

Climate Change Around the World

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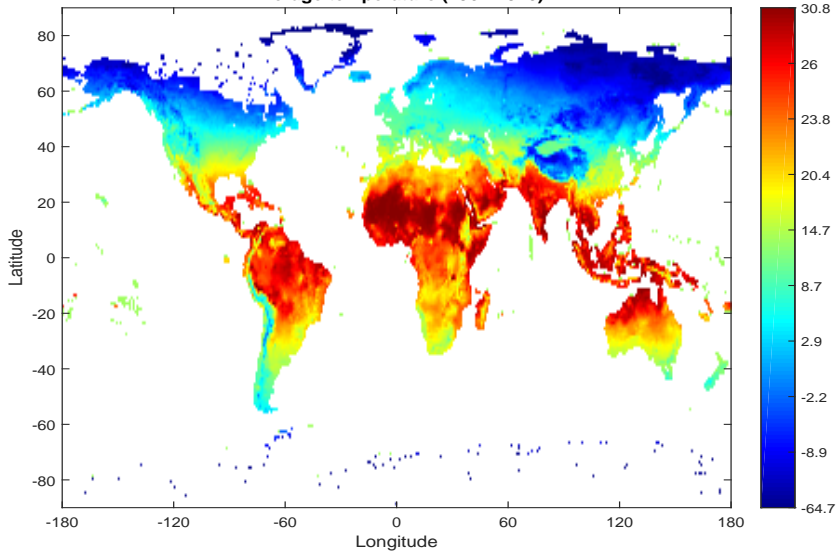
The project

- ▶ 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 (or a quantity restriction on emissions), 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.

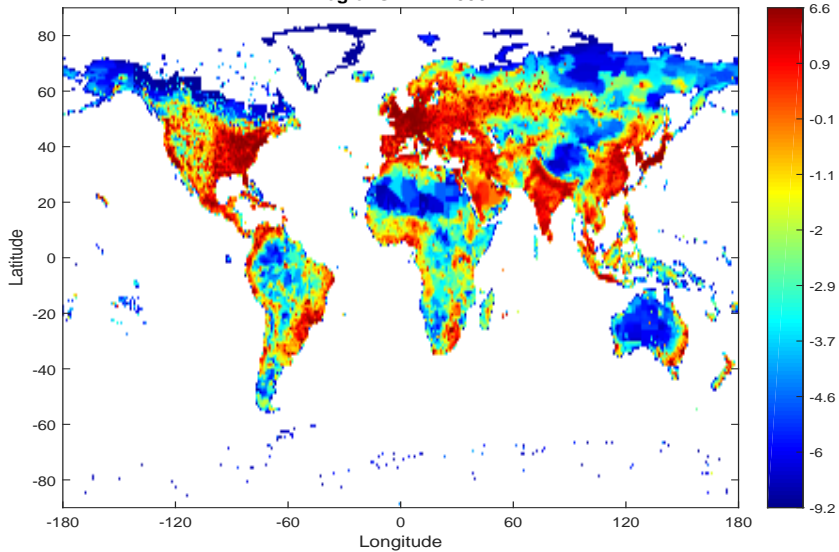
The data

- ▶ 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)



Log of GDP in 1990



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 CO₂ in the atmosphere (relative to pre-industrial) is:

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

where $S = 840\text{GtC}$ and $\bar{S} = 600\text{GtC}$ 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.
- ▶ Key: emissions spread globally very quickly (“global externality”).
- ▶ Depreciation structure of atmospheric CO_2 :
 - ▶ smooth, but very slow; some stays “forever” in atmosphere
 - ▶ nonlinear but linear approximation okay.
- ▶ Emissions: $10\text{GtC}/\text{year}$; $\Delta S_t \approx 4.5\text{GtC}/\text{year}$.
- ▶ Estimated remaining carbon: oil + gas = 300GtC , coal much bigger ($> 3,000\text{GtC}$?). So coal is key!
- ▶ To summarize:
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 climate modeling
3. our 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

$$\begin{aligned} \blacktriangleright v_t(\omega, A, \Gamma, S; \ell) = \\ \max_{k', b'} [U(c) + \beta v_{t+1}(\omega', A', \Gamma', S'; \ell)], \text{ s.t.} \end{aligned}$$

$$c = \omega - k' - q_t(\Gamma, S)b'$$

$$\begin{aligned} \omega' = \max_{e'} [F(k', D(T_\ell(S')))A', e') - pe'] + \\ (1 - \delta)k' + b' \end{aligned}$$

$$A' = (1 + g)A$$

$$\Gamma' = H_t(\Gamma, S)$$

$$S' = \Phi_t(\Gamma, S).$$

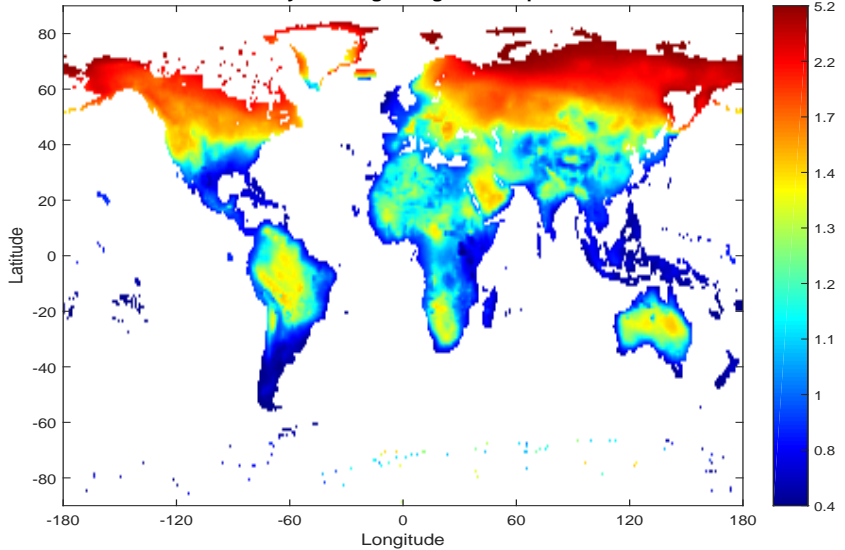
- ▶ Can be interpreted as a decentralized equilibrium.
- ▶ Set up to deal with shocks, aggregate and/or local.

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.

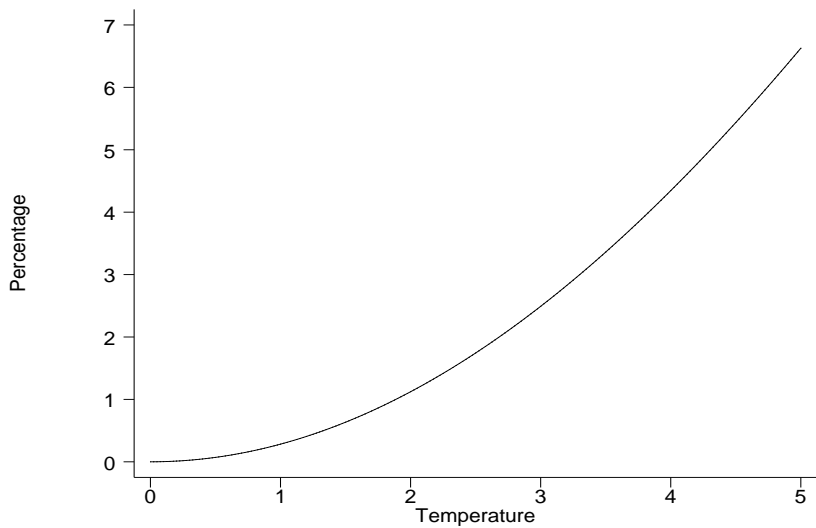
Sensitivity to changes in global temperature



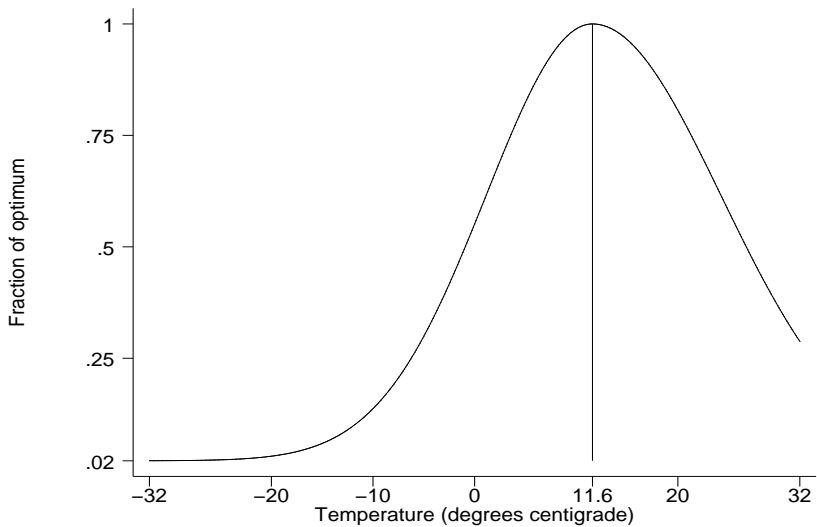
Our damage specification

- ▶ 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.

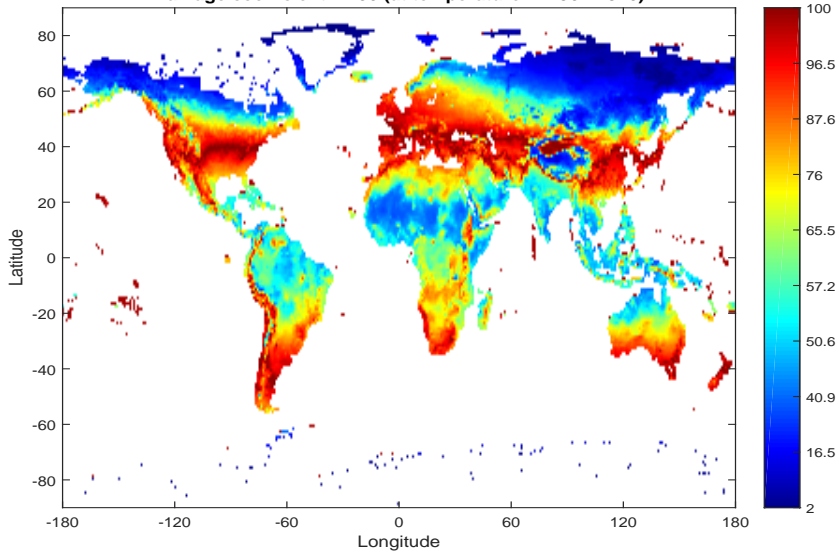
Nordhaus's damage function (percentage of GDP)



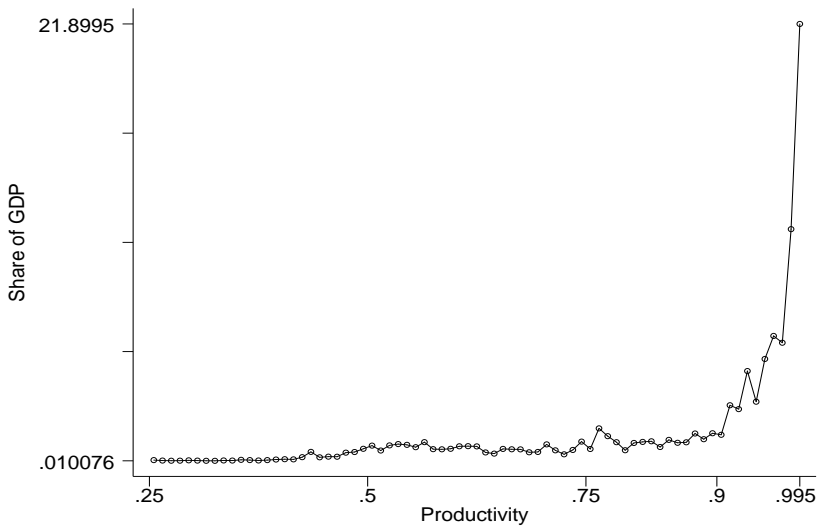
Damage function: productivity vs. temperature



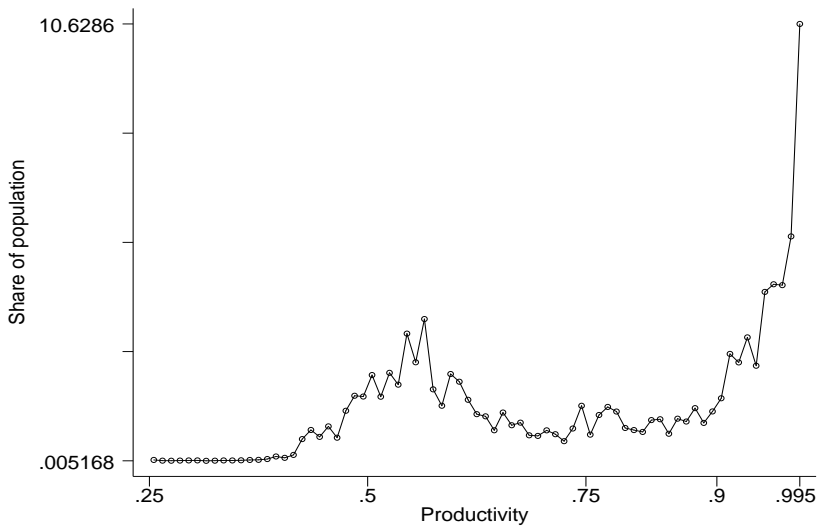
Damage coefficient x 100 (at temperature in 1901-1920)



Share of world GDP vs. productivity (as a fraction of optimum)



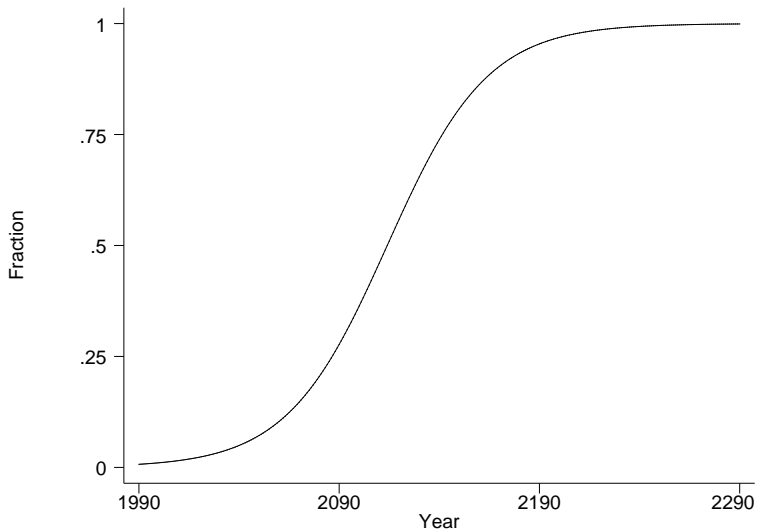
Share of world population vs. productivity (as a fraction of optimum)



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



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.

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).

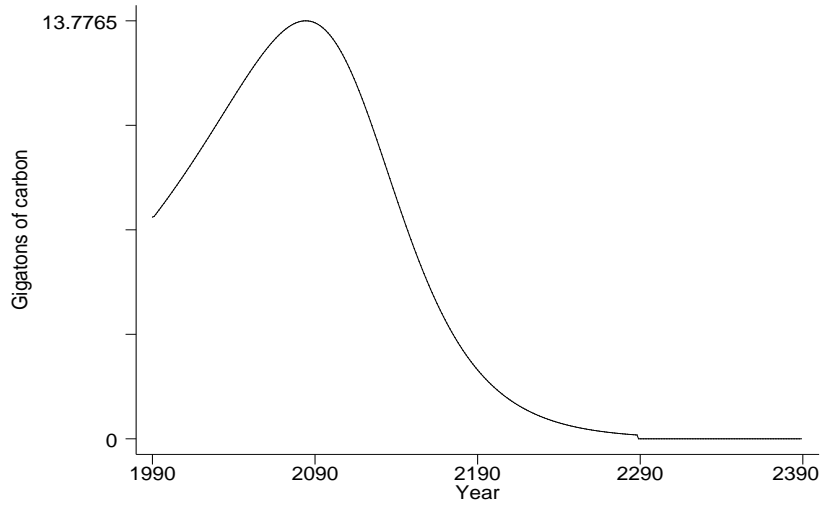
Throughout: focus on relative effects, not aggregates.

Main findings

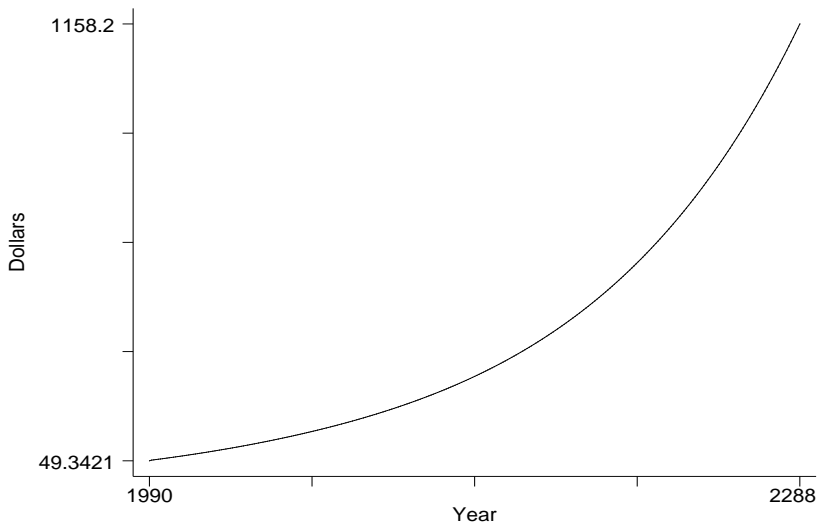
- ▶ Climate change affects regions *very* differently. Stakes big at regional level.
- ▶ Though a tax on carbon would affect welfare positively in some average sense, there is a large disparity of views across regions (56% of regions gain, while 44% lose).
- ▶ Findings are very close for two extreme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

behavior of aggregates over time

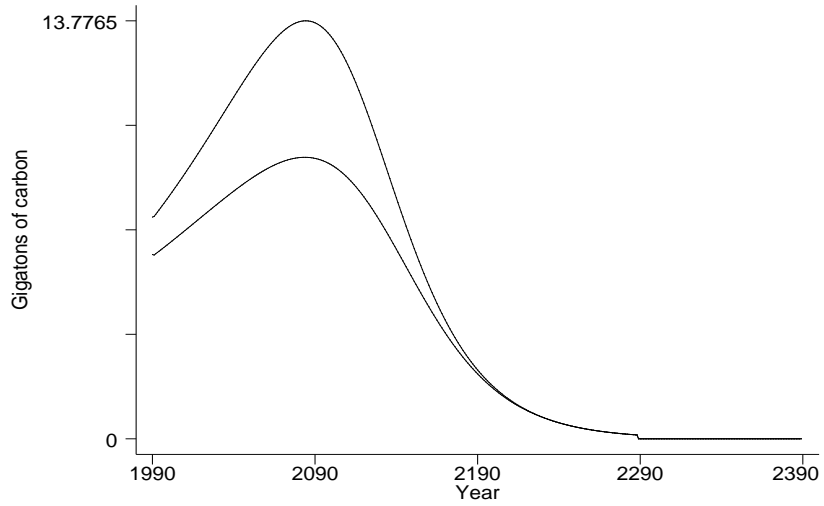
Global emissions of atmospheric carbon (in gigatons)
(no taxes; free capital movement)



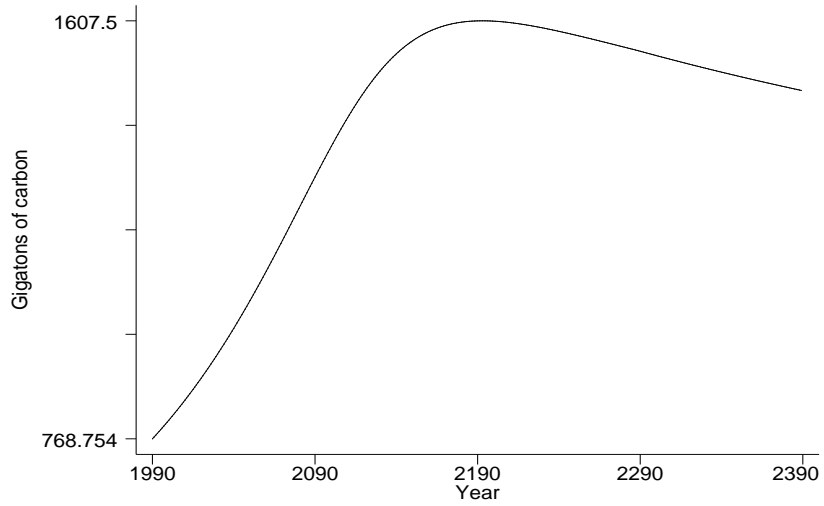
Optimal carbon tax (dollars per ton of carbon)



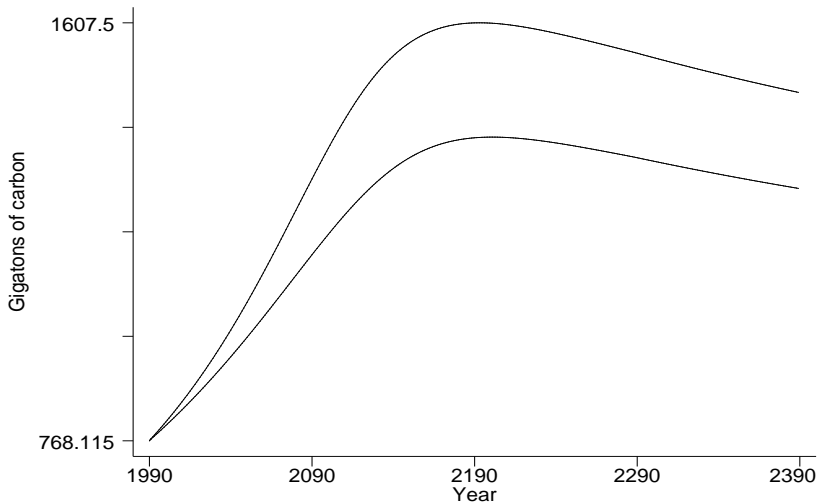
Global emissions of atmospheric carbon (in gigatons)
(taxes vs. no taxes; free capital movement)



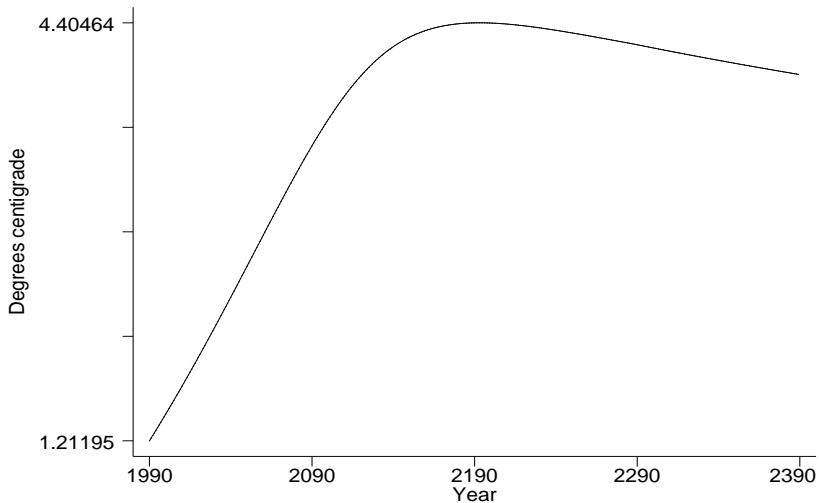
Gigatons of atmospheric carbon
(no taxes; free capital movement)



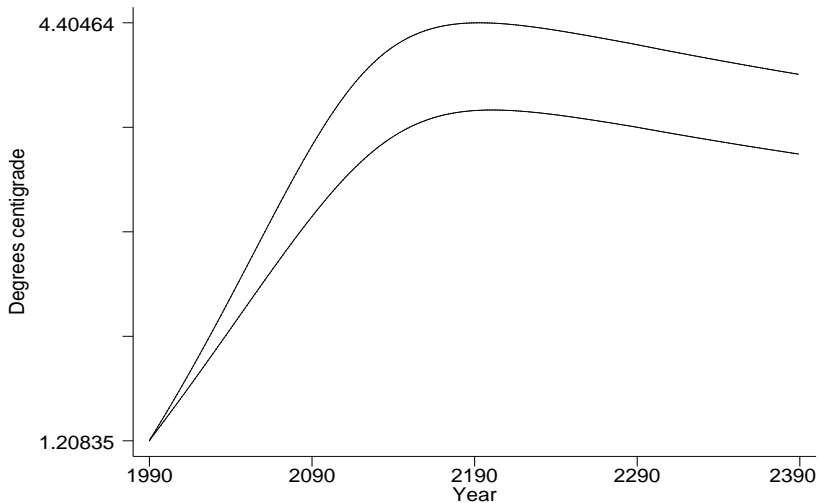
Gigatons of atmospheric carbon
(taxes vs. no taxes; free capital movement)



Temperature (degrees centigrade above pre-industrial)
(no taxes; free capital movement)



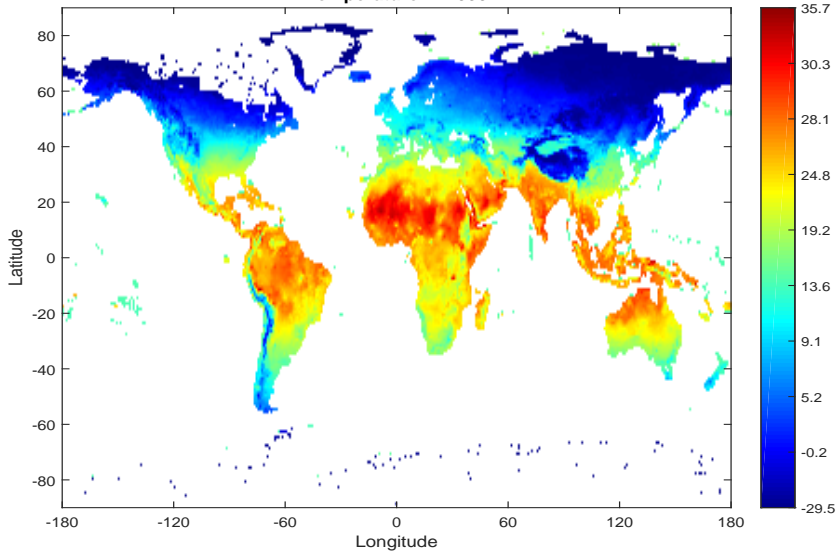
Temperature (degrees centigrade above pre-industrial)
(taxes vs. no taxes; free capital movement)



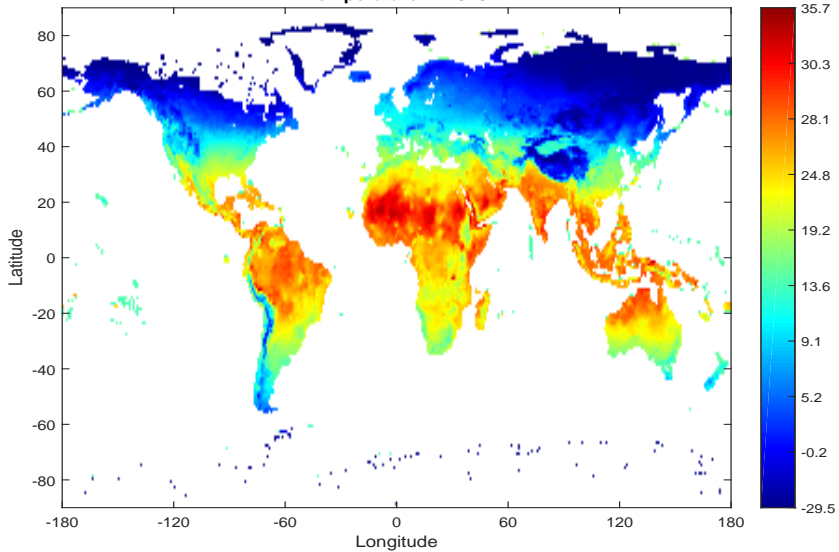
movie: temperature, laissez-faire

animation: www.econ.yale.edu/smith/temperature1.mp4

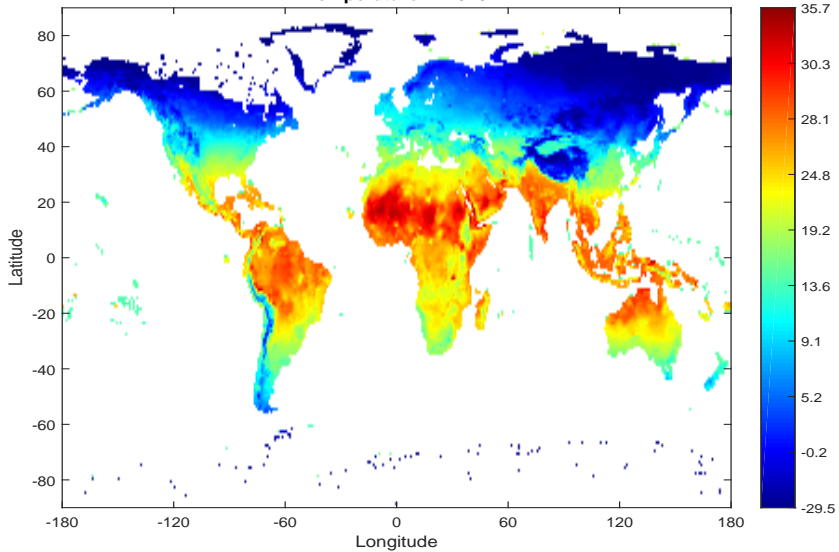
Temperature in 2000



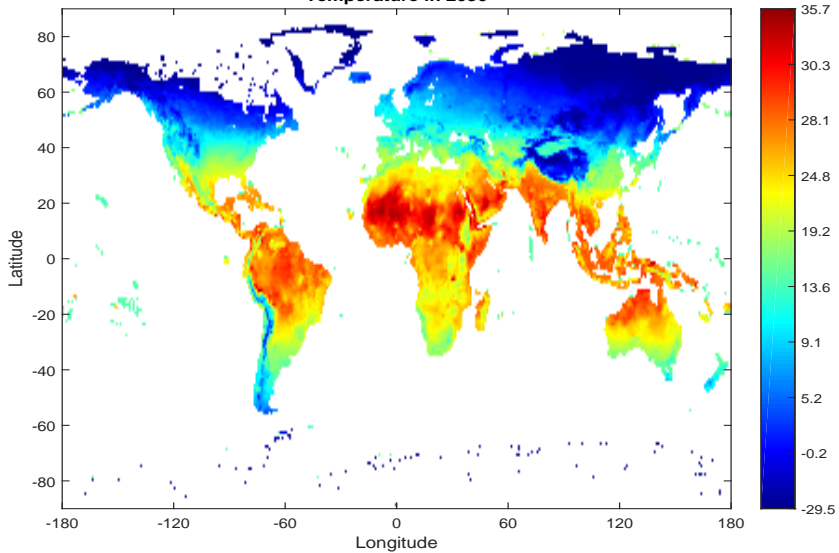
Temperature in 2010



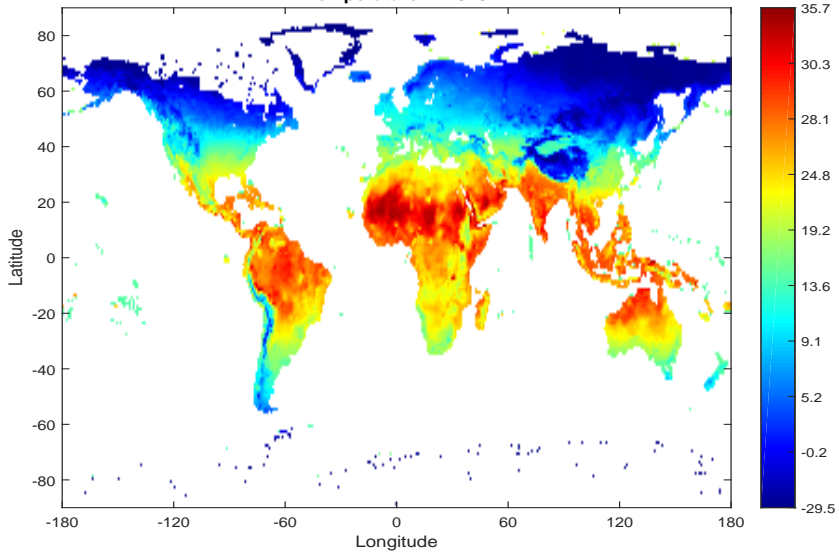
Temperature in 2020



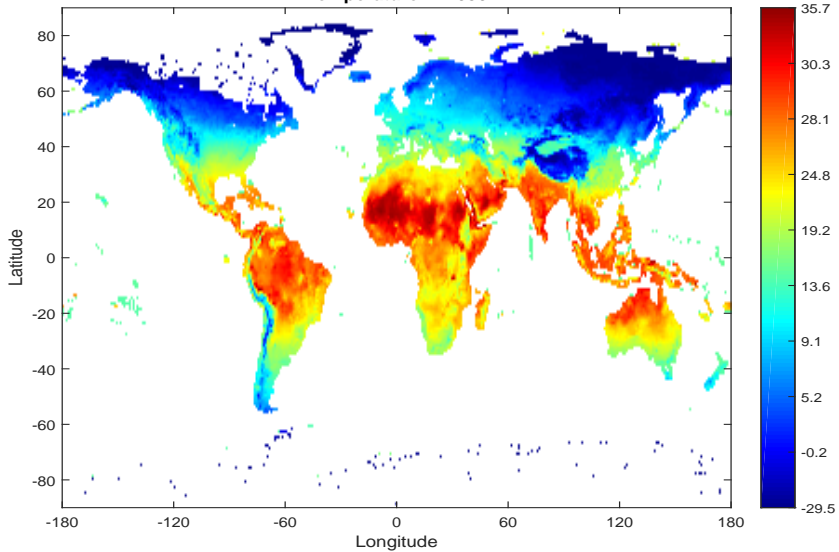
Temperature in 2030



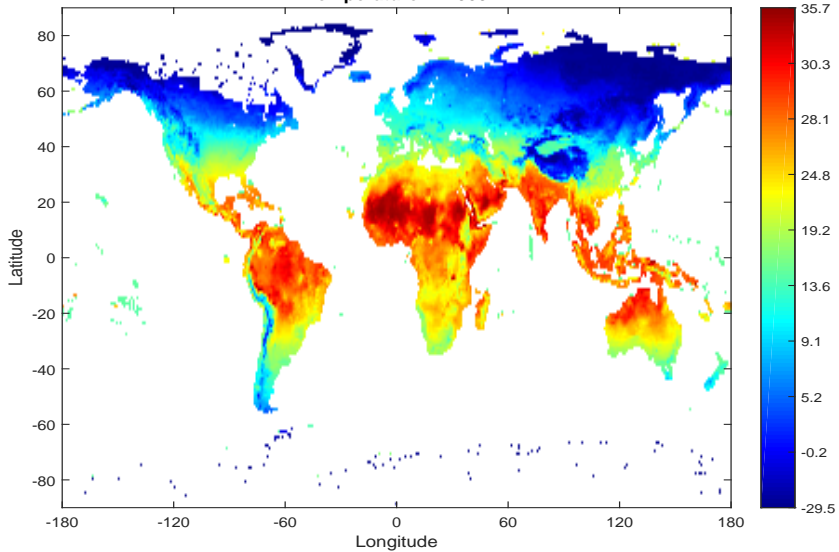
Temperature in 2040



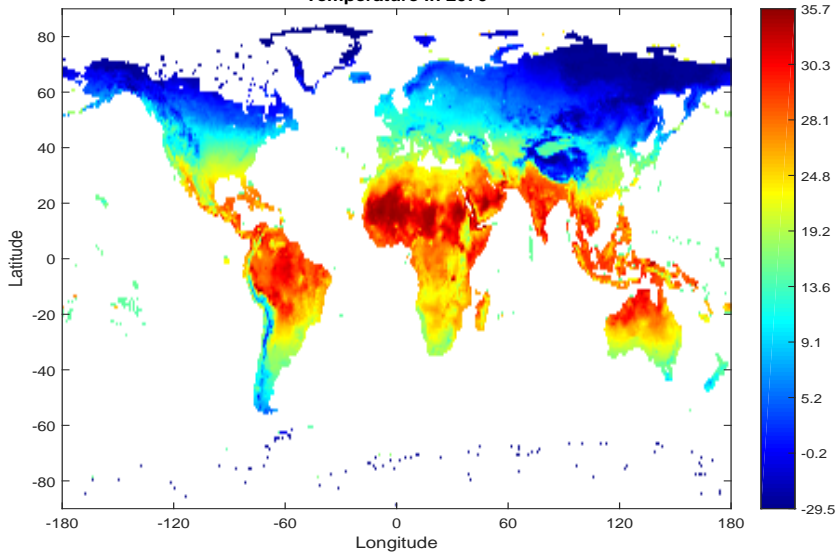
Temperature in 2050



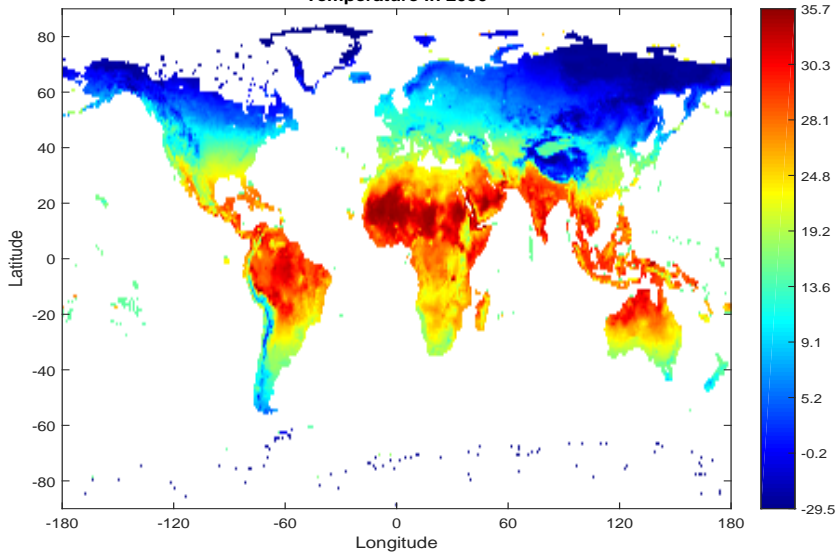
Temperature in 2060



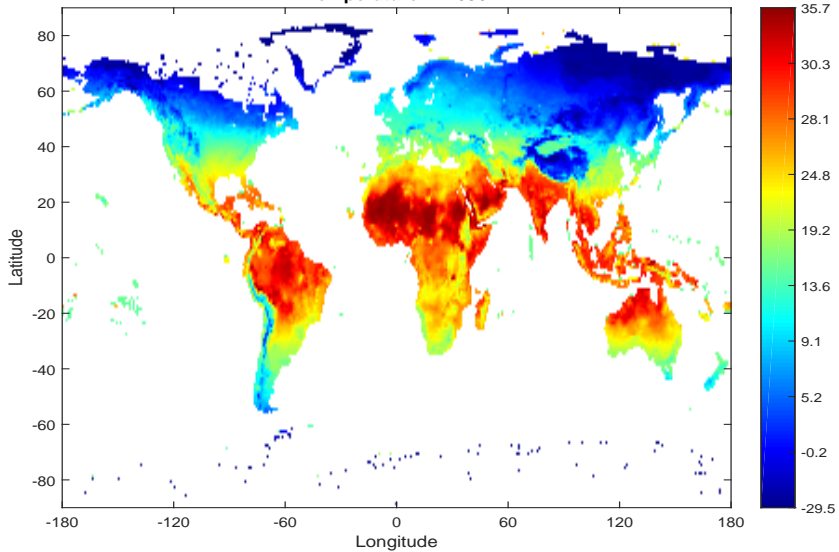
Temperature in 2070



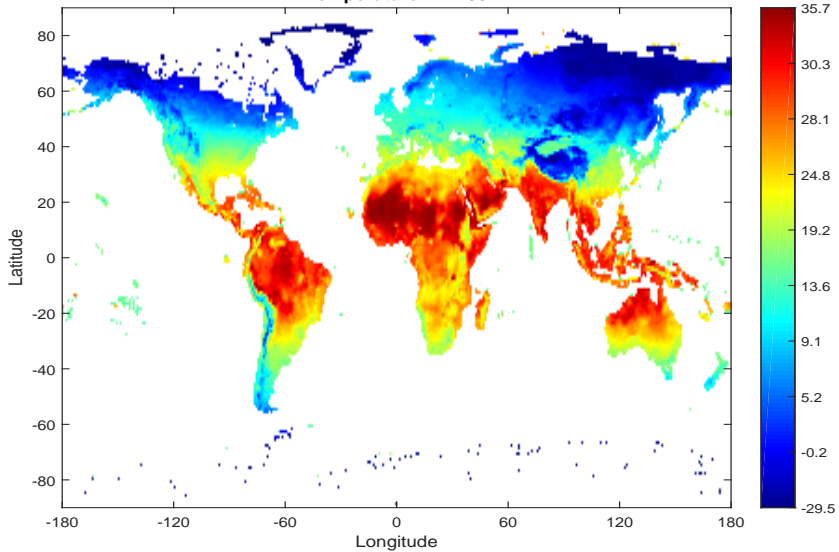
Temperature in 2080



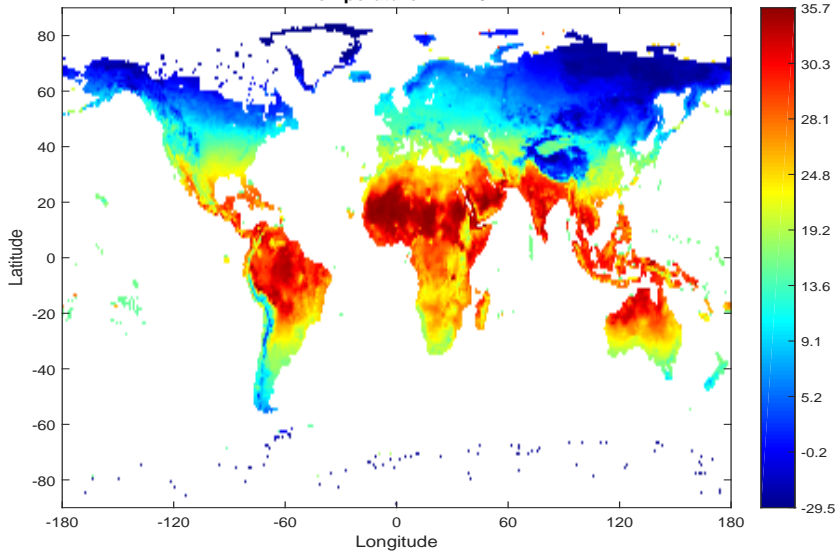
Temperature in 2090



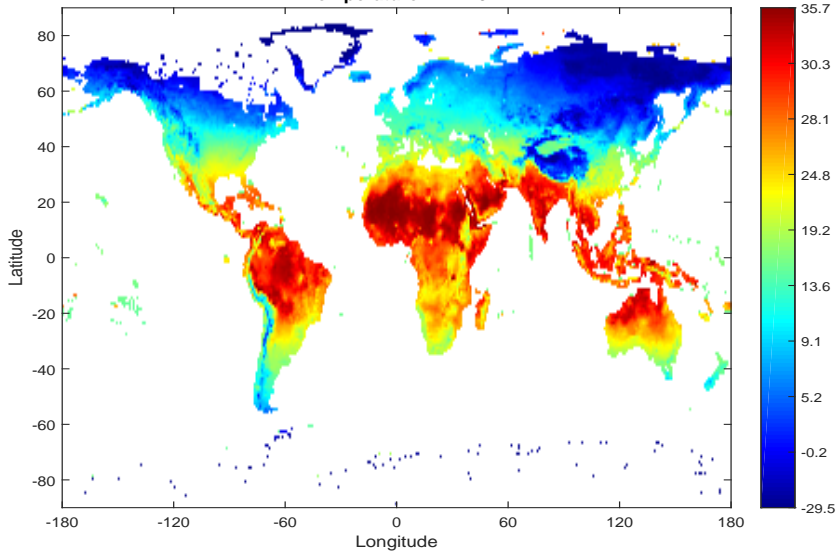
Temperature in 2100



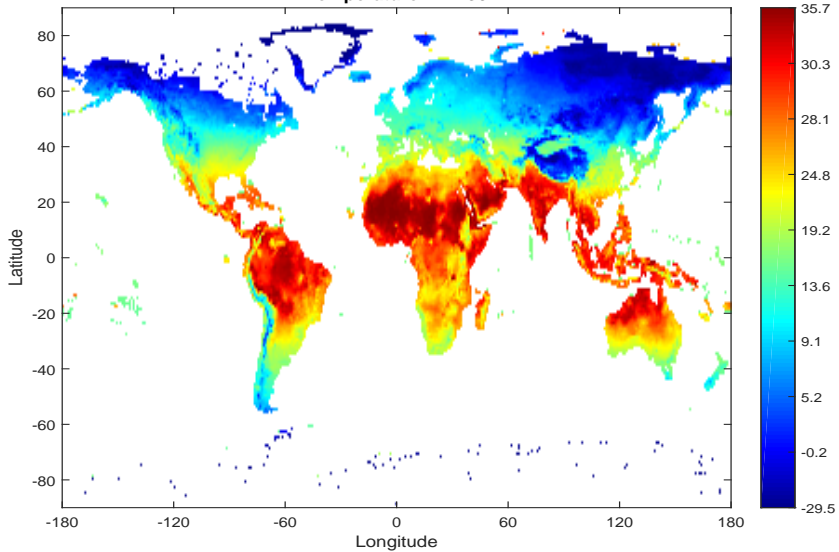
Temperature in 2110



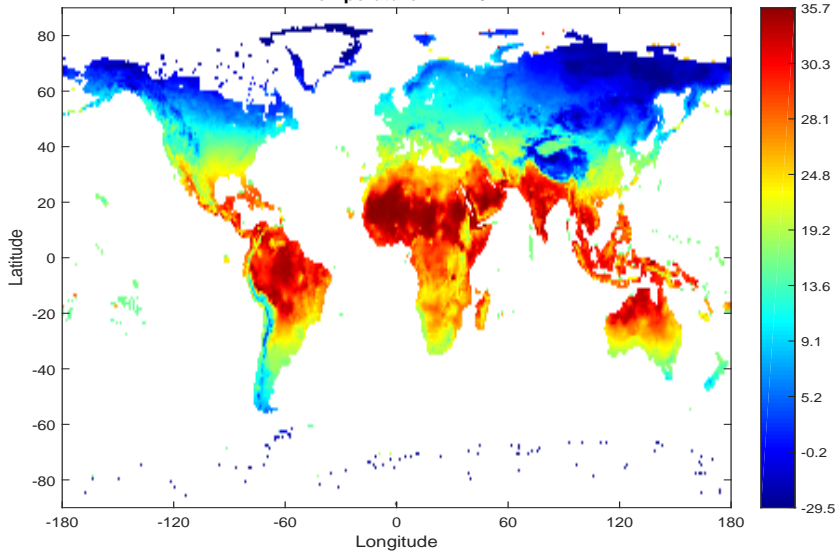
Temperature in 2120



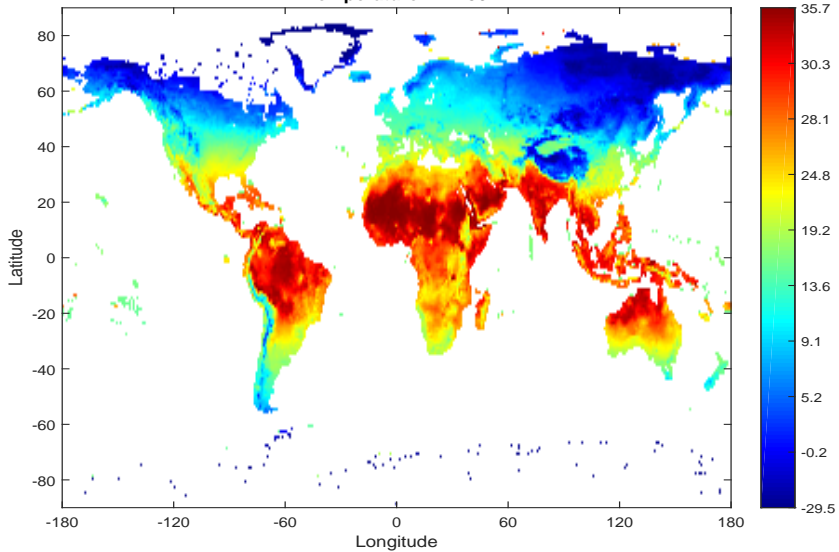
Temperature in 2130



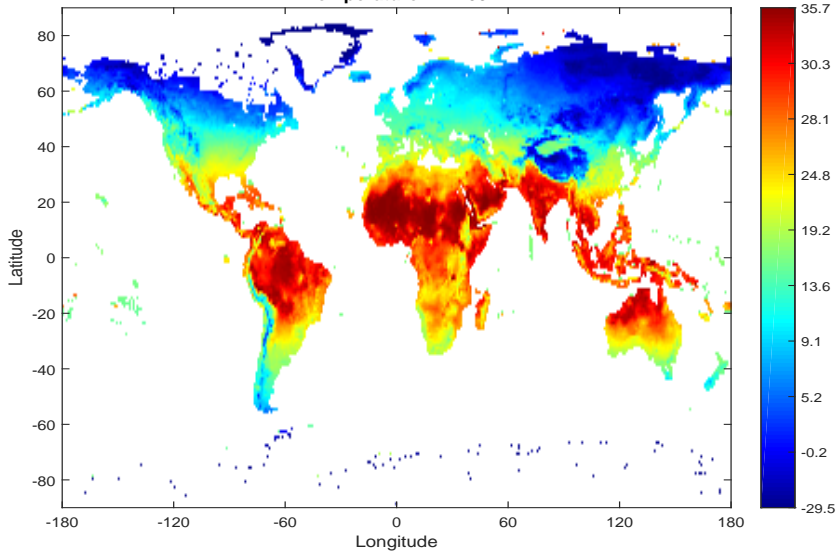
Temperature in 2140



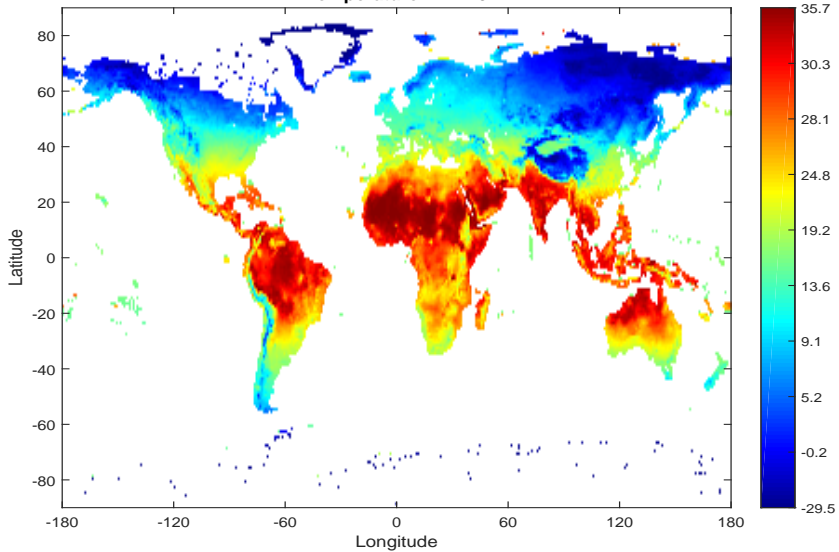
Temperature in 2150



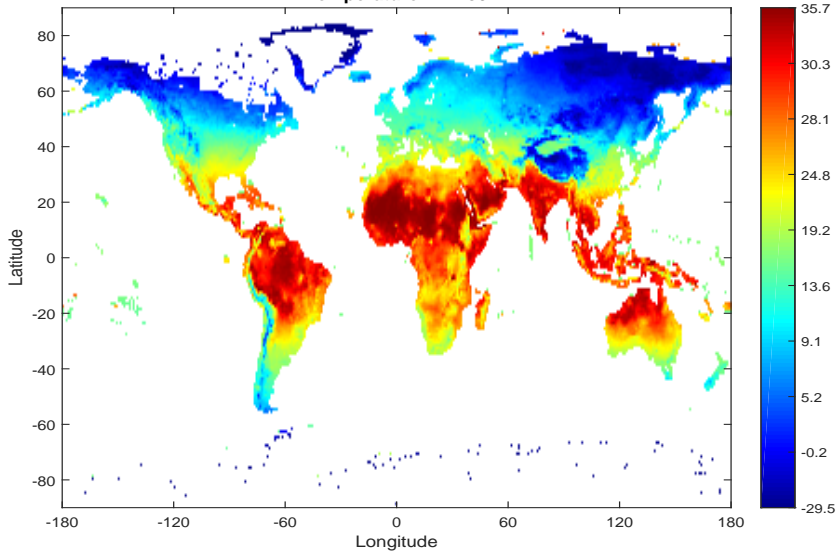
Temperature in 2160



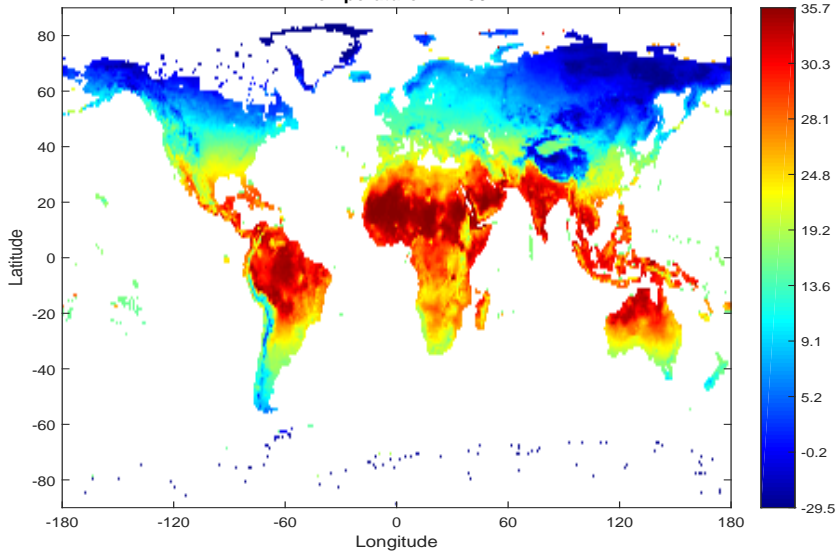
Temperature in 2170



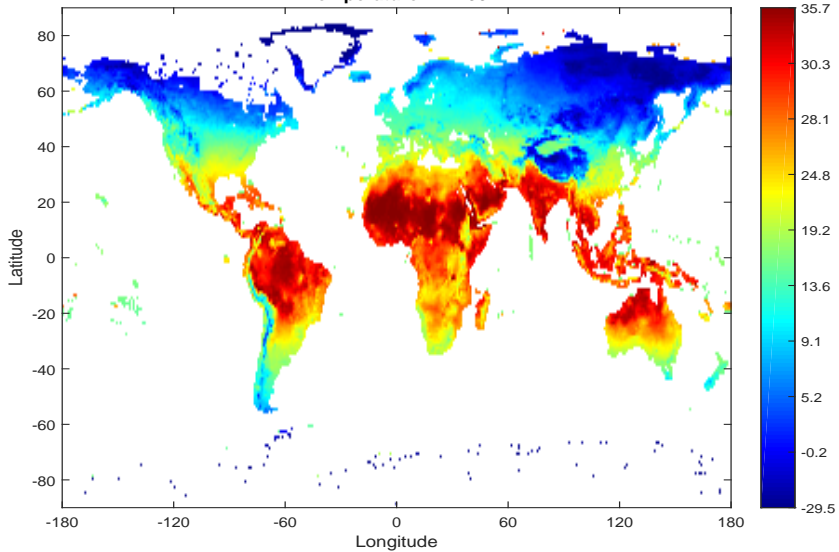
Temperature in 2180



Temperature in 2190



Temperature in 2200



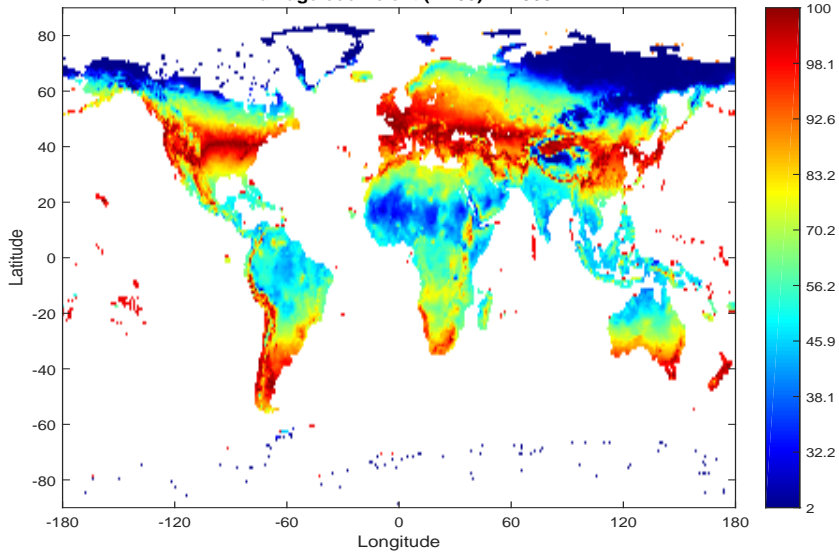
movie: change in temperature, laissez-faire

animation: www.econ.yale.edu/smith/deltatemperature1.mp4

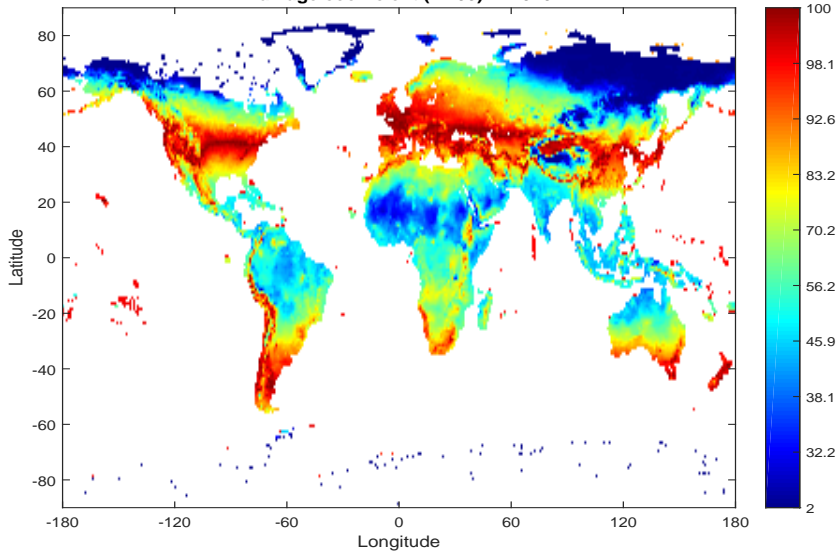
movie: 1 minus damage coefficient, laissez-faire

animation: www.econ.yale.edu/smith/damage1.mp4

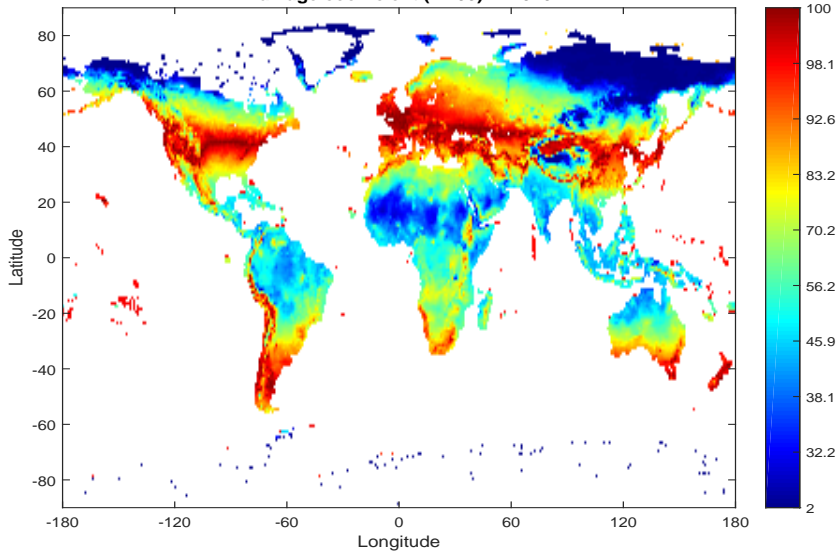
Damage coefficient (x 100) in 2000



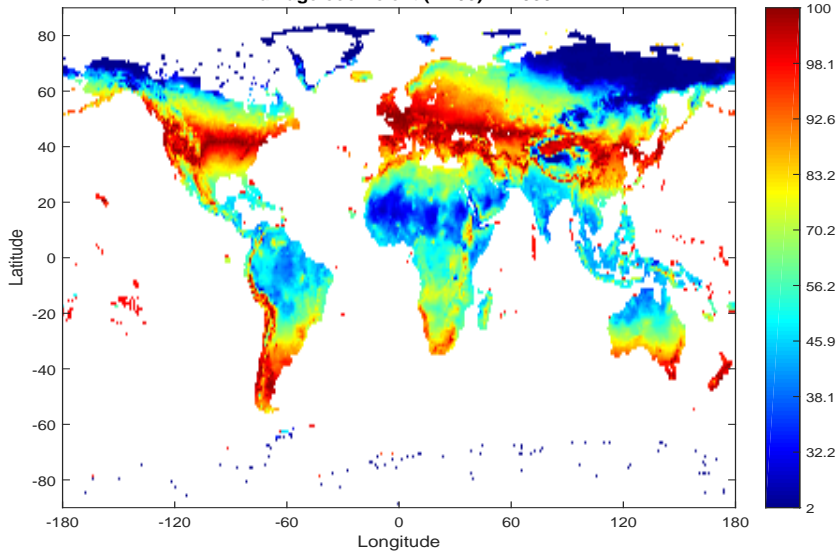
Damage coefficient (x 100) in 2010



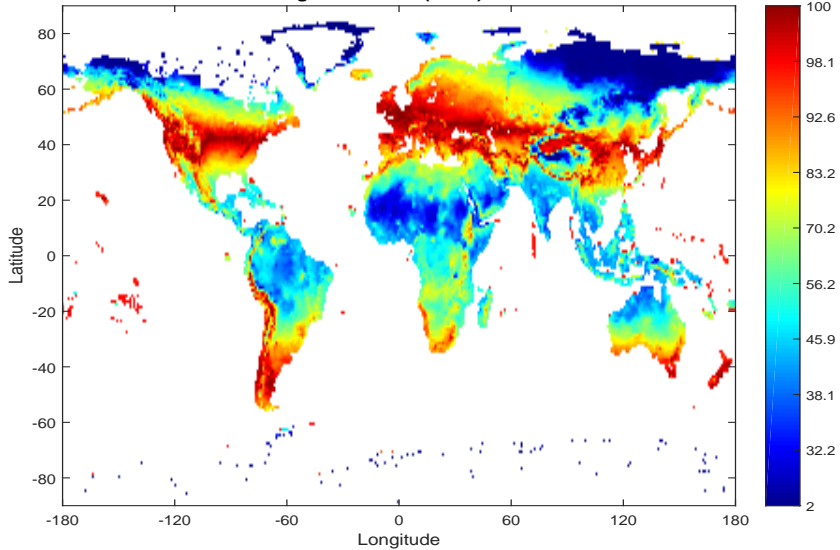
Damage coefficient (x 100) in 2020



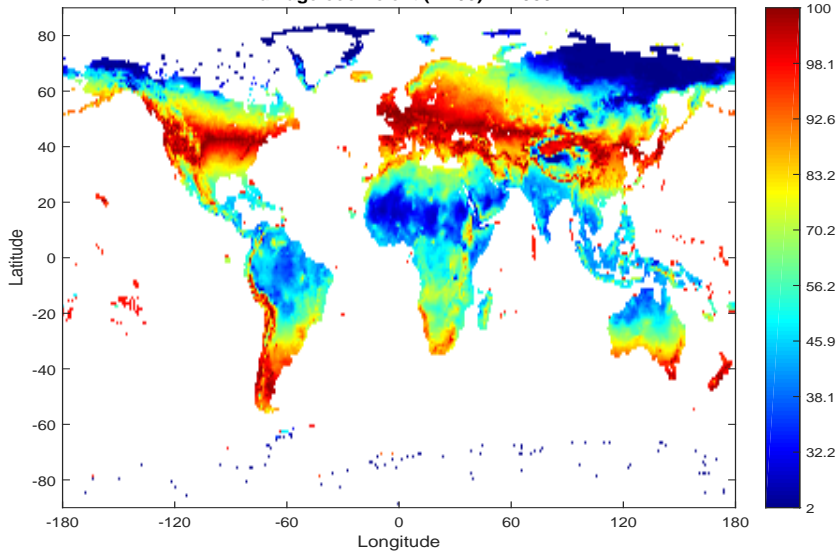
Damage coefficient (x 100) in 2030



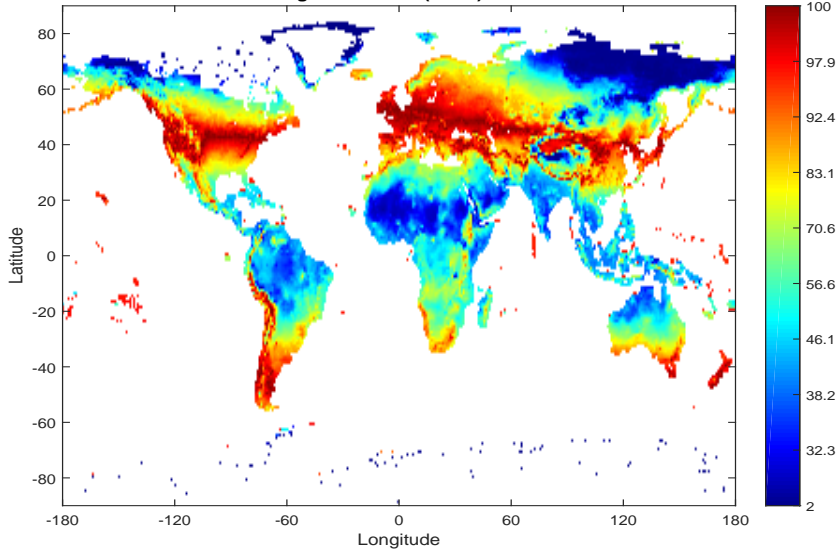
Damage coefficient (x 100) in 2040



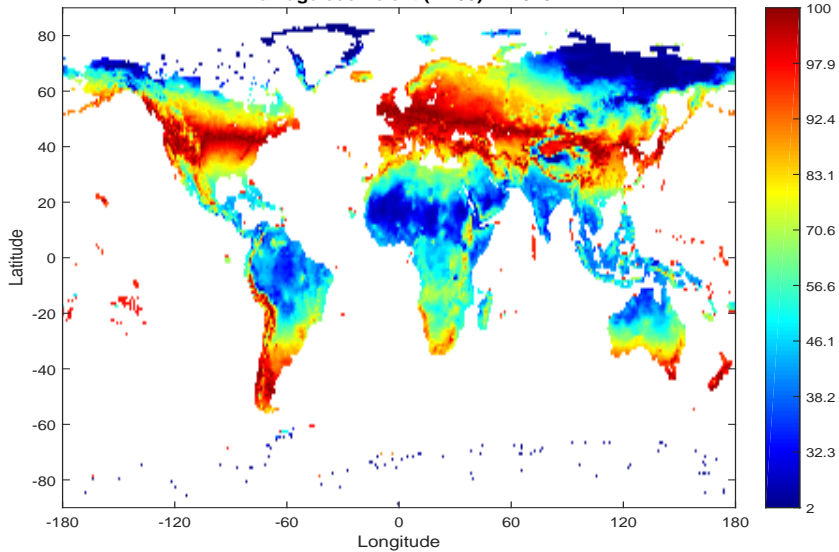
Damage coefficient (x 100) in 2050



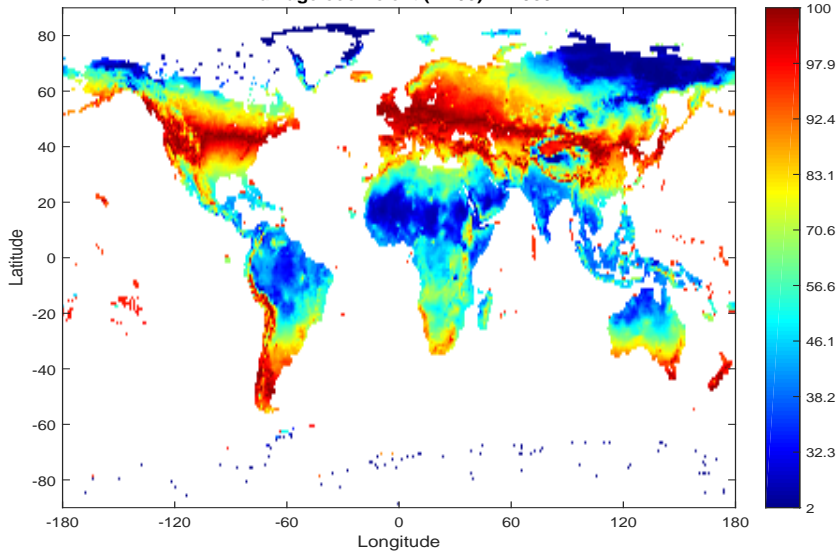
Damage coefficient (x 100) in 2060



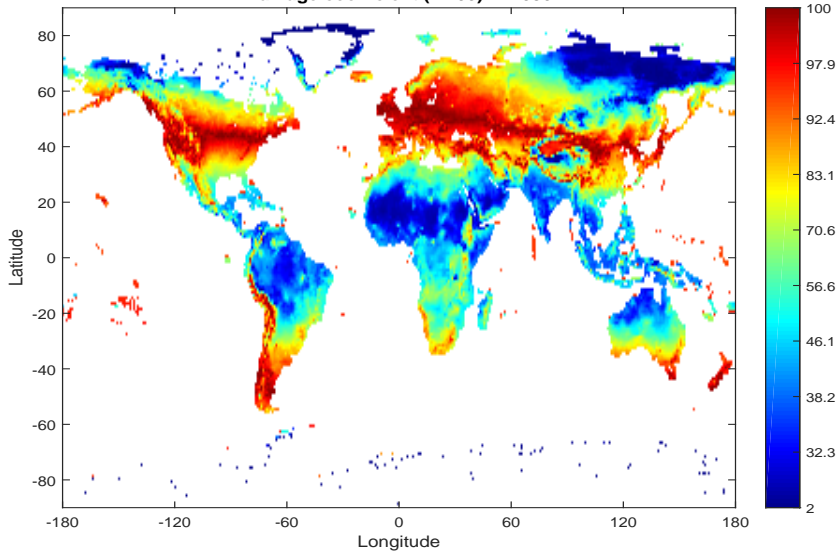
Damage coefficient (x 100) in 2070



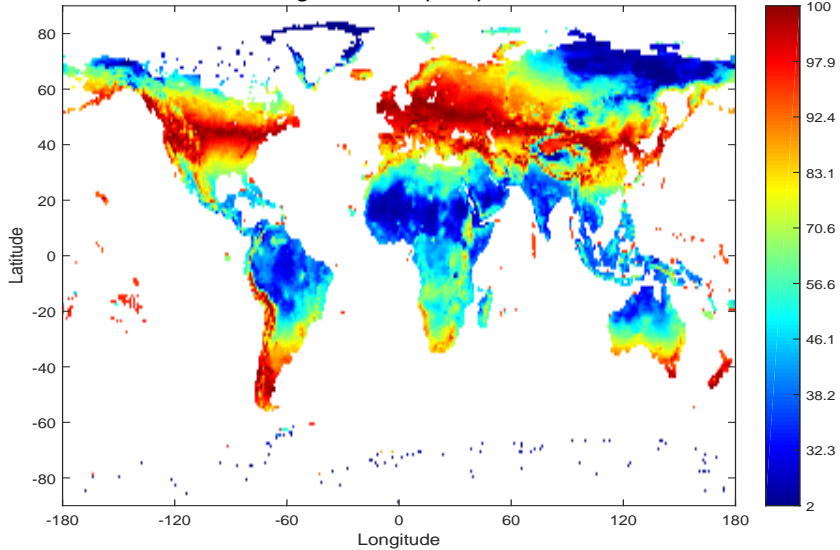
Damage coefficient (x 100) in 2080



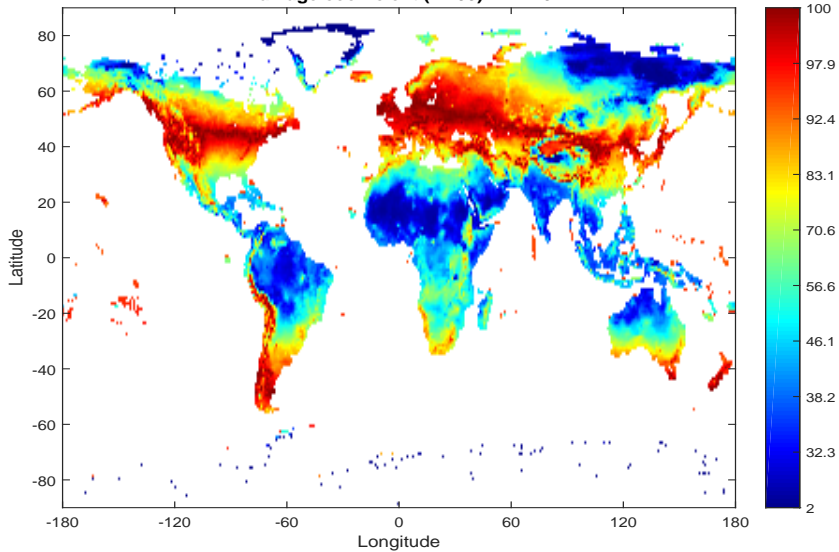
Damage coefficient (x 100) in 2090



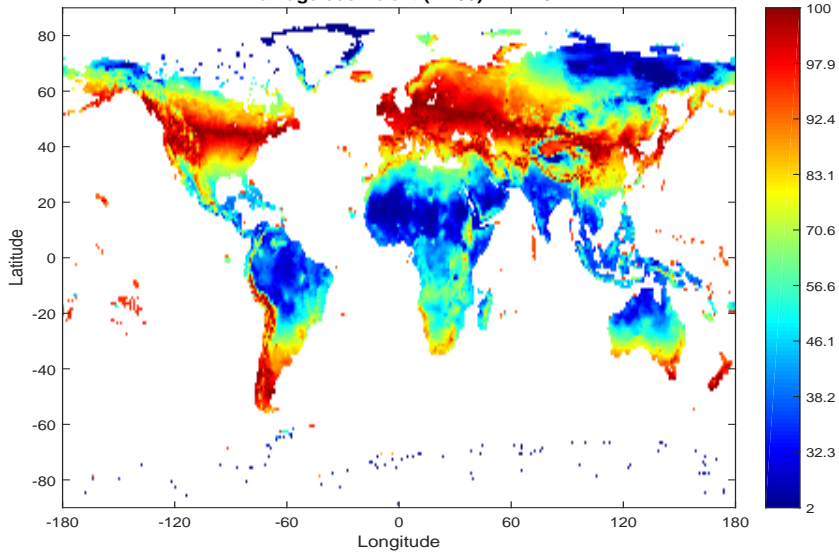
Damage coefficient (x 100) in 2100



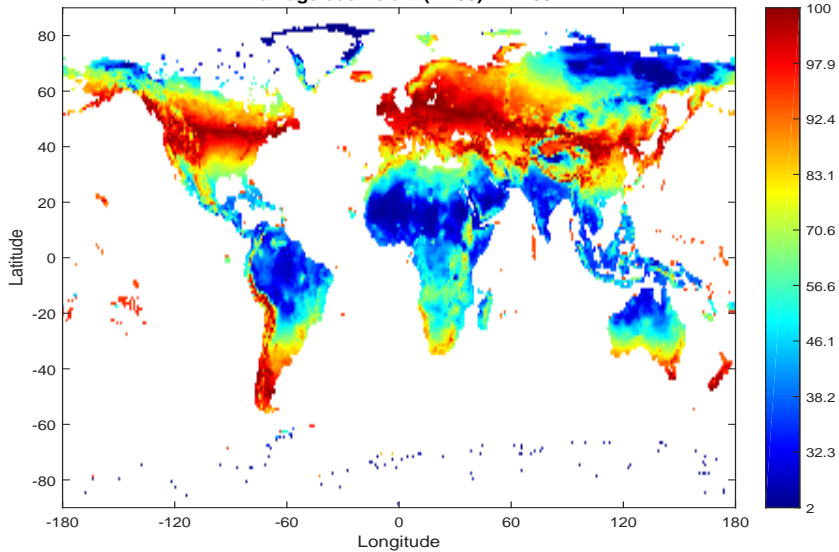
Damage coefficient (x 100) in 2110



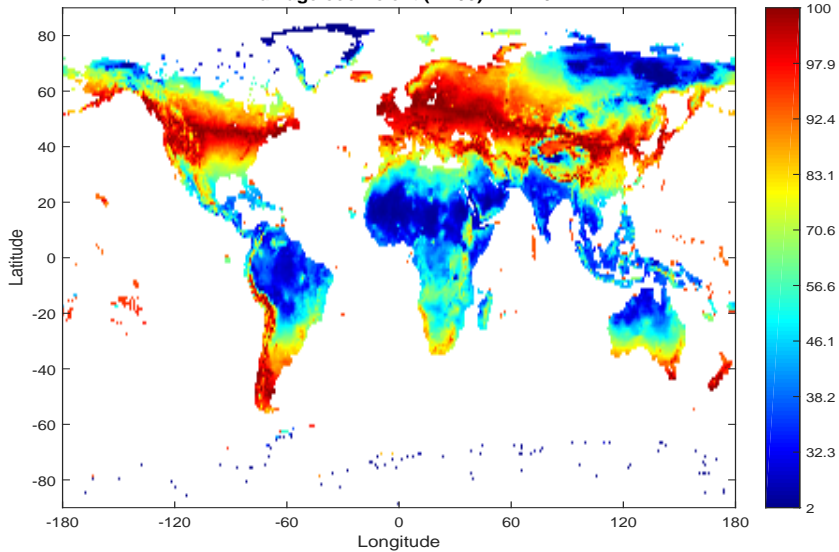
Damage coefficient (x 100) in 2120



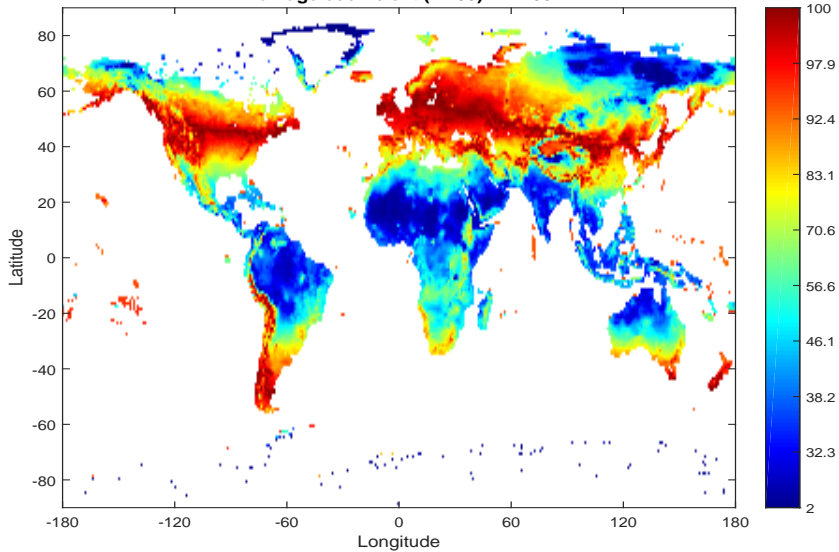
Damage coefficient (x 100) in 2130



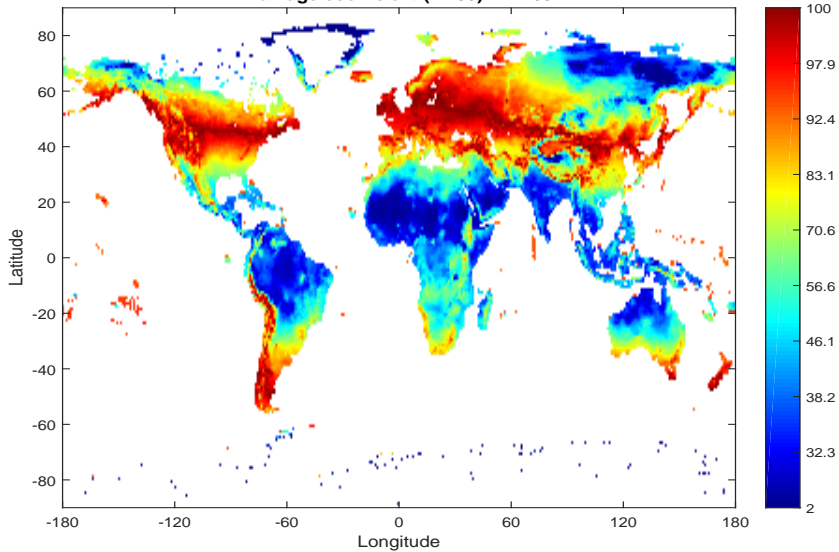
Damage coefficient (x 100) in 2140



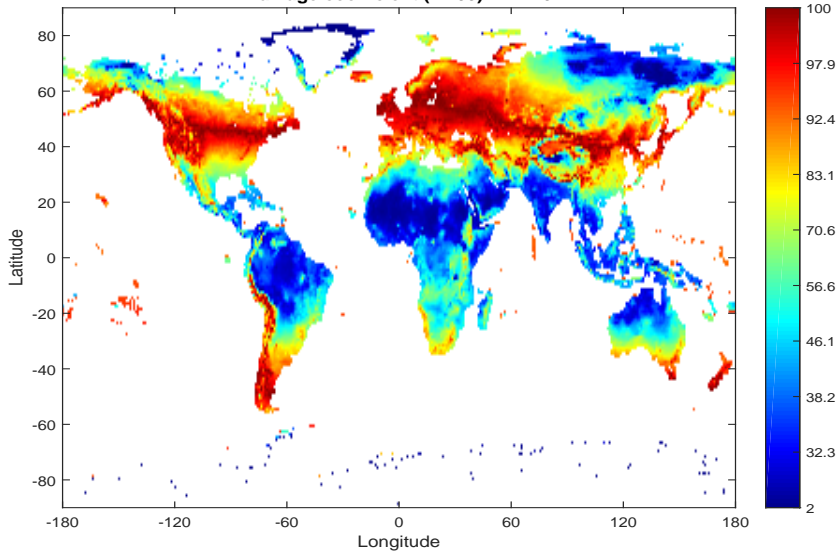
Damage coefficient (x 100) in 2150



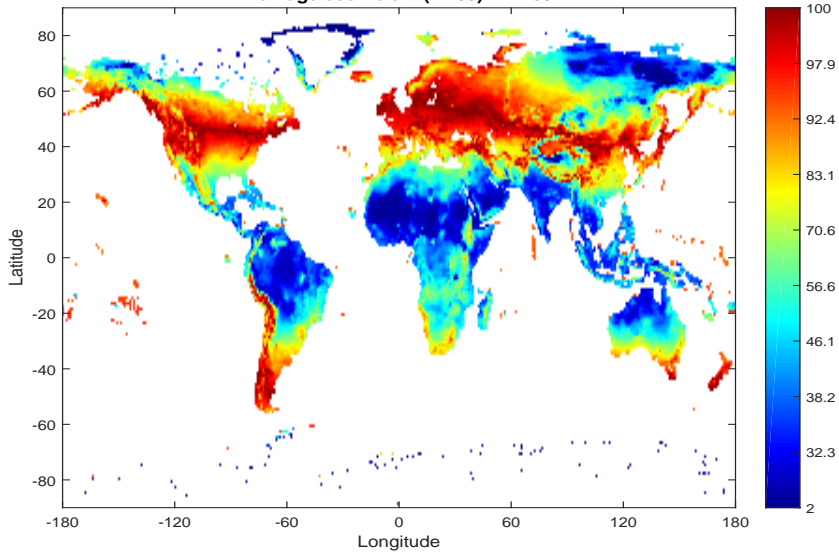
Damage coefficient (x 100) in 2160



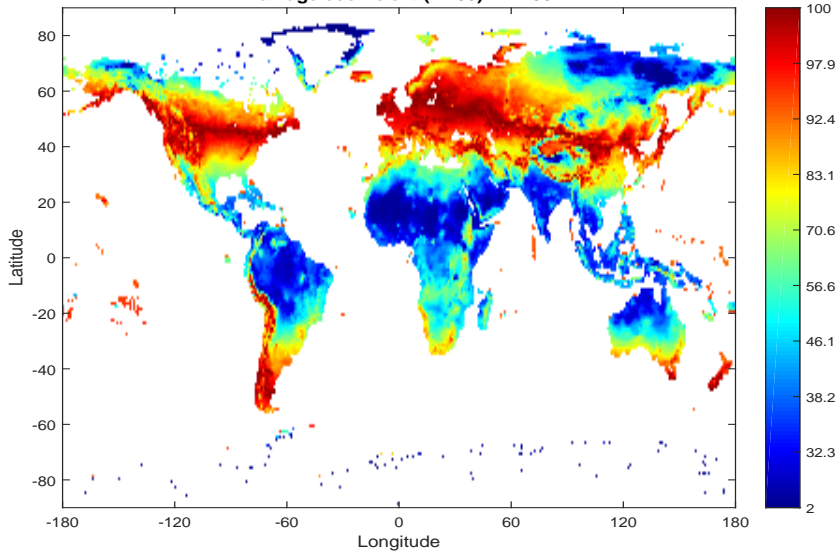
Damage coefficient (x 100) in 2170



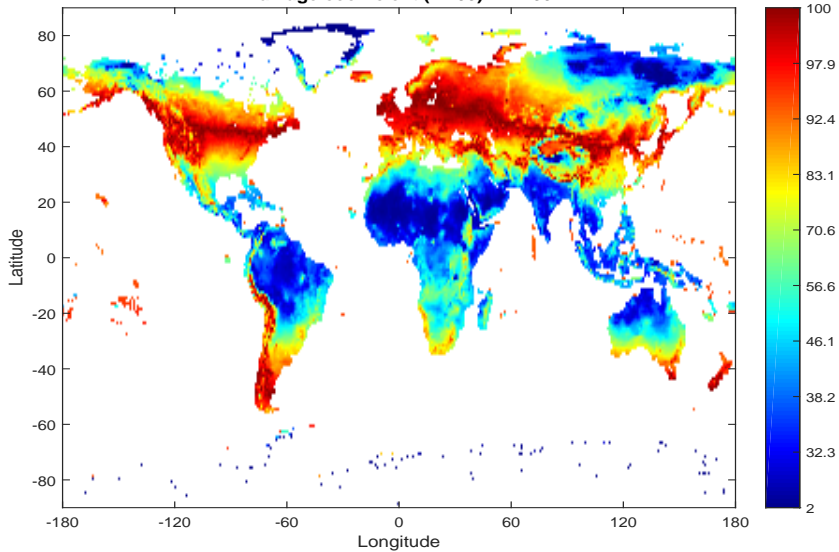
Damage coefficient (x 100) in 2180



Damage coefficient (x 100) in 2190



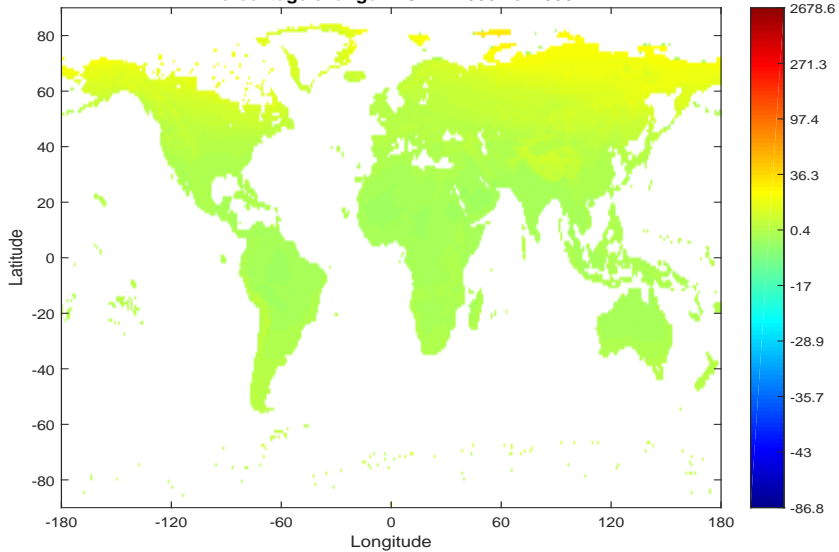
Damage coefficient (x 100) in 2200



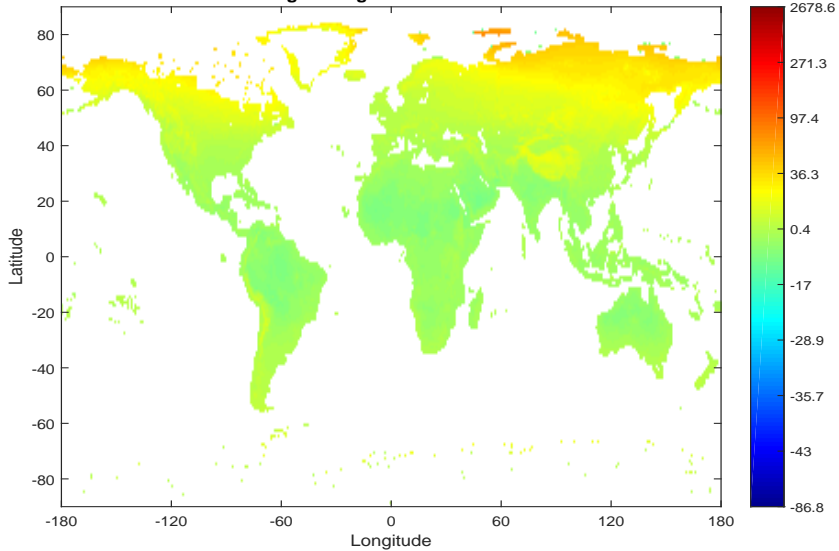
movie: percentage change in gdp, laissez-faire

animation: www.econ.yale.edu/smith/pctgdp1.mp4

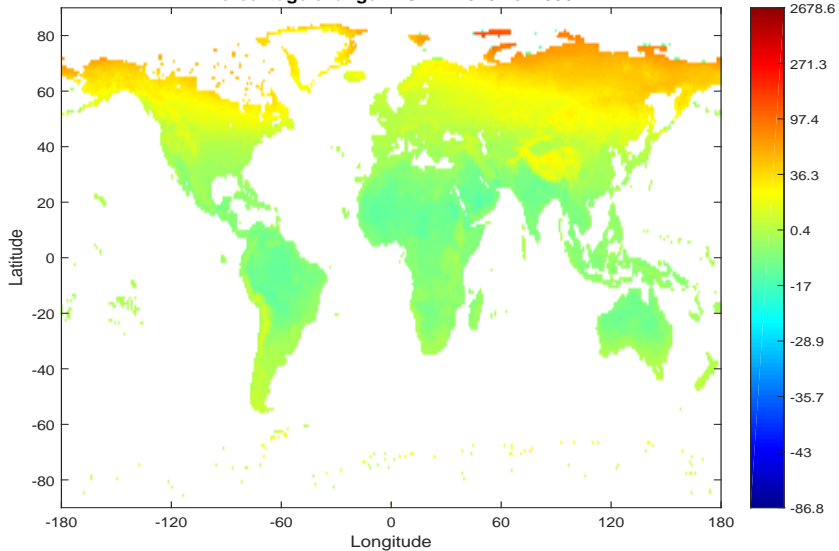
Percentage change in GDP: 2000 vs. 1990



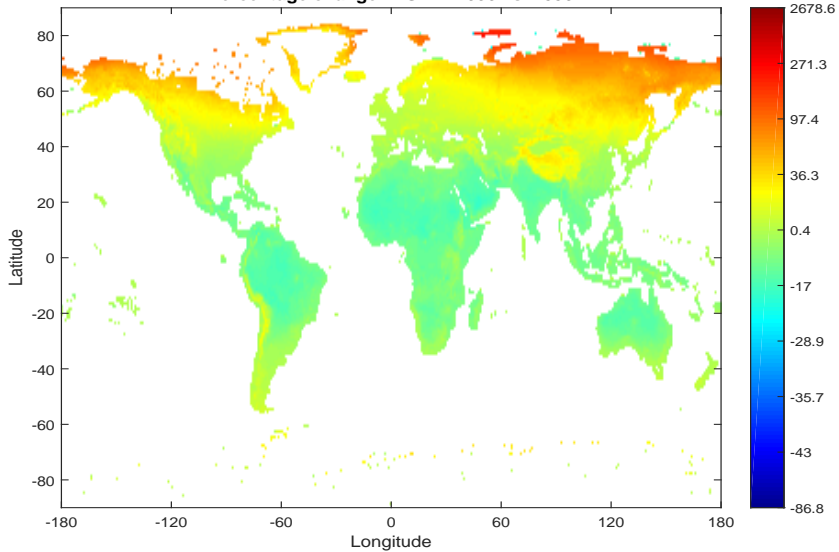
Percentage change in GDP: 2010 vs. 1990



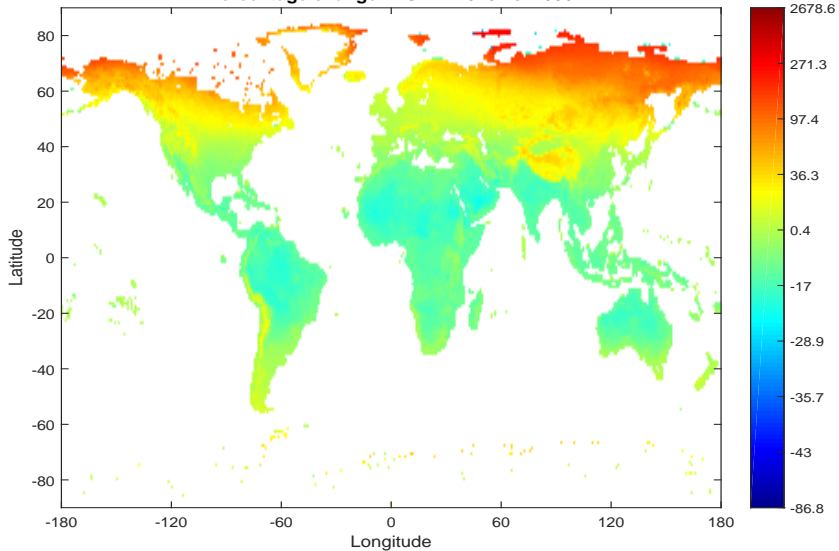
Percentage change in GDP: 2020 vs. 1990



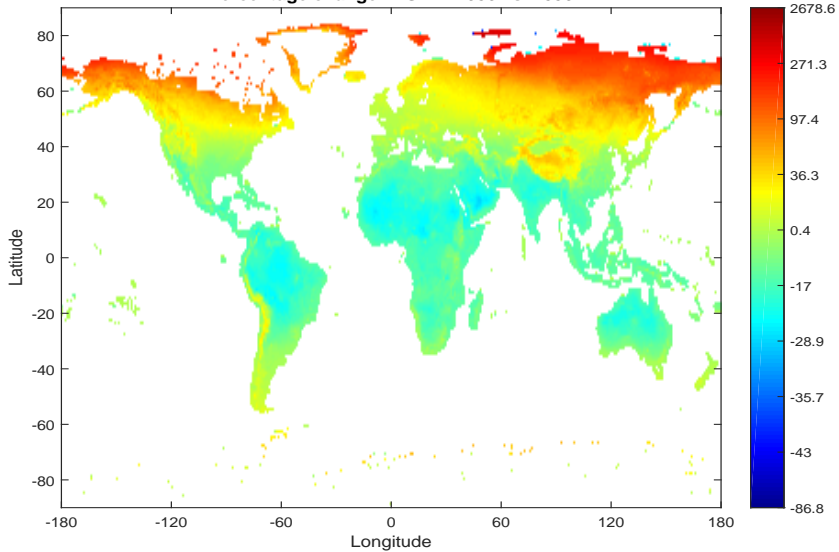
Percentage change in GDP: 2030 vs. 1990



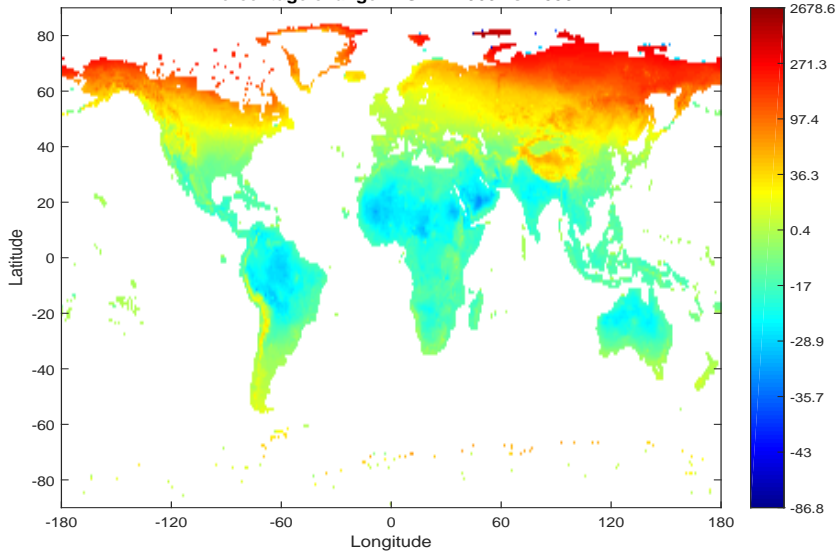
Percentage change in GDP: 2040 vs. 1990



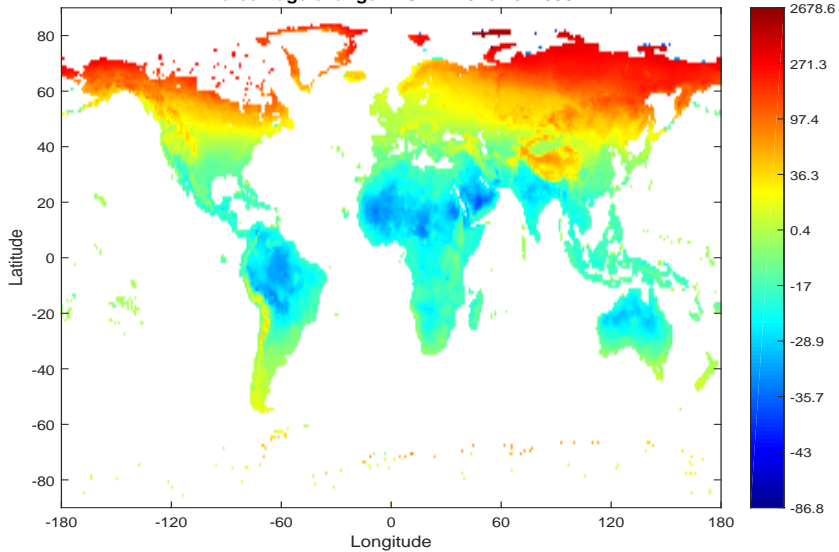
Percentage change in GDP: 2050 vs. 1990



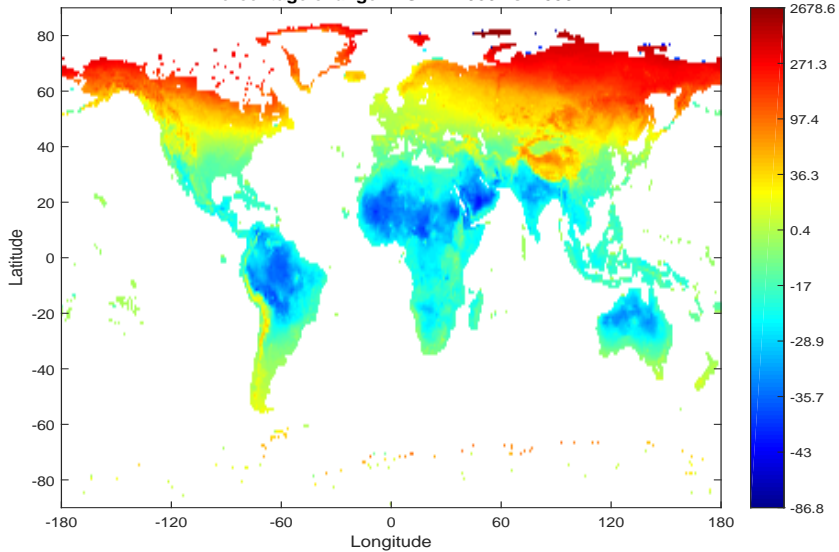
Percentage change in GDP: 2060 vs. 1990



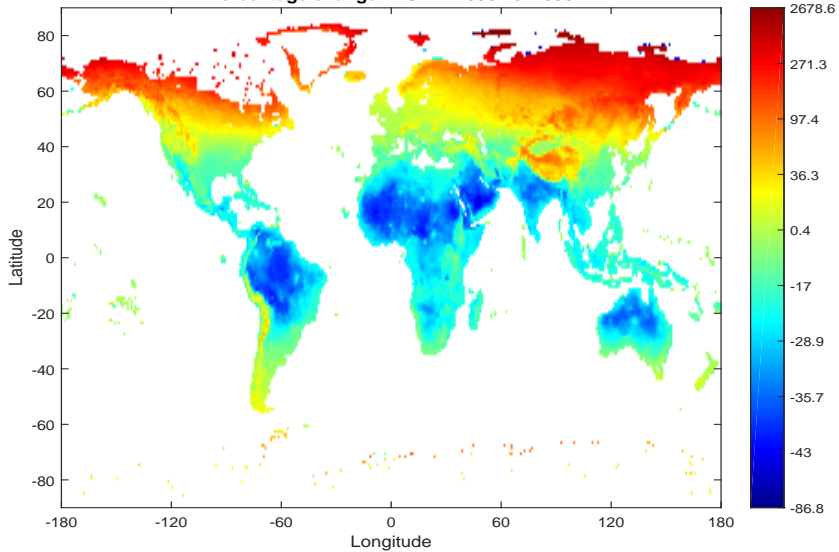
Percentage change in GDP: 2070 vs. 1990



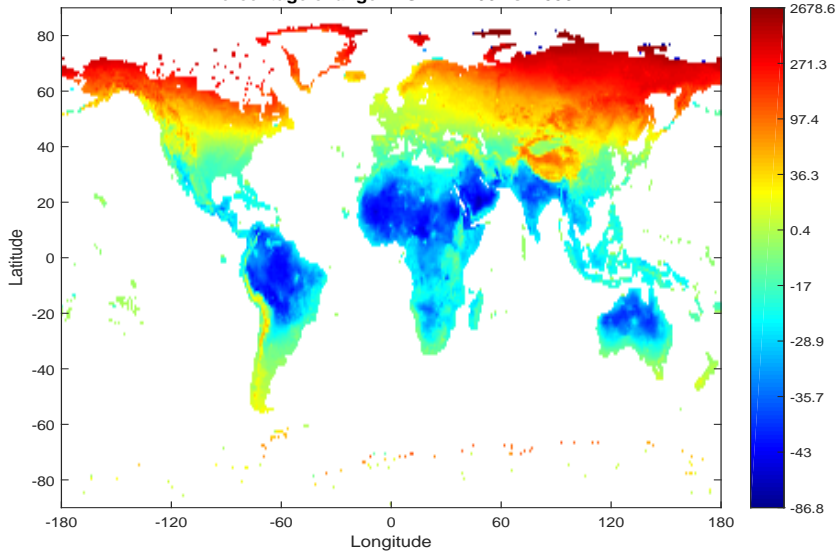
Percentage change in GDP: 2080 vs. 1990



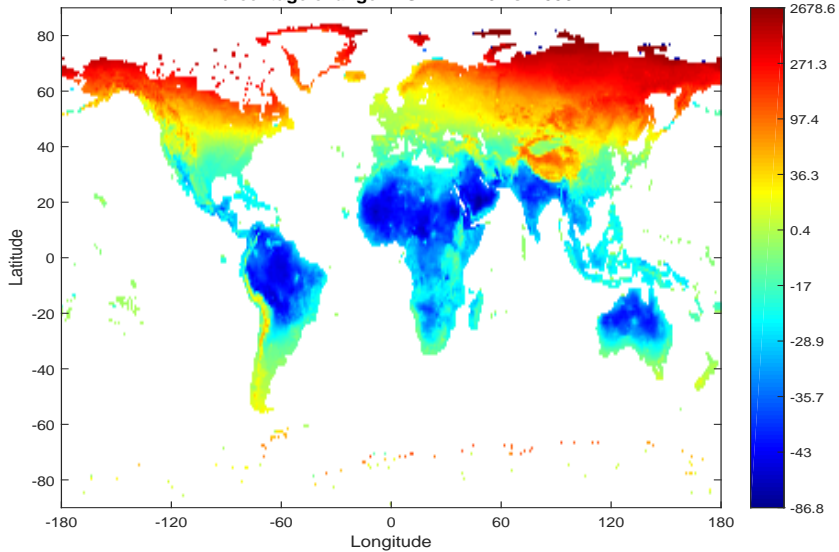
Percentage change in GDP: 2090 vs. 1990



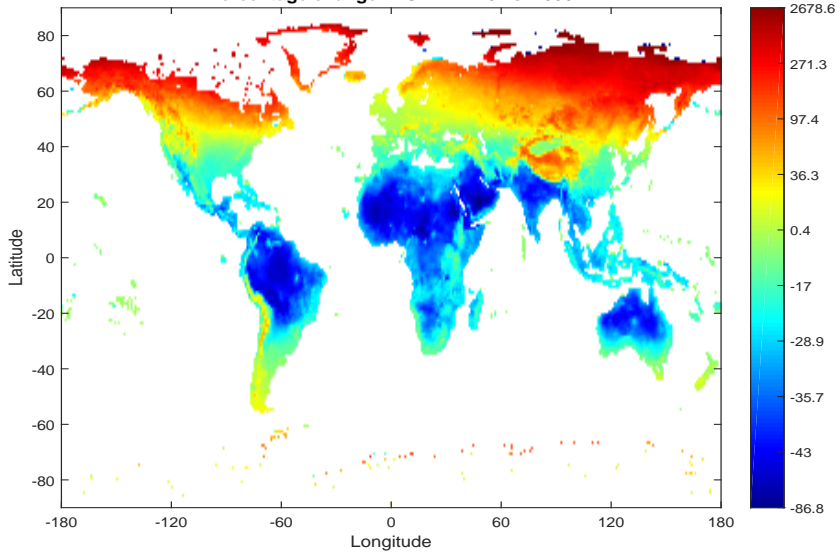
Percentage change in GDP: 2100 vs. 1990



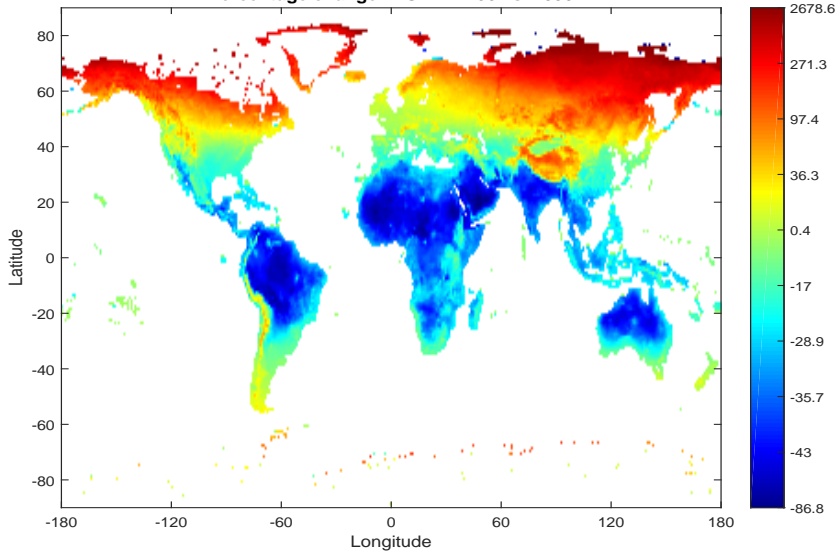
Percentage change in GDP: 2110 vs. 1990



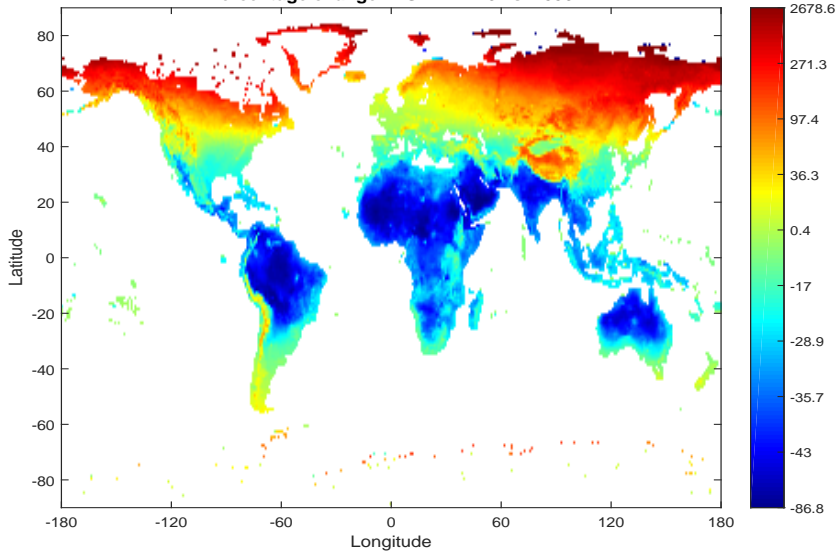
Percentage change in GDP: 2120 vs. 1990



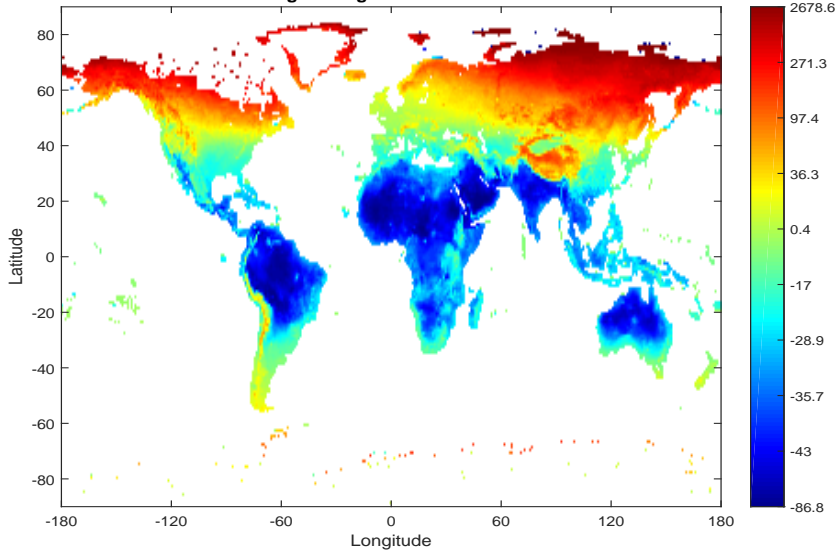
Percentage change in GDP: 2130 vs. 1990



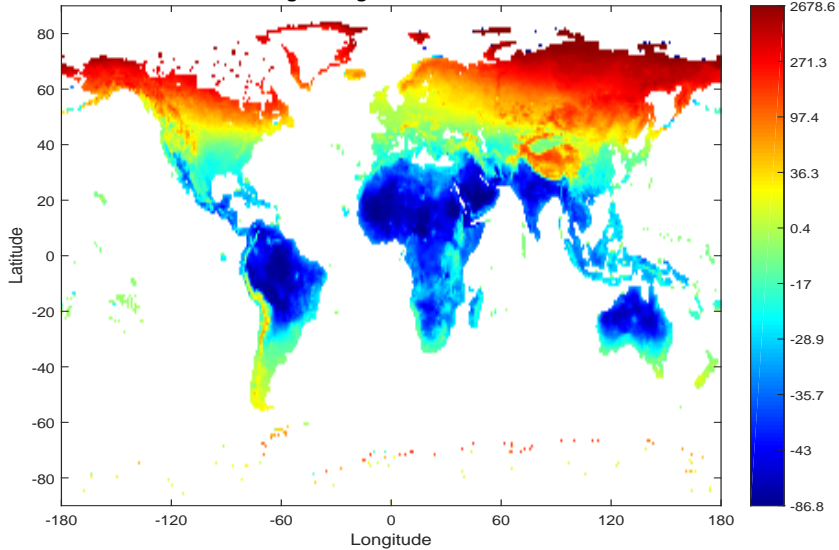
Percentage change in GDP: 2140 vs. 1990



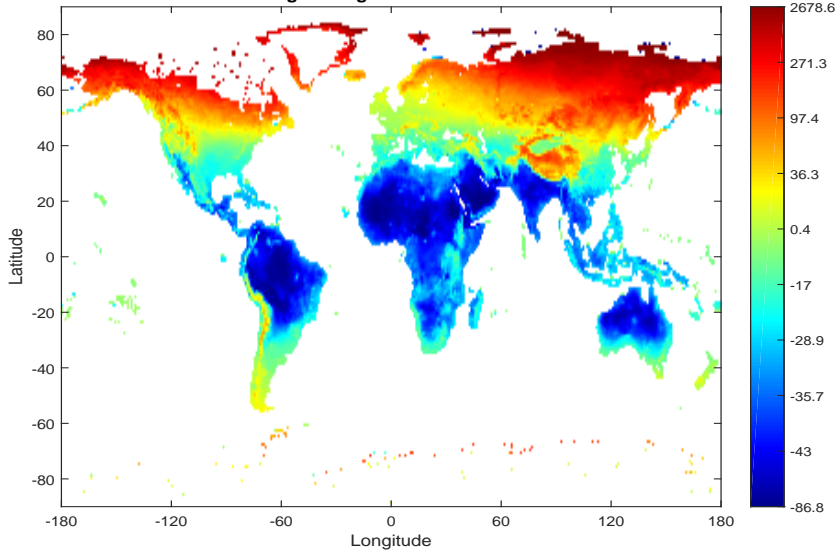
Percentage change in GDP: 2150 vs. 1990



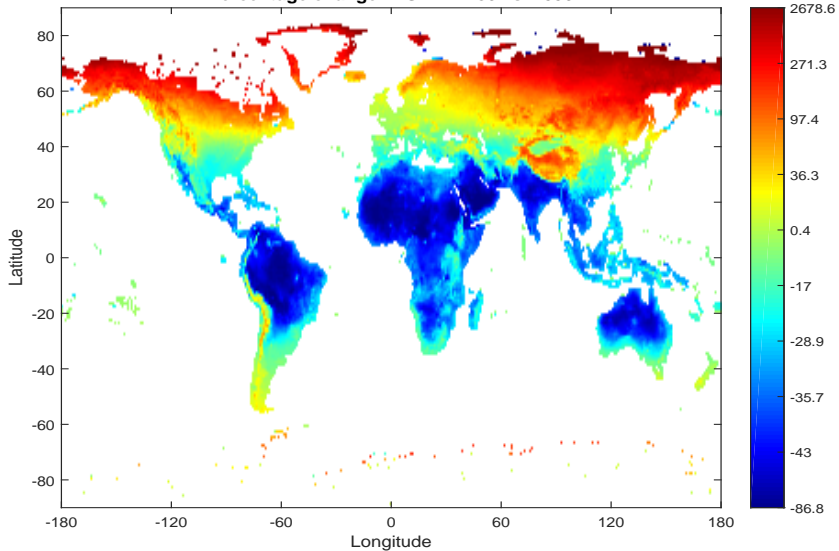
Percentage change in GDP: 2160 vs. 1990



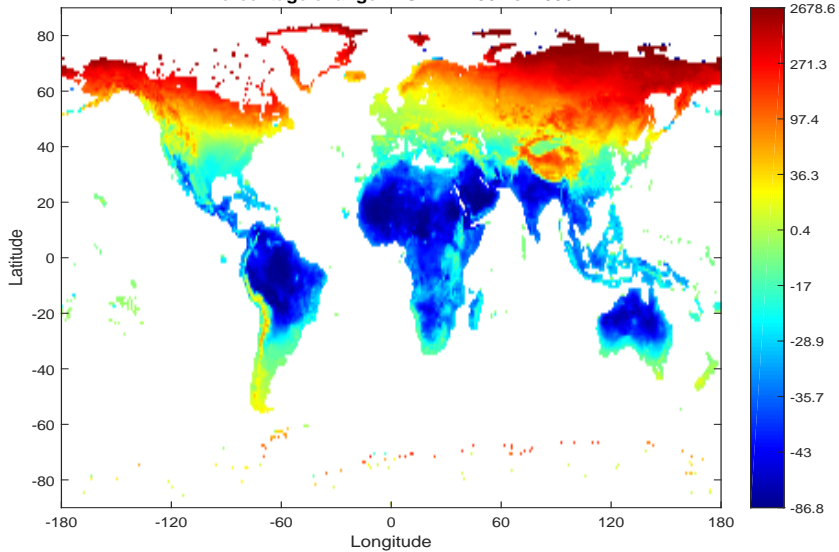
Percentage change in GDP: 2170 vs. 1990



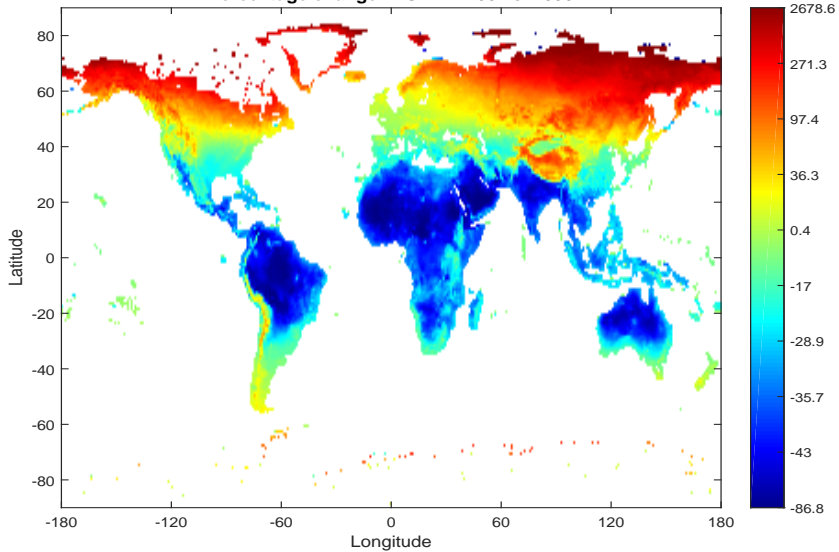
Percentage change in GDP: 2180 vs. 1990



Percentage change in GDP: 2190 vs. 1990



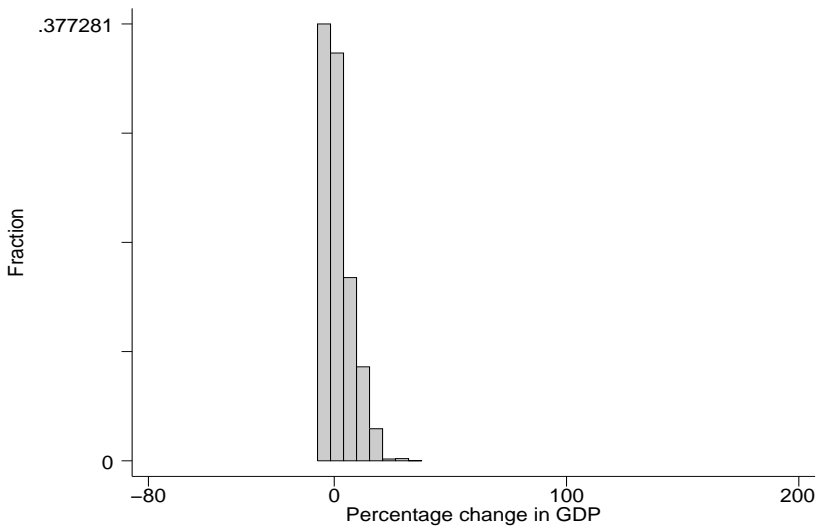
Percentage change in GDP: 2200 vs. 1990



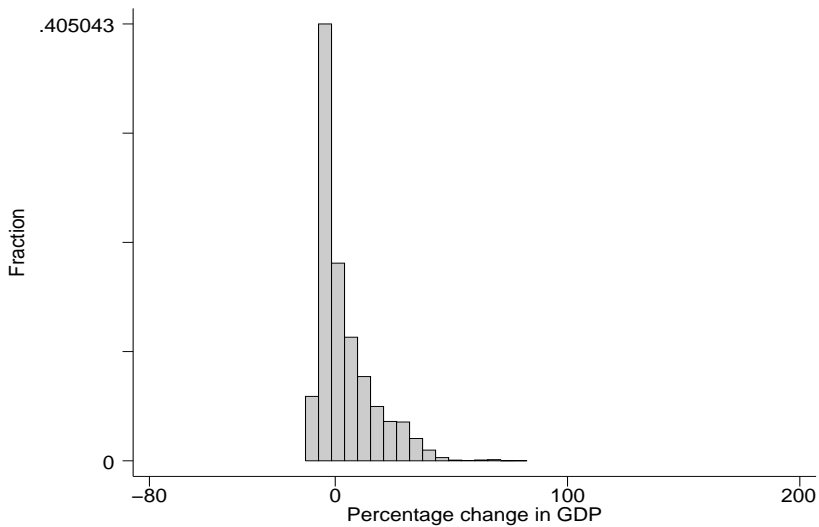
movie: distribution of percentage changes in GDP

animation: www.econ.yale.edu/smith/distpctgdp1.mp4

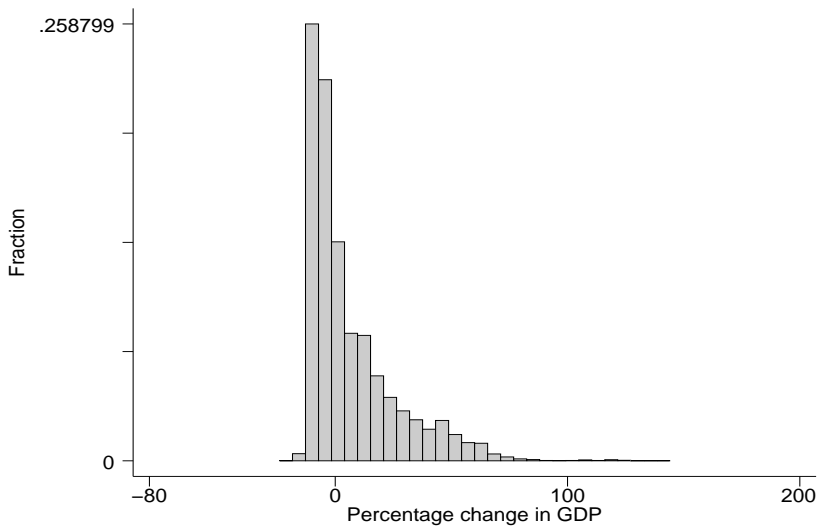
Distribution of percentage change in GDP: 2000 vs. 1990



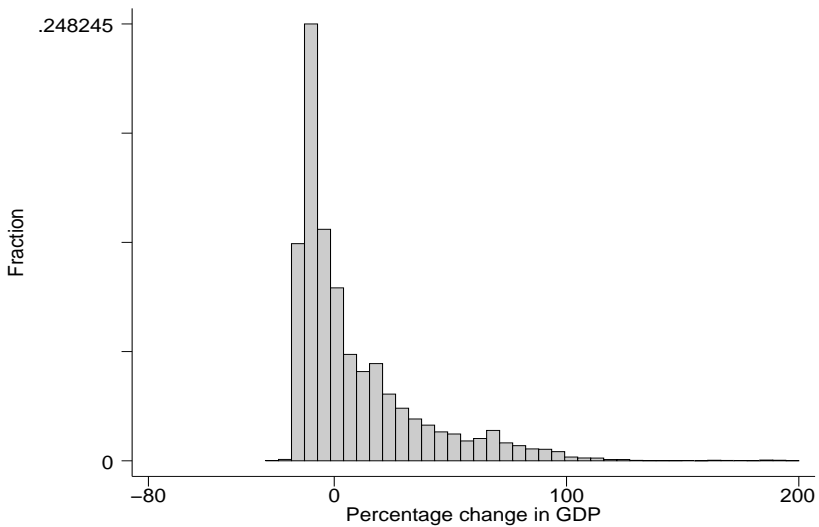
Distribution of percentage change in GDP: 2010 vs. 1990



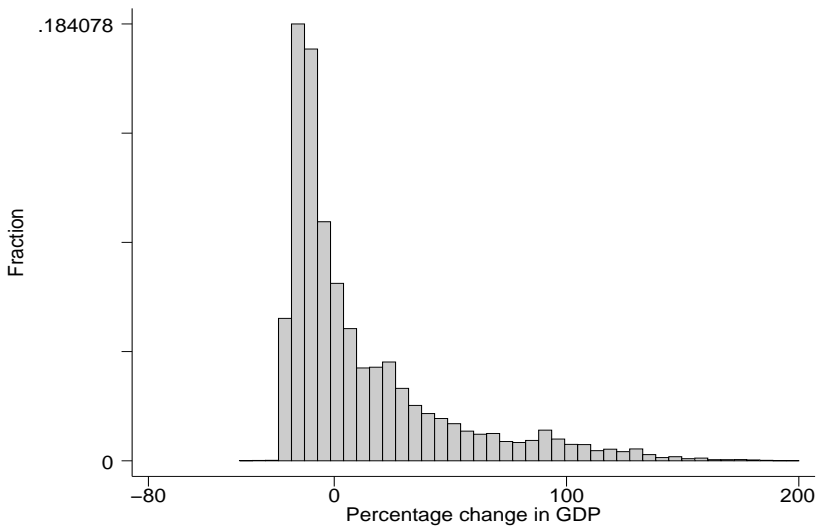
Distribution of percentage change in GDP: 2020 vs. 1990



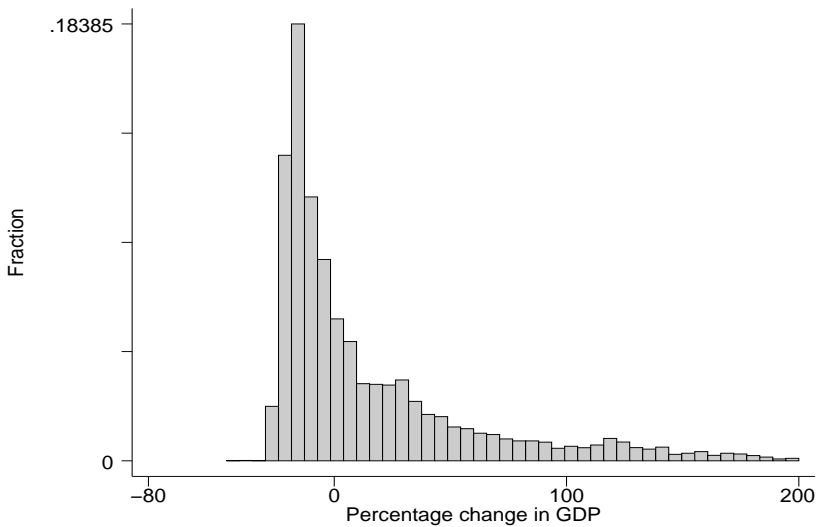
Distribution of percentage change in GDP: 2030 vs. 1990



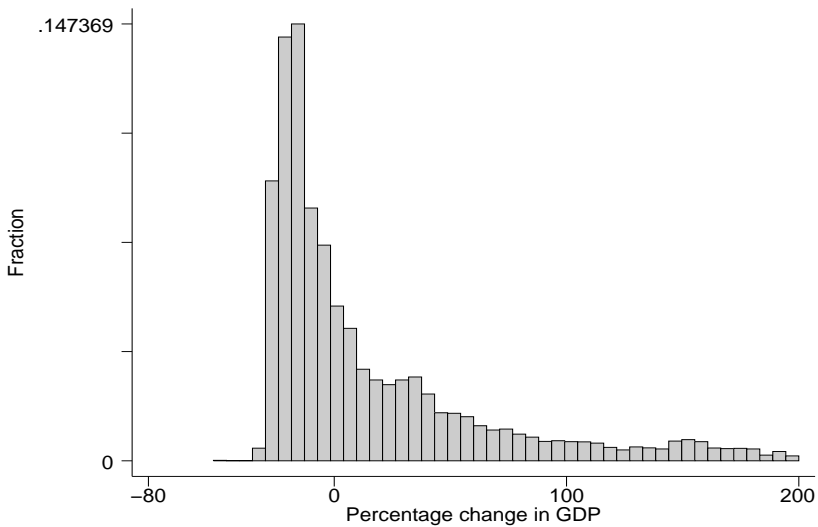
Distribution of percentage change in GDP: 2040 vs. 1990



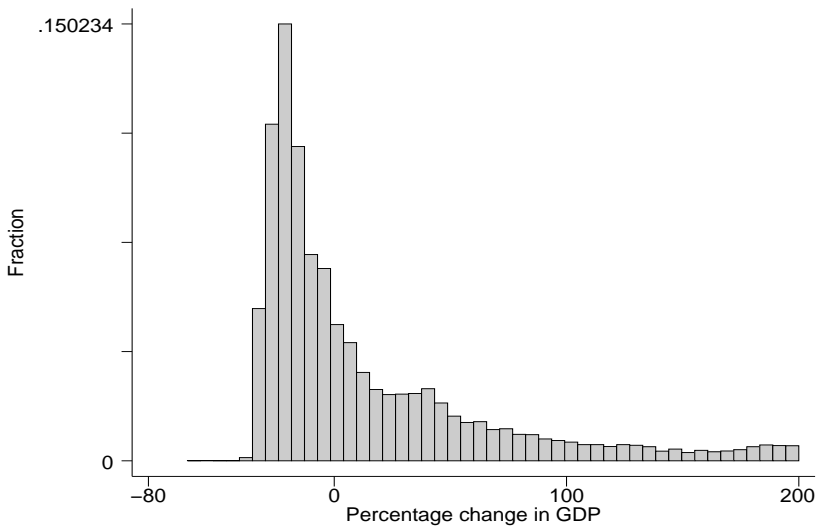
Distribution of percentage change in GDP: 2050 vs. 1990



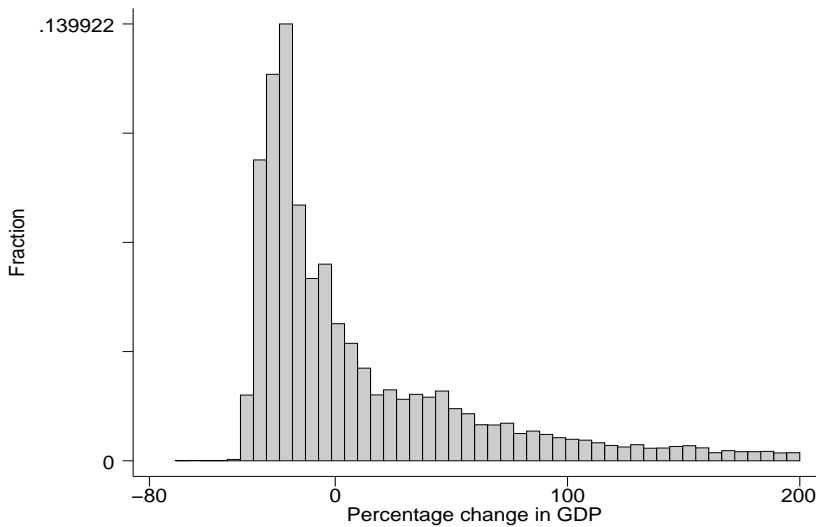
Distribution of percentage change in GDP: 2060 vs. 1990



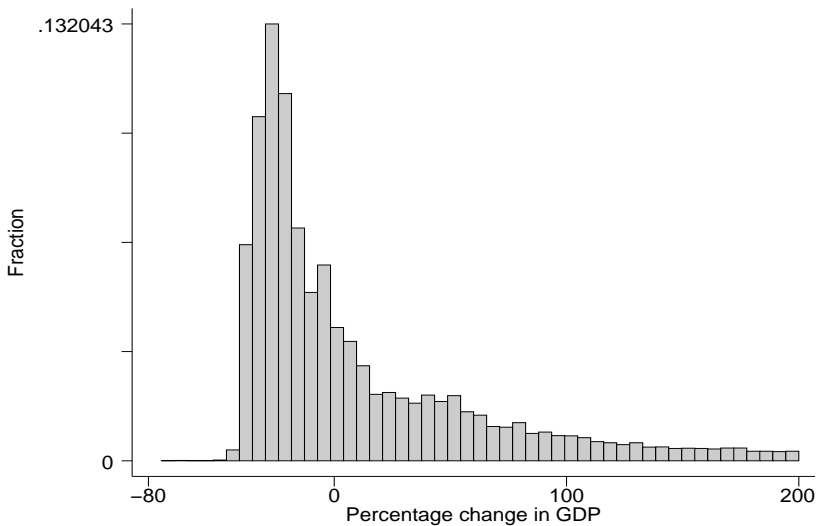
Distribution of percentage change in GDP: 2070 vs. 1990



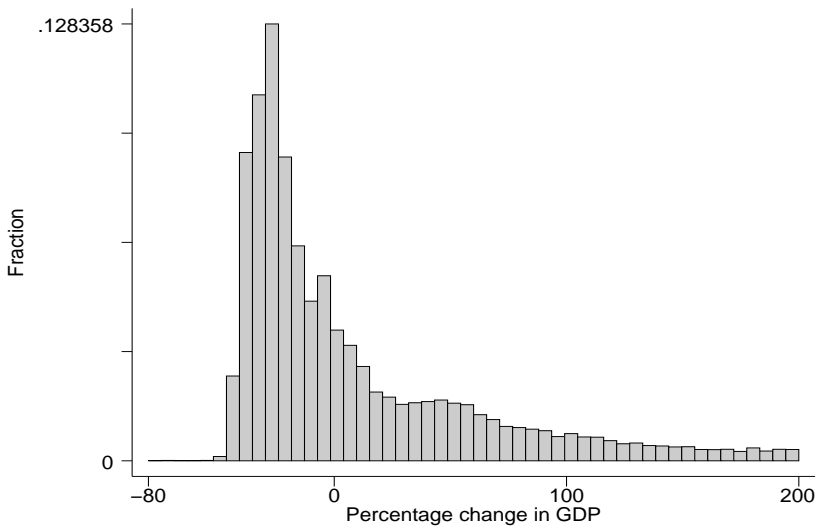
Distribution of percentage change in GDP: 2080 vs. 1990



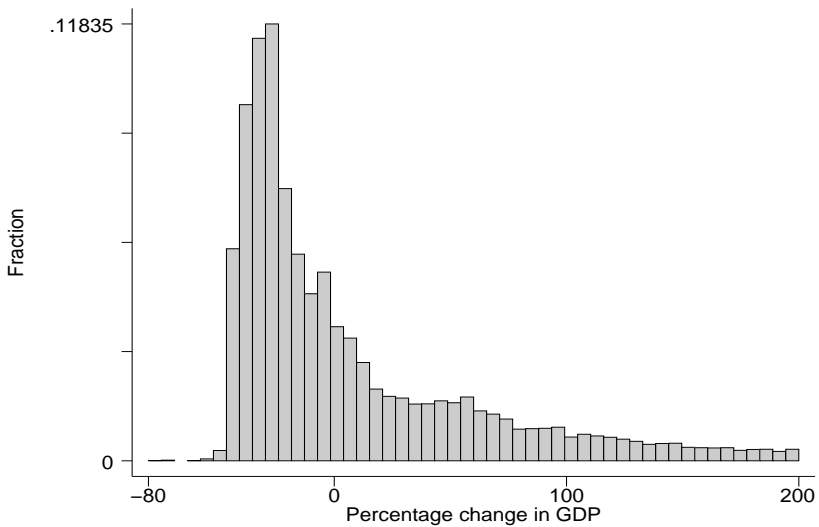
Distribution of percentage change in GDP: 2090 vs. 1990



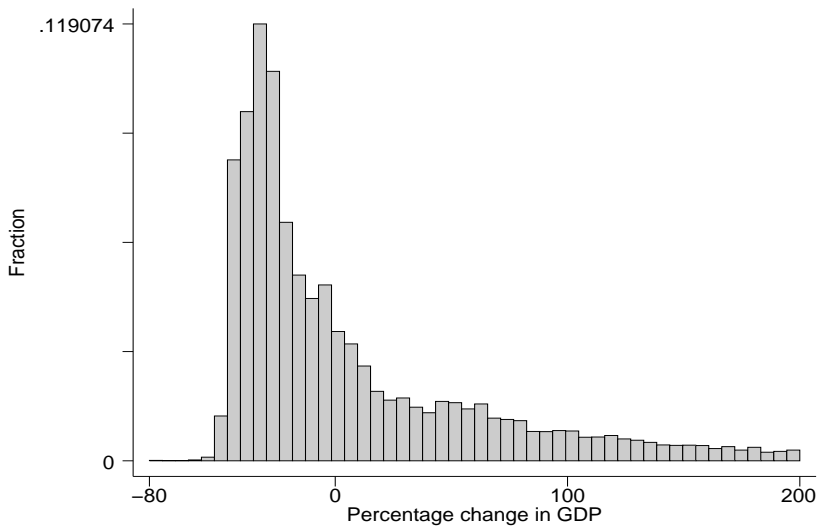
Distribution of percentage change in GDP: 2100 vs. 1990



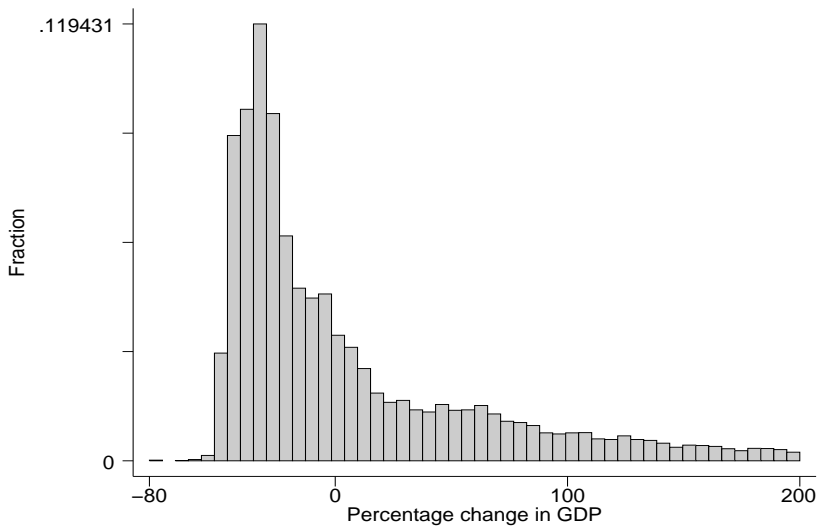
Distribution of percentage change in GDP: 2110 vs. 1990



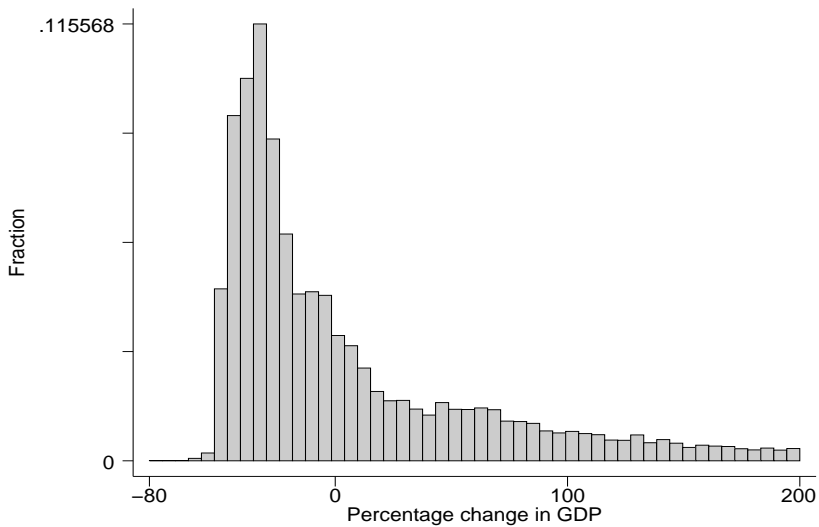
Distribution of percentage change in GDP: 2120 vs. 1990



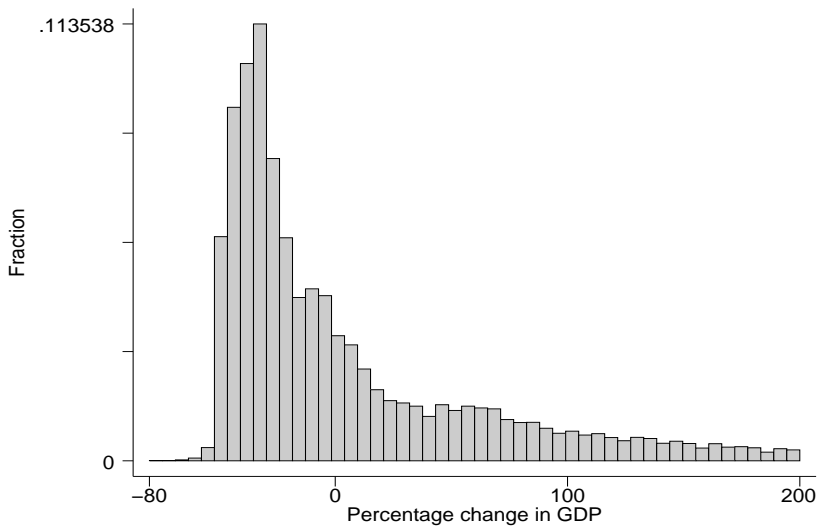
Distribution of percentage change in GDP: 2130 vs. 1990



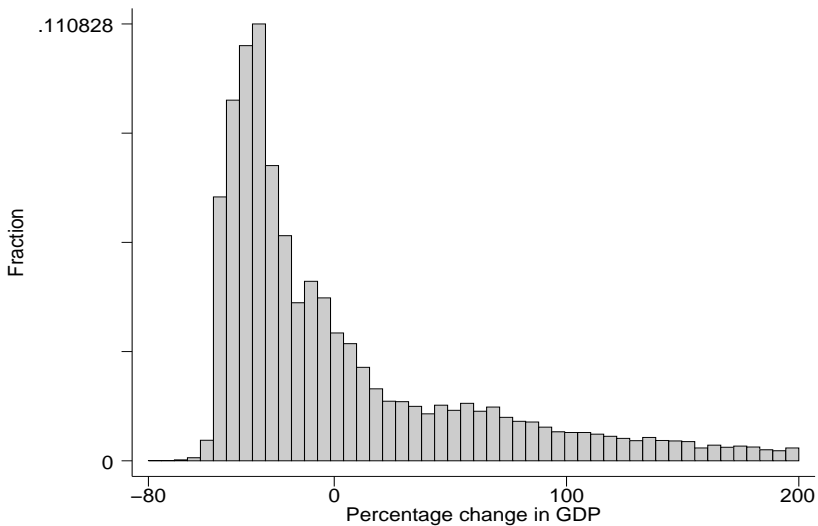
Distribution of percentage change in GDP: 2140 vs. 1990



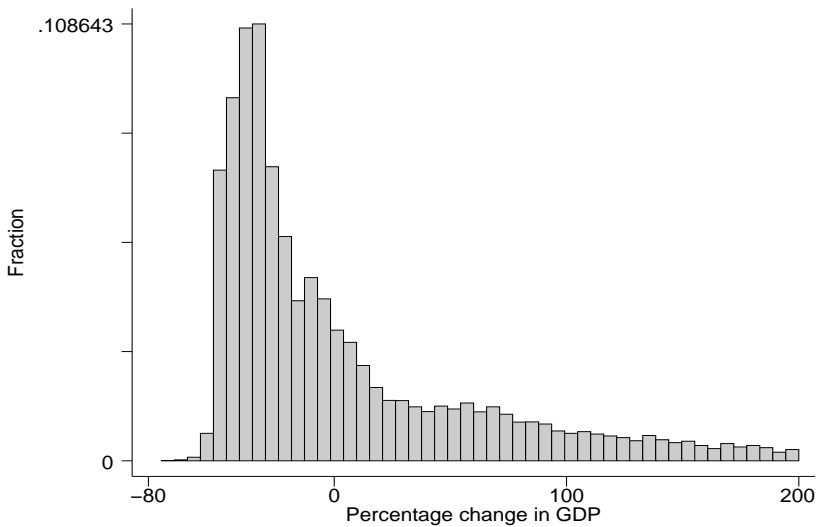
Distribution of percentage change in GDP: 2150 vs. 1990



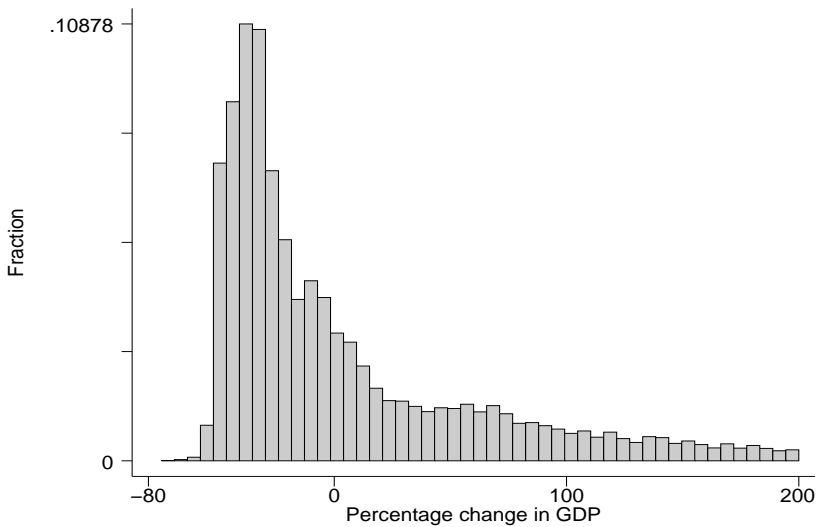
Distribution of percentage change in GDP: 2160 vs. 1990



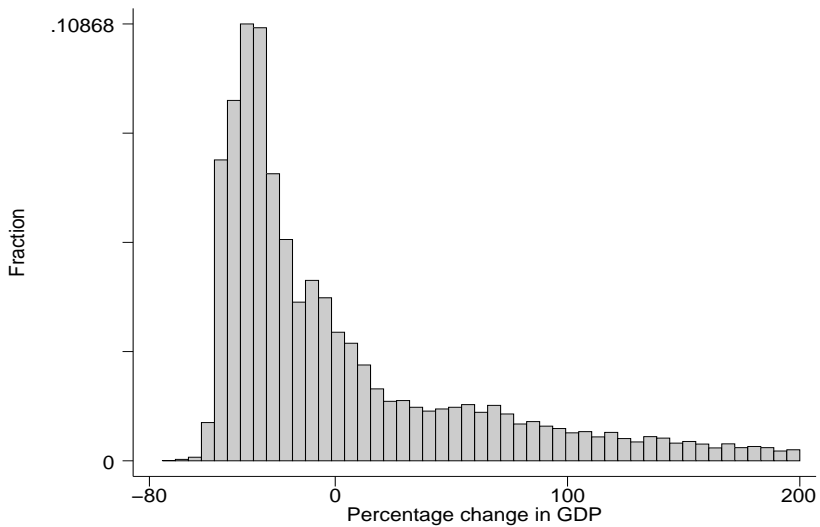
Distribution of percentage change in GDP: 2170 vs. 1990



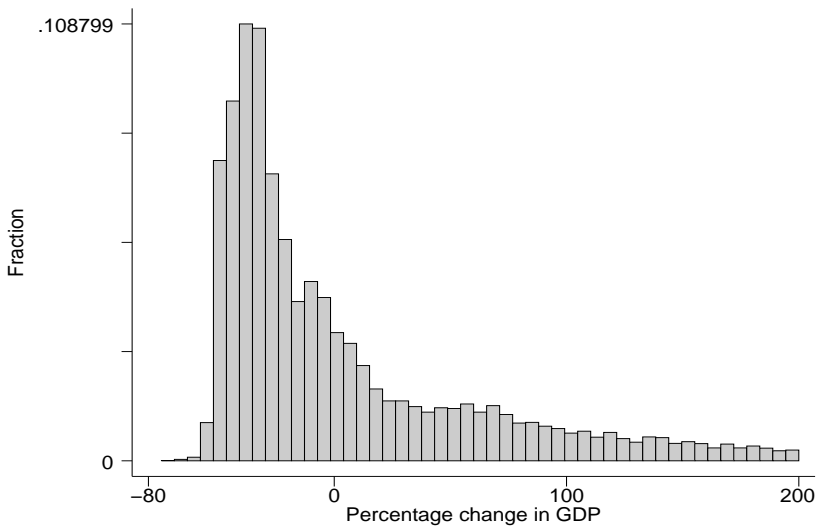
Distribution of percentage change in GDP: 2180 vs. 1990



Distribution of percentage change in GDP: 2190 vs. 1990

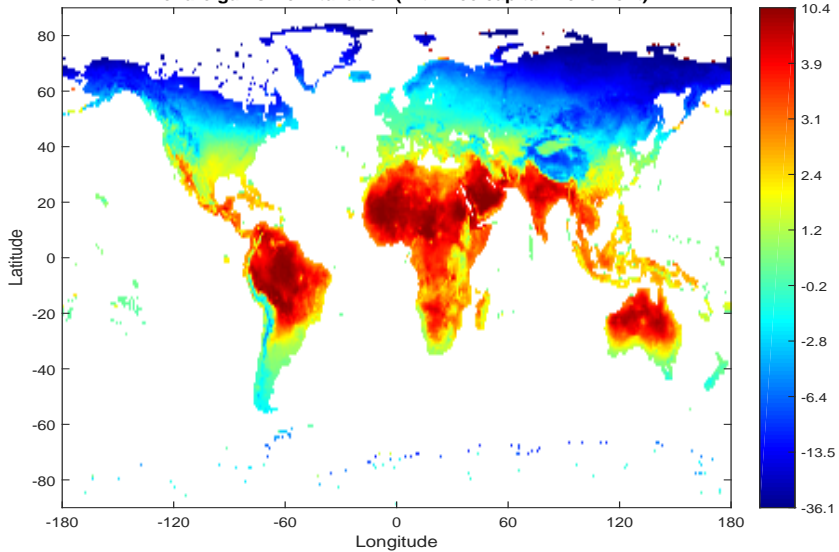


Distribution of percentage change in GDP: 2200 vs. 1990

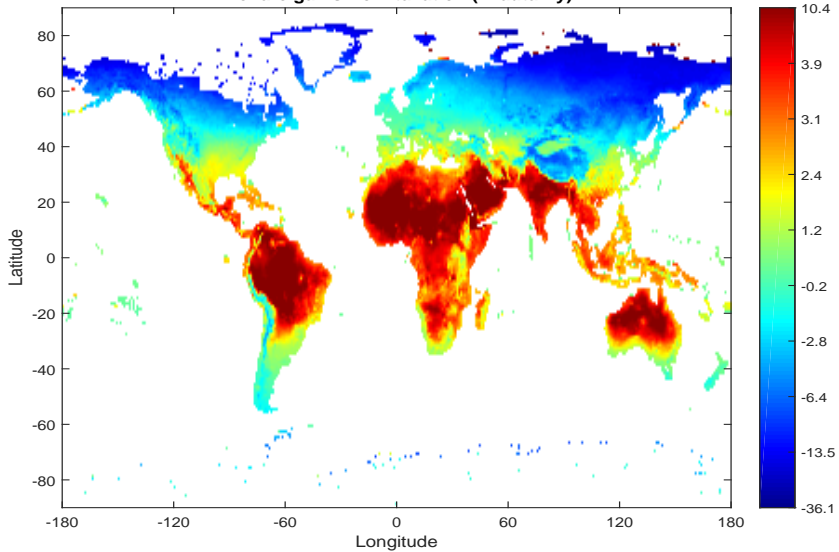


pictures: winners and losers from tax

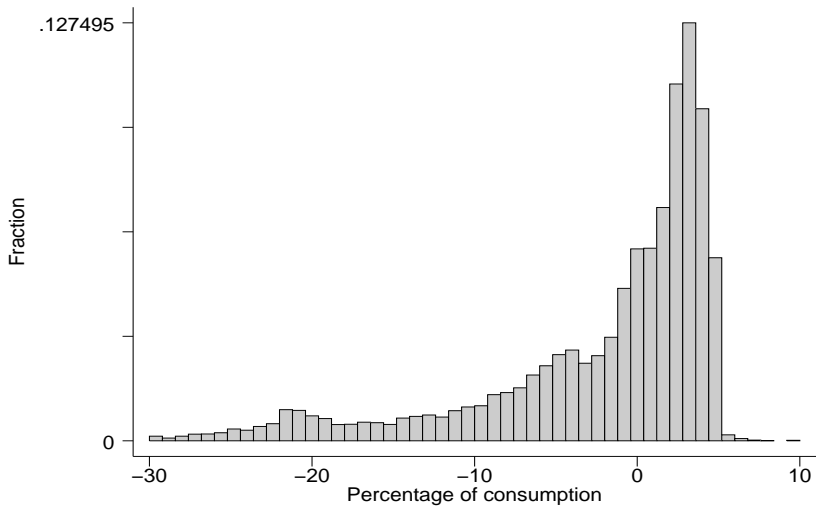
Welfare gains from taxation (with free capital movement)



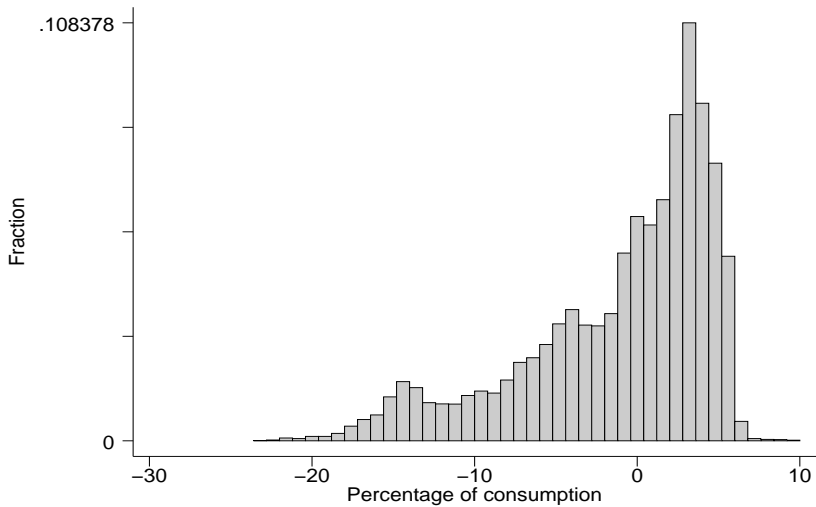
Welfare gains from taxation (in autarky)



Welfare gains from taxation (with free movement)
(as a percentage of consumption)



Welfare gains from taxation (in autarky)
(as a percentage of consumption)



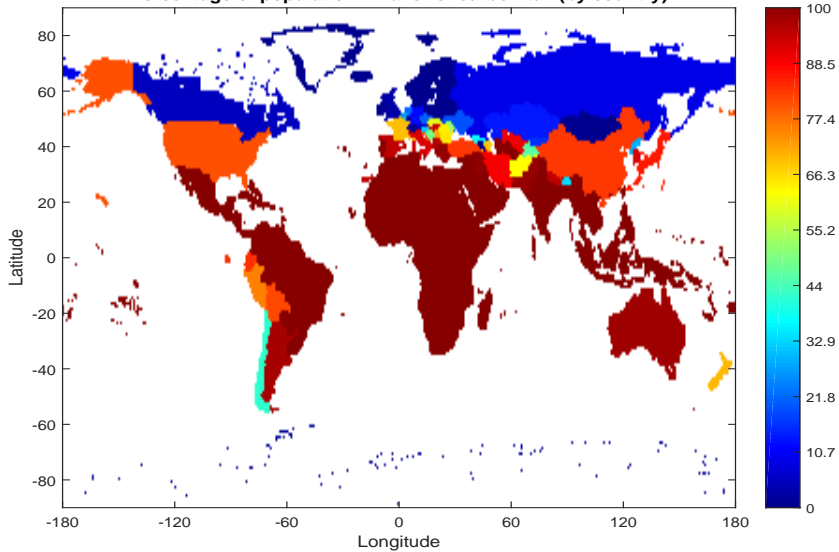
Welfare changes from tax: summary measures

- ▶ 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% .

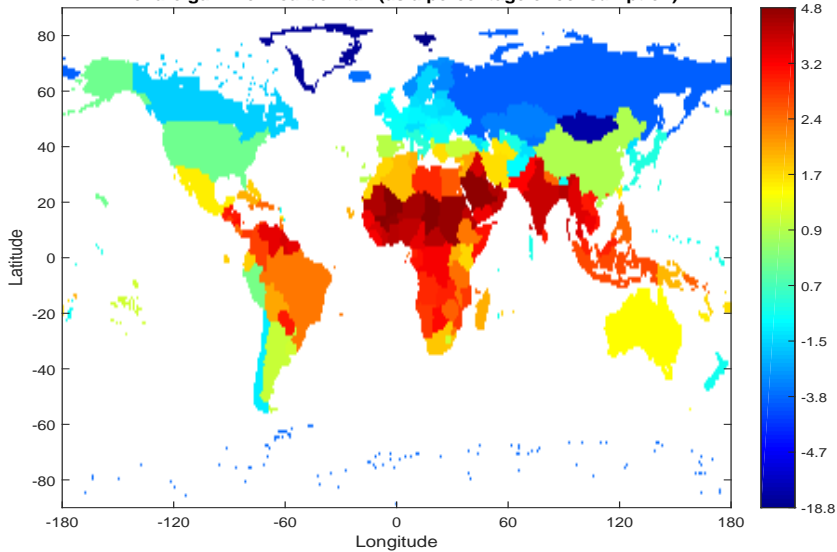
Welfare changes from tax in U.S. and China only

- ▶ One region = one vote: 56% gain (vs. 56%).
- ▶ One person = one vote: 83% gain (vs. 84%).
- ▶ One dollar = one vote: 69% gain (vs. 68%).
- ▶ Average gain across all regions: -0.55% (vs. -2.11%).
- ▶ Average gain weighted by GDP: 0.16% (vs. 0.60%).
- ▶ Average gain weighted by population: 0.44% (vs. 1.74%).
- ▶ World consumption path: gain of 0.10% (vs. 0.37%).
- ▶ 27% of regions in U.S. gain (vs. 41%).
- ▶ 27% of regions in China gain (vs. 36%).
- ▶ 60% of regions in rest of world gain (vs. 58%).

Percentage of population in favor of carbon tax (by country)



Welfare gain from carbon tax (as a percentage of consumption)



movie: distribution of mpks

animation: www.econ.yale.edu/smith/distmpk1.mp4

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.

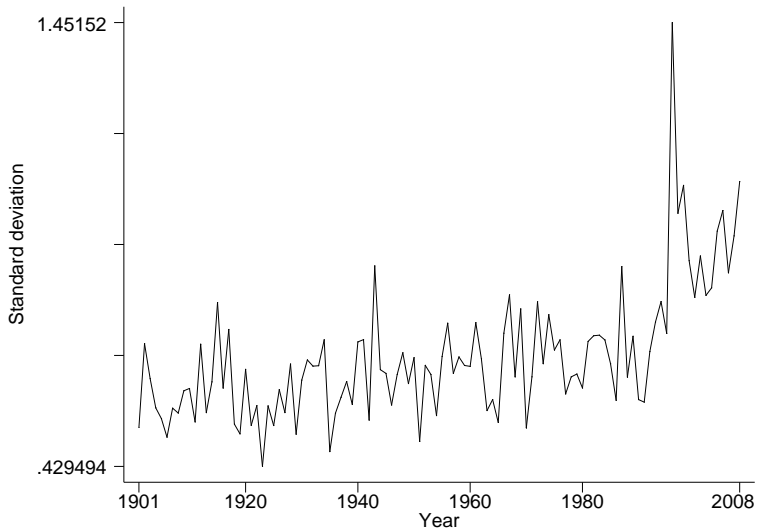
Building on the platform

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.

“Coupling” with NorESM (with Storelvmo and Bjordal)

- ▶ Couple: Disaggregated Integrated Assessment Model (DIAM?) *and* a regional “global circulation model”, the Norwegian Earth System Model (NorESM).
- ▶ No need for a simplified geophysical model in DIAM!
- ▶ Coupling can be accomplished “off-line”: DIAM need not touch NorESM when it is generating an aggregate emissions path, and NorESM need not touch DIAM when it is generating a time path for regional temperatures.
- ▶ Define: $\mathbb{T} \equiv \{ \{ T_{it} \}_{t=0}^T \}_{i=1}^M$ and $\mathbb{E} \equiv \{ E_t \}_{t=0}^T$.
- ▶ DIAM: $\mathbb{E} = G(\mathbb{T})$. NorESM: $\mathbb{T} = H(\mathbb{E})$.
- ▶ Equilibrium is a fixed point: $\mathbb{T}^* = H(G(\mathbb{T}^*))$.

Standard deviation of temperature shock (by year)



Lifetime wealth (per effective unit of labor)

