A Global Economy-Climate Model with High Regional Resolution

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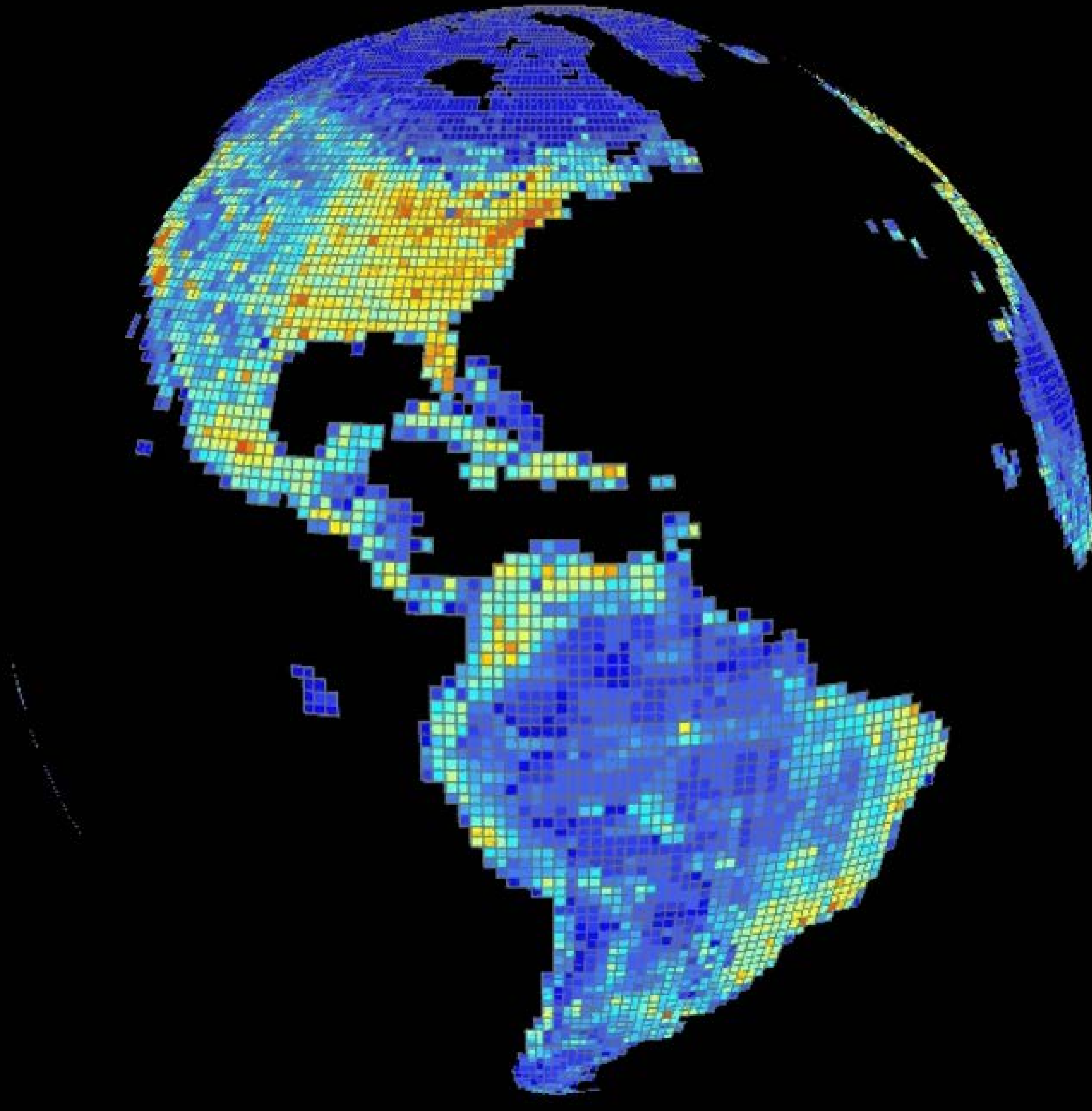
An increase of two or three degrees wouldn't be so bad for a northern country like Russia. We could spend less on fur coats, and the grain harvest would go up.

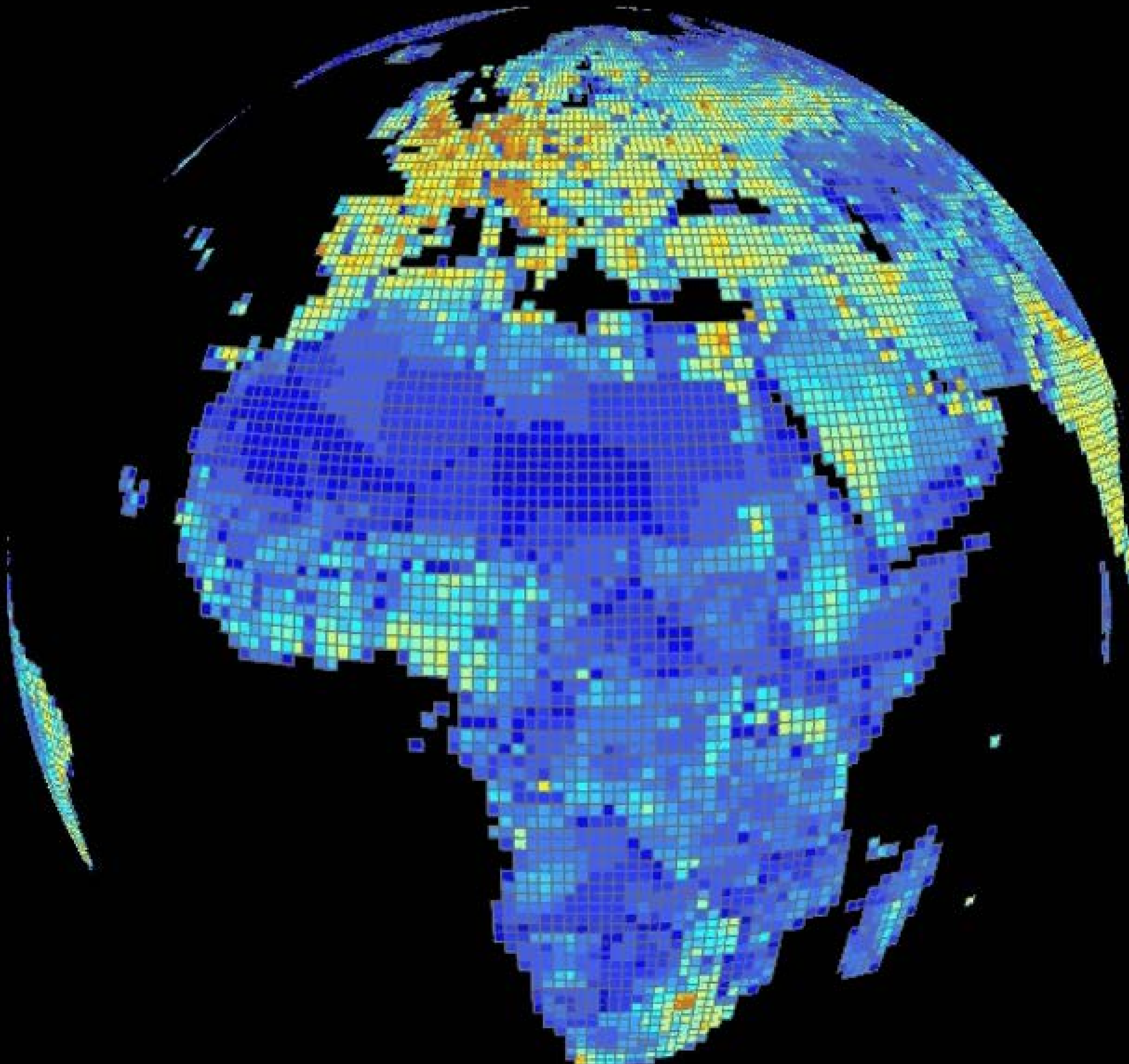
VLADIMIR PUTIN, President of Russia, *World Climate Change Conference*, Moscow, 2003

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.



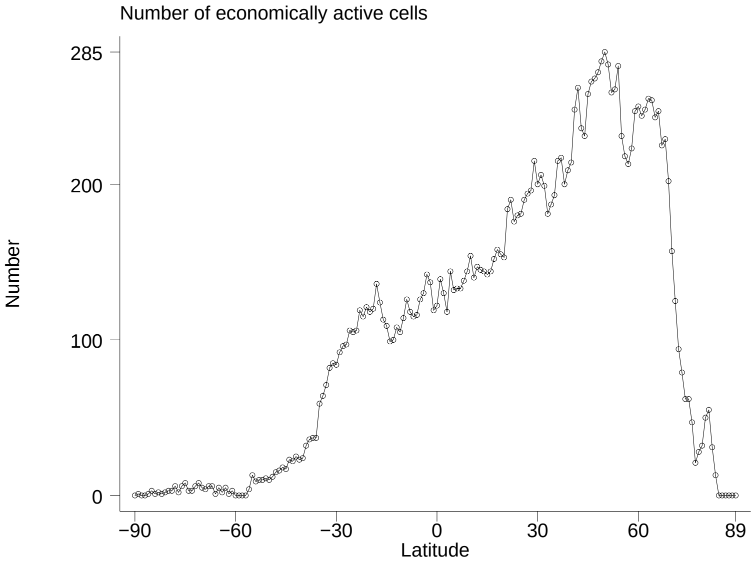


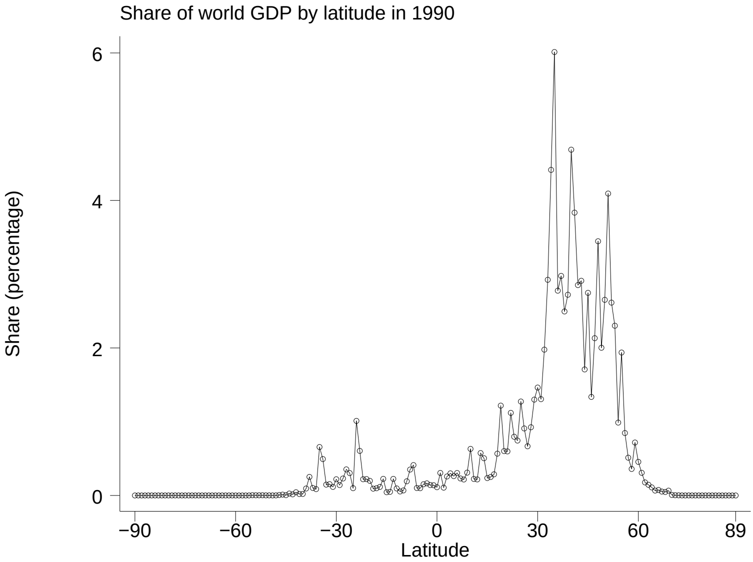
The project

- SimGlobe: a global model of economy-climate interactions featuring a high degree of geographic resolution ($1^\circ \times 1^\circ$ regions).
- The model extends Nordhaus's DICE and RICE models—which have little (or no) regional detail—to a dynamic, general equilibrium setting with many regions.
- Use the model as a laboratory to quantify the distributional effects of climate change and climate policy.
- If one group of regions imposes a carbon tax, how does the path of global emissions respond? Which regions gain and which lose, and by how much?
- Related work on spatial equilibrium models of climate change: Desmet and Rossi-Hansberg, Krusell and Hassler, and Brock, Engström, and Xepapadeas.

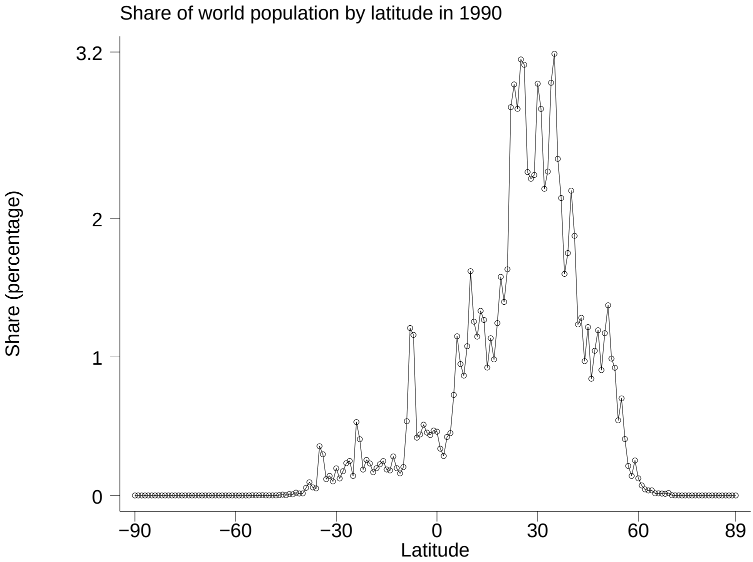
The data

- The unit of analysis is a $1^\circ \times 1^\circ$ cell containing land.
- Nordhaus's G-Econ database: gross domestic product (GDP) and population for all such cells in 1990, 1995, 2000, and 2005.
- The model contains $\sim 19,000$ regions (or cell-countries).
- Matsuura and Willmott: gridded ($0.5^\circ \times 0.5^\circ$) monthly terrestrial temperature data for 1900–2008.

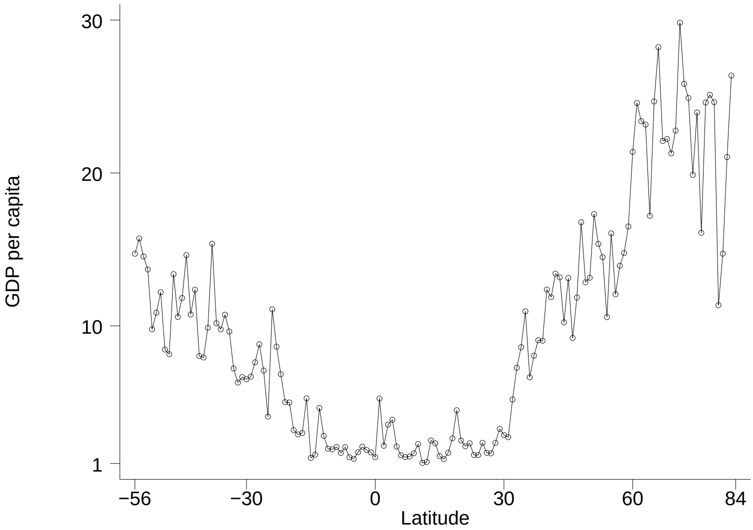

Number of economically active cells
Number
285
200
100
0
−90
−60
−30
0
30
60
89
Latitude

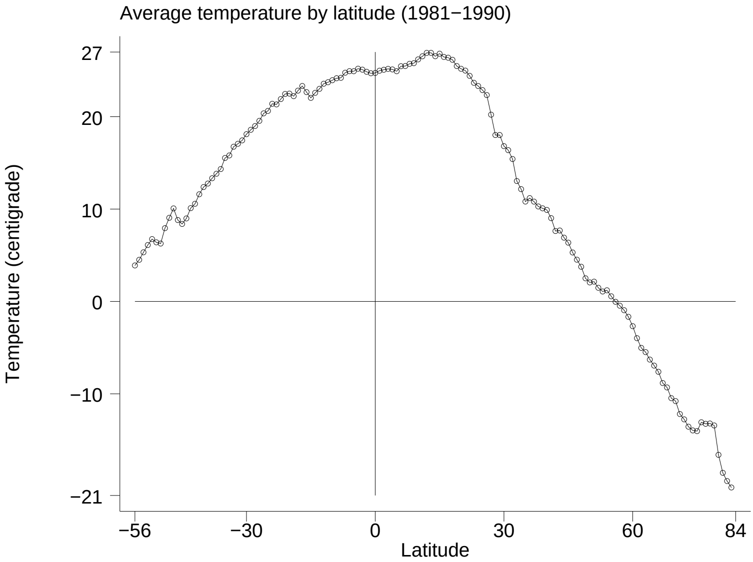


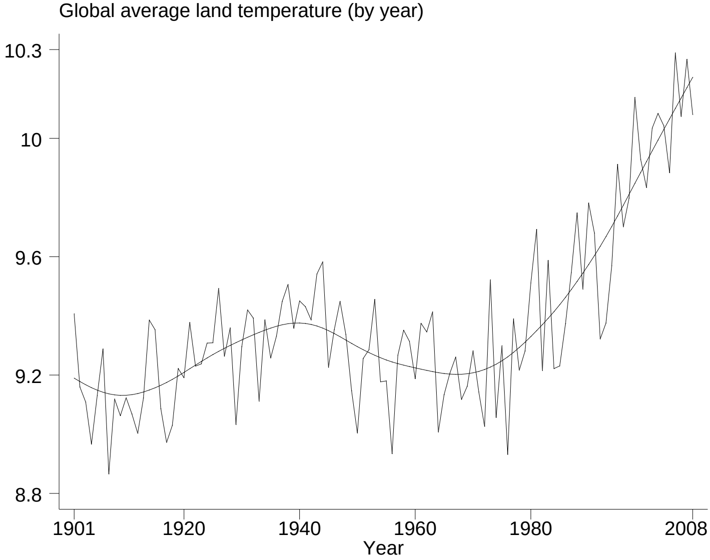
Share of world GDP by latitude in 1990
Share (percentage)
0
2
4
6
−90
−60
−30
0
30
60
89
Latitude


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

GDP per capita by latitude in 1990




Average temperature by latitude (1981−1990)
Temperature (centigrade)
27
20
10
0
−10
−21
−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

The model

- Regional planner who decides on consumption, portfolio choice (invest at home or lend abroad), and energy use.
- Neoclassical production technology with energy as an input.
- Energy input is coal (later green energy) produced at constant marginal cost.
- Weather (temperature) fluctuates and climate (the probability distribution over weather) changes in response to carbon emissions.
- Climate-economy feedback: global temperature affects regional temperature, which in turn affects regional TFP.
- World equilibrium determining the world interest rate.
- Adaptation mechanisms:
  - Self-insurance against shocks.
  - Labor is immobile but capital leaks between regions (subject to a one-year lag and a regional collateral constraint).

Dynamic program of a typical region: steady state

- Eventual steady state after global temperature stabilizes.
- Angeletos-Castro-Covas (i.e., Bewley-Huggett-Aiyagari meets entrepreneurs) with shocks to temperature.
- $v(\omega, z, A, \bar{k}, \bar{z}) =$
  $\max_{k', b'} \left[U(c) + \beta \mathbf{E}_{z', \bar{z}' | z, \bar{z}} \, v(\omega', z', A', \bar{k}', \bar{z}') \right]$, s.t.

$$
\begin{aligned}
c &= \omega - k' - q(\bar{k}, \bar{z}) b' \\
\omega' &= \max_{e'} \left[G(f(\ell) T) \exp(-\theta z') \, F(k', A', e') - p e' \right] + \\
&\quad (1 - \delta) k' + b' \\
A' &= (1 + g) A \\
b' &\geq \underline{b}(k') \\
\bar{k}' &= H(\bar{k}, \bar{z})
\end{aligned}
$$

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

Dynamic program of a typical region: transition

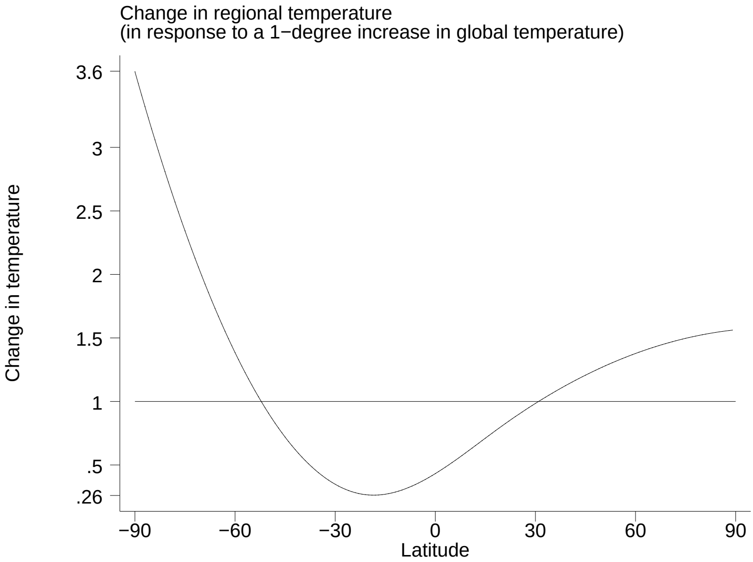
- $v_t(\omega, z, A, \bar{k}, \bar{z}, S_1, S_2) =$
  $\max_{k',b'} \left[U(c) + \beta \mathbf{E}_{z',\bar{z}'|z,\bar{z}}\, v_{t+1}(\omega', z', A', \bar{k}', \bar{z}', S_1', S_2')\right]$, s.t.

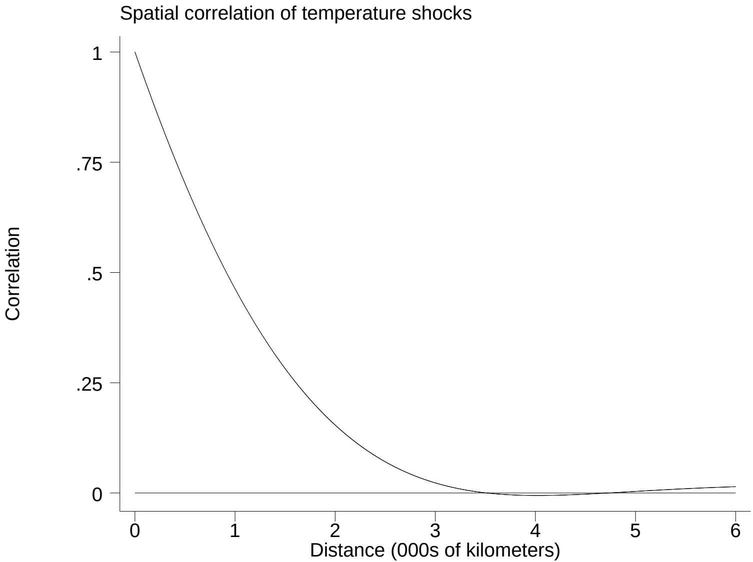
$$
\begin{aligned}
c &= \omega - k' - q_t(\bar{k}, \bar{z}, S_1, S_2)b' \\
\omega' &= \max_{e'} \left[G(f(\ell)T(S))\exp(-\theta z')\, F(k', A', e') - pe'\right] + \\
&\quad (1-\delta)k' + b' \\
A' &= (1+g)A \\
b' &\geq \underline{b}(k') \\
\bar{k}' &= H_t(\bar{k}, \bar{z}, S_1, S_2) \\
S_1' &= \phi_1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

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

The statistical downscaling model

- Regional temperature $T_i = f(\text{latitude}_i) \times T +$ a shock, where T is global temperature.
- The shock is correlated in space and time.
- The model is estimated using the panel data on annual average temperature.
- The shock follows an AR(1) process with an AR coefficient equal 0.4 and an innovation standard deviation equal to 0.7 ($^\circ$C).
- Spatial correlation decays with distance and is zero at 3000K.


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)

Economic effects of shocks to temperature

- Use the panel data on GDP and temperature to estimate the effect of a shock to temperature (i.e., a temporary deviation from a region's average temperature) on a region's GDP per capita:

$$\begin{aligned} y_{it} &= \gamma_1 T_{it} + \log(A_{it}) \\ \Delta \log(A_{it}) &= g_i + \gamma_2 T_{it} + \text{time fixed effects} + \text{error}, \end{aligned}$$

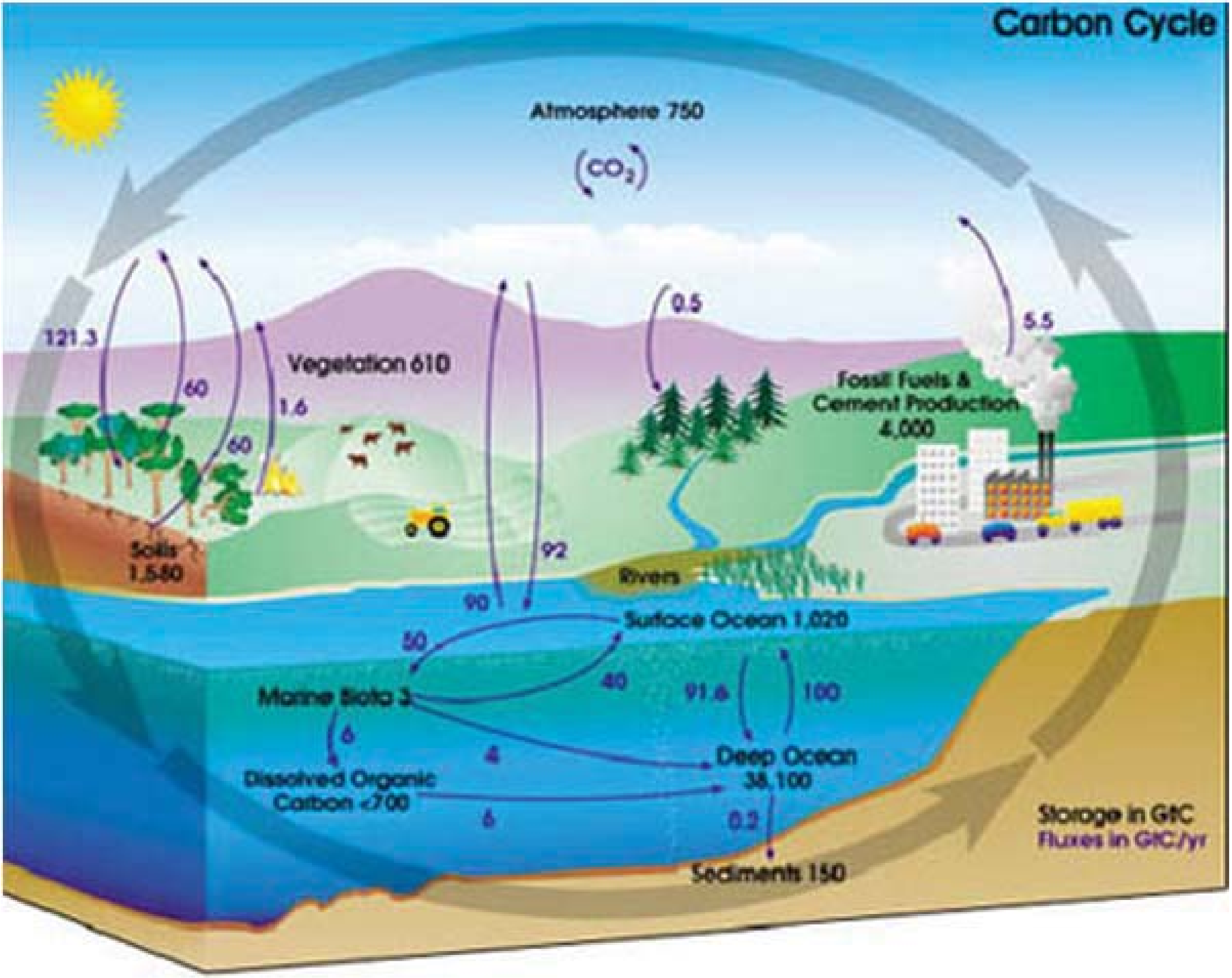
  where γ_1 is a level effect and γ_2 is a growth-rate effect.
- A top-down approach to measuring economic damages from weather (following Dell, Jones, and Olken). Captures effects of temperature shocks, but not changing climate.
- Pooling all the data: $\hat{\gamma}_1 = -1.65$ and $\hat{\gamma}_2 = -0.09$.

Calibration

- Annual time step, log utility, $\delta = 10\%$, $g = 1\%$, $\beta = 0.985$.
- Production function is CES in $k^{\alpha}(AL)^{1-\alpha}$ and Be, with elasticity 0.1.
- Initial distribution of region-specific capital and level of productivity chosen to: (1) match regional GDP per capita in 1990 and; (2) equalize MPK 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.
- Can borrow up to $\underline{b}(k') = 0.1(1-\delta)k'$.
- Shocks to regional temperature have common effects on TFP.
- Economic damages from changes in regional climate are common across all regions: $G(T_i) = (1 + 0.00284\, T_i^2)^{-1}$.
- Green energy replaces coal after 140 years.

Calibrating damages from weather shocks

- Use indirect inference (a way of implementing 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: $\hat{\gamma}_1 = -1.72\%$ (level effect), $\hat{\gamma}_2 = -0.27\%$ (growth-rate effect); compare to -1.65% and -0.09% in the observed data.


Carbon Cycle
Atmosphere 750
(CO_2)
121.3
60
60
1.6
Vegetation 610
90
92
0.5
5.5
Fossil Fuels & Cement Production 4,000
Soils 1,580
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

Geophysics

- The total stock of atmospheric carbon, S, is the sum of a permanent stock, S_1, and a (slowly) depreciating stock, S_2: $S = S_1 + S_2$.
- 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 $\lambda = 3$).
- $S_{1t} = 0.25E_t + S_{1,t-1}$, 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.

A hard computational problem

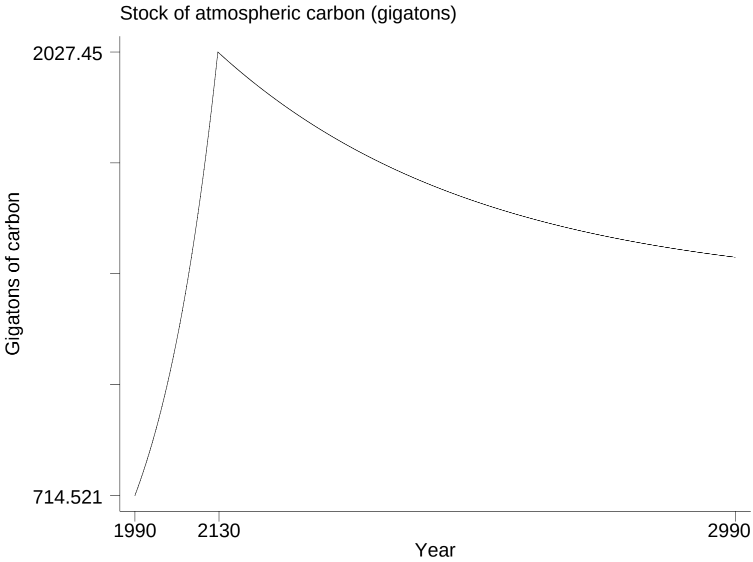
- Richard Feynman: Imagine how much harder physics would be if electrons had feelings!
- Transition + heterogeneity + an aggregate shock (global temperature fluctuates stochastically as in the data, leading to global fluctuations in *aggregate* TFP).
- Rational expectations: need to solve for time-varying *functions* mapping the state (including the joint distribution of capital and TFP across regions) into the market-clearing global interest rate, global emissions, and global saving.
- Exploiting approximate aggregation, we develop new methods that go well beyond what has been done in macro so far.
- Key innovation: at every point in time in a forward simulation, perturb the aggregate state variables to estimate the slopes of the forecasting functions.

Aggregate fluctuations from idiosyncratic shocks

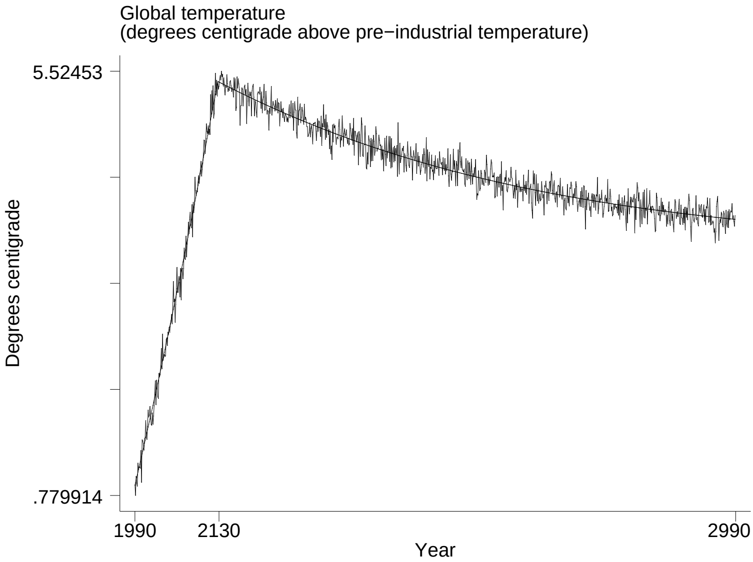
- GDP is highly concentrated spatially: top 1% of regions (192 cells) produce 44% of world GDP; top 15% of regions (2840 cells) produce 90% of world GDP.
- Temperature shocks are correlated in space.
- Implication: using the calibrated damage parameter, regional temperature shocks produce aggregate fluctuations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

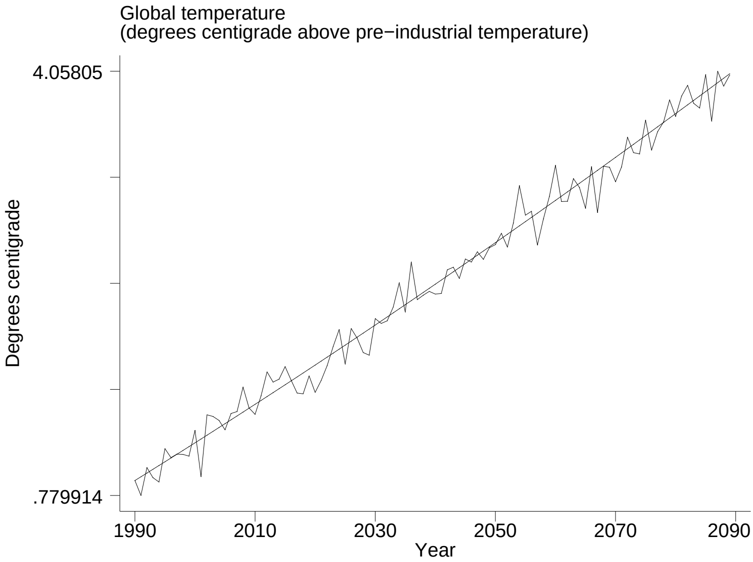
Two sets of experiments

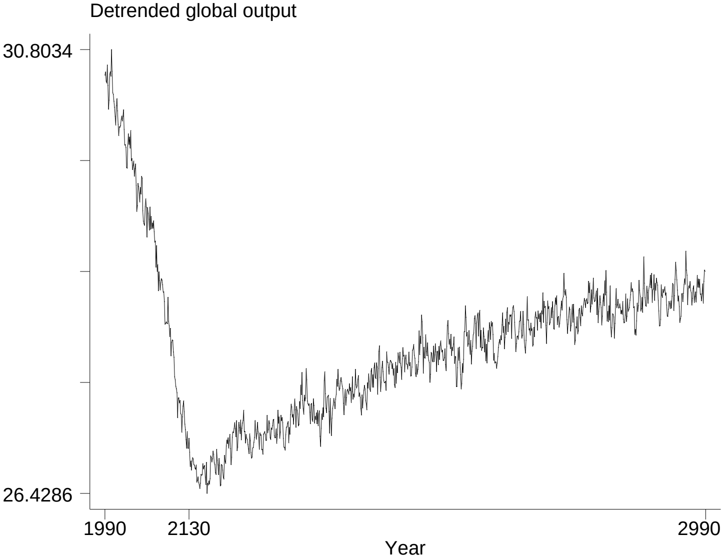
- Compare aggregate outcomes: one-region model vs. many-region model.
- Conduct two policy experiments: all regions (or just the U.S.) impose a carbon tax.
- *Resources (capital) will flow over time to where they are most productive.*

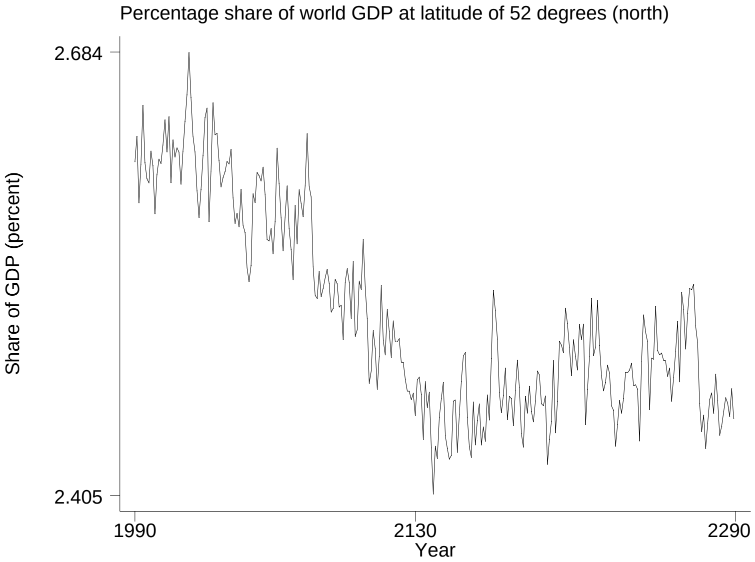


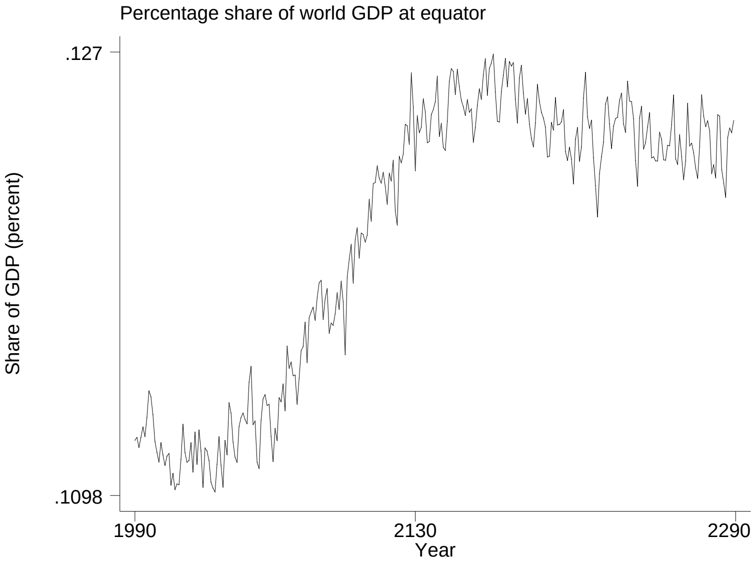
Stock of atmospheric carbon (gigatons)
2027.45
714.521
Gigatons of carbon
1990
2130
2990
Year

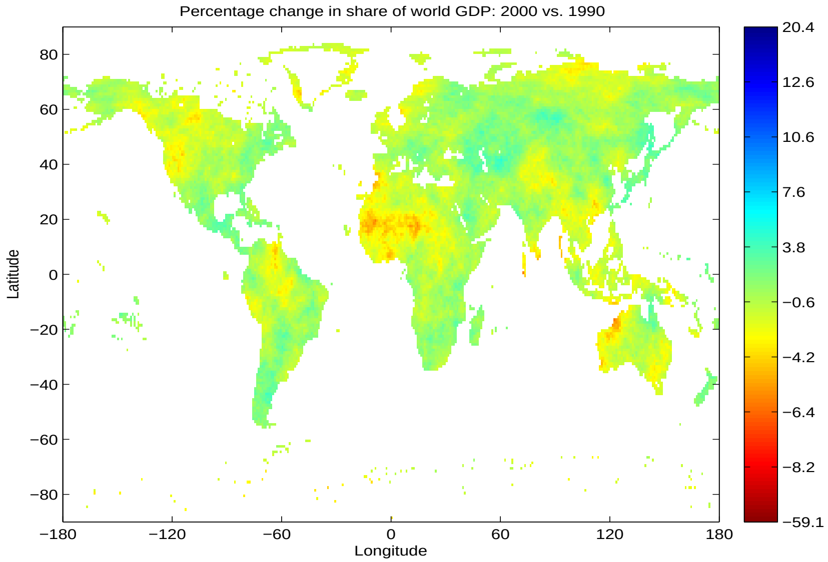

Global temperature
(degrees centigrade above pre−industrial temperature)
Degrees centigrade
5.52453
.779914
1990
2130
2990
Year


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

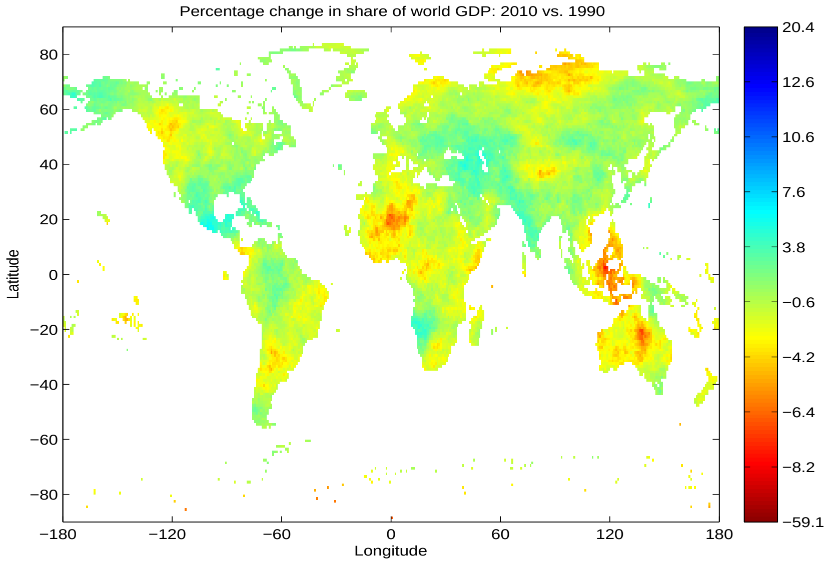

Detrended global output
30.8034
26.4286
1990
2130
2990
Year

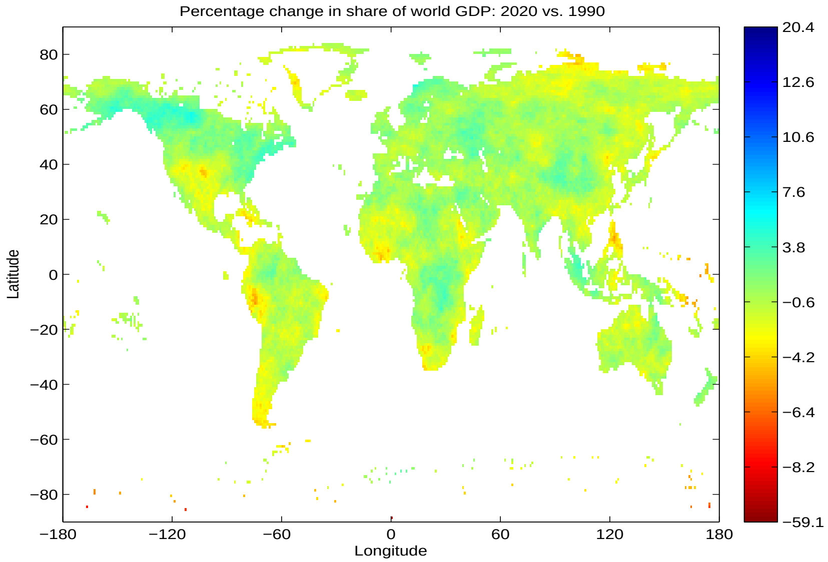

Percentage share of world GDP at latitude of 52 degrees (north)
Share of GDP (percent)
2.684
2.405
1990
2130
2290
Year


Percentage share of world GDP at equator
.127
.1098
Share of GDP (percent)
1990
2130
2290
Year

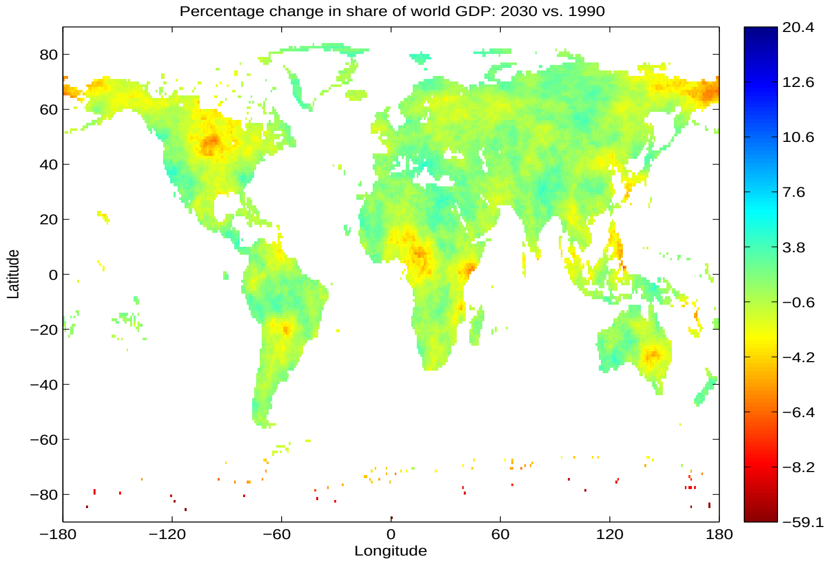


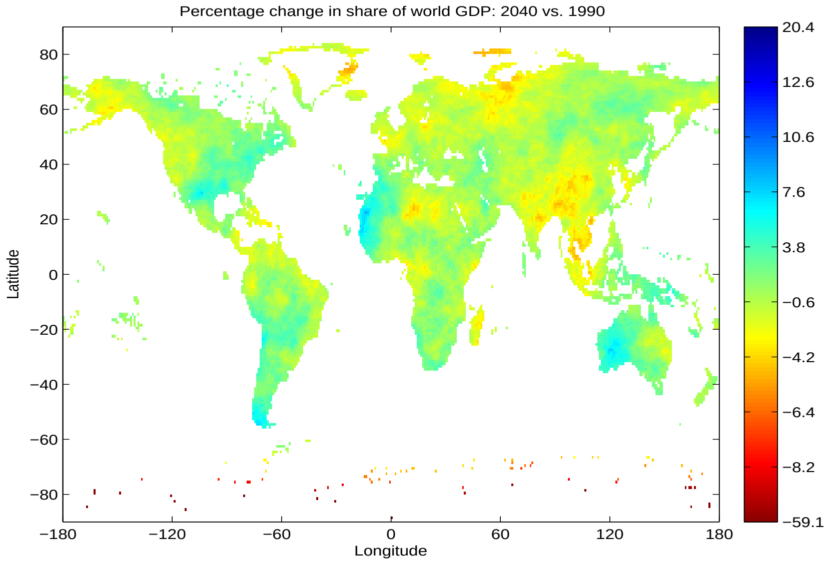
Percentage change in share of world GDP: 2000 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

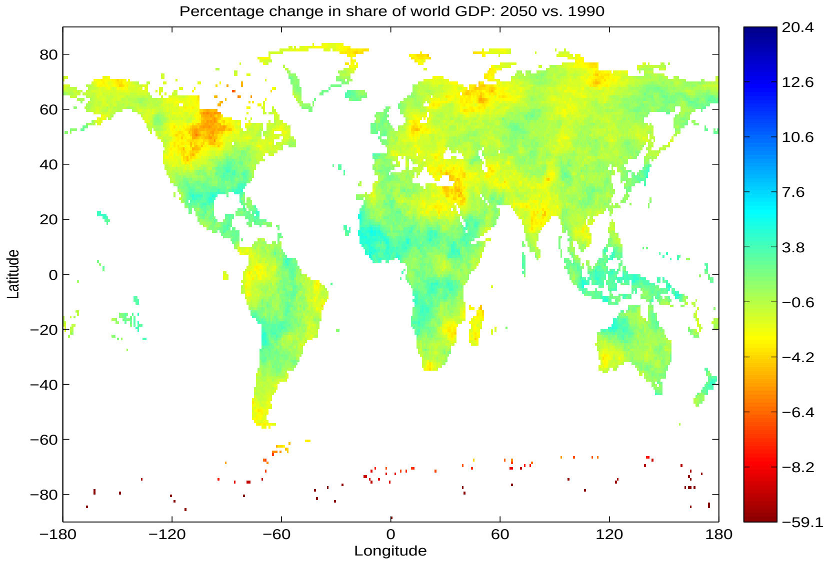

Percentage change in share of world GDP: 2010 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1



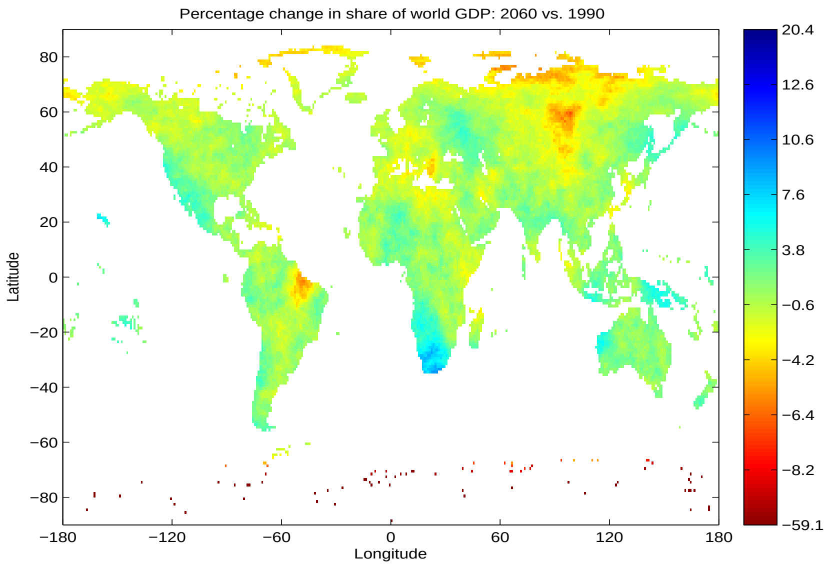
Percentage change in share of world GDP: 2020 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1


Percentage change in share of world GDP: 2030 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

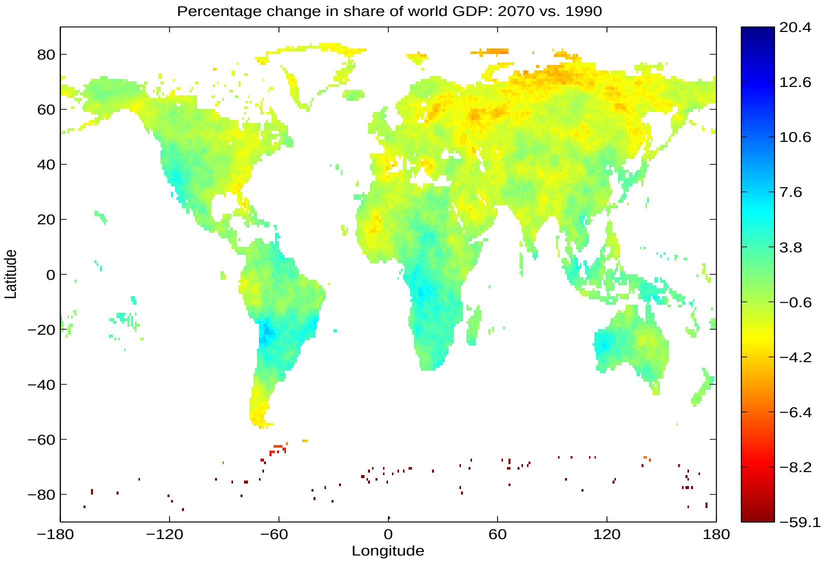

Percentage change in share of world GDP: 2040 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1



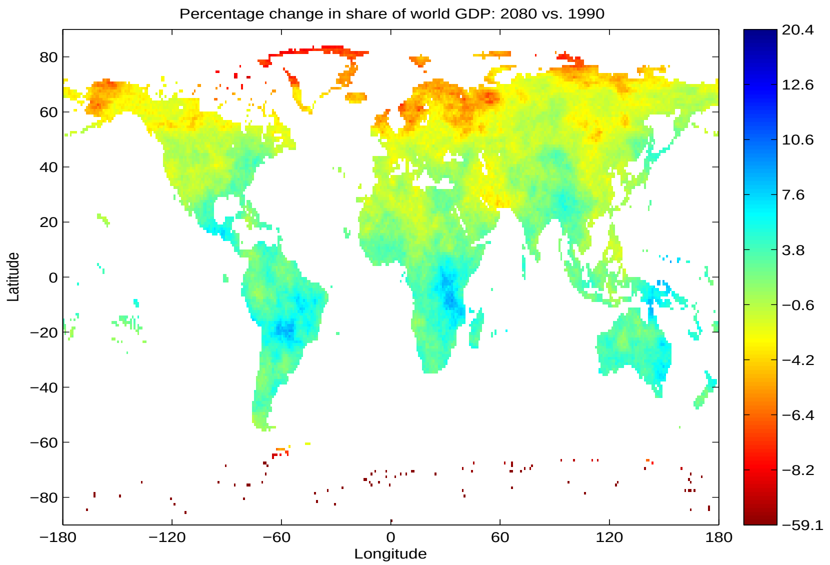
Percentage change in share of world GDP: 2050 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1



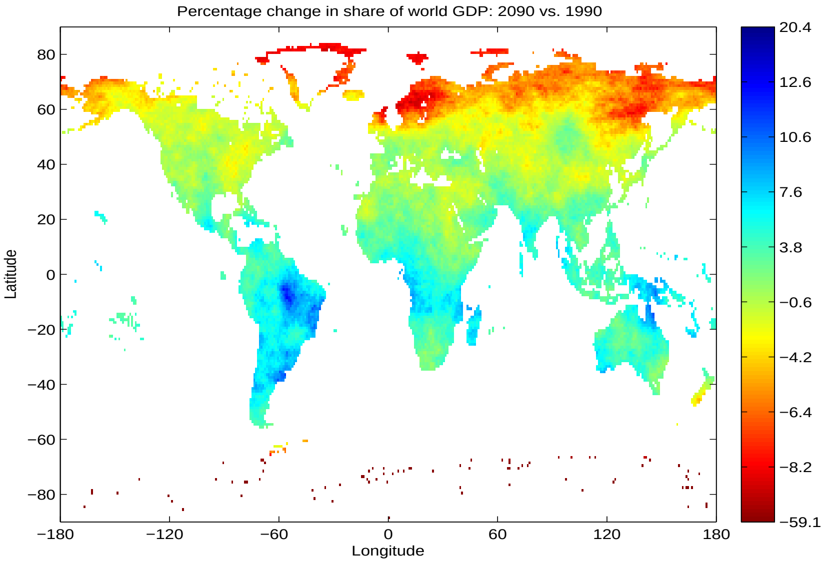
Percentage change in share of world GDP: 2060 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

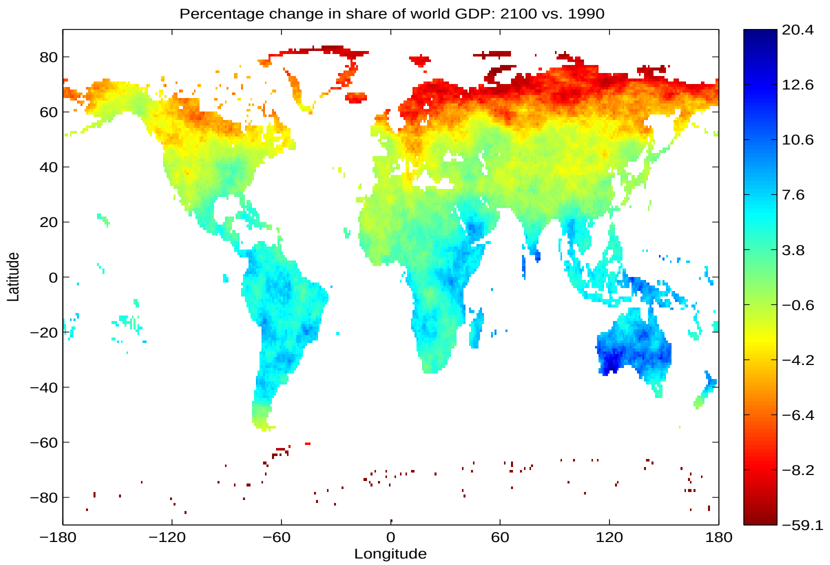


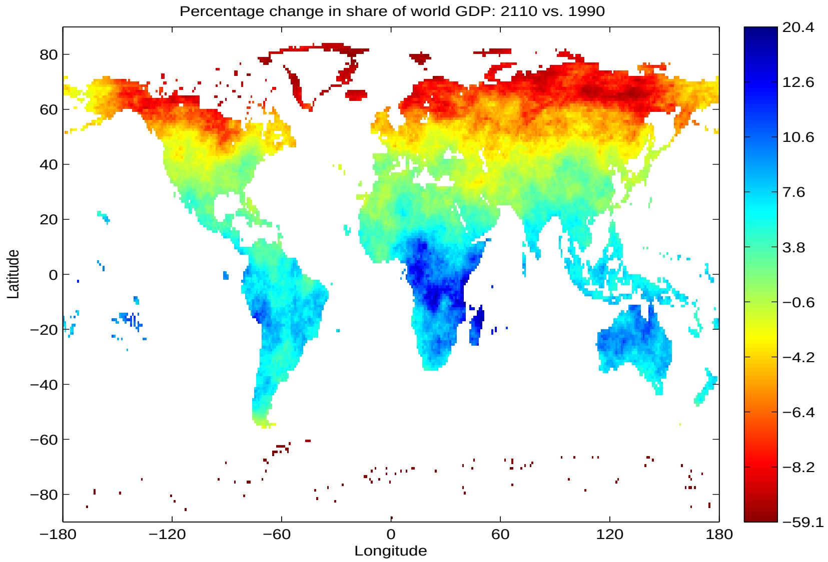
Percentage change in share of world GDP: 2070 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

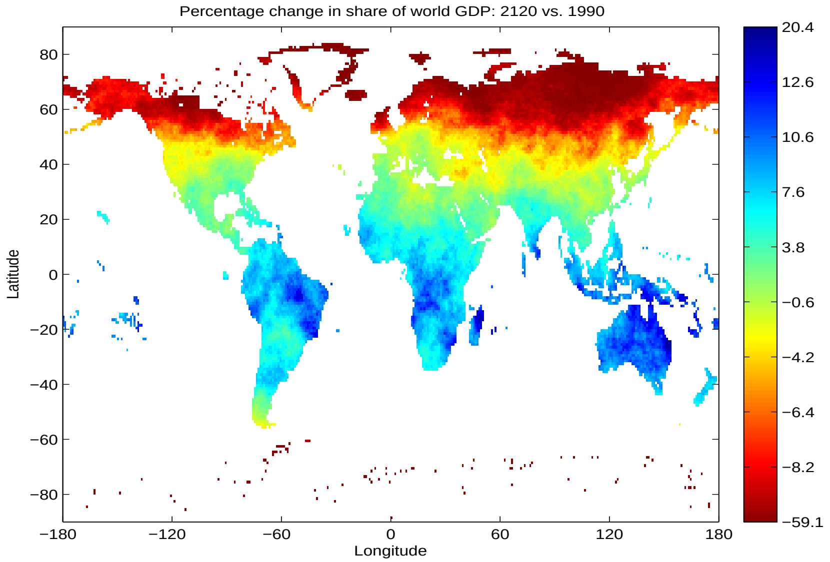


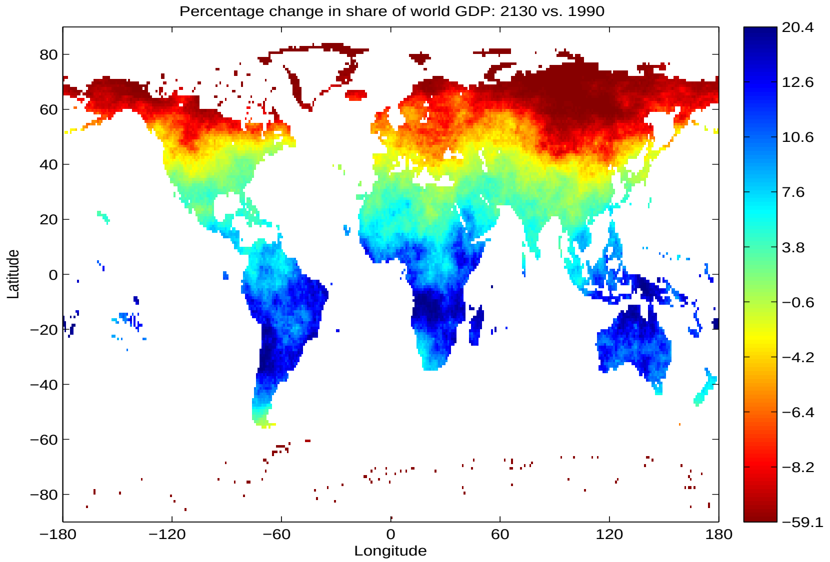
Percentage change in share of world GDP: 2080 vs. 1990
Latitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
Longitude
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1


Percentage change in share of world GDP: 2090 vs. 1990
Latitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
Longitude
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

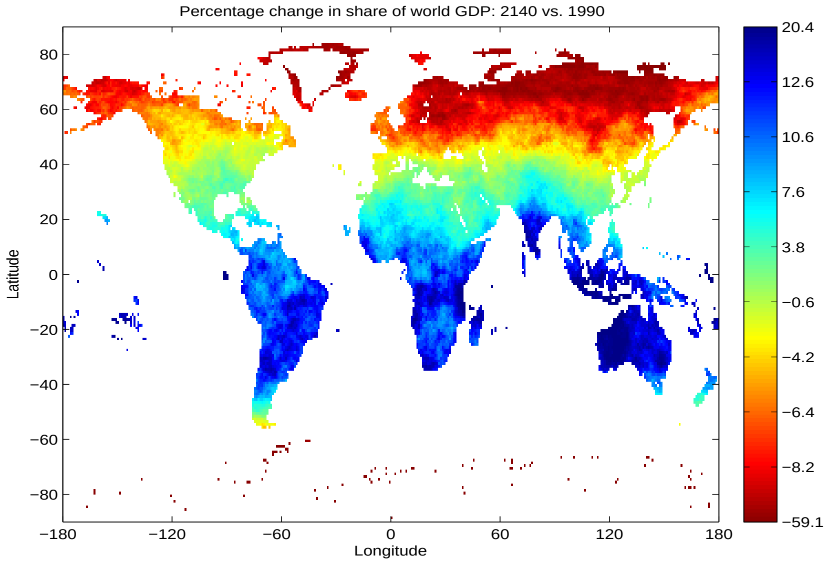

Percentage change in share of world GDP: 2100 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

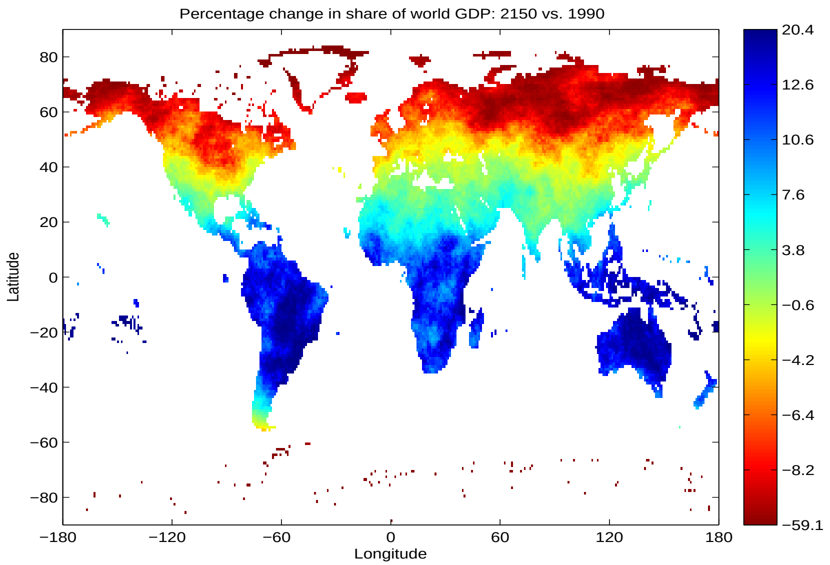

Percentage change in share of world GDP: 2110 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

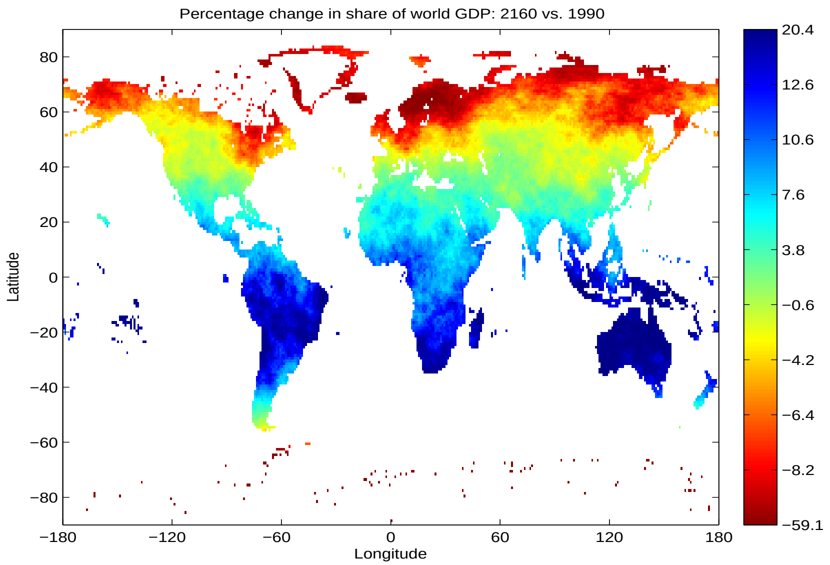

Percentage change in share of world GDP: 2120 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1



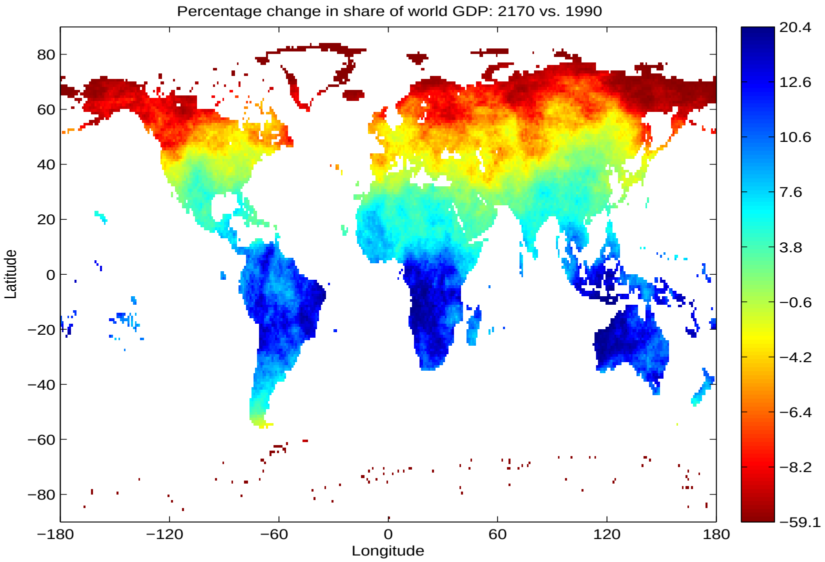
Percentage change in share of world GDP: 2130 vs. 1990
Latitude
80
60
40
20
0
−20
−40
−60
−80
Longitude
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

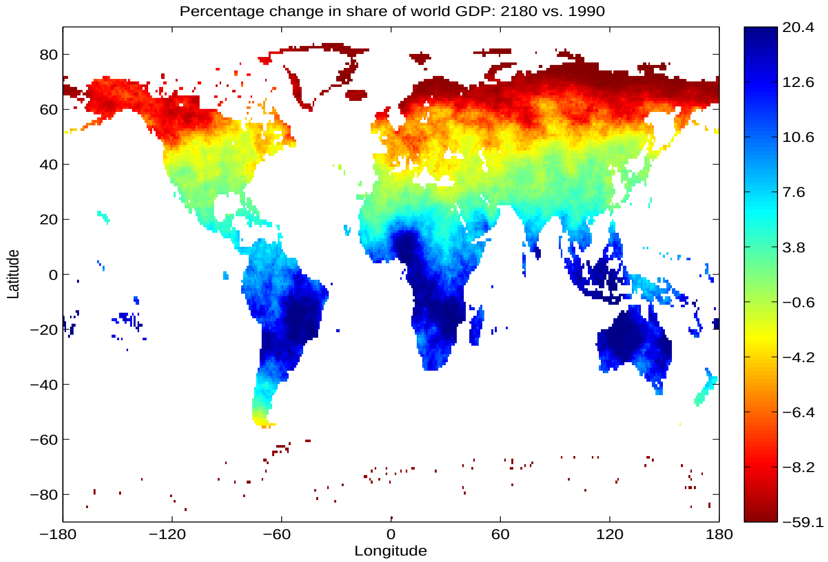

Percentage change in share of world GDP: 2140 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1


Percentage change in share of world GDP: 2150 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

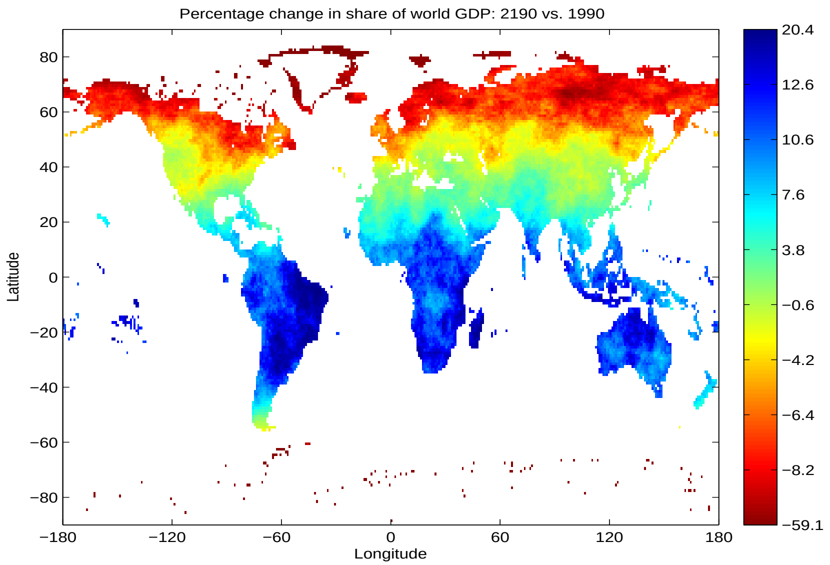


Percentage change in share of world GDP: 2160 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

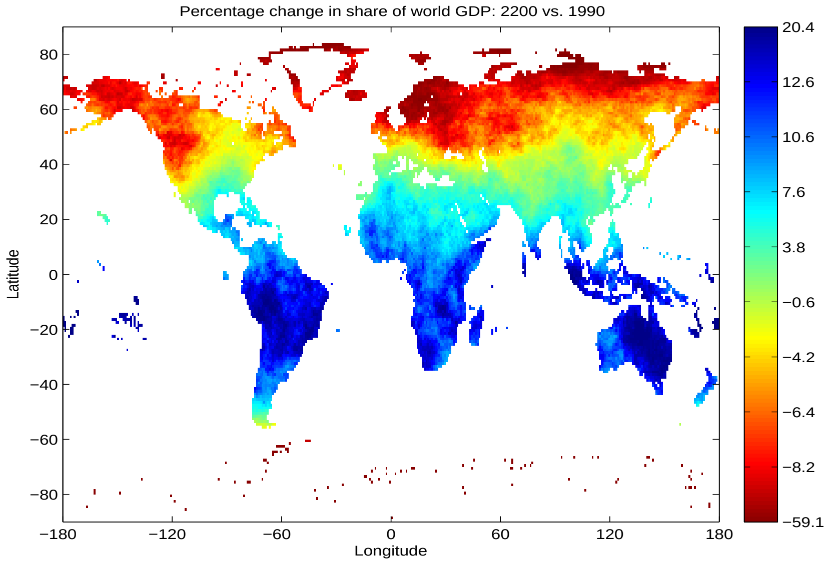

Percentage change in share of world GDP: 2170 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

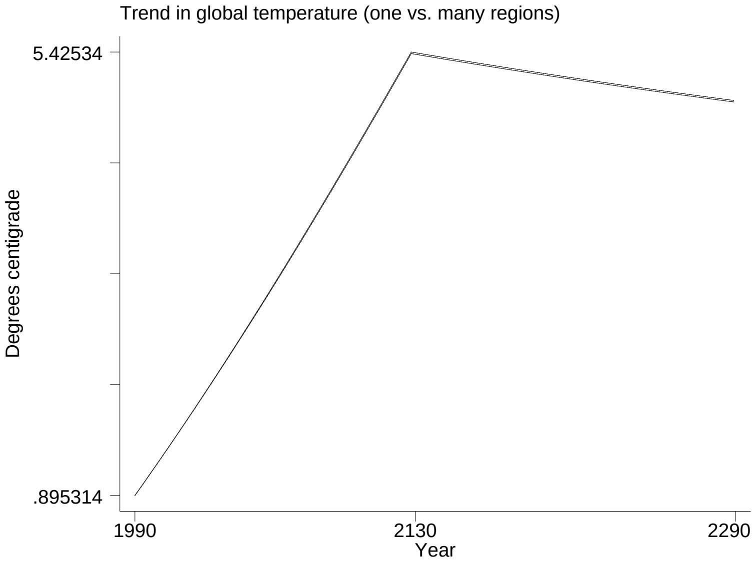


Percentage change in share of world GDP: 2180 vs. 1990
80
60
40
20
0
−20
−40
−60
−80
Latitude
−180
−120
−60
0
60
120
180
Longitude
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1



Percentage change in share of world GDP: 2190 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1


Percentage change in share of world GDP: 2200 vs. 1990
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−80
−180
−120
−60
0
60
120
180
20.4
12.6
10.6
7.6
3.8
−0.6
−4.2
−6.4
−8.2
−59.1

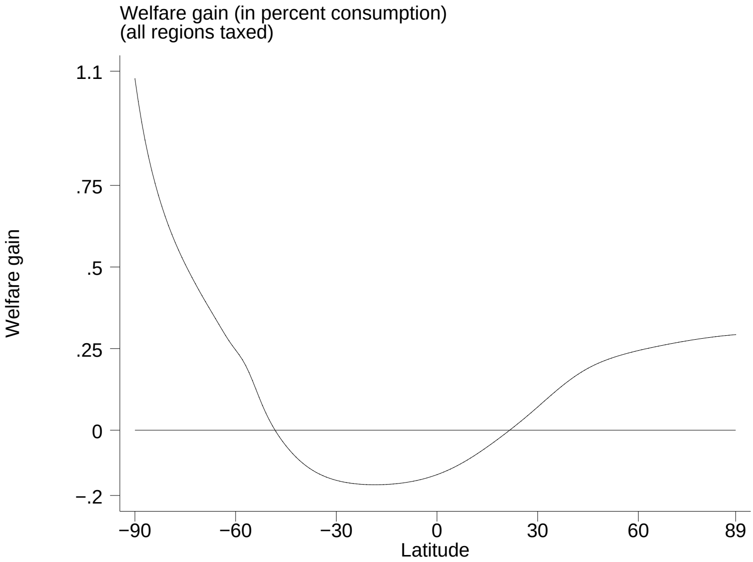

Trend in global temperature (one vs. many regions)
5.42534
.895314
Degrees centigrade
1990
2130
2290
Year

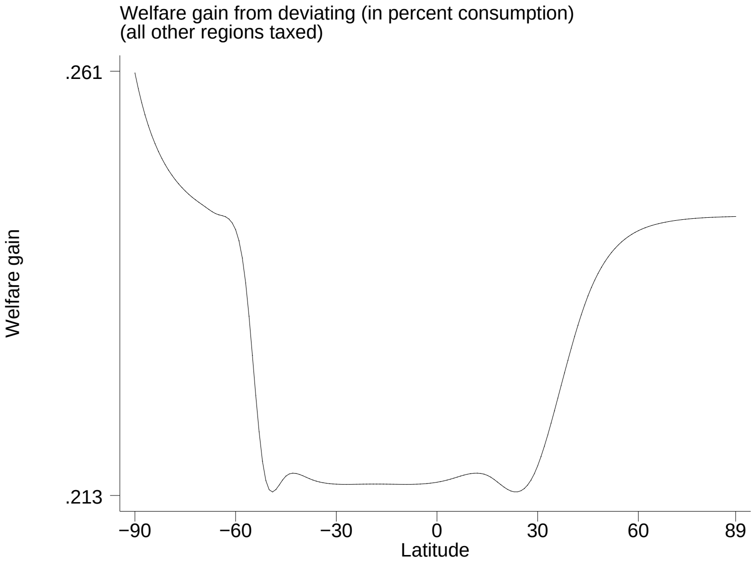
A regional tax on carbon emissions

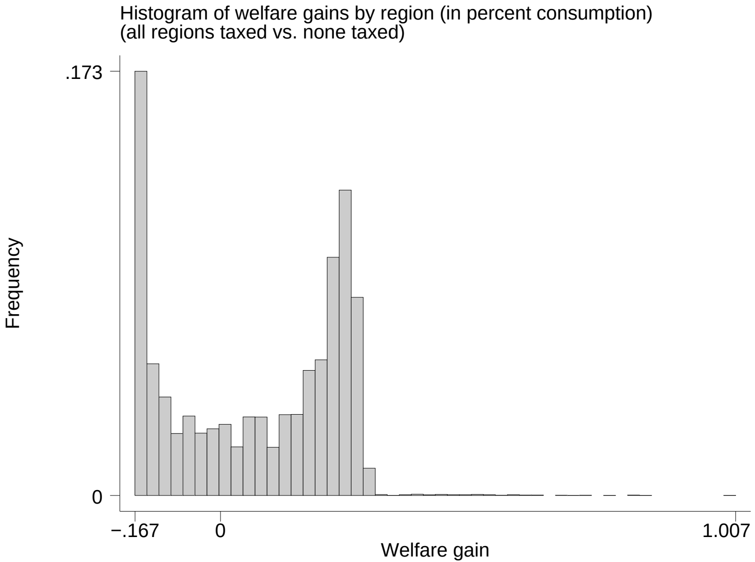
- Next-period wealth given by:

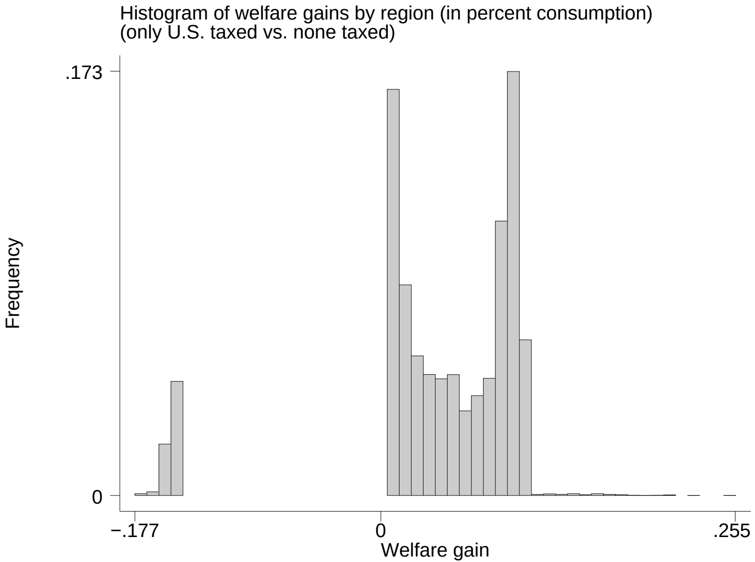
$$\max_{e'} [G(f(\ell)T(S))] \exp(-\theta z')\, F(k', A', e') - p(1+\tau)e')] + (1-\delta)k' + b + D$$

- 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. With elasticity of substitution equal to 0.1, energy use drops roughly 10%.


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


Welfare gain from deviating (in percent consumption)
(all other regions taxed)
Welfare gain
.261
.213
−90
−60
−30
0
30
60
89
Latitude


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

Next steps

- Increase the realism of the downscaling model (using data generated by global circulation models with help from climate scientists). Add teleconnections to the spatial covariances (ENSO, etc.).
- Incorporate regional heterogeneity in how shocks to weather and changes in climate affect economic outcomes. (Exploit parallelism to compute models with fixed heterogeneity.)
- Allow the spread (variance) of temperature shocks to vary with global temperature.

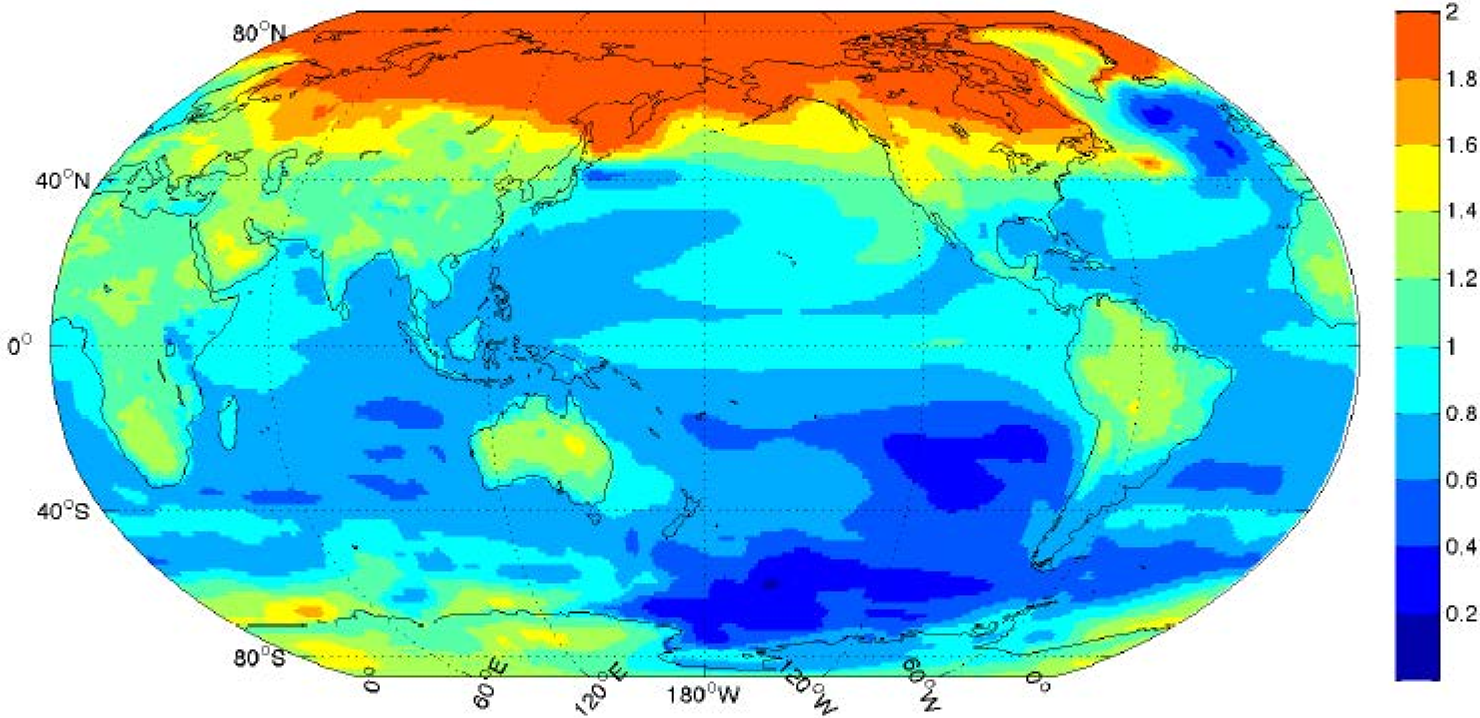
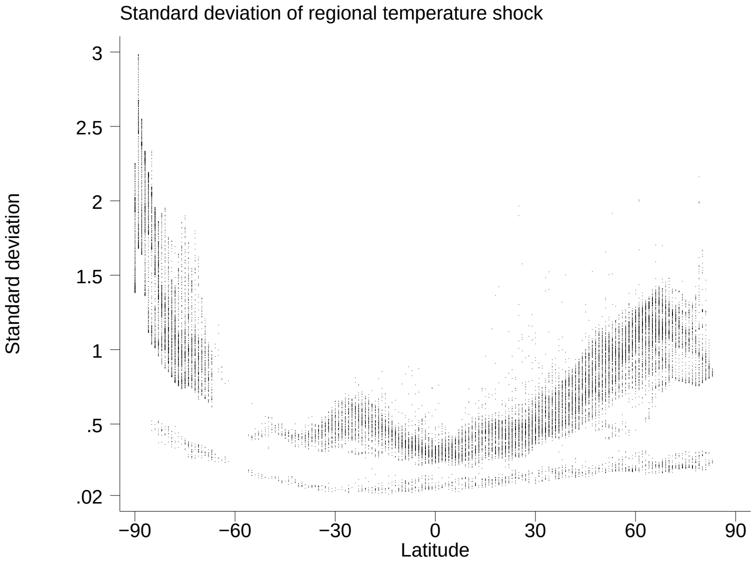
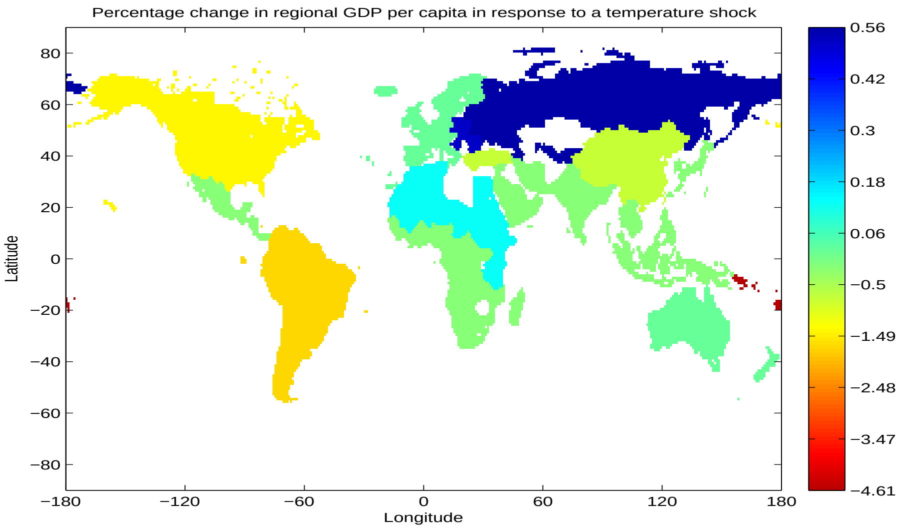


Figure 2: Global temperature pattern. Units in degrees per degree of global warming



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


Percentage change in regional GDP per capita in response to a temperature shock
80
60
40
20
0
−20
−40
−60
−80
Latitude
−180
−120
−60
0
60
120
180
Longitude
0.56
0.42
0.3
0.18
0.06
−0.5
−1.49
−2.48
−3.47
−4.61

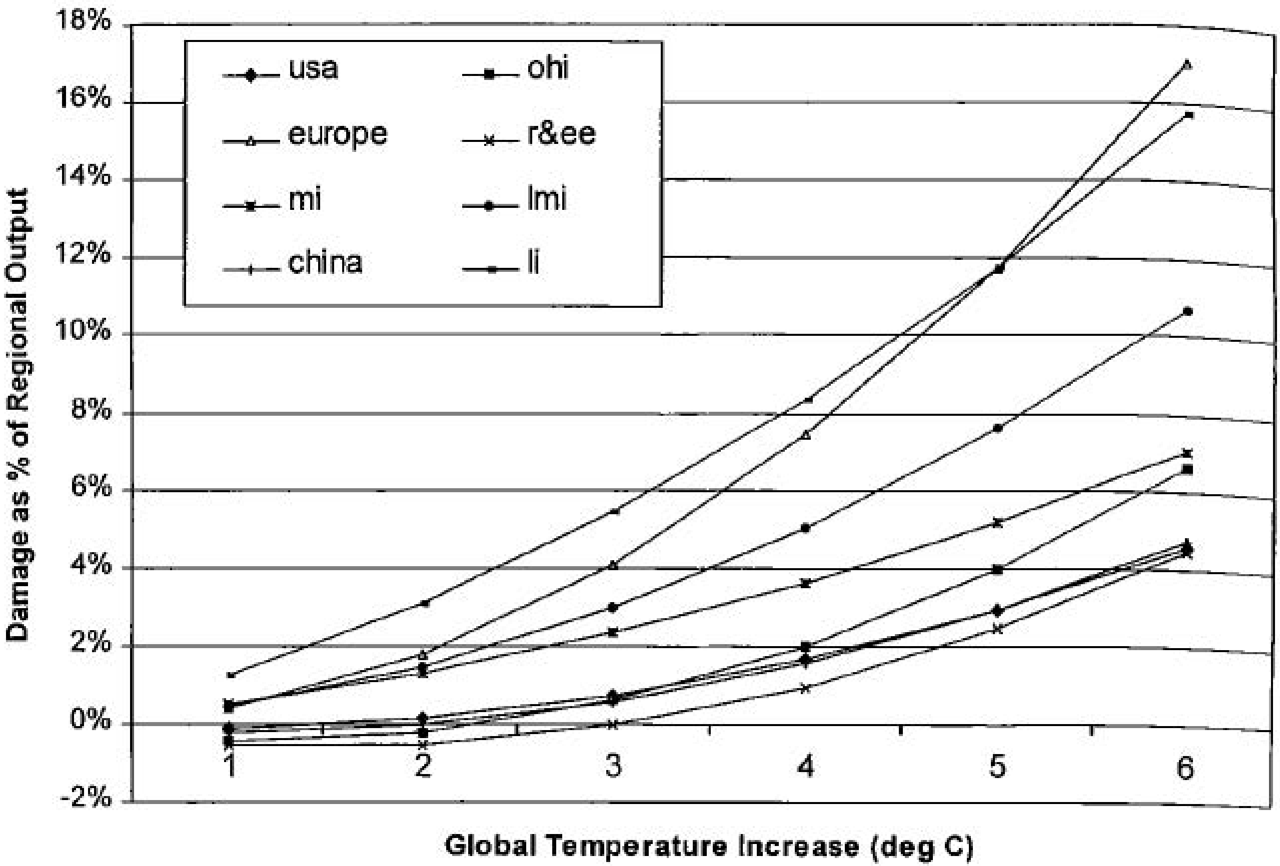
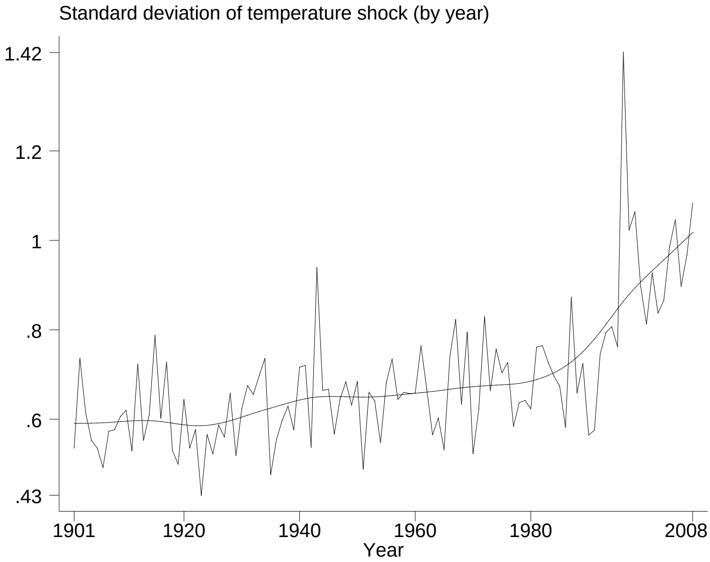


Figure 4.4
Regional damage functions


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

Extensions

- Richer damages: precipitation (floods), capital destruction (storms, sea-level rise), utility costs (health), large-scale disasters (reversal of Gulf Stream), ...
- Risk-sharing and resource transfers within countries (draw borders around groups of regions).
- Introduce static trade (in addition to intertemporal trade). Would allow the study of the interaction of (heterogeneous) tariff and carbon policies.

Conclusions

- This project builds a high-resolution global economy-climate model.
- The model is a platform for studying the *distributional* effects (across different regions) of climate change and (differential) climate policy.
- *Spatial adaptation* (resource flows between regions in response to variations in productivity) is a key mechanism in the model.
- Very next step is to fill in geographic detail!