe'\right] + \\
&\quad (1-\delta)k' + b' \\
A' &= (1+g)A \\
b' &\geq \underline{b}(k') \\
\bar{k}' &= H_t(\bar{k}, \bar{z}, S_1, S_2) \\
S_1' &= \phi_1 E_{t+1}(\bar{k}',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

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

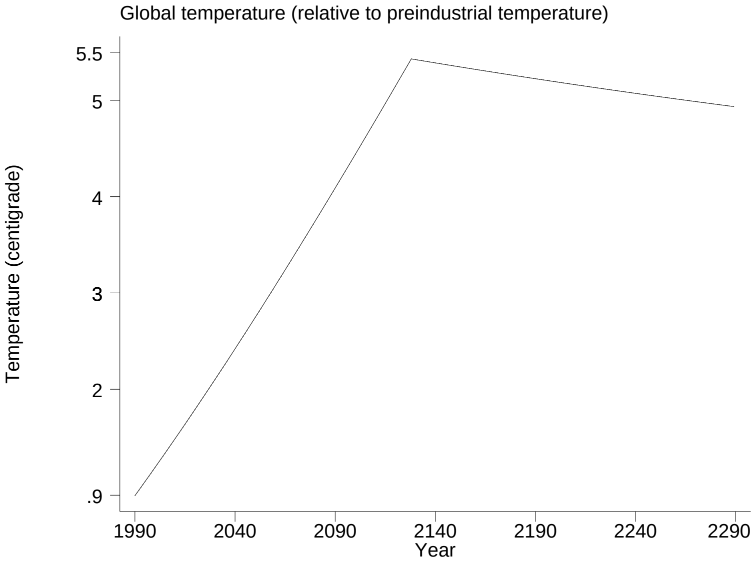


Growth rate of world GDP
1.02
.92
.82
Growth rate (percent)
1990
2040
2090
2140
2190
2240
2290
Year

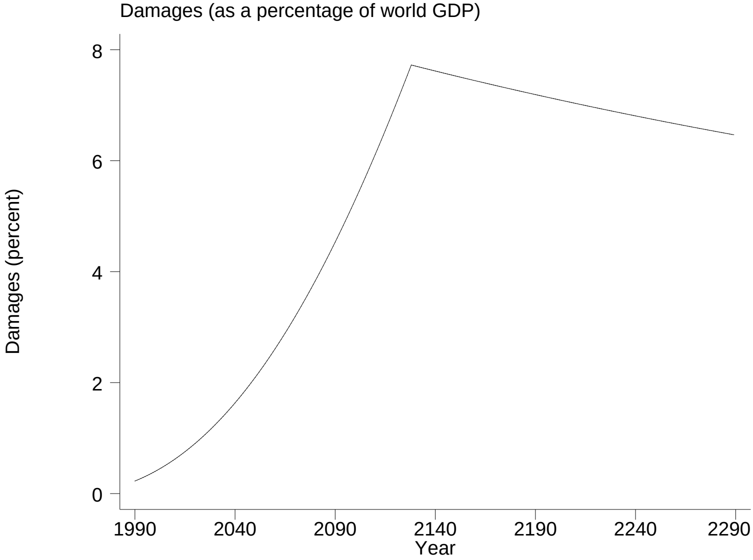

Cumulative carbon emissions
Carbon emissions (gigatons)
2800
11
1990
2040
2090
2140
2190
2240
2290
Year



Total stock of atmospheric carbon
Carbon stock (gigatons)
2100
1750
1400
1050
700
1990
2040
2090
2140
2190
2240
2290
Year



Global temperature (relative to preindustrial temperature)
Temperature (centigrade)
5.5
5
4
3
2
.9
1990
2040
2090
2140
2190
2240
2290
Year


Damages (as a percentage of world GDP)
Damages (percent)
8
6
4
2
0
1990
2040
2090
2140
2190
2240
2290
Year

An out-of-sample downscaling model

- 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.

Missing ingredients

Our baseline model abstracts from several features that may be quantitatively important for some questions:

- Separate roles for oil, natural gas, coal, and "green" energy.
- Endogenous improvements in energy technology.
- Richer carbon cycle (to capture additional persistence in temperature movements).
- A theory of (relative) movements in productivity across regions.
- Richer structure of trade (to allow for static gains from trade).

Next steps

- Solve for the transition in the multi-region model with feedback (ongoing).
- Use the model to quantify region-specific effects of climate change.
- Use the model as a laboratory to conduct policy experiments. Suppose Europe (or California) enacts a carbon tax (or suppose that the WTO imposes tariffs on imports from regions that do not implement a carbon tax): which regions around the world gain and which lose?
- Extensions:
  - Additional risk-sharing mechanisms within some groups of regions (within a country, say).
  - Additional interactions between countries: trade, migration.
  - Study political economy of climate agreements.