Climate Change Around the World

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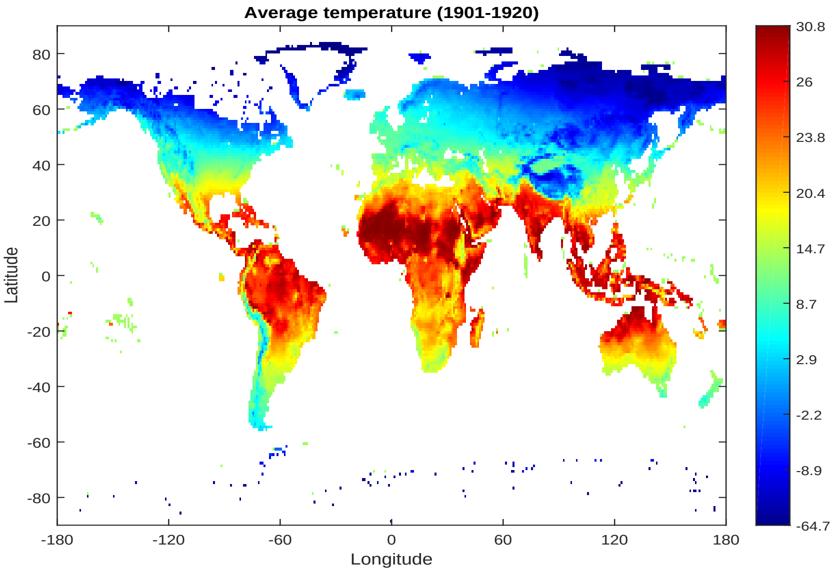
The project

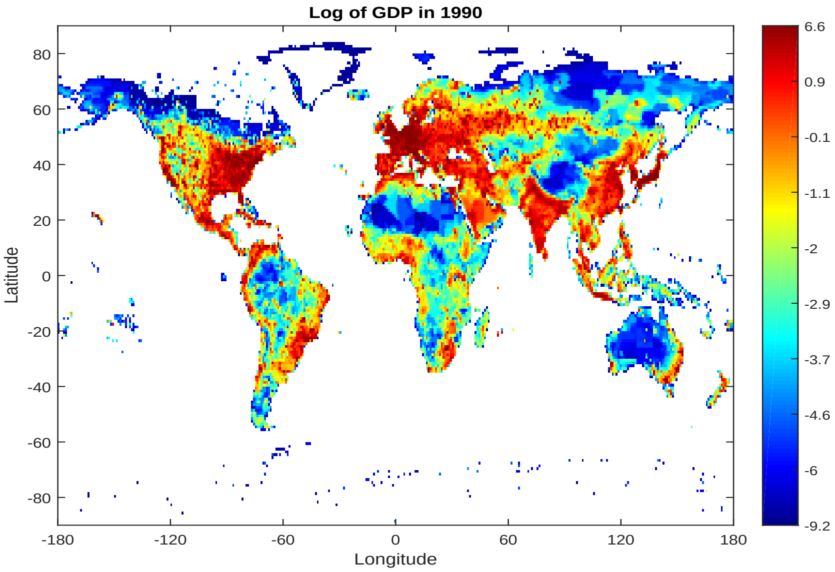
- Construct global model of economy-climate interactions featuring a high degree of geographic resolution ($1^\circ \times 1^\circ$ regions).
- Use the model as a laboratory to quantify the distributional effects of climate change and climate policy.
- If a set of regions imposes a carbon tax how does the path of global emissions respond? Which regions gain and which lose, and by how much?
- Related to growing new(ish) literature on spatial equilibrium models of climate change: Brock, Cai, and Xepapadeas; Brock, Engström, Grass, and Xepapadeas; Desmet and Rossi-Hansberg; Hassler and Krusell; Fried; Hassler, Krusell, Olovsson, and Reiter; Hillebrand and Hillebrand.

The data

- Unit of analysis: $1^\circ \times 1^\circ$ cells containing land.
- 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.
- Nordhaus's G-Econ database: gross domestic product (GDP) and population for all such cells in 1990.



Average temperature (1901-1920)
80
60
40
20
0
-20
-40
-60
-80
Latitude
-180
-120
-60
0
60
120
180
Longitude
30.8
26
23.8
20.4
14.7
8.7
2.9
-2.2
-8.9
-64.7



Log of GDP in 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6.6
0.9
-0.1
-1.1
-2
-2.9
-3.7
-4.6
-6
-9.2

Natural-science background I: the climate

- Energy balance (inflow from the Sun equals outflow from the Earth) determines the Earth's temperature.
- "Forcing", F, from CO_2 in the atmosphere (relative to pre-industrial) is:

$$F = \eta \frac{\ln(S/\bar{S})}{\ln(2)},$$

  where $S = 840$GtC and $\bar{S} = 600$GtC are current and pre-industrial stocks.
- Equilibrium temperature, T (relative to pre-industrial), is:

$$T = \kappa F = \lambda \frac{\ln(S/\bar{S})}{\ln(2)},$$

  where κ depends on various feedback effects.
- $\lambda \approx 3 \pm 1.5$ is "climate sensitivity".

Natural-science background II: the carbon cycle

- Carbon cycle: how emissions of CO_2 enter/exit atmosphere. Emissions spread globally very quickly ("global externality").
- The total stock of atmospheric carbon, S_t, is the sum of a permanent stock, S_{1t}, and a (slowly) depreciating stock, S_{2t}: $S_t = S_{1t} + S_{2t}$, where $S_{1t} = 0.25E_t + S_{1,t-1}$ and $S_{2t} = 0.36(1 - 0.25)E_t + 0.998S_{2,t-1}$,
- Emissions (E_t): 10GtC/year; $\Delta S_t \approx 4.5$GtC/year.
- Estimated remaining carbon: oil + gas = 300GtC, coal much bigger ($>$ 3,000GtC?). So coal is key!
- Feedback loop: emissions $\rightarrow$ carbon in atmosphere $\rightarrow$ forcing $\rightarrow$ temperature.
- Bad if higher T causes "damages": the mother of all externalities (Stern).

Integrated assessment models

- Pioneered by Nordhaus (DICE, RICE). Quantitative theory, computational.
- Key components:
  - climate system (as above)
  - carbon cycle (as above)
  - economic model of emissions AND damages
- Economic model: needs to be dynamic, forward-looking, possibly allowing stochastics (temperature variations, disasters).
- Here:
  - climate system more elaborate (regional variation)
  - economic model and damages new
  - the one-region version of the model is close to the representative-agent DSGE climate-economy model in Golosov, Hassler, Krusell, and Tsyvinski (2014)

Overview for remainder of talk

1. economic model
2. our regional climate modeling
3. our regional damage specification
4. calibration, computation
5. results
6. conclusions, future

The economic model

- Forward-looking consumers and firms in each region determine their consumption, saving, and energy use. No migration.
- Neoclassical production technologies, different TFPs both exogenously and due to climate.
- Energy as an input: coal, produced locally, at constant marginal cost (no profits).
- Coal slowly, exogenously replaced by (same-cost) green energy.
- Market structure: two cases.
  - Autarky (regions only linked via emission externality).
  - Unrestricted borrowing/lending (world interest rate clears market).
- Summary: like Aiyagari/Angeletos, though no shocks in this version.
- Adaptation: consumption smoothing and, in case with international markets, capital mobility ("leakage").

Regional problem

In a recursive equilibrium, region ℓ solves

- $v_t(\omega, A, \Gamma, S; \ell) =$
  $\max_{k', b'} \left[U(c) + \beta\, v_{t+1}(\omega', A', \Gamma', S'; \ell)\right]$, s.t.

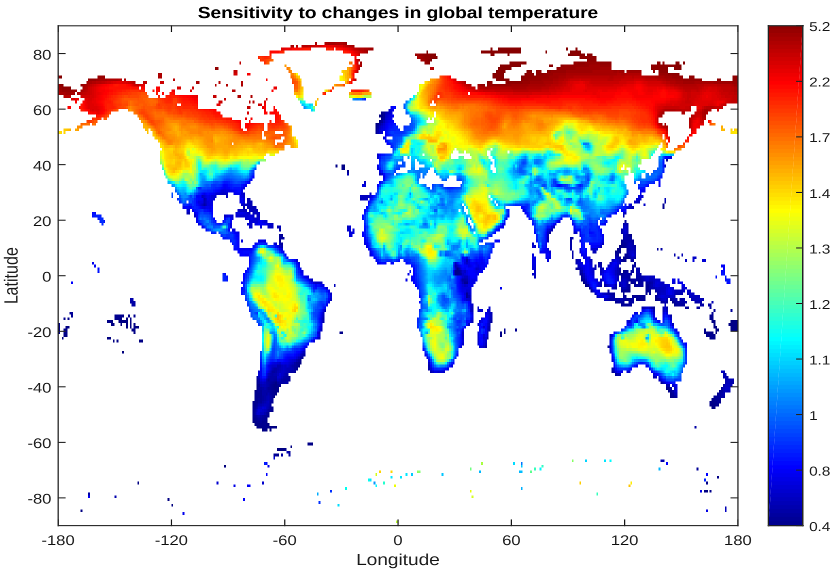
$$
\begin{aligned}
c &= \omega - k' - q_t(\Gamma, S) b' \\
\omega' &= \max_{e'} \left[F(k', D(T_\ell(S'))A', e') - pe'\right] + \\
&\quad (1-\delta)k' + b' \\
A' &= (1+g)A \\
\Gamma' &= H_t(\Gamma, S) \\
S' &= \Phi_t(\Gamma, S)\,.
\end{aligned}
$$

- Can be interpreted as a decentralized equilibrium.
- Set up to deal with shocks, aggregate and/or local.

Our climate modeling

How will region ℓ's climate respond to global warming?

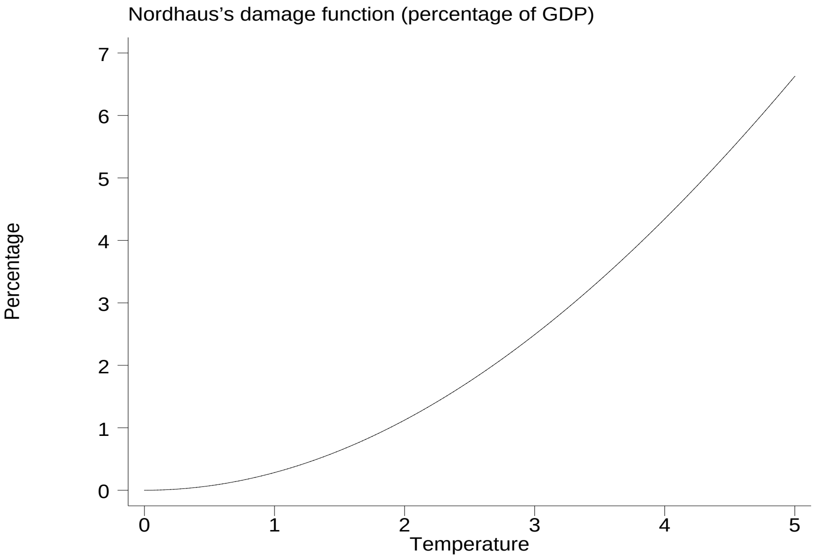
- Answer given by complex global and regional climate models. But not feasible (yet) to combine these with economic model.
- Therefore, use "pattern scaling" (aka "statistical downscaling"): statistical description of temperature in a given region as a function of a single state variable—average global temperature.
- Capture sensitivity of temperature in region ℓ to global temperature T in a coefficient (linear structure; standard).
- With help of climate scientists, use runs of (highly) complex climate models into the future to estimate sensitivities.

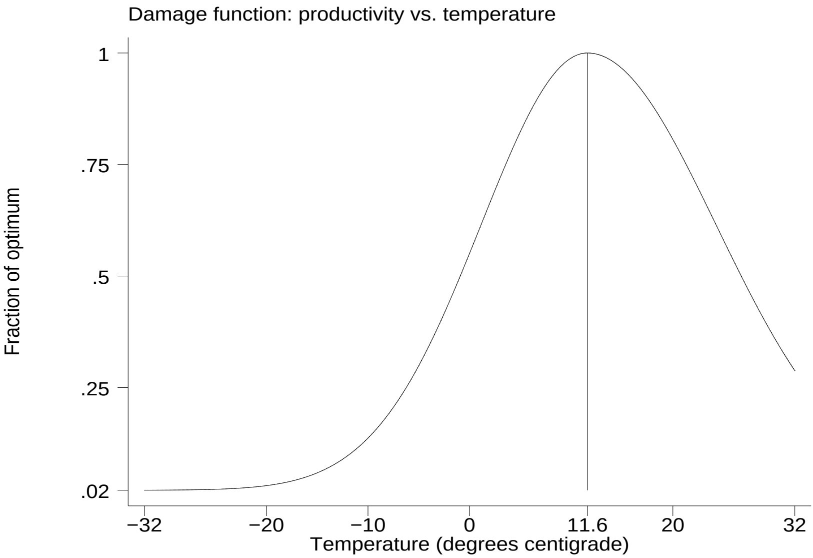


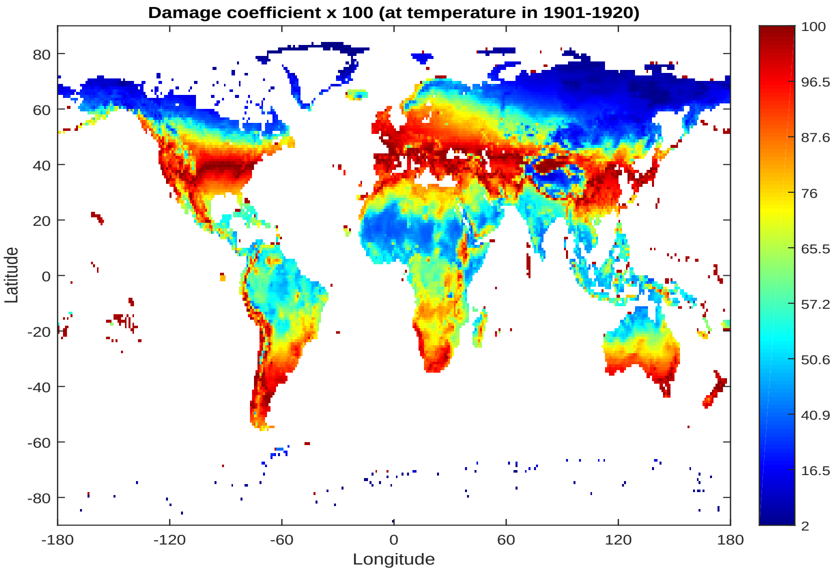
Sensitivity to changes in global temperature
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
5.2
2.2
1.7
1.4
1.3
1.2
1.1
1
0.8
0.4

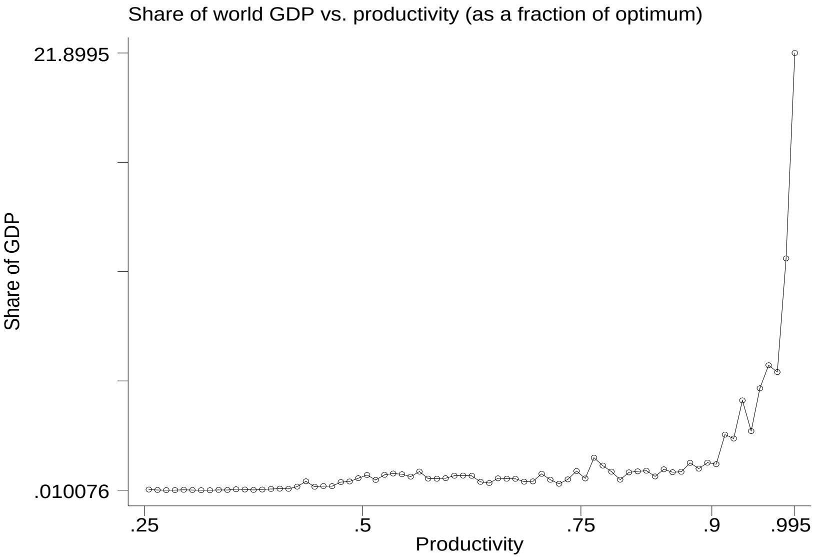
Our damage specification

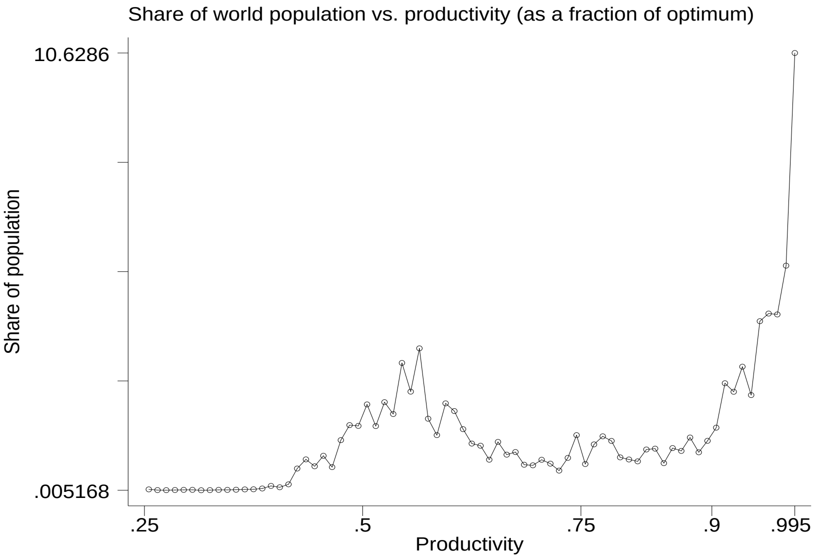
- What are the damages in region ℓ as a result of global warming?
- Our approach: formulate a damage function *D of local temperature* that is:
  - common across all regions;
  - like Nordhaus's, a drag on total factor productivity (TFP);
  - consistent with Nordhaus's worldwide damage function when aggregated across all regions.
- Desmet and Rossi-Hansberg (2014) also use a common U-shape in a spatial application.


Nordhaus's damage function (percentage of GDP)
Percentage
0
1
2
3
4
5
6
7
0
1
2
3
4
5
Temperature


Damage function: productivity vs. temperature
Fraction of optimum
1
.75
.5
.25
.02
−32
−20
−10
0
11.6
20
32
Temperature (degrees centigrade)

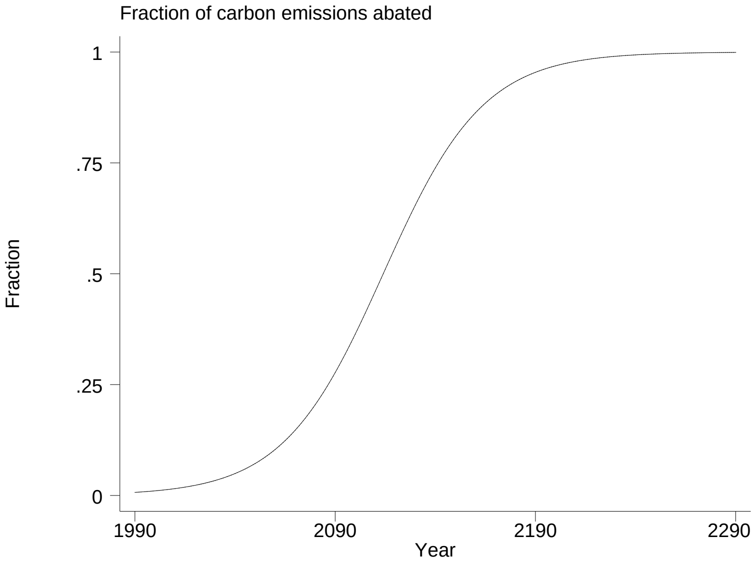

Damage coefficient x 100 (at temperature in 1901-1920)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
96.5
87.6
76
65.5
57.2
50.6
40.9
16.5
2


Share of world GDP vs. productivity (as a fraction of optimum)
21.8995
.010076
Share of GDP
.25
.5
.75
.9
.995
Productivity


Share of world population vs. productivity (as a fraction of optimum)
10.6286
.005168
Share of population
.25
.5
.75
.9
.995
Productivity

Calibration

- Annual time step, log utility, discount factor $\beta = 0.985$.
- Production function in region ℓ: CES in $k_\ell^\alpha (D_\ell A_\ell L)^{1-\alpha}$ and energy e_ℓ, with:
  - share parameter θ;
  - elasticity $= (1-\rho)^{-1}$ (set $\rho = 0$ for now);
  - $\alpha = 0.36$;
  - A_ℓ grows at rate $g = 1\%$.
- Capital depreciates at rate $\delta = 6\%$.
- Initial distribution of region-specific capital, k_ℓ, and level of productivity, A_ℓ, chosen to: (1) match regional GDP per capita in 1990 and; (2) equalize MPKs across regions.
- Price of coal and θ chosen to match: (1) total carbon emissions in 1990; and (2) energy share of 6% along a balanced growth path.
- Green energy replaces coal slowly (logistic).


Fraction of carbon emissions abated
Fraction
1
.75
.5
.25
0
1990
2090
2190
2290
Year

Computation

- Richard Feynman: Imagine how much harder physics would be if electrons had feelings!
- Transition + heterogeneity = nontrivial fixed-point problem: guess on a temperature path, solve backwards for decisions, run globe forwards to confirm guessed path.
- Use mostly well-known methods but heterogeneity vast:
  - exogenous TFP
  - wealth/capital
  - ℓ captures entire path of future regional TFP endogenous to climate (this feature NOT one-dimensional);
    - we don't actually solve 19,235 DP problems
    - but so much heterogeneity that we need to solve 700 DPs
    - and then nonlinearly interpolate decision rules between 700 "types".
- Fortran 90 + OpenMP with 20 cores: less than five minutes.

Experiments

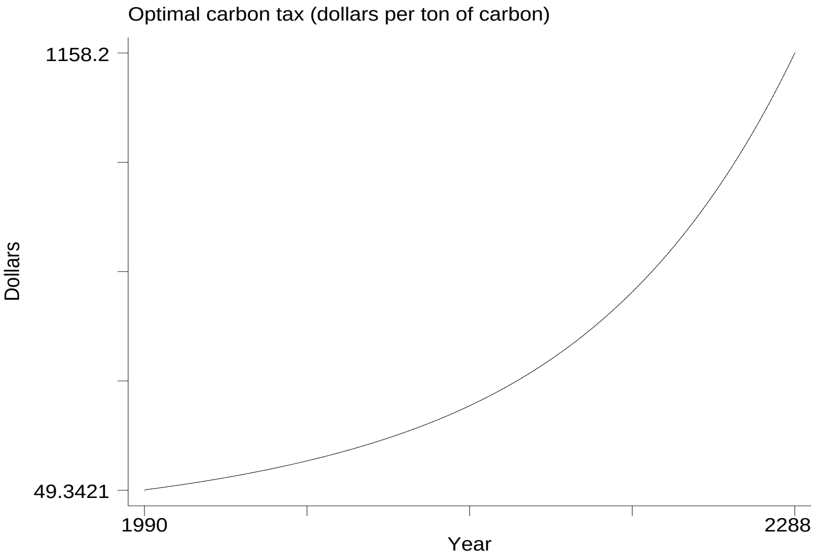
- Laissez-faire.
- Main policy experiment: all regions impose common path for carbon taxes, financed locally (no interregional transfers).

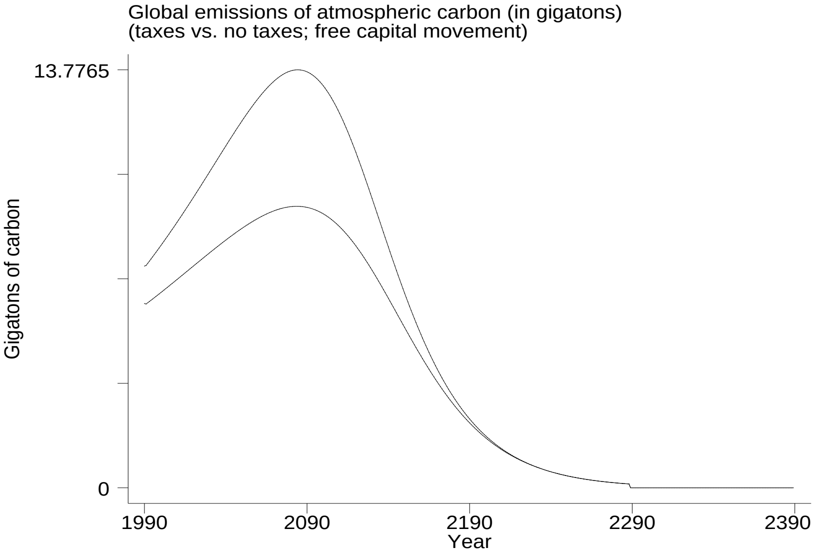
Throughout: focus on relative effects, not aggregates.

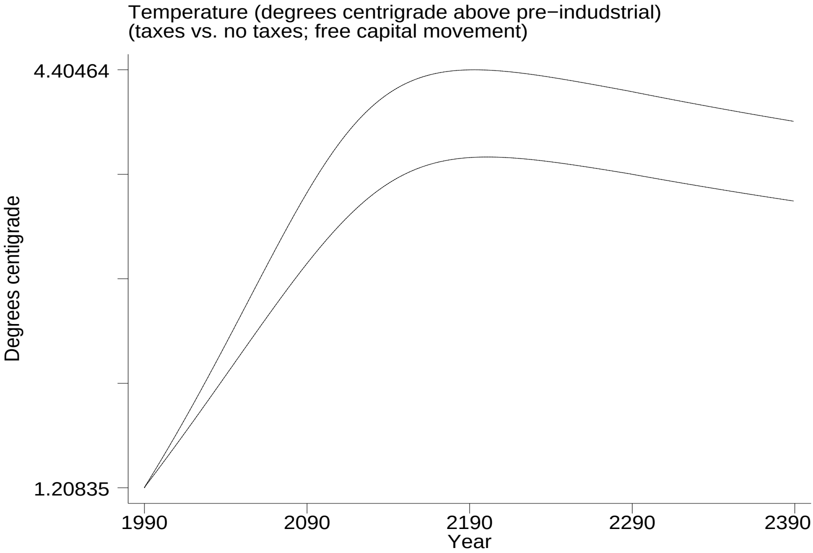
Main findings

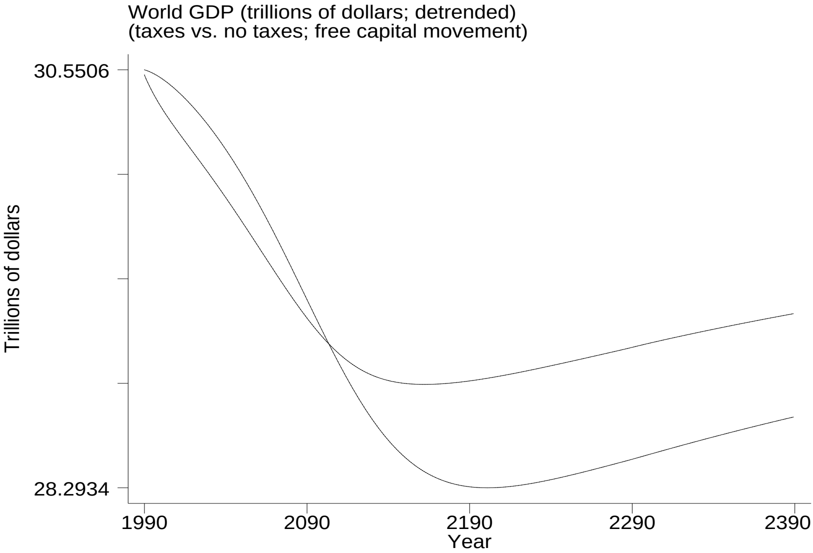
- Climate change affects regions *very* differently. Stakes big at regional level.
- Though a tax on carbon would affect welfare positively in some average sense, there is a large disparity of views across regions (56% of regions gain, while 44% lose).
- Findings are very close for two extreme market structures (autarky and international capital markets).

behavior of aggregates over time

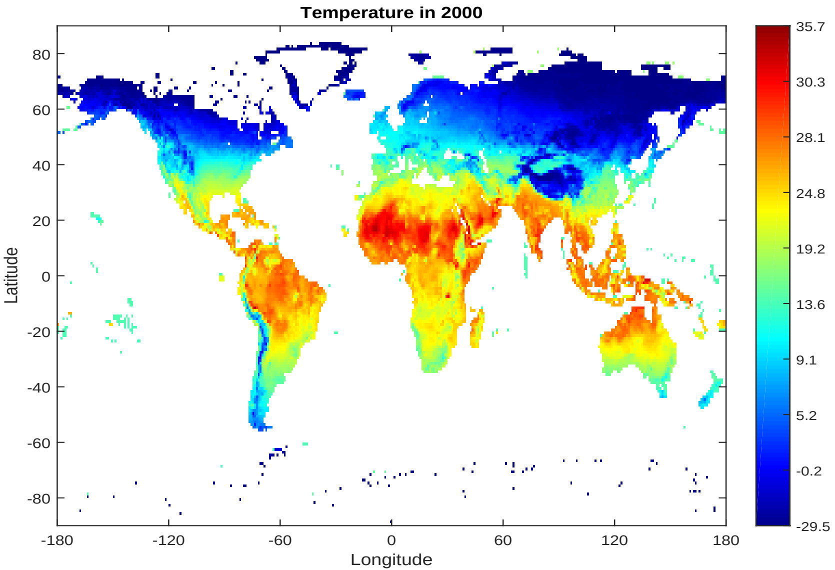

Optimal carbon tax (dollars per ton of carbon)
1158.2
49.3421
Dollars
1990
2288
Year

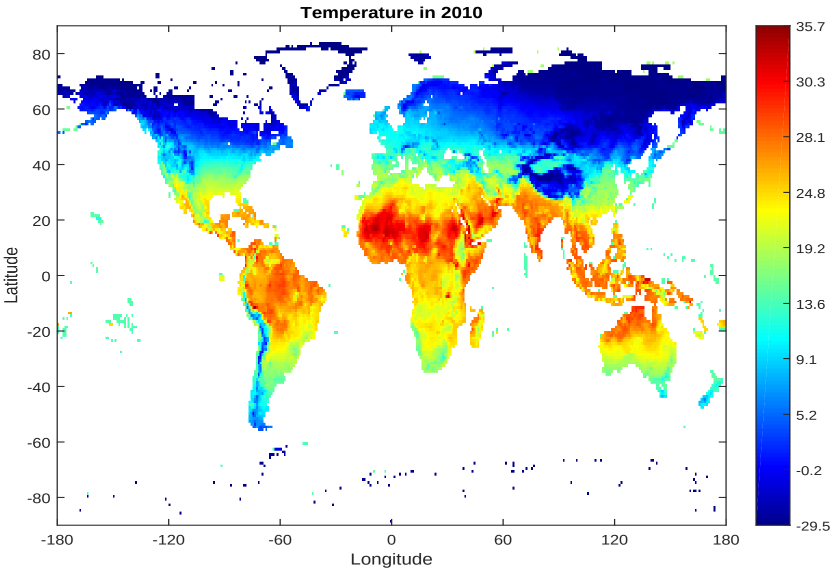

Global emissions of atmospheric carbon (in gigatons)
(taxes vs. no taxes; free capital movement)
13.7765
0
Gigatons of carbon
1990
2090
2190
2290
2390
Year


Temperature (degrees centrigrade above pre−indudstrial)
(taxes vs. no taxes; free capital movement)
4.40464
1.20835
Degrees centigrade
1990
2090
2190
2290
2390
Year

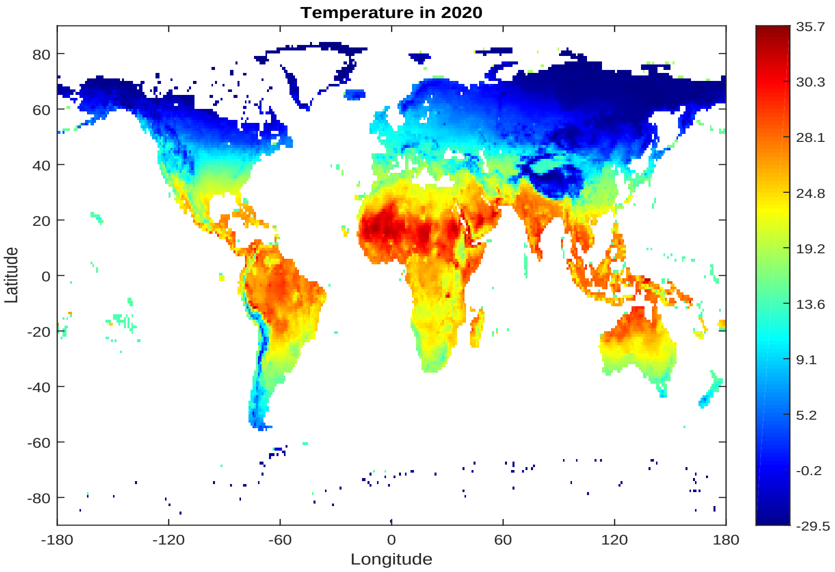

World GDP (trillions of dollars; detrended)
(taxes vs. no taxes; free capital movement)
30.5506
28.2934
Trillions of dollars
1990
2090
2190
2290
2390
Year

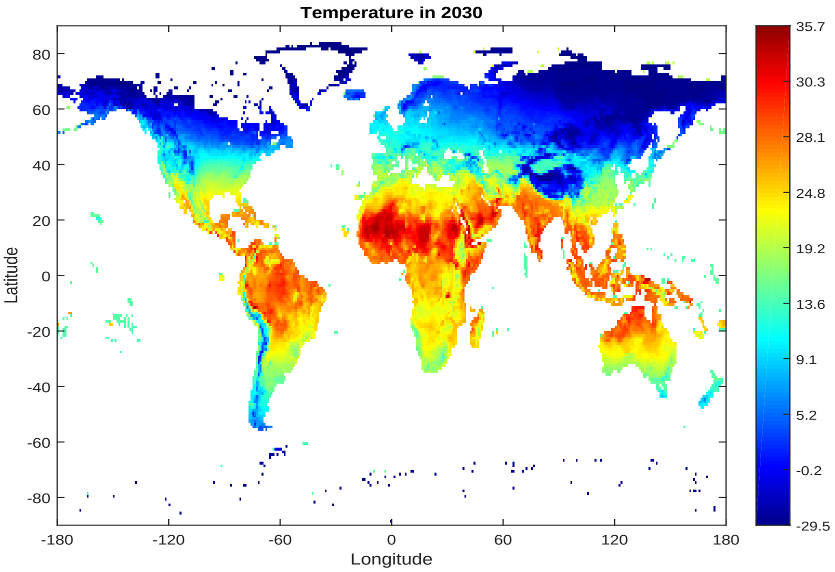
movie: temperature, laissez-faire
animation: www.econ.yale.edu/smith/temperature1.mp4

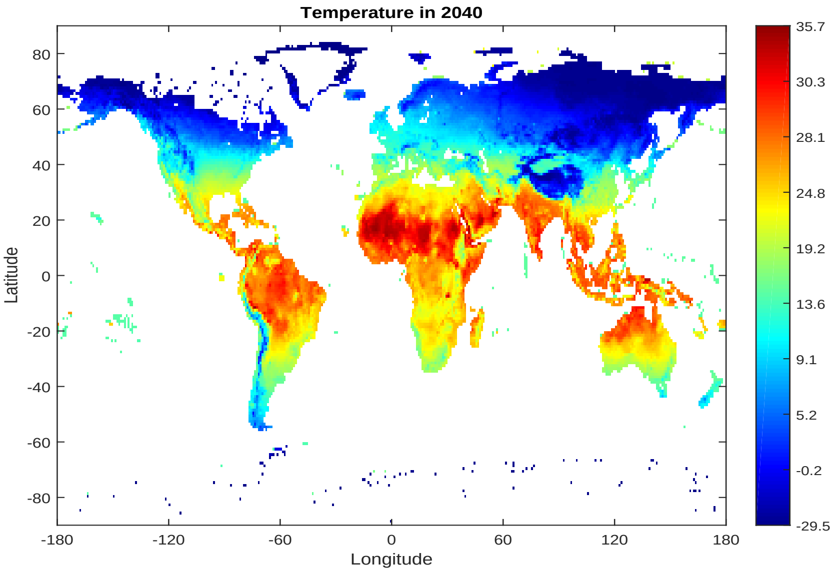

Temperature in 2000
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

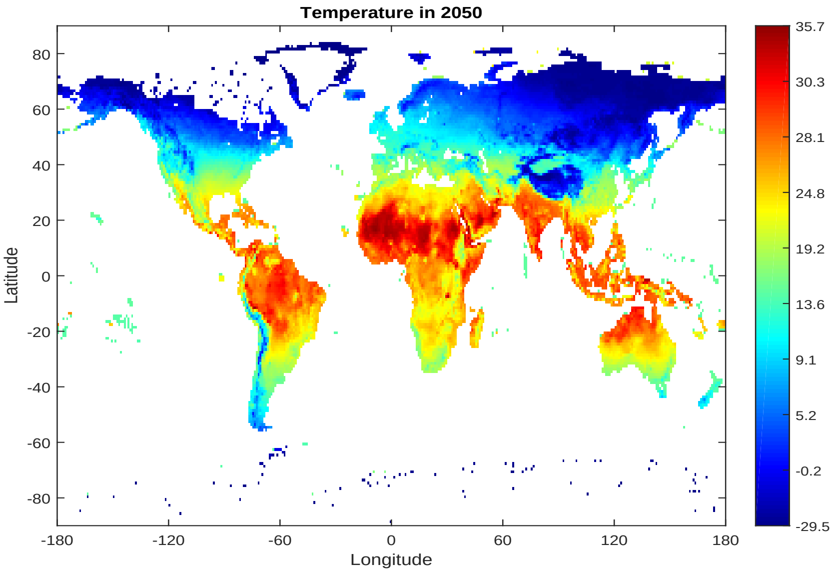


Temperature in 2010
80
60
40
20
0
-20
-40
-60
-80
Latitude
-180
-120
-60
0
60
120
180
Longitude
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

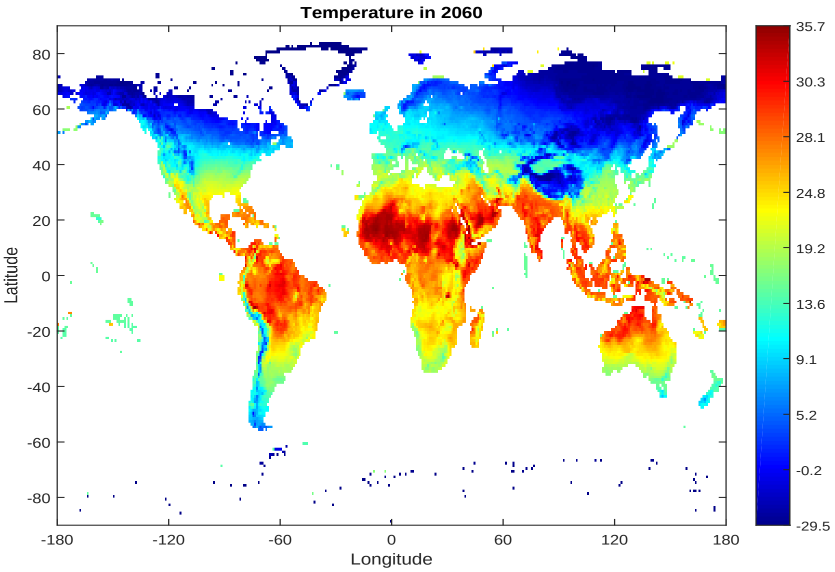

Temperature in 2020
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

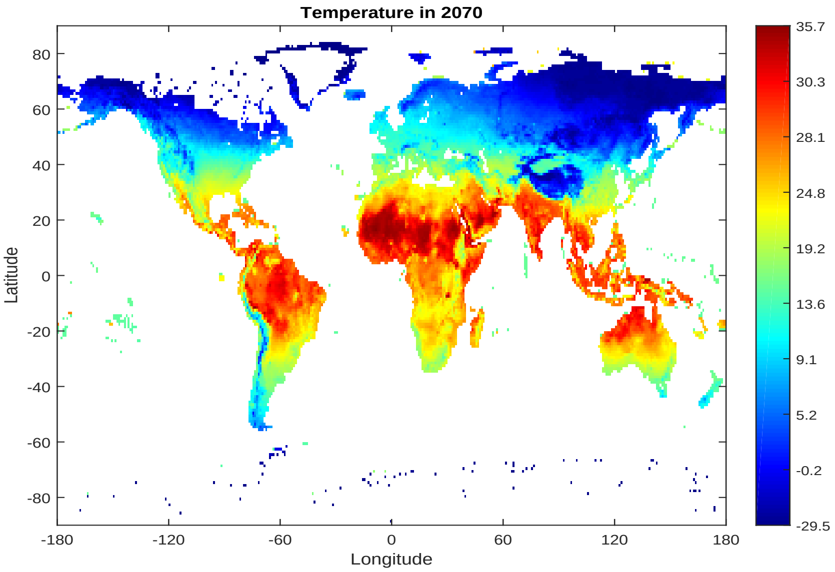

Temperature in 2030
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5


Temperature in 2040
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

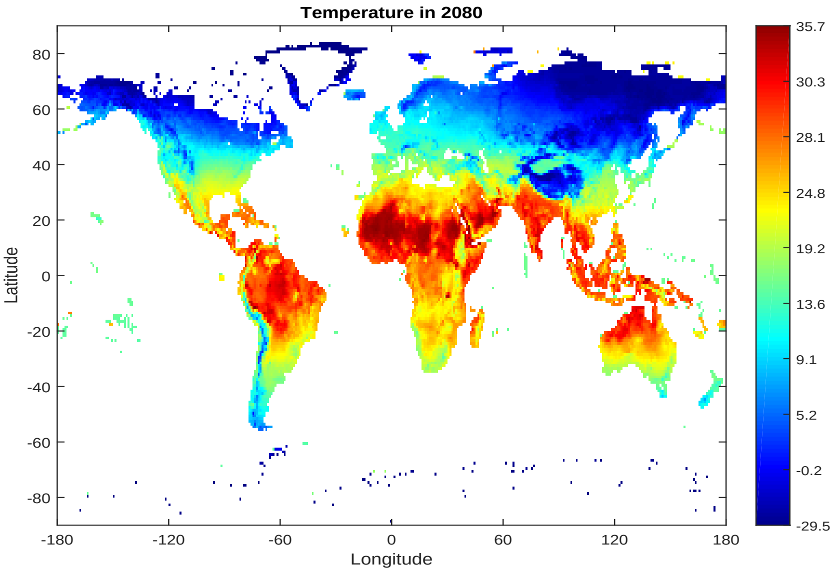


Temperature in 2050
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

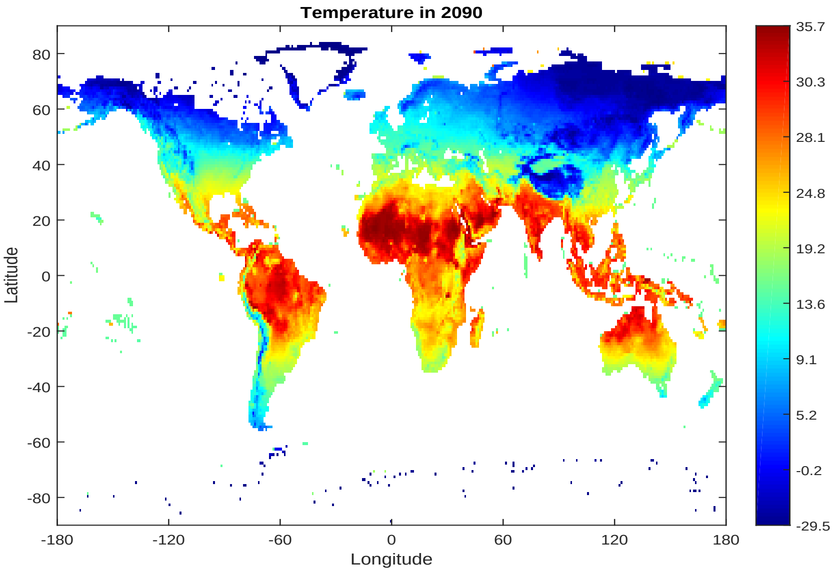

Temperature in 2060
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5



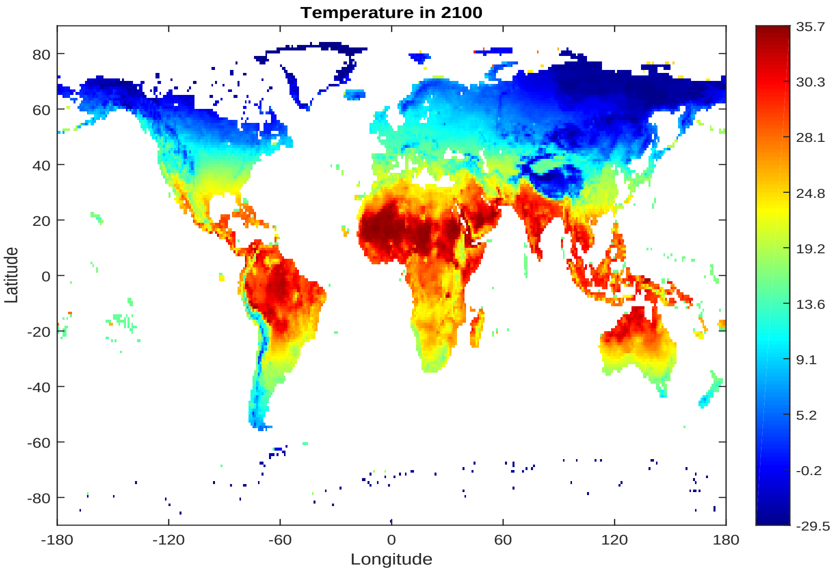
Temperature in 2070
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5



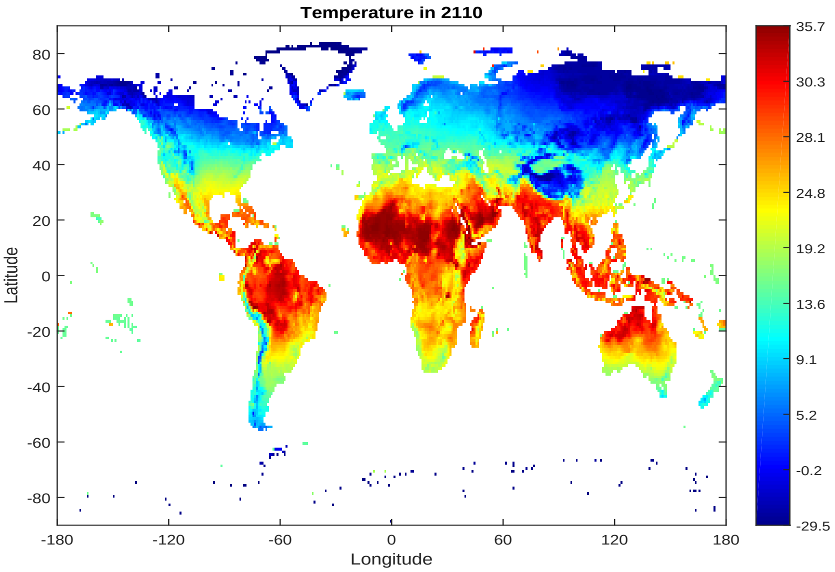
Temperature in 2080
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

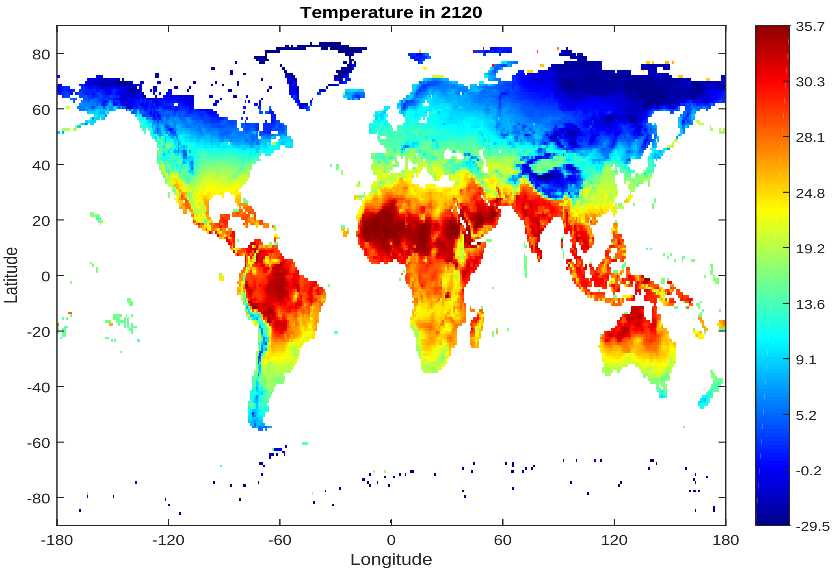


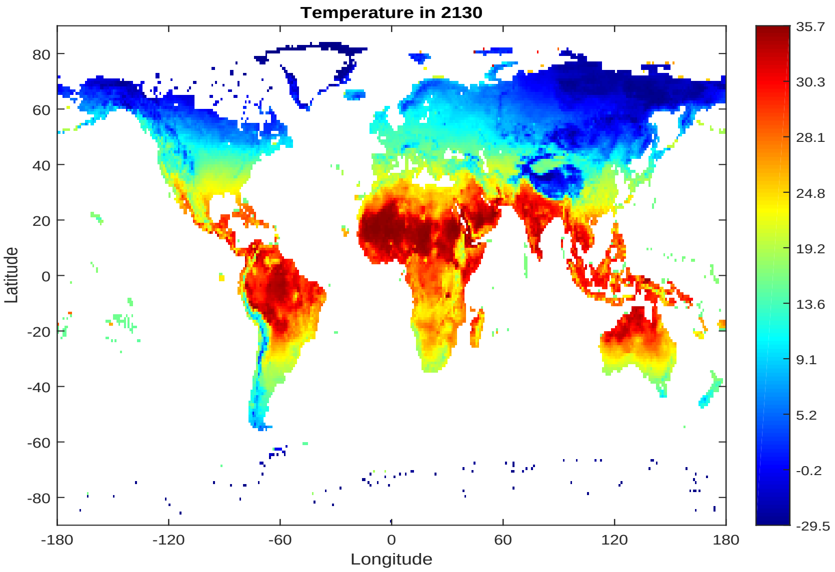
Temperature in 2090
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

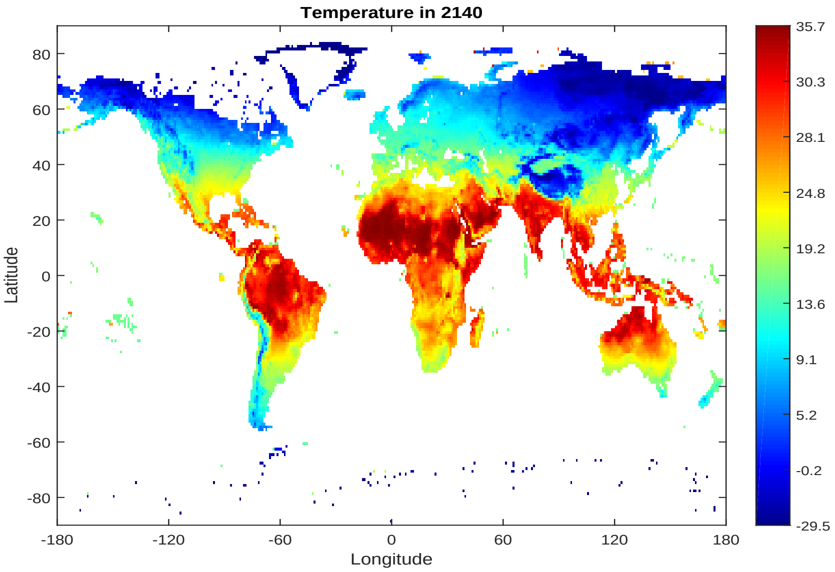


Temperature in 2100
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

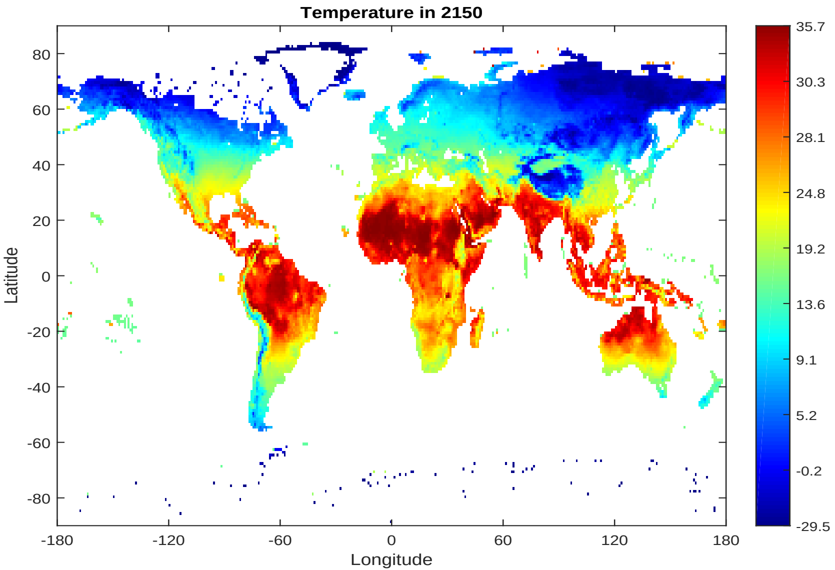

Temperature in 2110
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

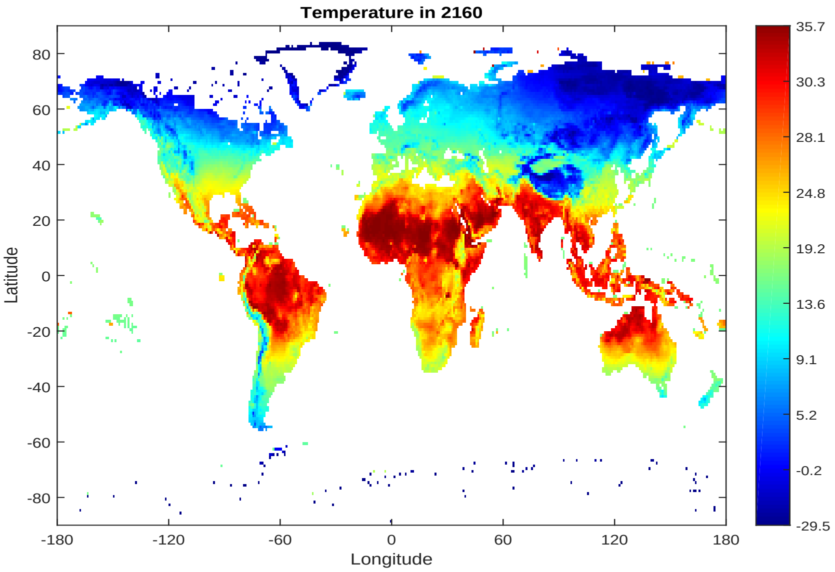

Temperature in 2120
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

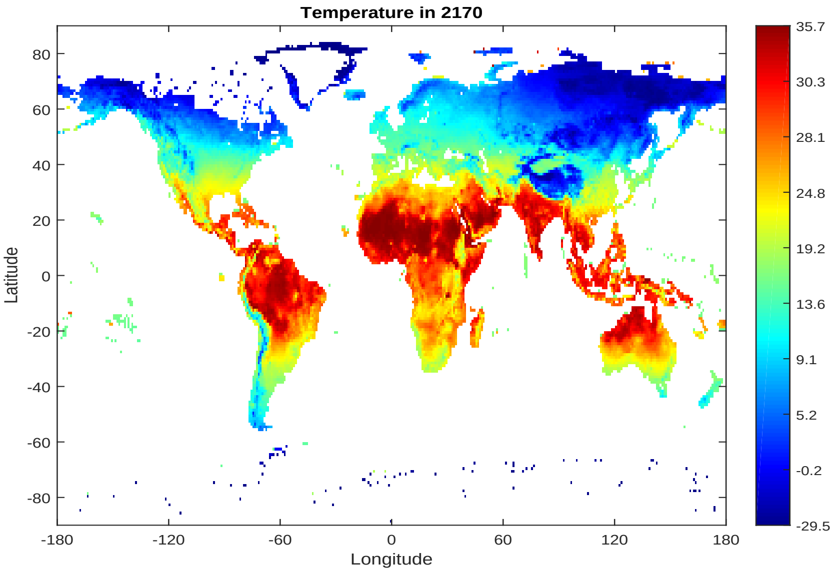

Temperature in 2130
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

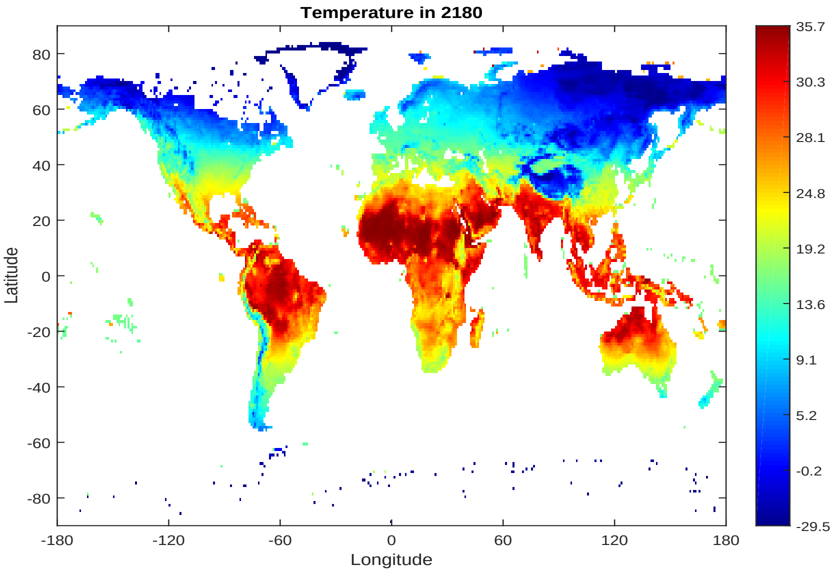


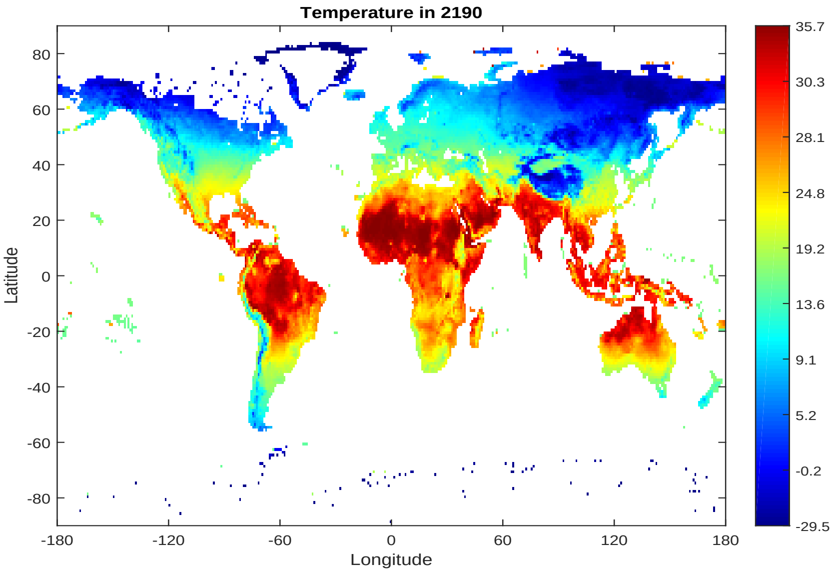
Temperature in 2140
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

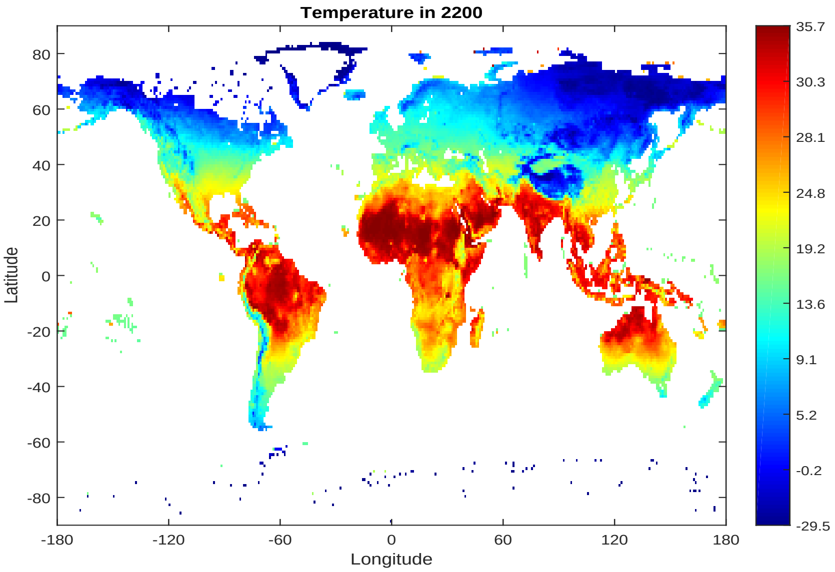

Temperature in 2150
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5


Temperature in 2160
Latitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
Longitude
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5


Temperature in 2170
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5


Temperature in 2180
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

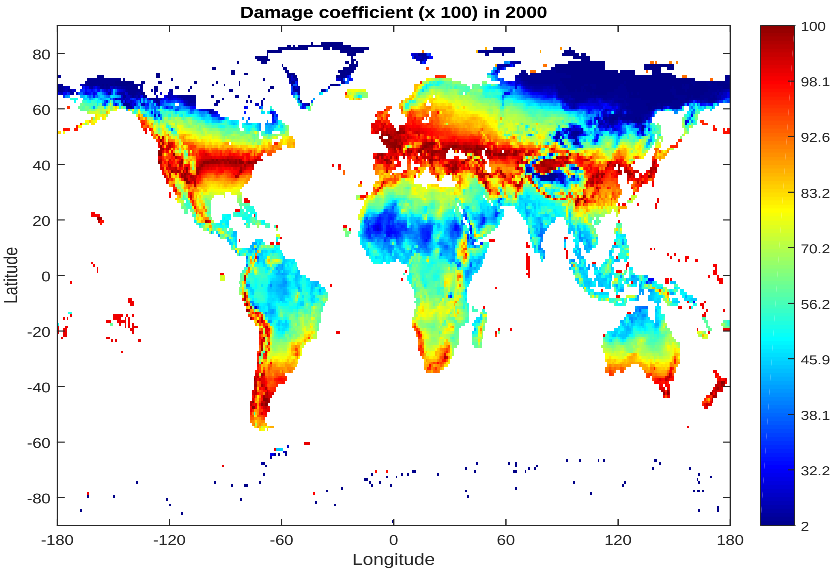

Temperature in 2190
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5



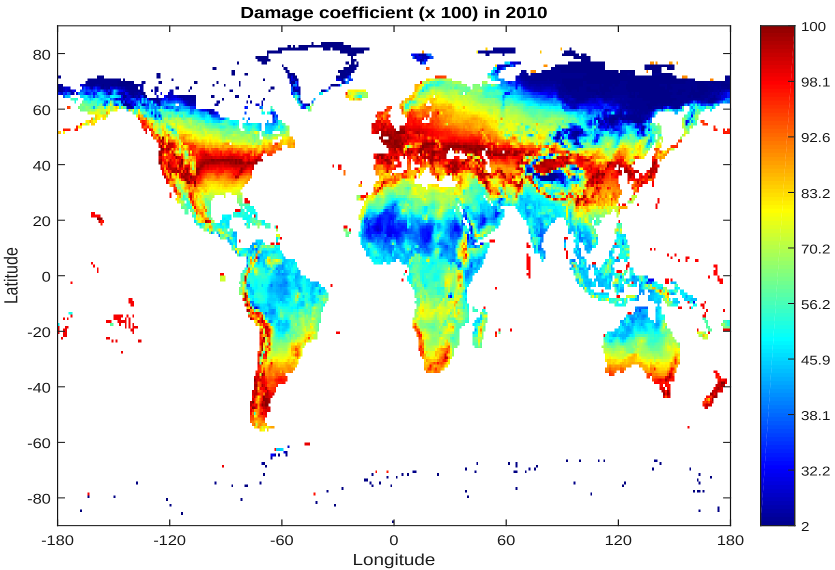
Temperature in 2200
80
60
40
20
0
-20
-40
-60
-80
Latitude
-180
-120
-60
0
60
120
180
Longitude
35.7
30.3
28.1
24.8
19.2
13.6
9.1
5.2
-0.2
-29.5

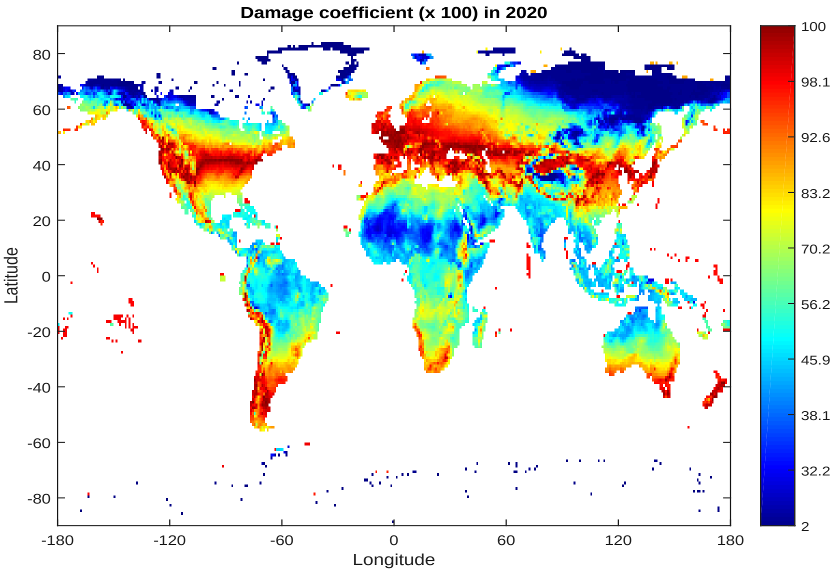
movie: change in temperature, laissez-faire
animation: www.econ.yale.edu/smith/deltatemperature1.mp4

movie: damage coefficient, laissez-faire
animation: www.econ.yale.edu/smith/damage1.mp4

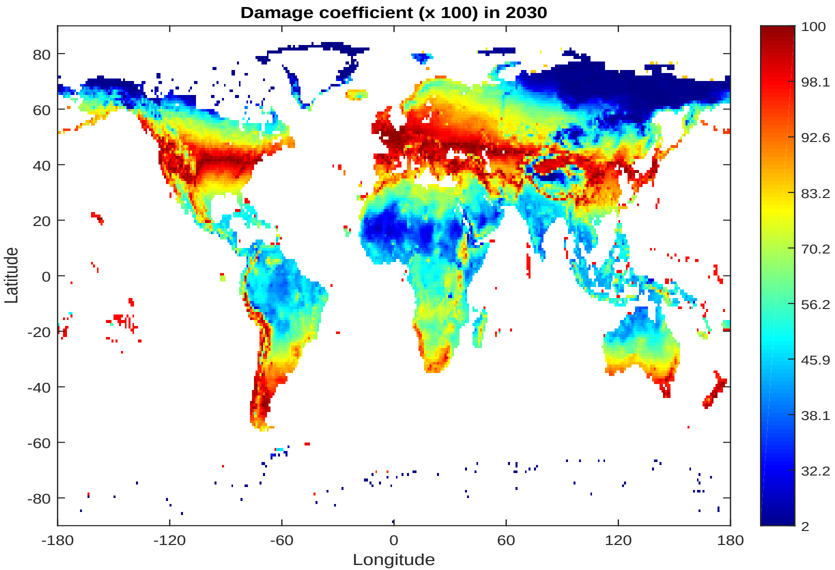


Damage coefficient (x 100) in 2000
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
98.1
92.6
83.2
70.2
56.2
45.9
38.1
32.2
2

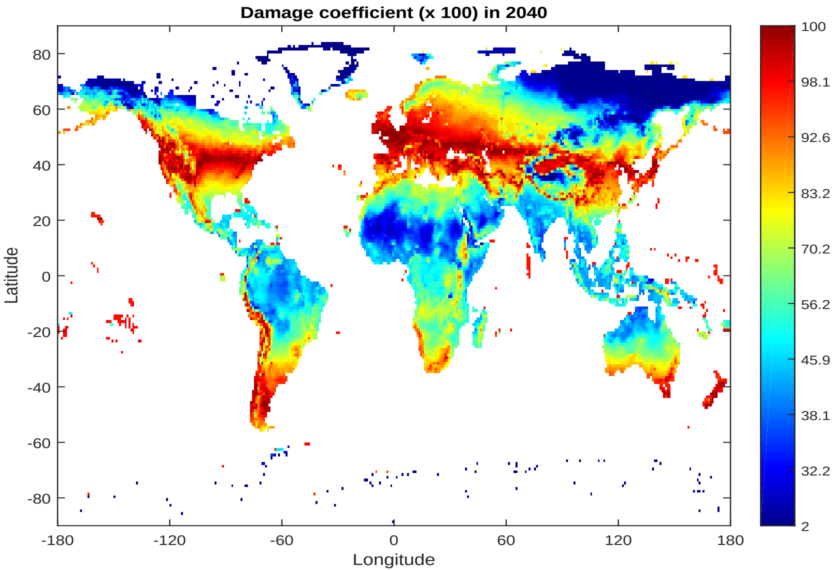

Damage coefficient (x 100) in 2010
80
60
40
20
0
-20
-40
-60
-80
Latitude
-180
-120
-60
0
60
120
180
Longitude
100
98.1
92.6
83.2
70.2
56.2
45.9
38.1
32.2
2

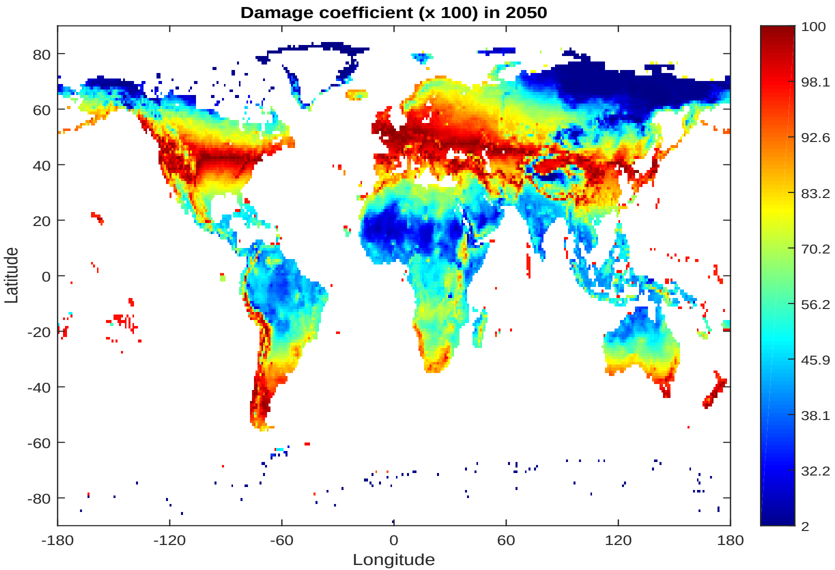


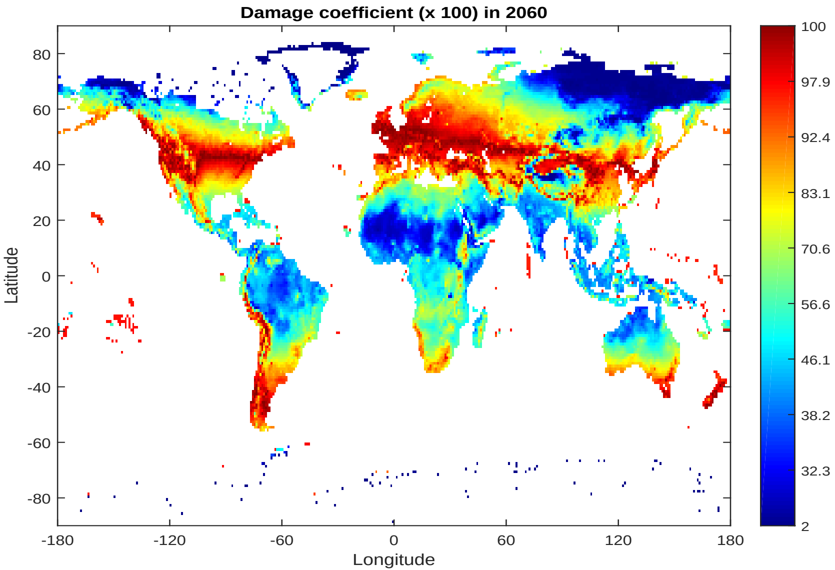
Damage coefficient (x 100) in 2020
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
98.1
92.6
83.2
70.2
56.2
45.9
38.1
32.2
2



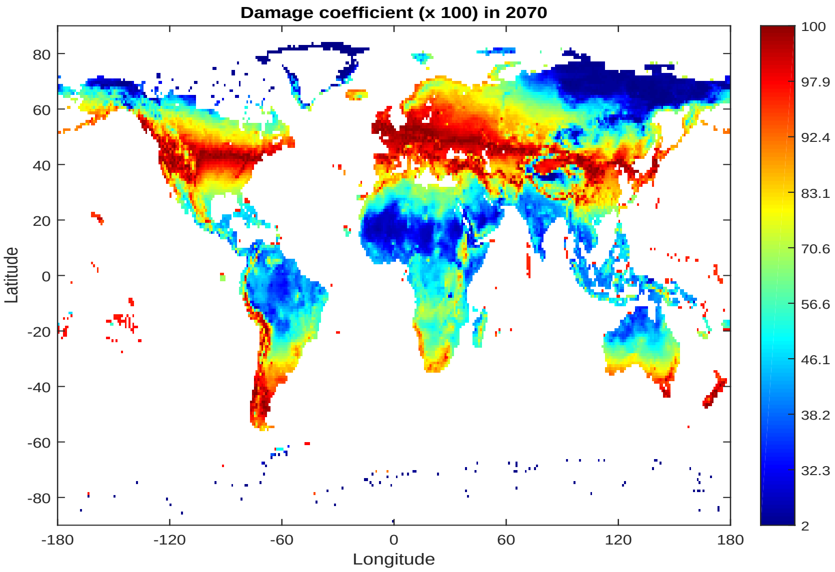
Damage coefficient (x 100) in 2030
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
98.1
92.6
83.2
70.2
56.2
45.9
38.1
32.2
2

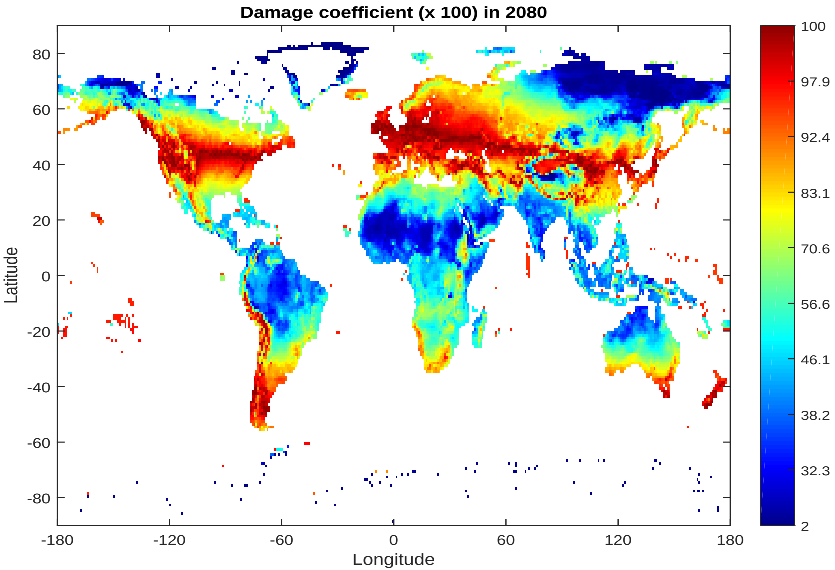

Damage coefficient (x 100) in 2040
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
98.1
92.6
83.2
70.2
56.2
45.9
38.1
32.2
2

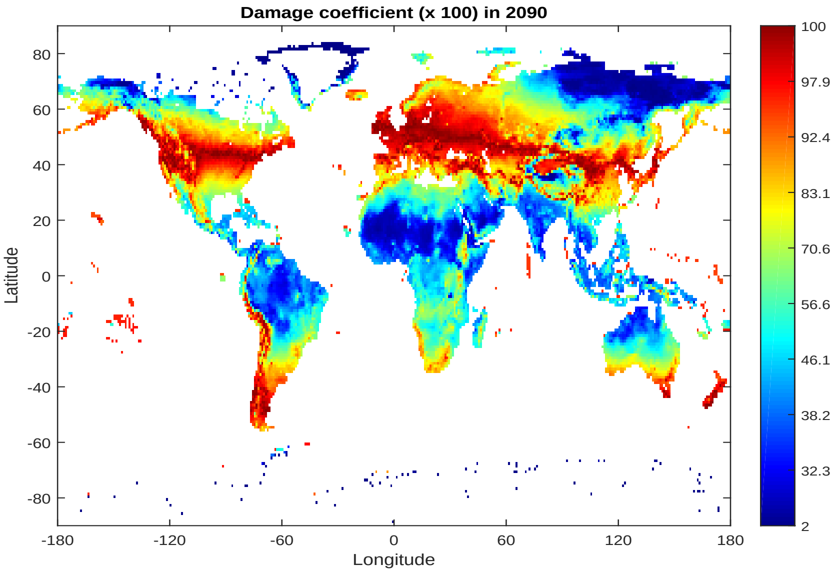

Damage coefficient (x 100) in 2050
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
98.1
92.6
83.2
70.2
56.2
45.9
38.1
32.2
2

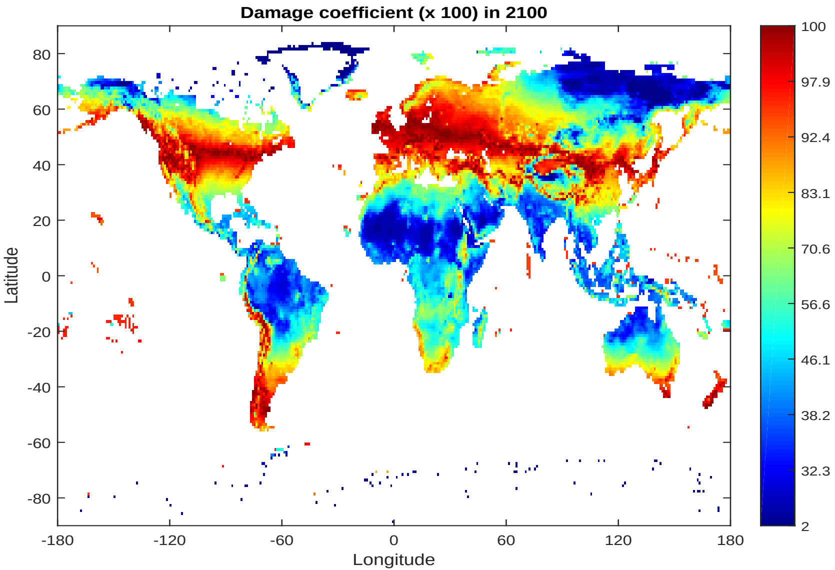


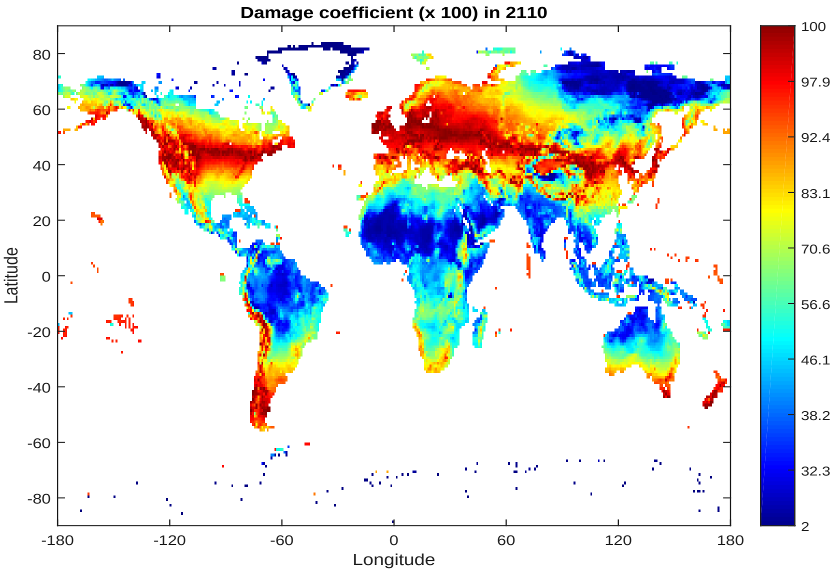
Damage coefficient (x 100) in 2060
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2


Damage coefficient (x 100) in 2070
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

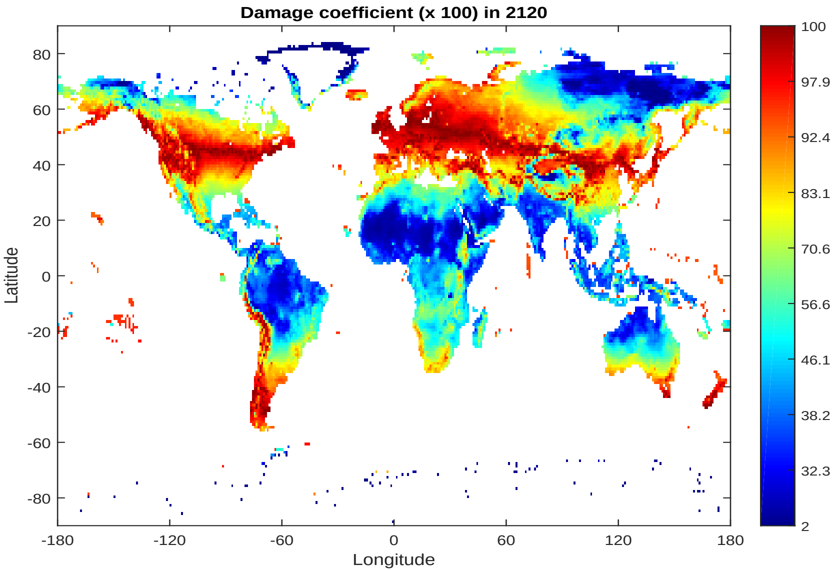

Damage coefficient (x 100) in 2080
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

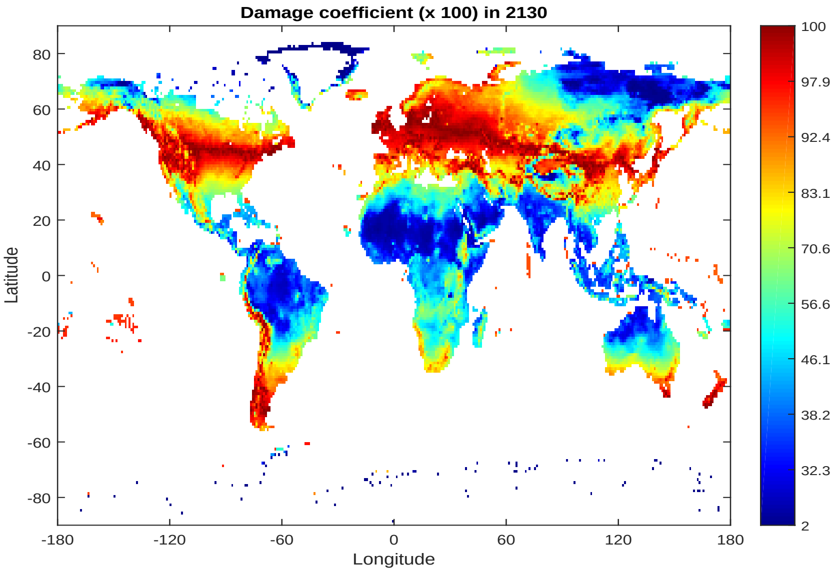

Damage coefficient (x 100) in 2090
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2


Damage coefficient (x 100) in 2100
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

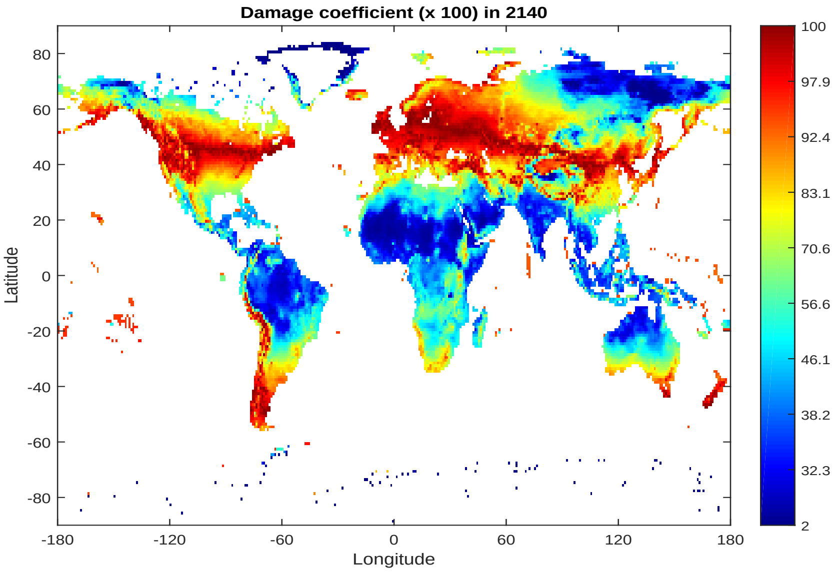


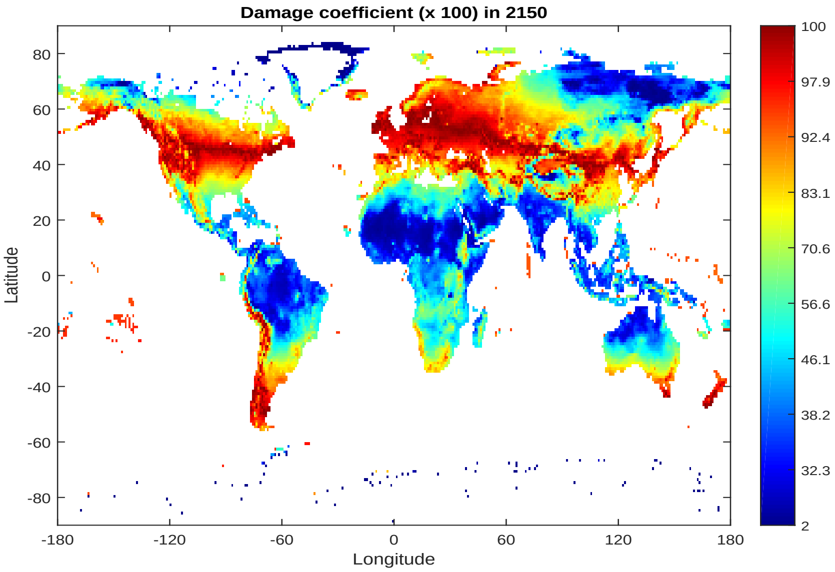
Damage coefficient (x 100) in 2110
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2


Damage coefficient (x 100) in 2120
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

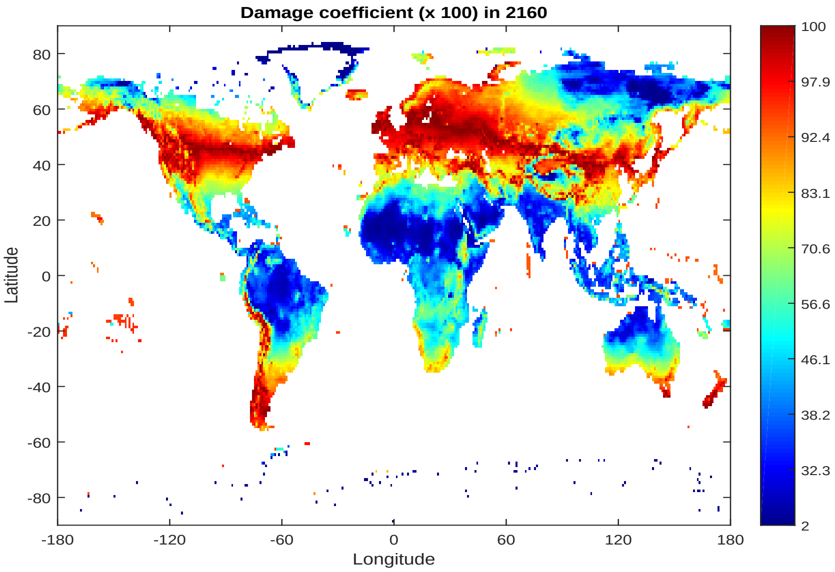


Damage coefficient (x 100) in 2130
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

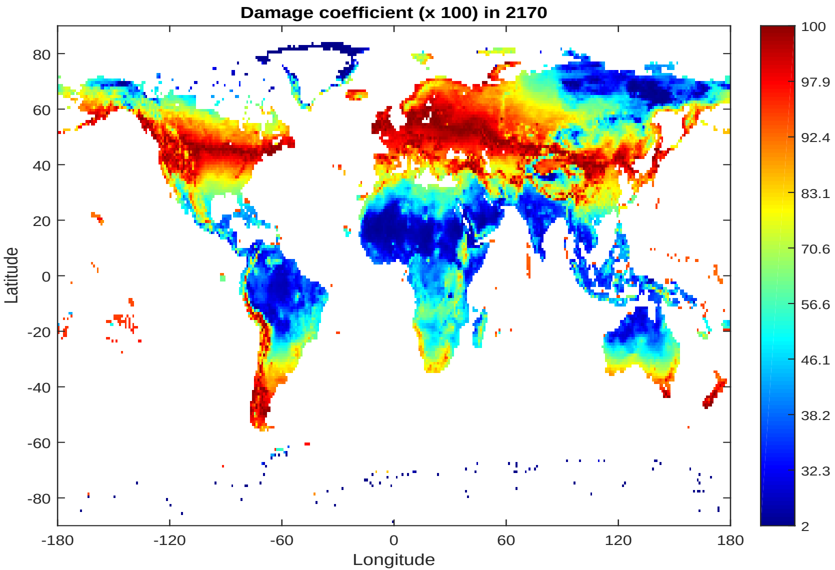

Damage coefficient (x 100) in 2140
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2



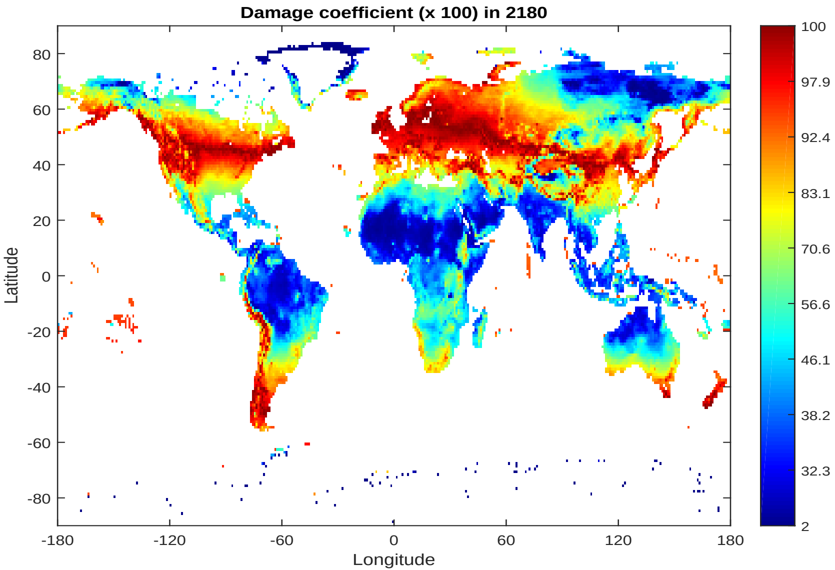
Damage coefficient (x 100) in 2150
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

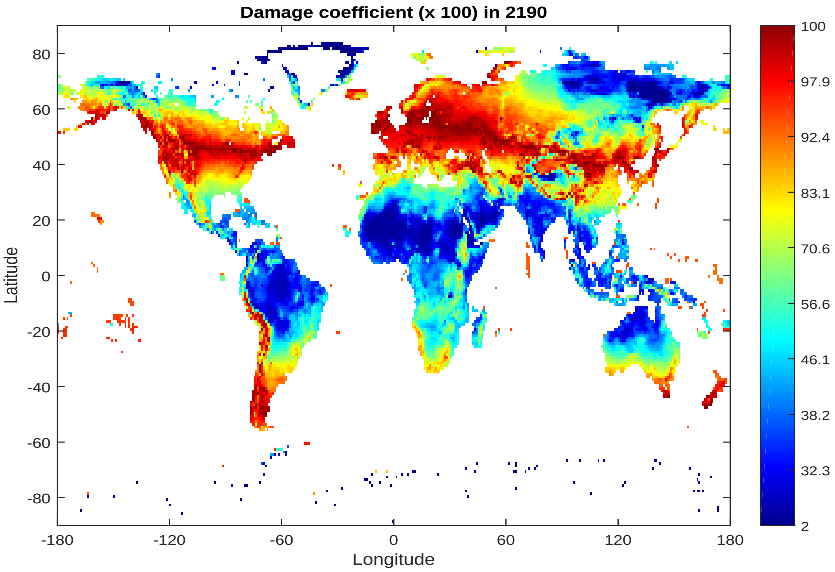


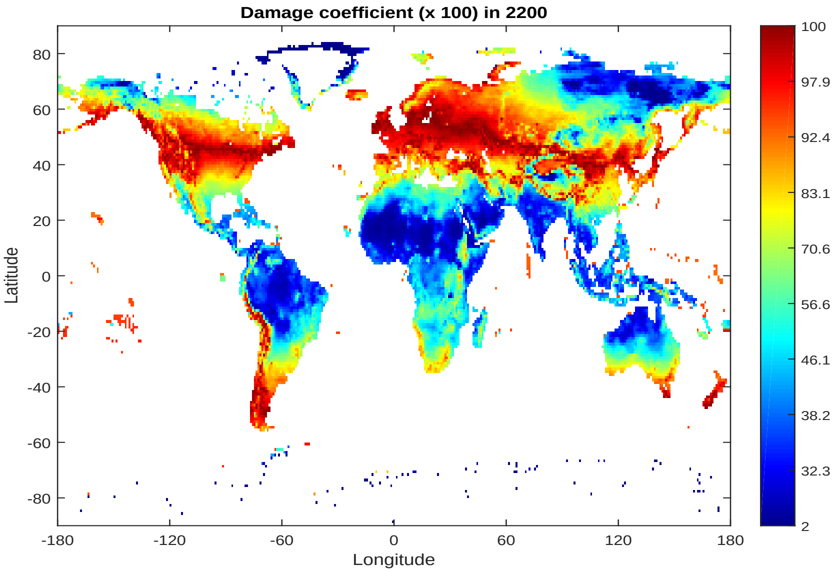
Damage coefficient (x 100) in 2160
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2



Damage coefficient (x 100) in 2170
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

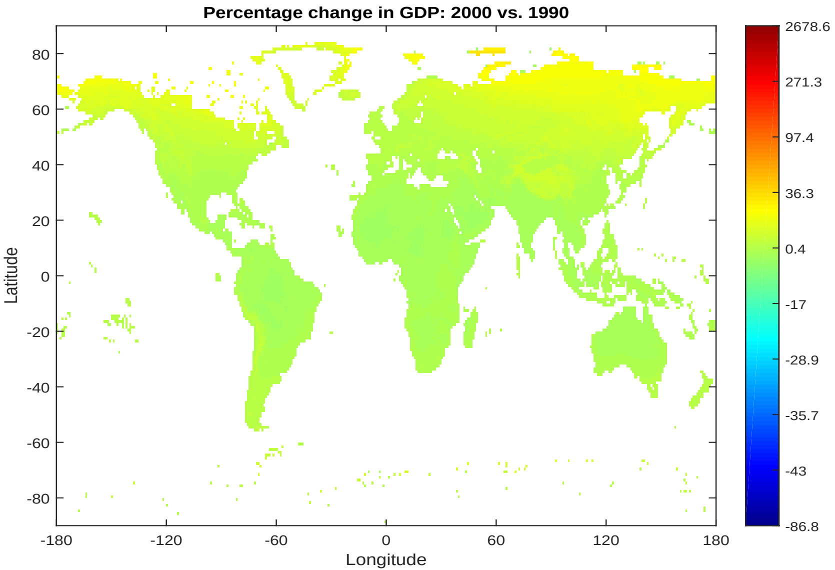

Damage coefficient (x 100) in 2180
80
60
40
20
0
-20
-40
-60
-80
Latitude
-180
-120
-60
0
60
120
180
Longitude
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

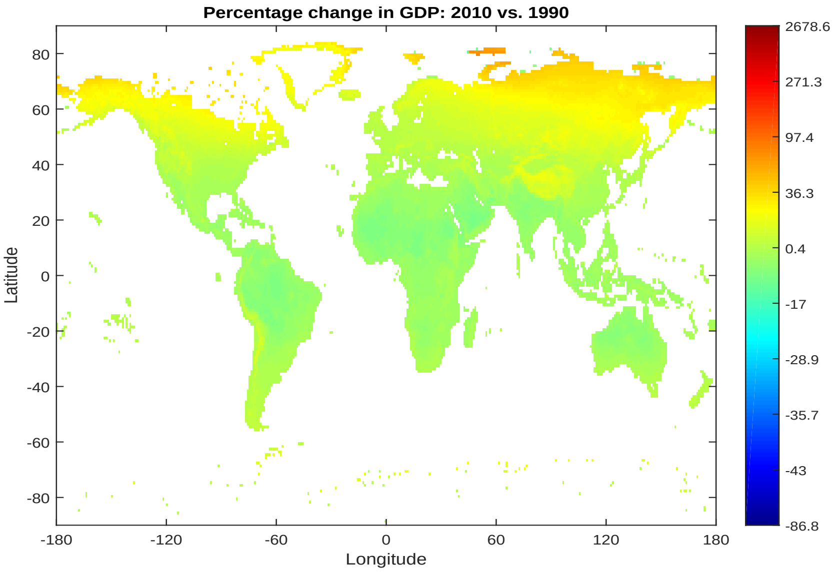

Damage coefficient (x 100) in 2190
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

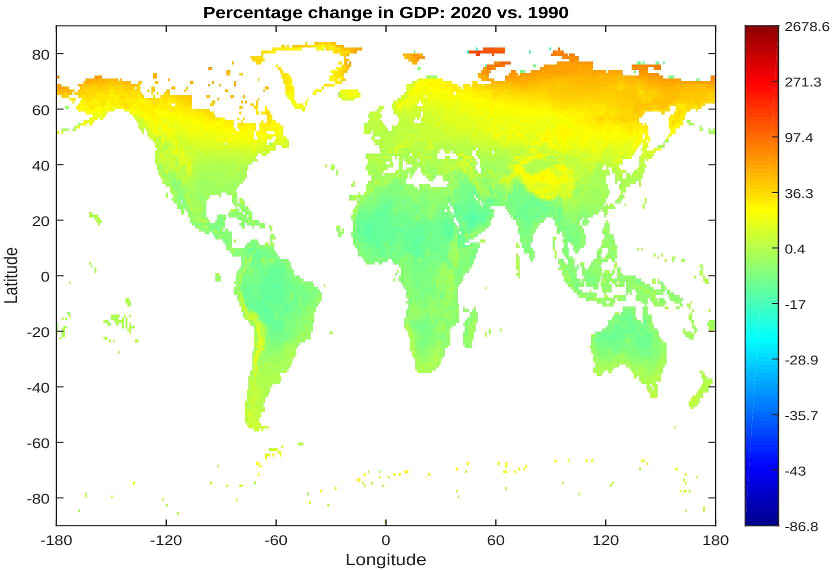


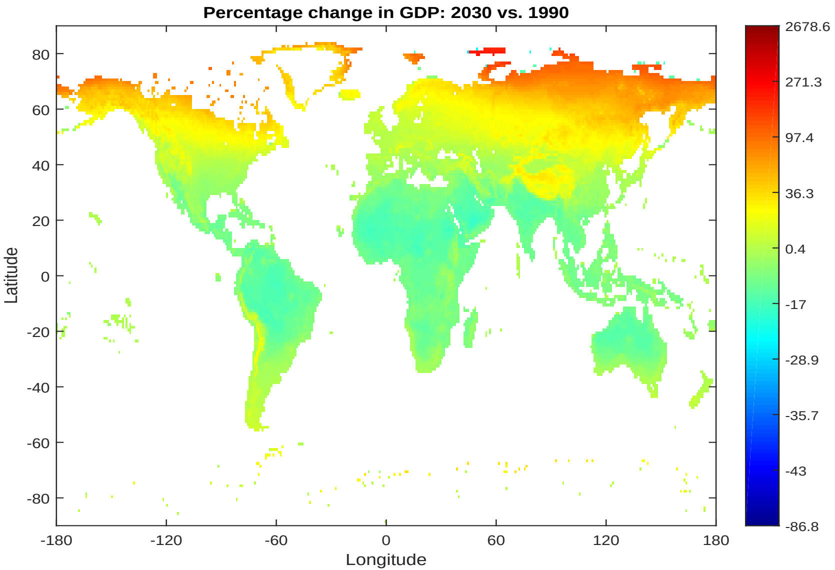
Damage coefficient (x 100) in 2200
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
97.9
92.4
83.1
70.6
56.6
46.1
38.2
32.3
2

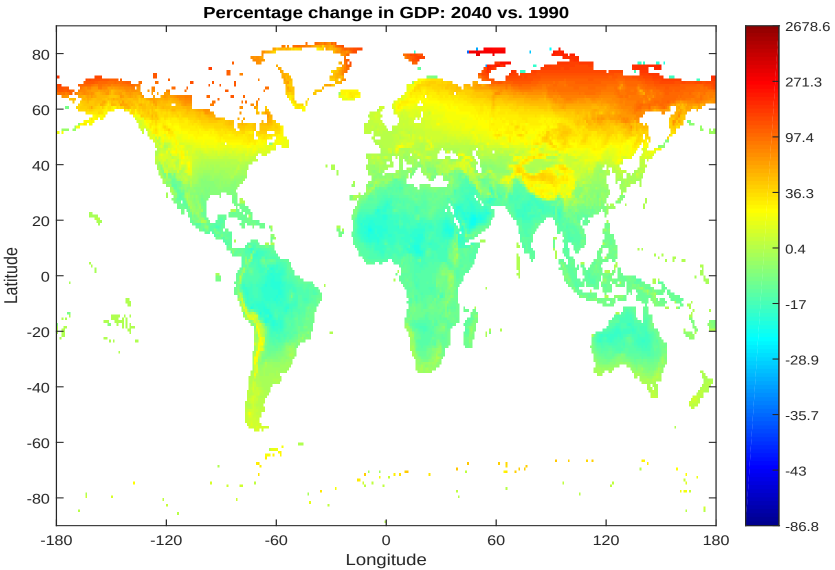
movie: percentage change in gdp, laissez-faire
animation: www.econ.yale.edu/smith/pctgdp1.mp4


Percentage change in GDP: 2000 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

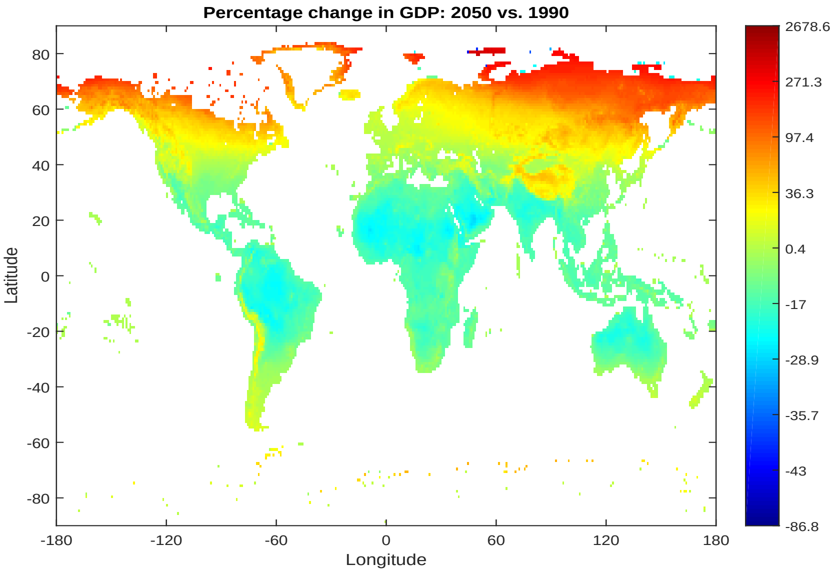

Percentage change in GDP: 2010 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

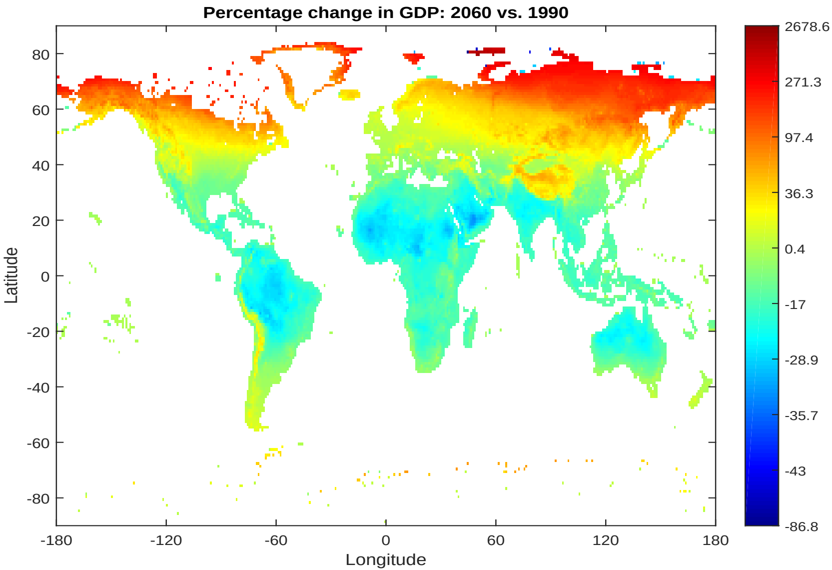

Percentage change in GDP: 2020 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

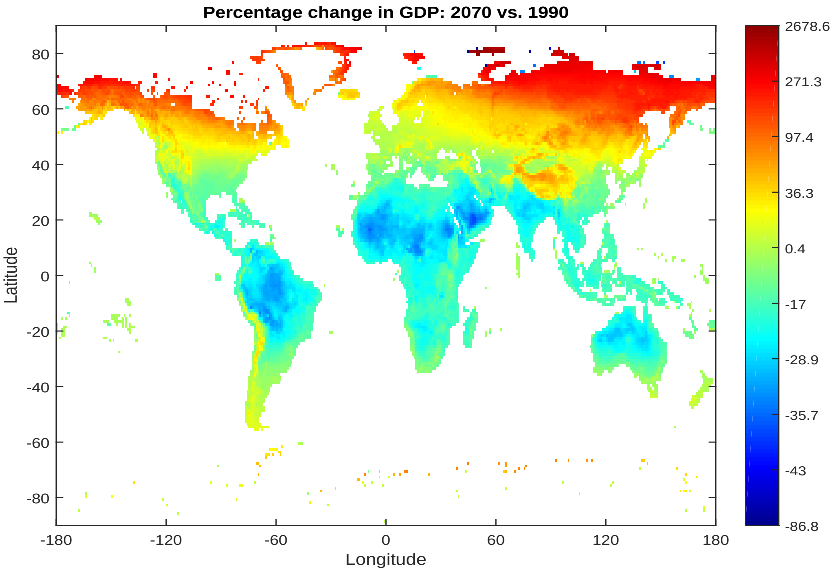

Percentage change in GDP: 2030 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

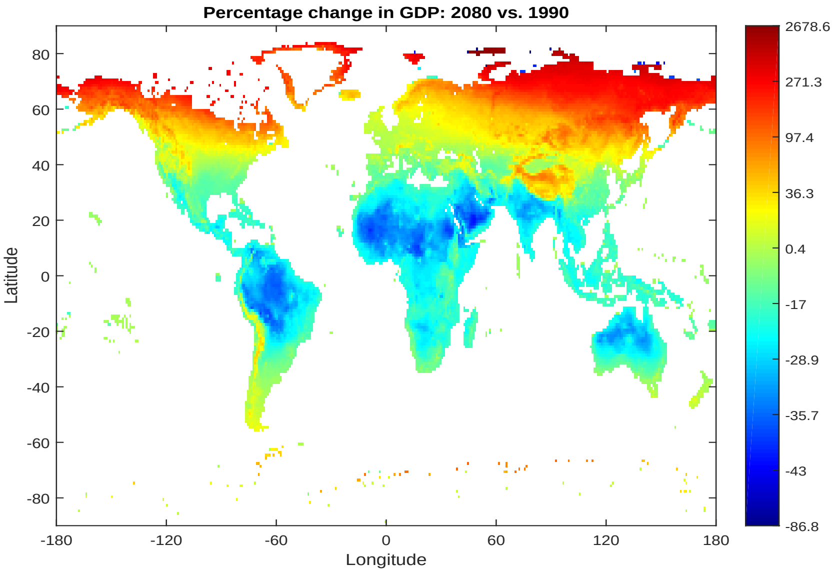


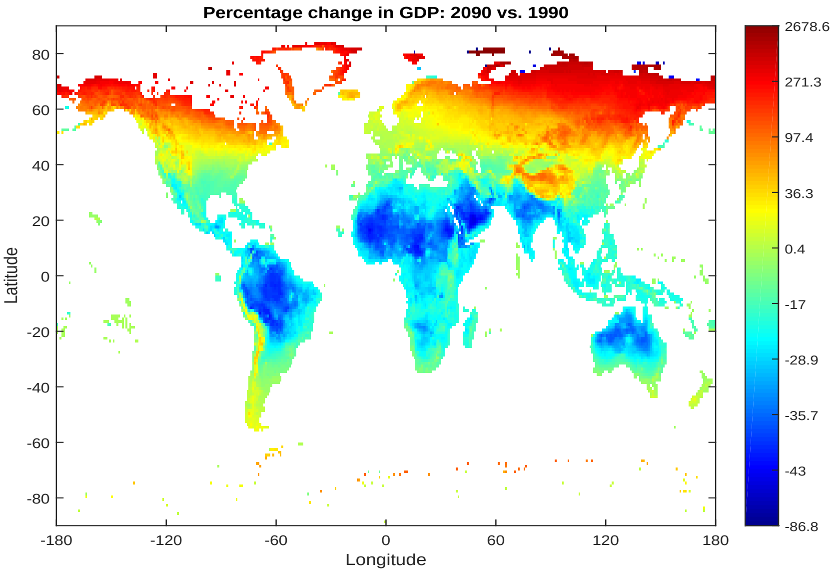
Percentage change in GDP: 2040 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8


Percentage change in GDP: 2050 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

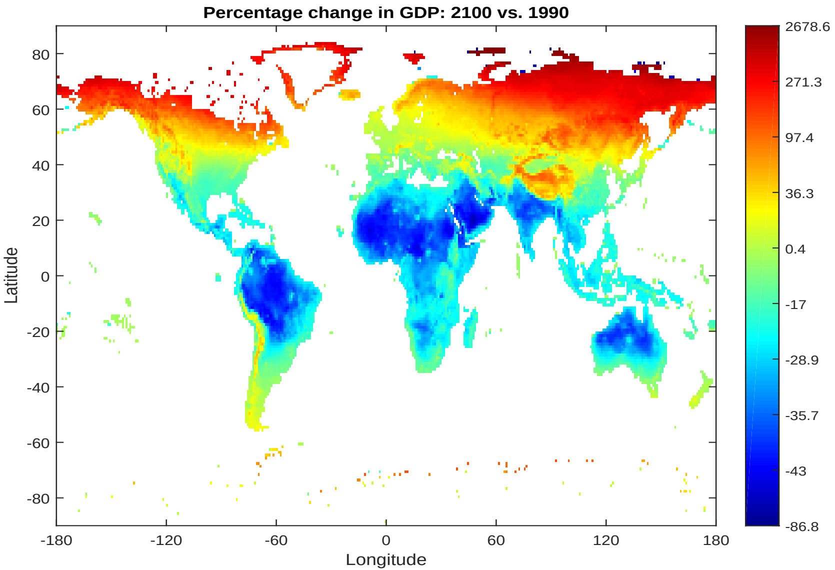

Percentage change in GDP: 2060 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8


Percentage change in GDP: 2070 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
Longitude
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

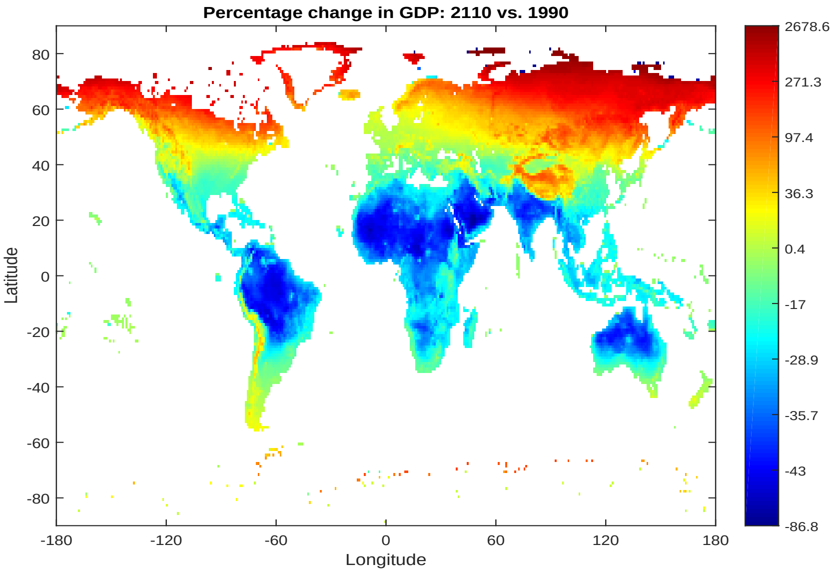

Percentage change in GDP: 2080 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



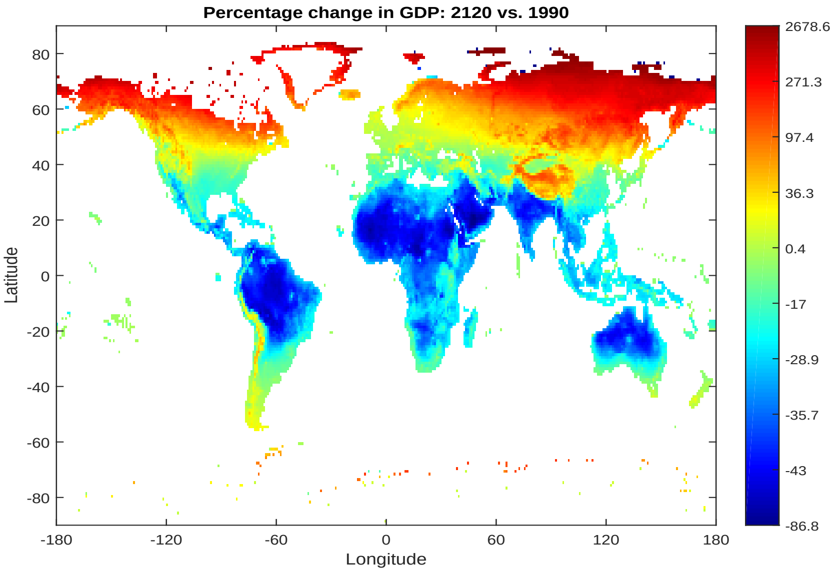
Percentage change in GDP: 2090 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



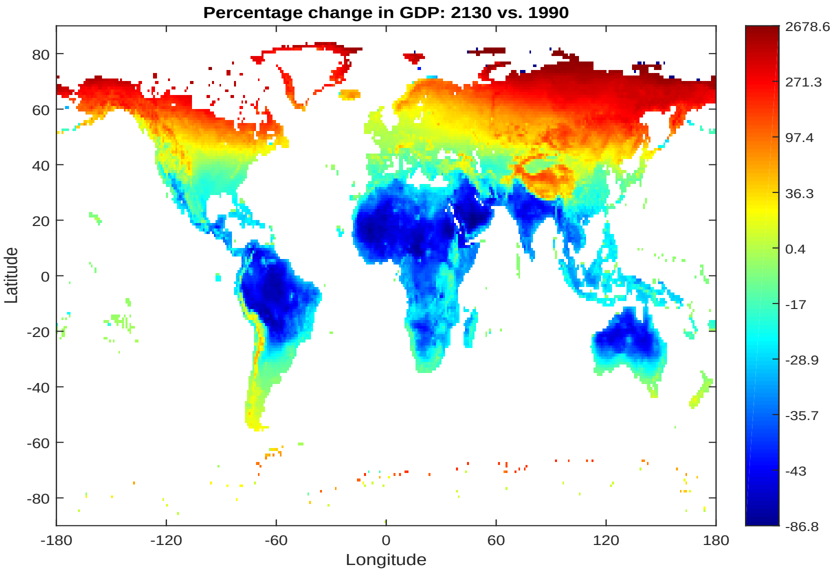
Percentage change in GDP: 2100 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

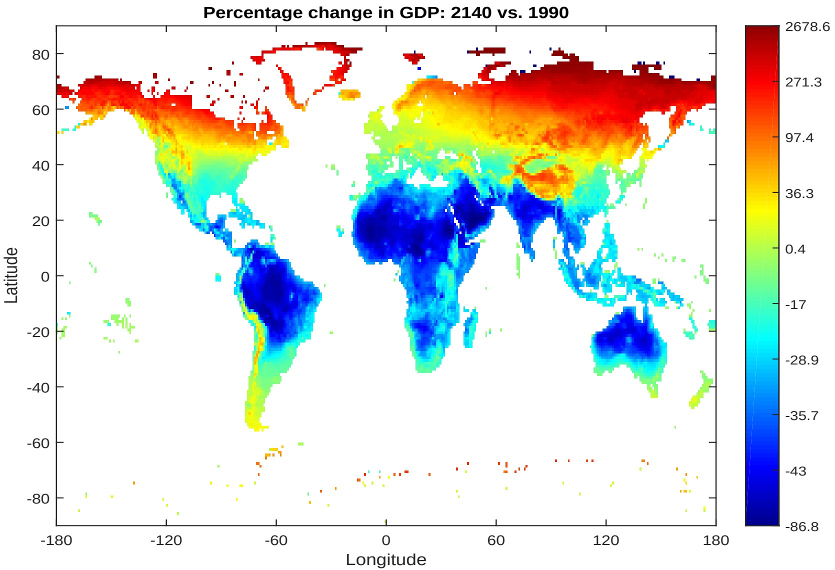


Percentage change in GDP: 2110 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

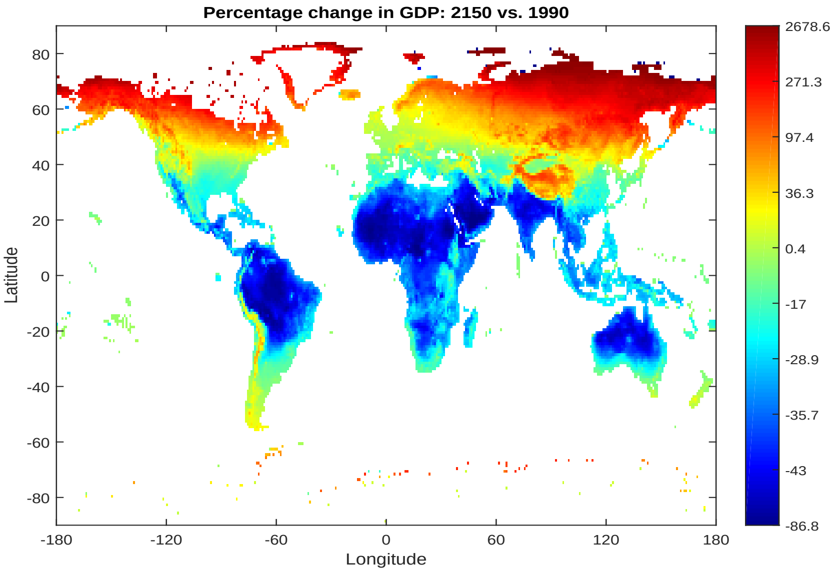


Percentage change in GDP: 2120 vs. 1990
80
60
40
20
0
-20
-40
-60
-80
Latitude
-180
-120
-60
0
60
120
180
Longitude
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

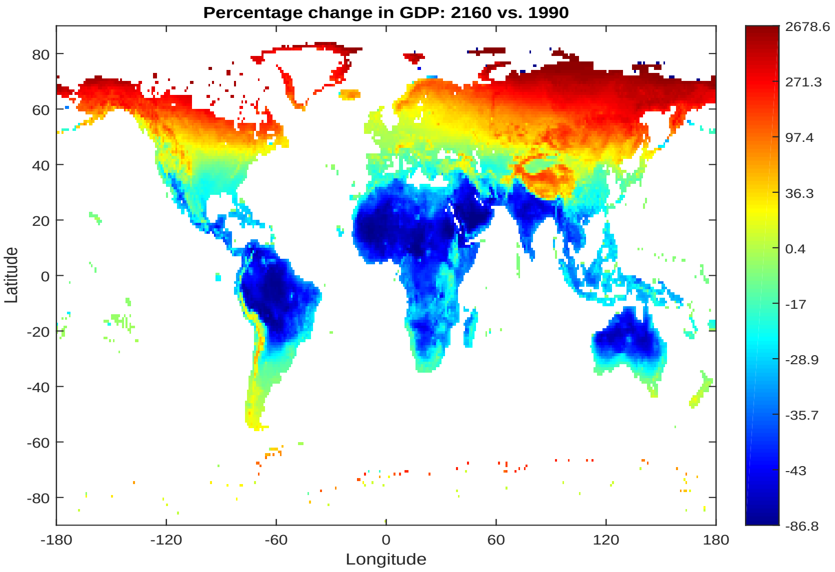

Percentage change in GDP: 2130 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



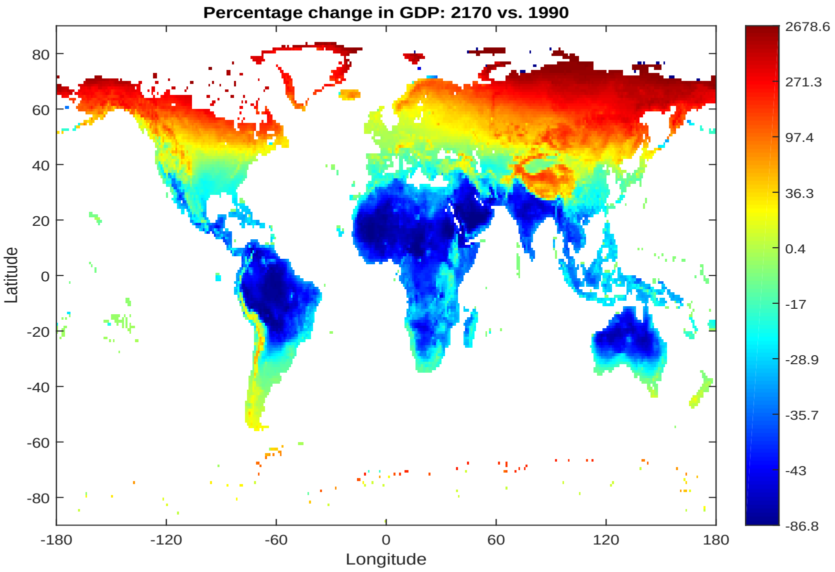
Percentage change in GDP: 2140 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



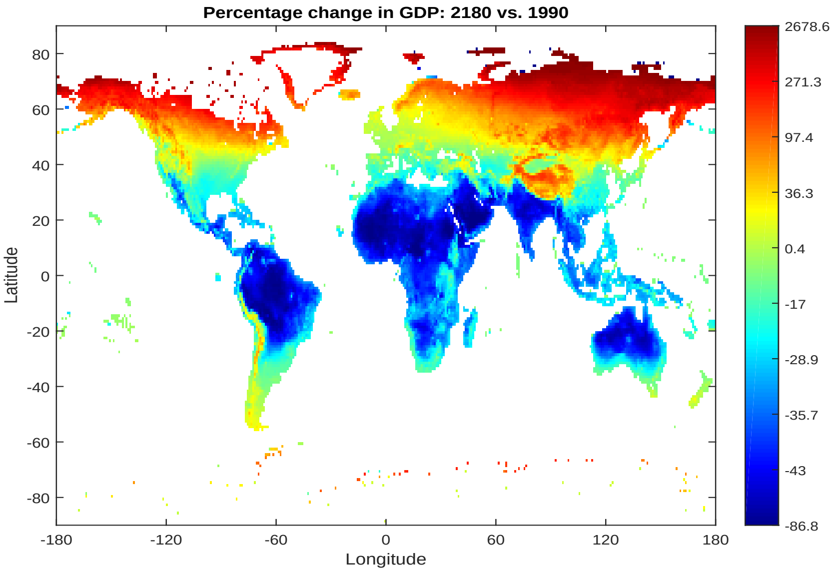
Percentage change in GDP: 2150 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



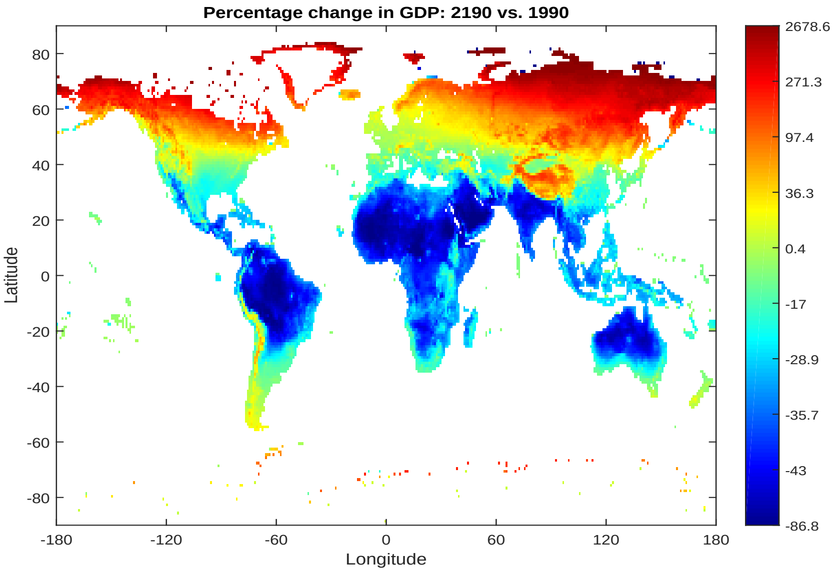
Percentage change in GDP: 2160 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

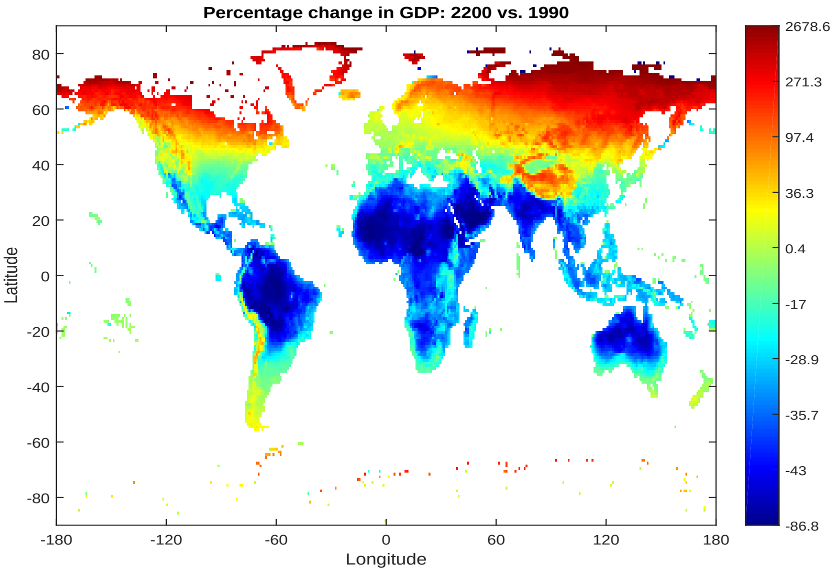


Percentage change in GDP: 2170 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



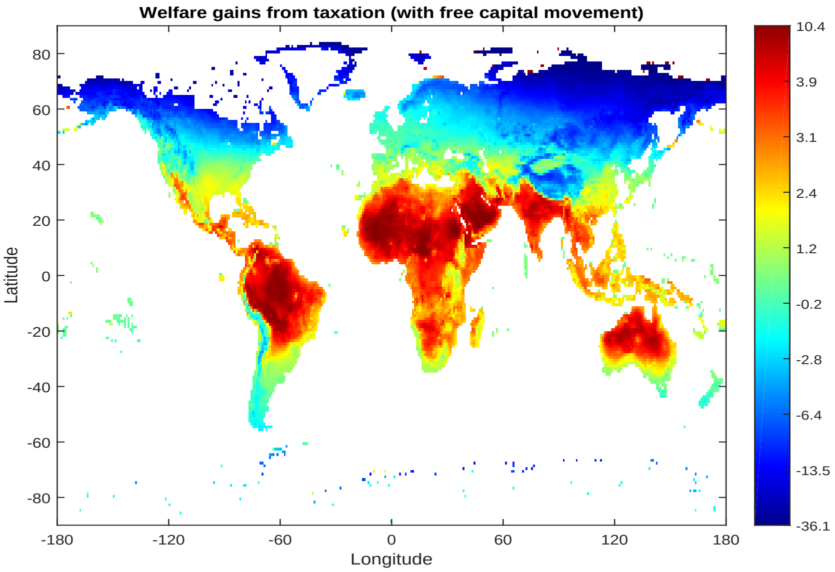
Percentage change in GDP: 2180 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8


Percentage change in GDP: 2190 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

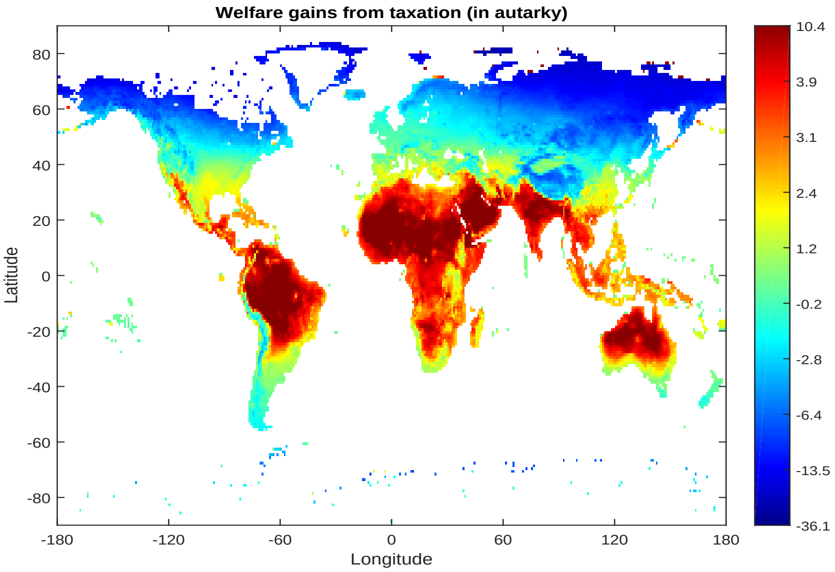


Percentage change in GDP: 2200 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

pictures: winners and losers from tax

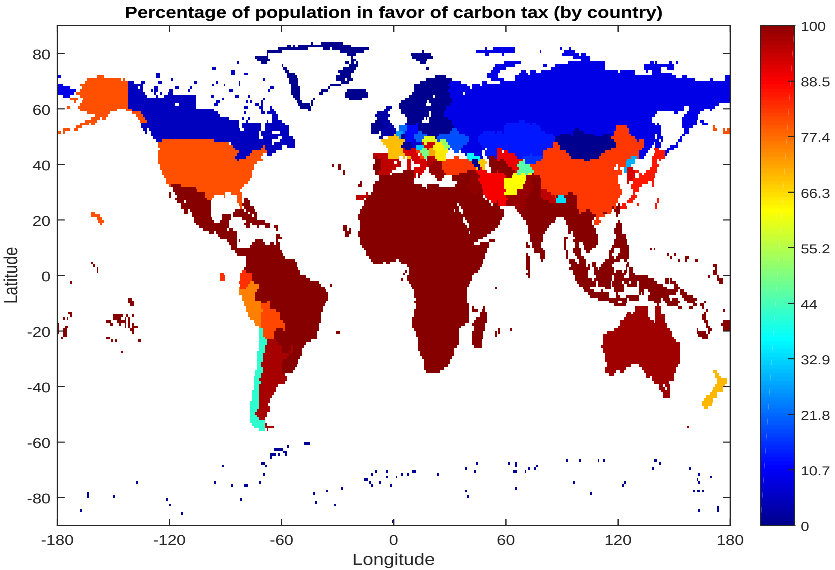


Welfare gains from taxation (with free capital movement)
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
10.4
3.9
3.1
2.4
1.2
-0.2
-2.8
-6.4
-13.5
-36.1

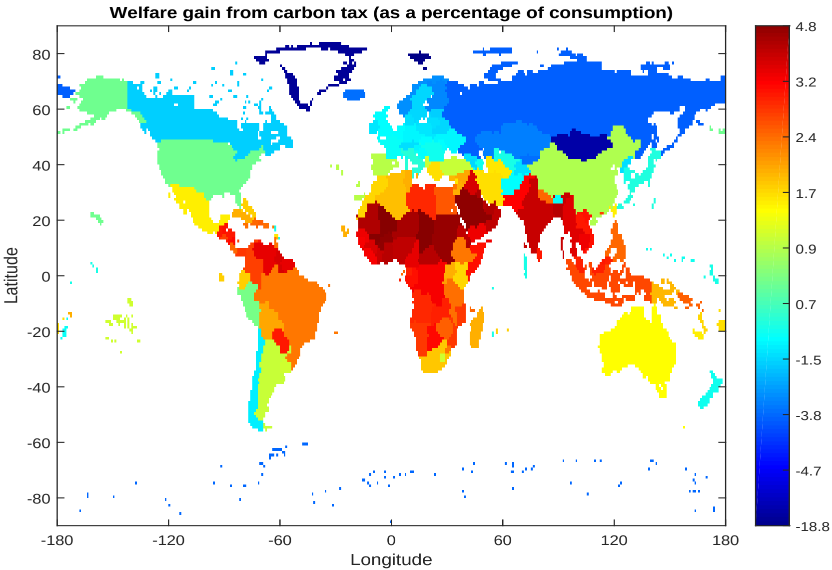

Welfare gains from taxation (in autarky)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
10.4
3.9
3.1
2.4
1.2
-0.2
-2.8
-6.4
-13.5
-36.1

Welfare changes from tax: summary measures

- One region = one vote: 56% gain.
- One person = one vote: 84% gain.
- One dollar = one vote: 68% gain.
- Average gain across all regions: -2.11% (of consumption).
- Average gain weighted by regional GDP: 0.60%.
- Average gain weighted by regional population: 1.74%.
- World consumption path: gain of 0.37%.



Percentage of population in favor of carbon tax (by country)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
100
88.5
77.4
66.3
55.2
44
32.9
21.8
10.7
0



Welfare gain from carbon tax (as a percentage of consumption)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
4.8
3.2
2.4
1.7
0.9
0.7
-1.5
-3.8
-4.7
-18.8

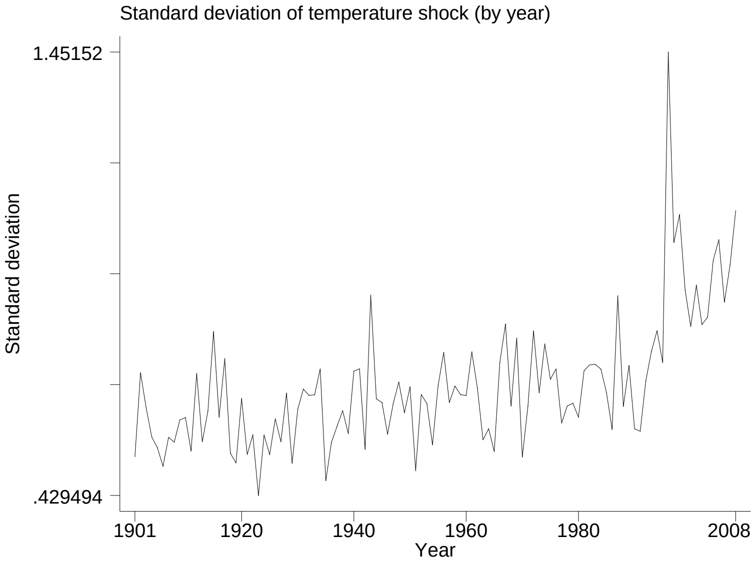
Conclusions

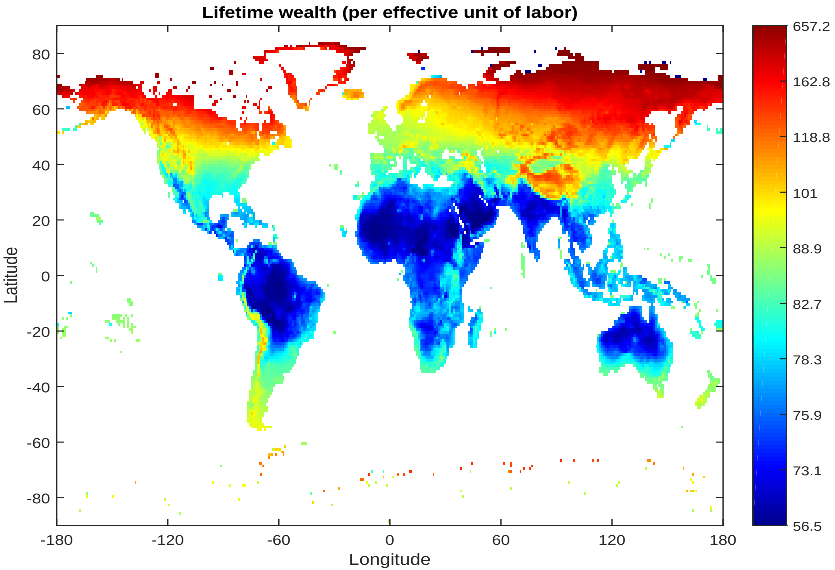
Takeaway:

- Results from our model: climate change is about relative effects much more than about average effects!
- In particular, large disagreements about taxes (so large transfer payments needed to compensate those losing from carbon tax).
- Methodological insight: we thought the market structure (because it admits more or less adaptation) would be important for the results, but it isn't.

Building on the platform

1. Sea-level rise. [Can easily handle region-specific damages.]
2. Merge with the Norwegian Earth System Model (NorESM). No need to simplify climate system, gain access to a rich set of weather variables (extreme weather events, wind, etc.).
3. Weather shocks (local and aggregate). [Developed new computational tools to handle aggregate uncertainty + transition.] Risk sharing.
4. More regional heterogeneity: rural vs. urban and/or manufacturing vs. agriculture, with separate U-shapes.
5. Migration.
6. Growth-rate effects of climate change.
7. Gradual adaptation.


Standard deviation of temperature shock (by year)
Standard deviation
1.45152
.429494
1901
1920
1940
1960
1980
2008
Year



Lifetime wealth (per effective unit of labor)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
657.2
162.8
118.8
101
88.9
82.7
78.3
75.9
73.1
56.5