# Climate Change Around the World

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Macroeconomic and Financial Stability"
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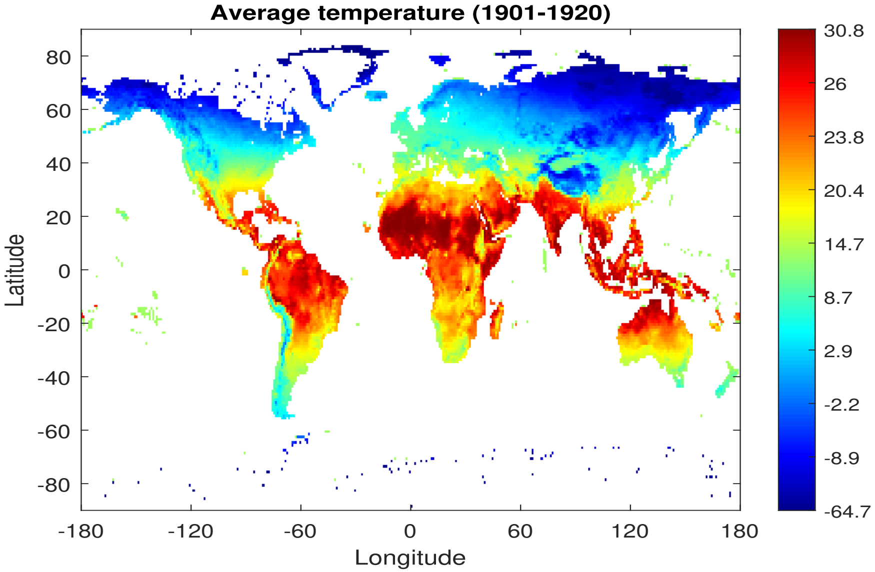
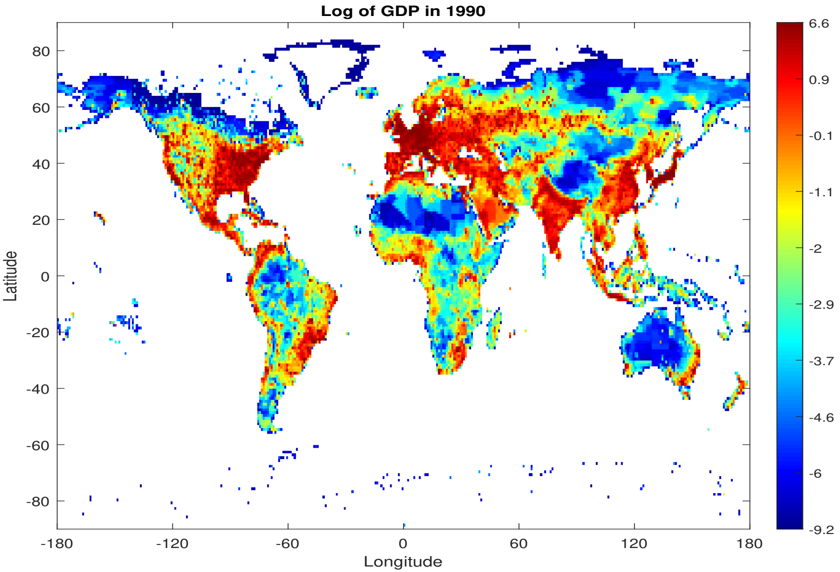
# Goals of the project

- Construct a global, dynamic, general equilibrium model of interactions between the economy, climate, and weather at 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.
- Long-range goal: "couple" the Norwegian Earth System Model (NorESM2) with the high-resolution economic model.

# Spatial models of climate change

- Part of a growing literature on spatial equilibrium models of climate change.
- Partial list of references: Brock, Cai, and Xepapadeas; Brock, Engström, Grass, and Xepapadeas; Bilal and Rossi-Hansberg; Cruz and Rossi-Hansberg; Desmet and Rossi-Hansberg; Hassler and Krusell; Fried; Hassler, Krusell, Olovsson, and Reiter; Hillebrand and Hillebrand; Rudik, Lyn, Tan, and Ortiz-Bobea.


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



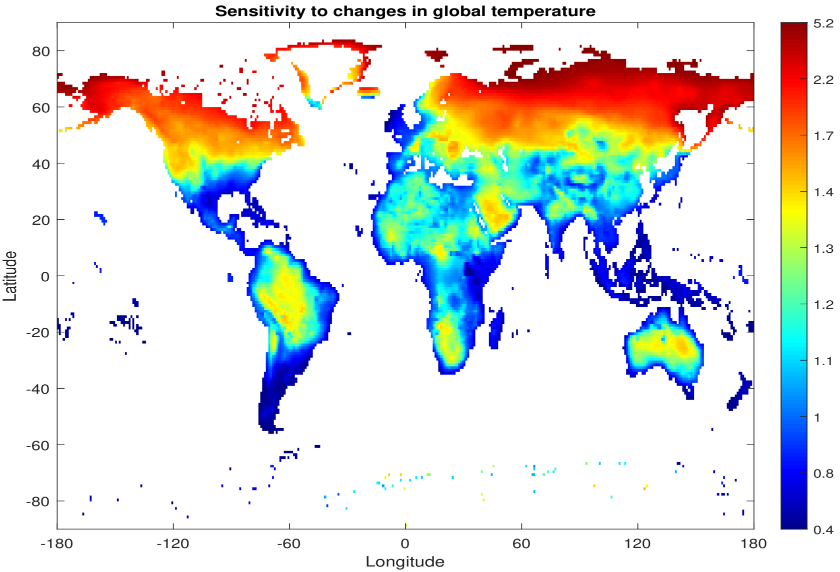
Log of GDP in 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6.6
0.9
-0.1
-1.1
-2
-2.9
-3.7
-4.6
-6
-9.2

# The economic model

- Forward-looking consumers and firms in each region determine their consumption, saving, and energy use. No migration.
- Neoclassical technologies for producing both final goods and energy, using capital, labor, and energy as inputs.
- Think of energy as coal (non-exhaustible). Energy slowly, exogenously, becomes green over time.
- Regional TFP is the product of an exogenous component and a component that varies with regional (average) temperature.
- Two polar cases for financial markets: autarky and unrestricted borrowing/lending. Under autarky, regions interact only through global emissions.
- Summary: like Aiyagari/Angeletos, though no shocks (such as weather) in this version.
- Adaptation: consumption smoothing and, when not in autarky, capital mobility ("leakage").

# The climate system and the carbon cycle

- Global (average) temperature varies with the global stock of atmospheric carbon.
- The stock of carbon obeys a linear law of motion, driven by global emissions of carbon.
- Alternatively, the global temperature varies linearly with cumulative emissions since the Industrial Revolution.
- Regional (average) temperature varies linearly with global temperature via a pattern-scaling (or statistical-downscaling) relationship with region-specific slope coefficients.
- These are all reasonable simplifications of the dynamics of Earth system models.



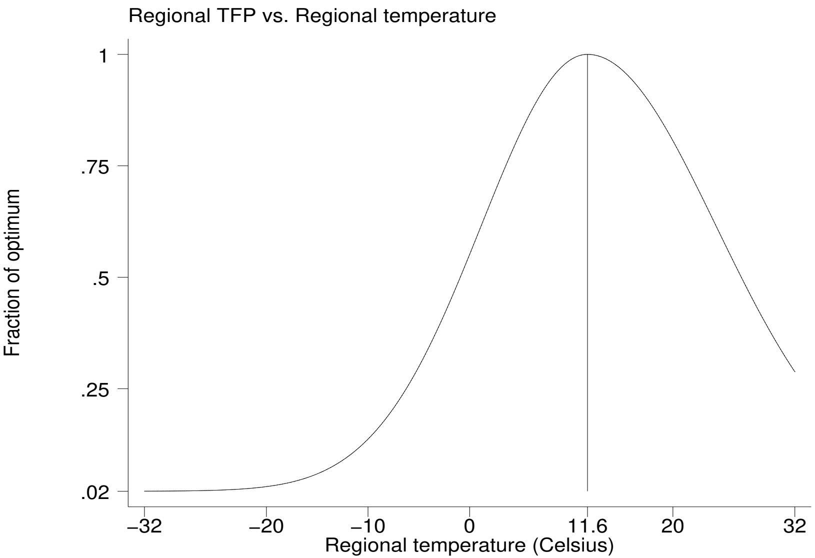
Sensitivity to changes in global temperature
Latitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
Longitude
5.2
2.2
1.7
1.4
1.3
1.2
1.1
1
0.8
0.4

# Global equilibrium

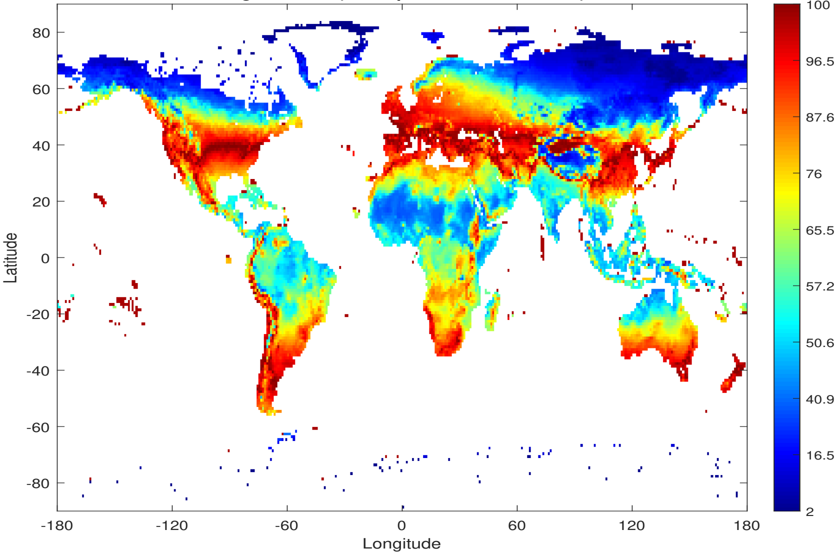
- Equilibrium conditions:
  - Consumer-entrepreneurs in each region behave optimally given paths for global temperature and the interest rate.
  - The implied path of global emissions generates the path for global temperature (perfect foresight).
  - The global bond market clears in every period.
- With free capital mobility, the model aggregates: need to solve only the problem of a global "stand-in" consumer, taking the global temperature path as given.
- In autarky, need to solve ∼19,000 dynamic programs! But can be done quickly using nonlinear interpolation across regional "types" and parallel methods.

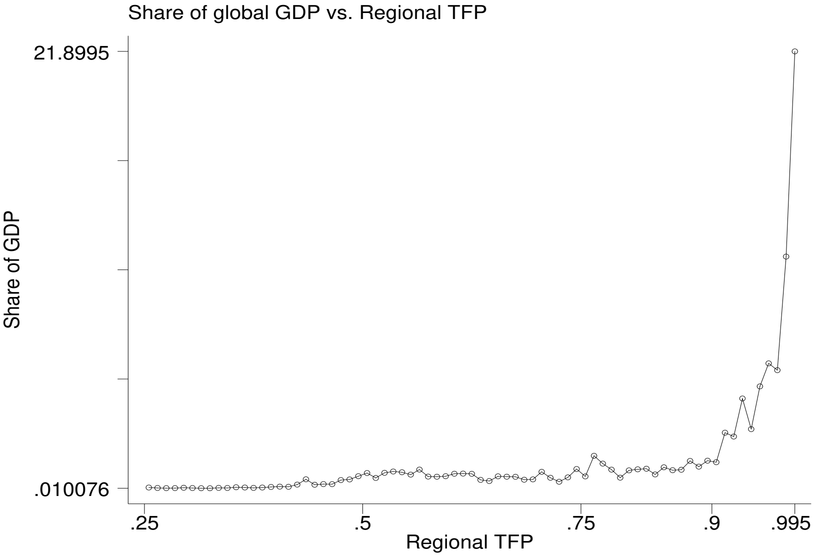
# Our damage specification

- What are the economic damages in region $i$ as a result of global warming?
- Our approach: let TFP (Total Factor Productivity) in region $i$ be a function $D$ of *local temperature* that is common across all regions.
- $D$ has an inverse $U$-shape and varies between 0 and 1 (so it captures variations in regional TFP *relative to* the exogenous component of regional TFP).
- Reverse engineering: calibrate $D$ so that the high-resolution model generates *aggregate* damages from changes in the global temperature (expressed as a percentage of global GDP) that match Nordhaus's DICE damage function (itself also modelled as a drag on global TFP).

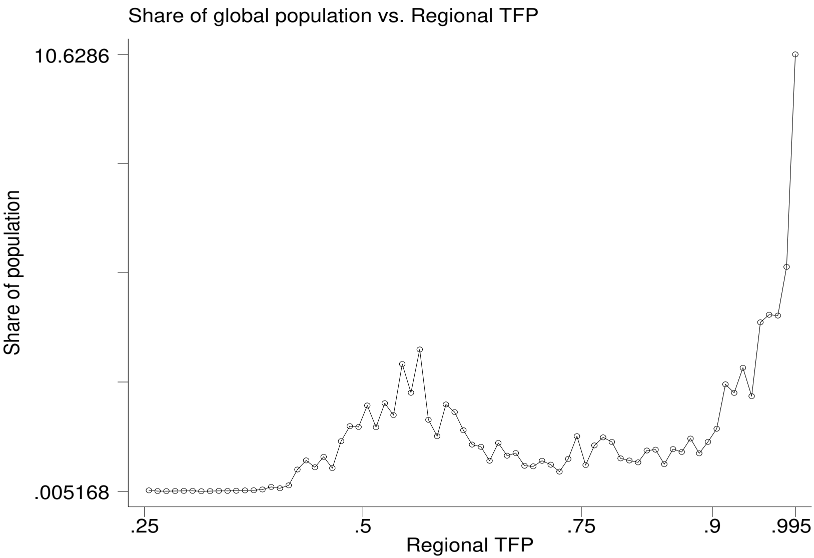

Regional TFP vs. Regional temperature
Fraction of optimum
1
.75
.5
.25
.02
–32
–20
–10
0
11.6
20
32
Regional temperature (Celsius)

**Regional TFP (at temperature in 1901-1920)**





Share of global GDP vs. Regional TFP
21.8995
.010076
Share of GDP
.25
.5
.75
.9
.995
Regional TFP


Share of global population vs. Regional TFP
10.6286
.005168
Share of population
.25
.5
.75
.9
.995
Regional TFP

# Comments on the model

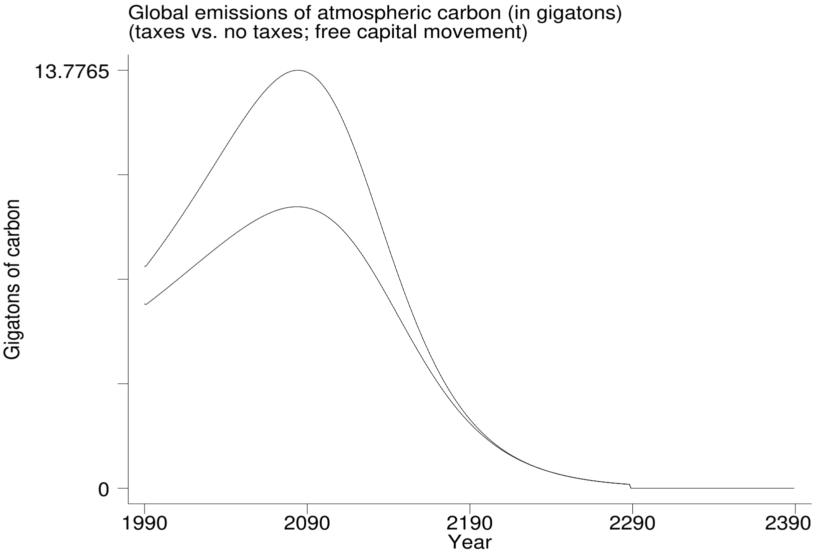
- At the aggregate level, the spatial model with free capital mobility nests the DICE model.
- Agents make forward-looking decisions, anticipating future climate change.
- Regional damages are assumed to have an inverse-$U$ shape calibrated to match aggregate damages in the DICE model.
- Spatial adaptation takes place through differing patterns of capital accumulation across regions.
- Fully-specified microfounded model that permits quantitative analysis of behavioral/equilibrium responses to counterfactual changes in climate policy. (Marginal externality damage of carbon emissions, keeping behavior constant in the given allocation $\neq$ optimal social cost of carbon.)

# 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.

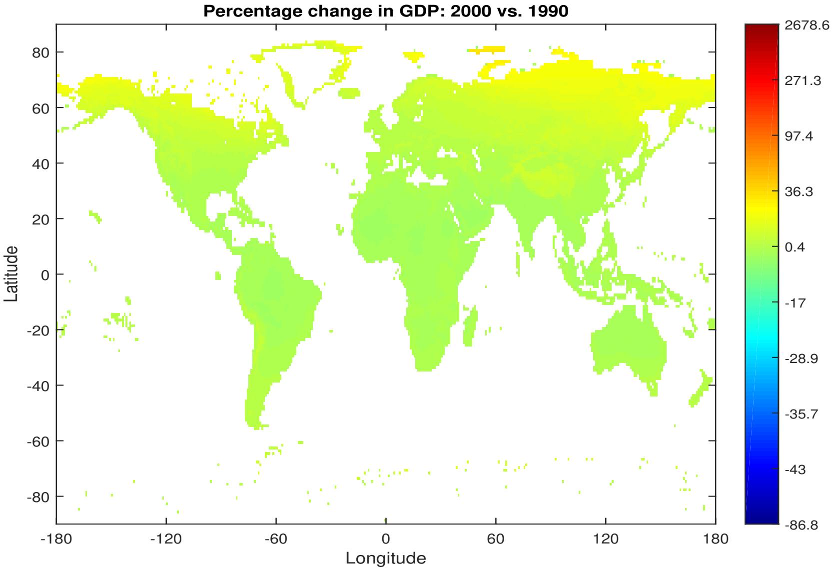
# Main findings

- Climate change affects regions *very* differently. Stakes big at regional level.
- Though an optimal tax on carbon would affect welfare positively in an 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).
- Climate change leads to large increases in global inequality in GDP per capita (both across regions and across countries); the tax on carbon mitigates these increases only to a small degree.

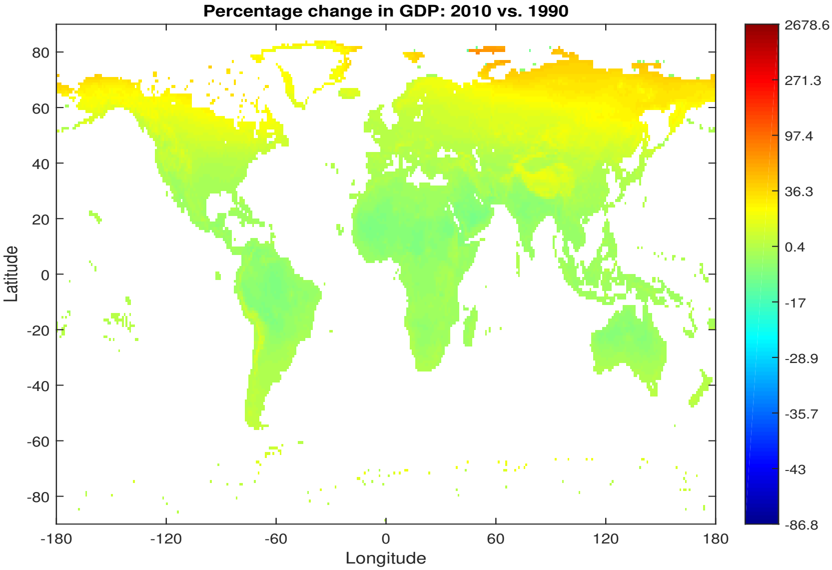


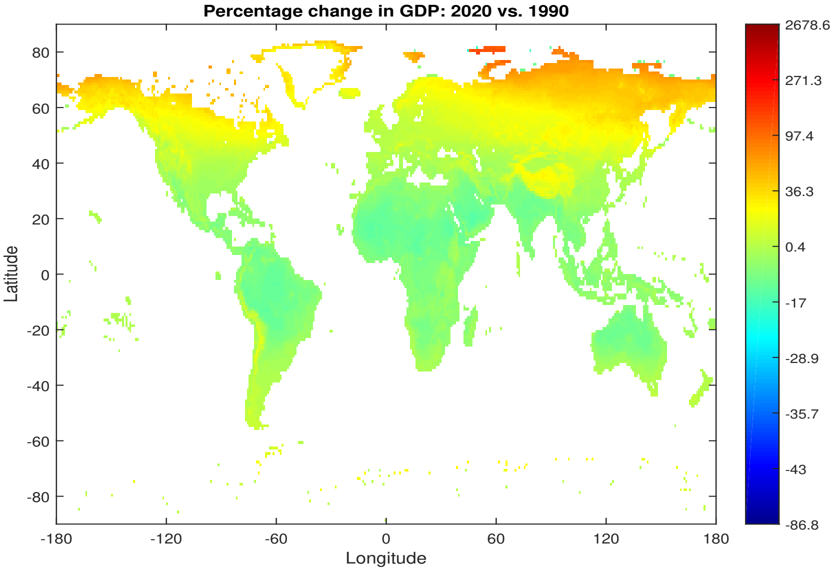
Global emissions of atmospheric carbon (in gigatons)
(taxes vs. no taxes; free capital movement)
13.7765
0
Gigatons of carbon
1990
2090
2190
2290
2390
Year

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

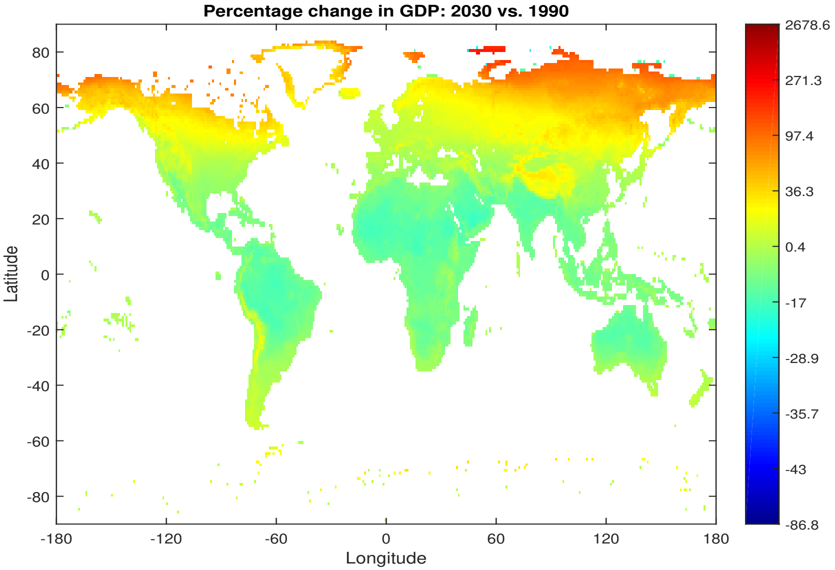


Percentage change in GDP: 2000 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

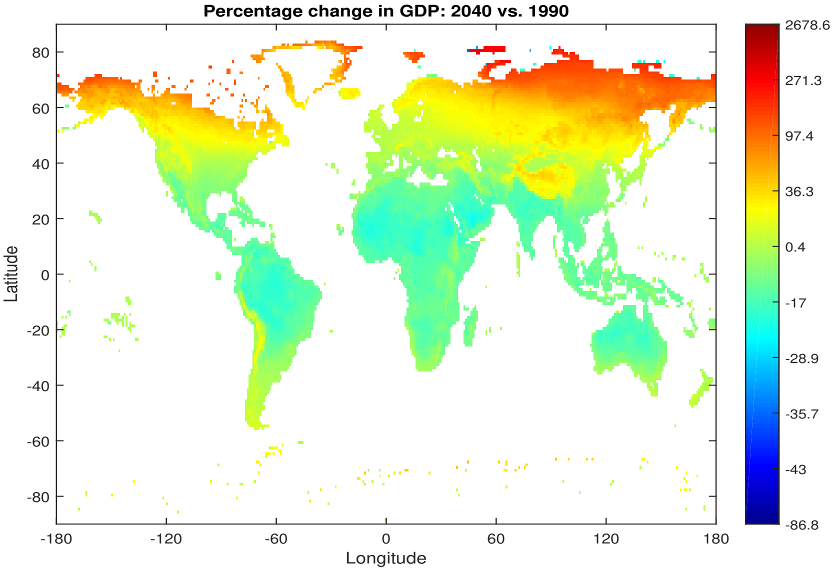

Percentage change in GDP: 2010 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



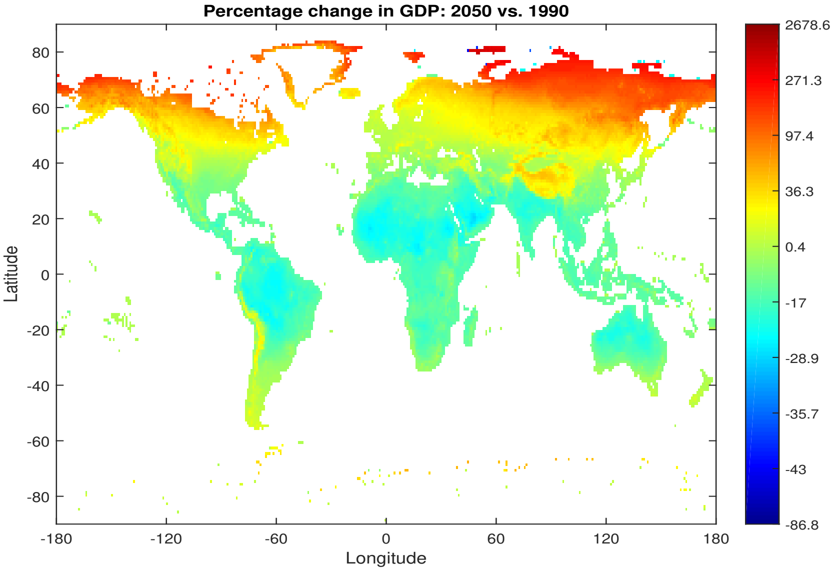
Percentage change in GDP: 2020 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

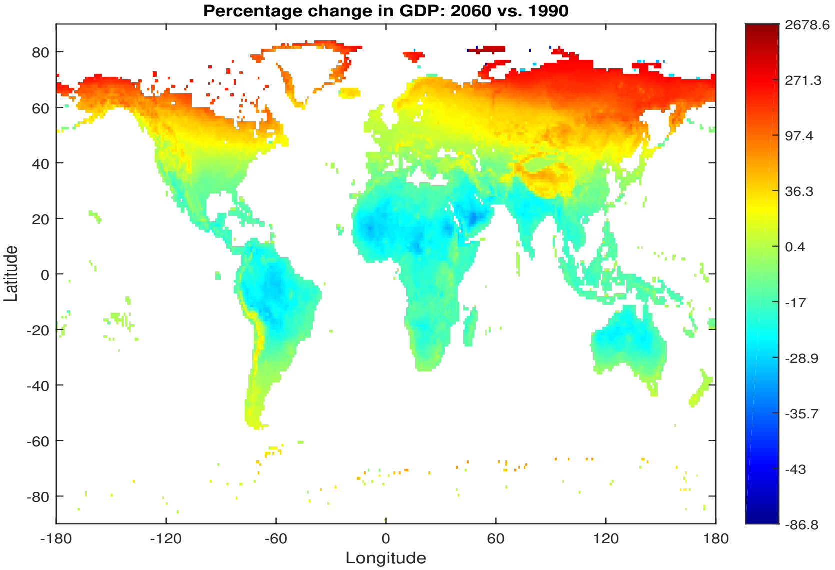


Percentage change in GDP: 2030 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

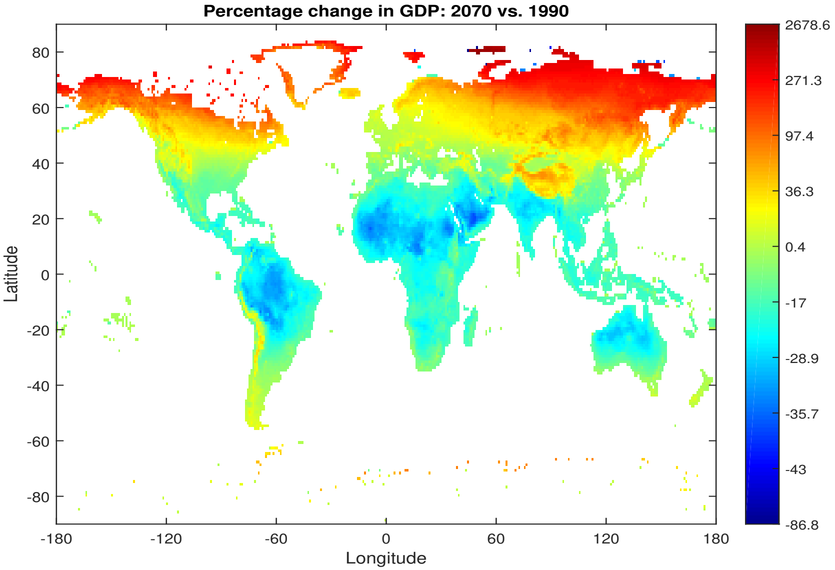


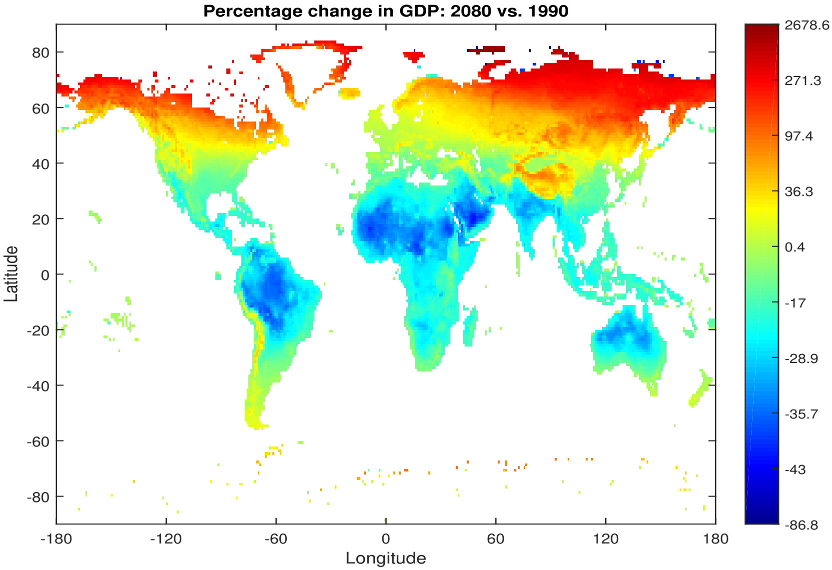
Percentage change in GDP: 2040 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

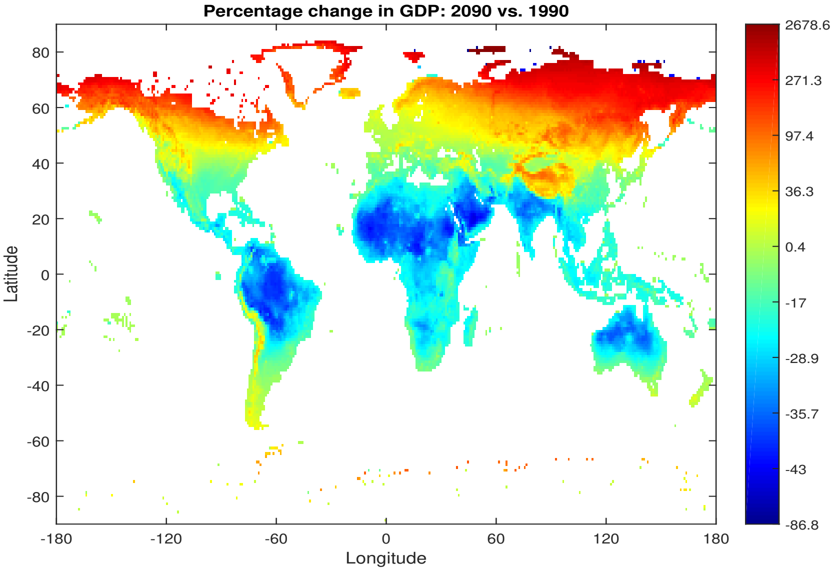

Percentage change in GDP: 2050 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



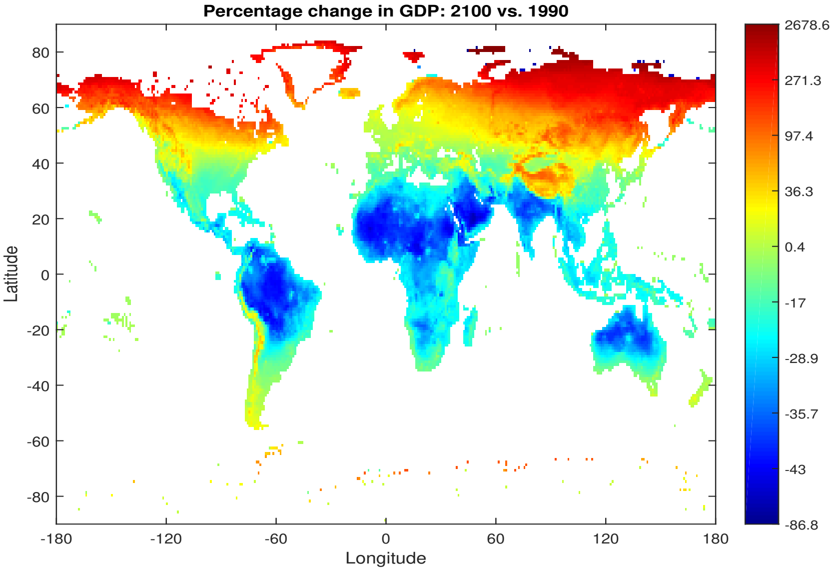
Percentage change in GDP: 2060 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

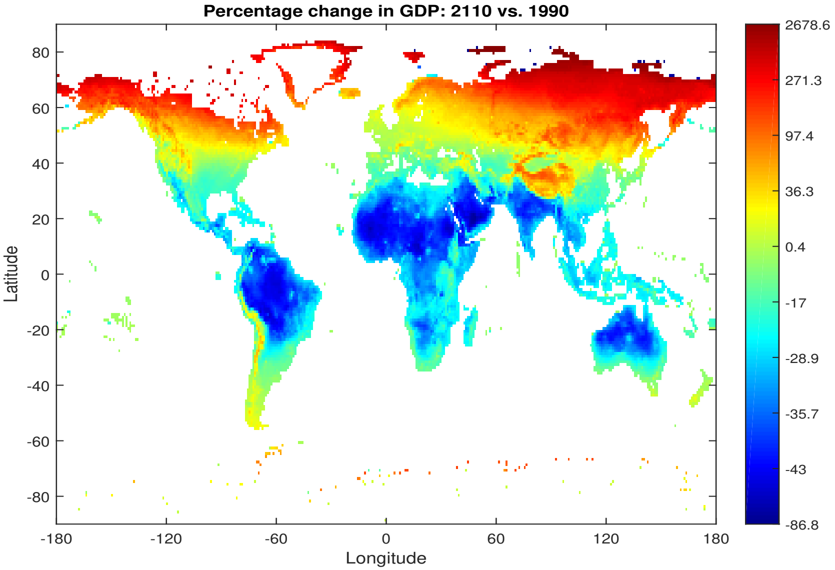

Percentage change in GDP: 2070 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

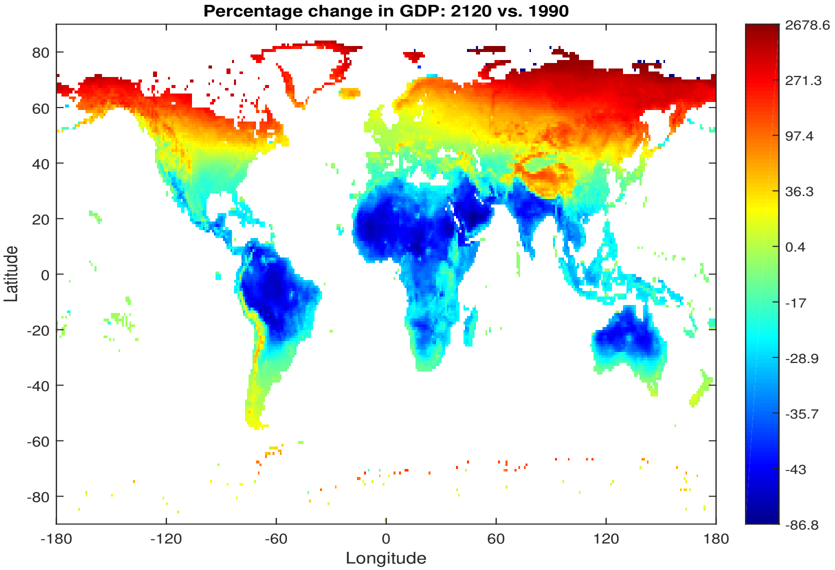

Percentage change in GDP: 2080 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



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
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
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271.3
97.4
36.3
0.4
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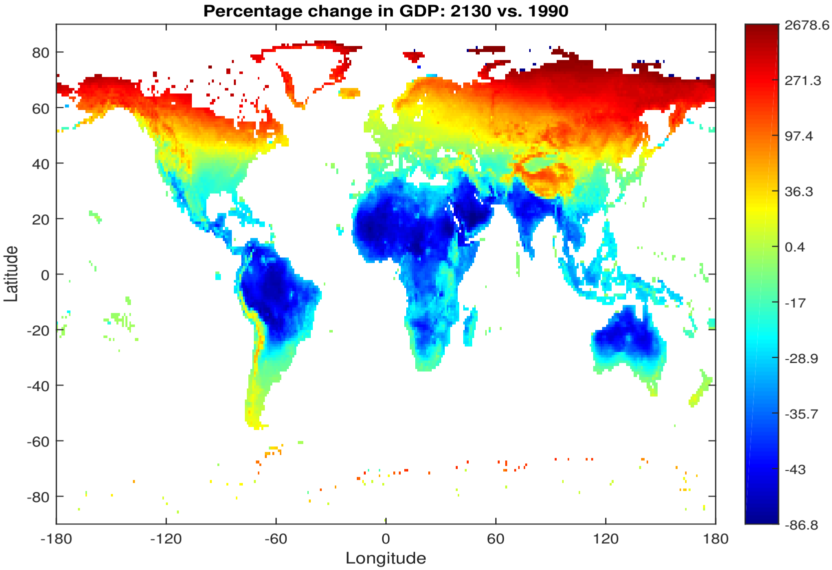
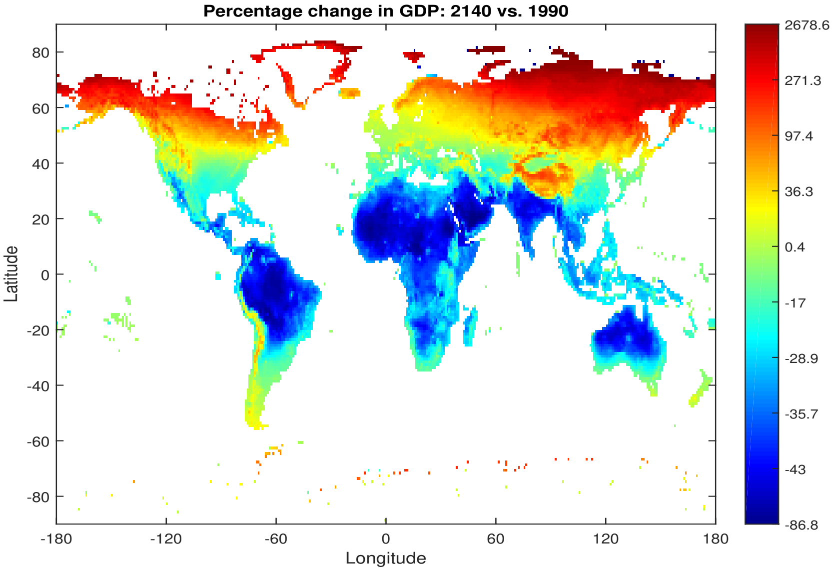
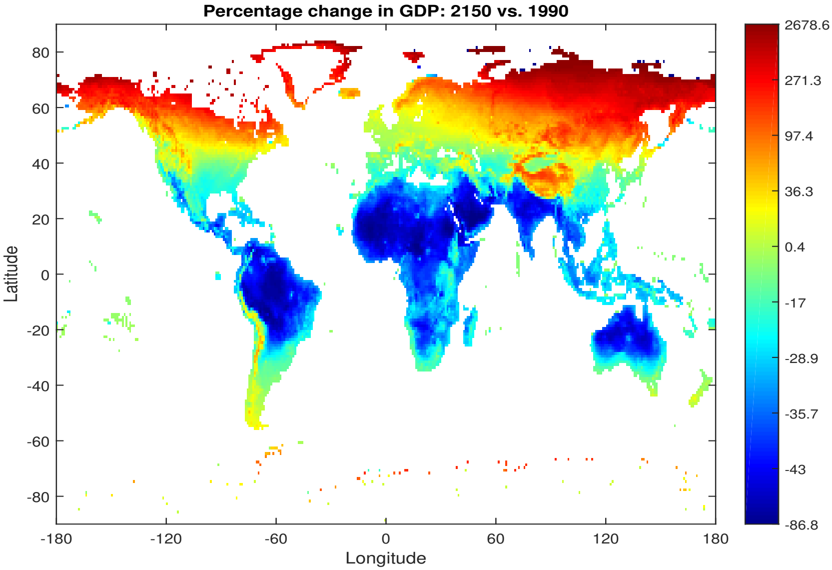
-28.9
-35.7
-43
-86.8

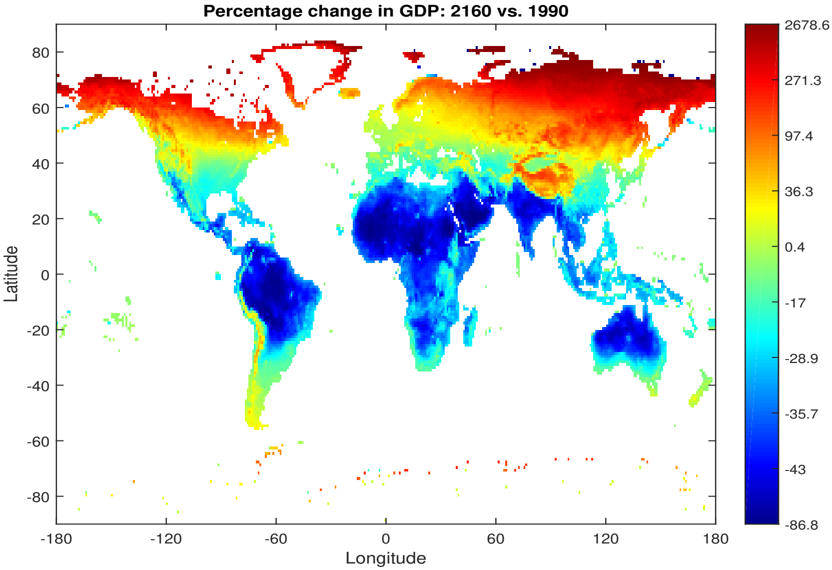


Percentage change in GDP: 2130 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

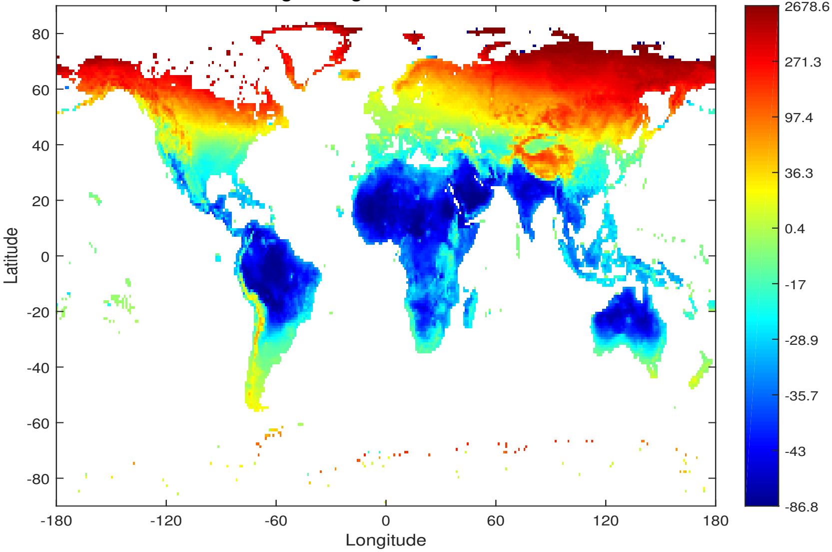

Percentage change in GDP: 2140 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8

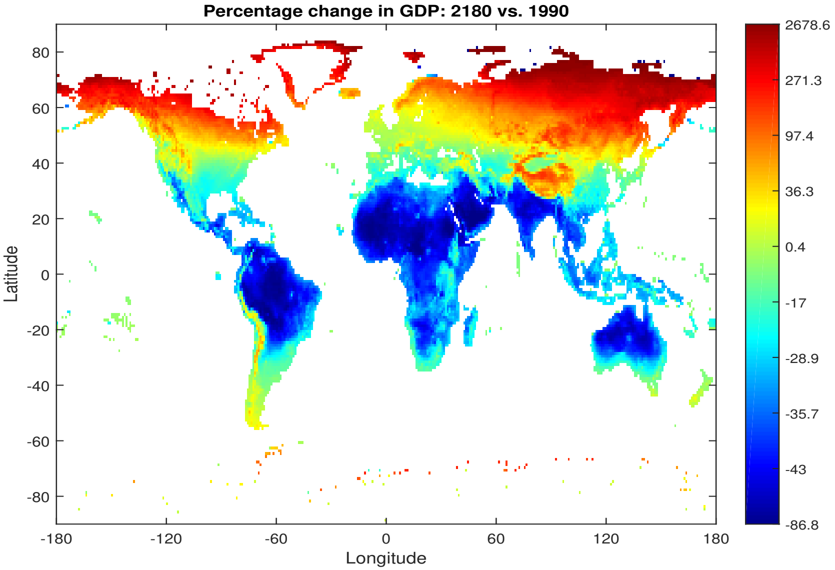


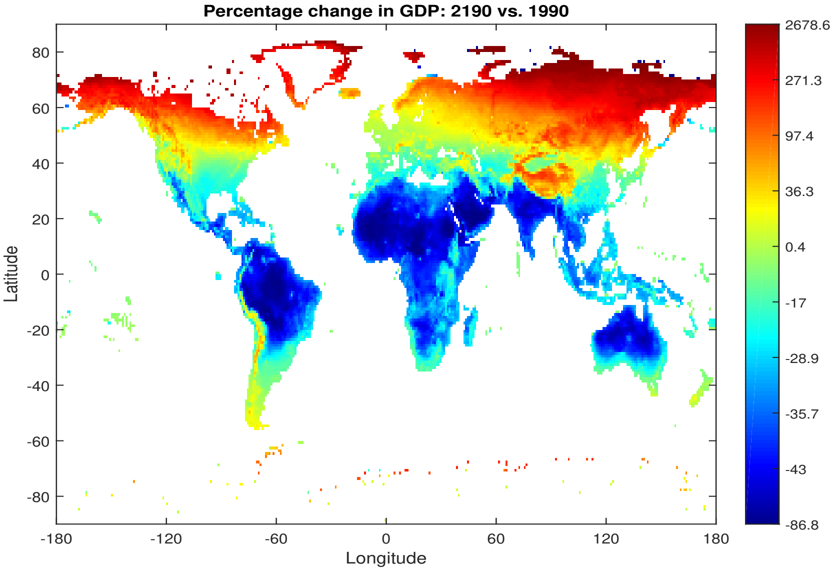
Percentage change in GDP: 2150 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8


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

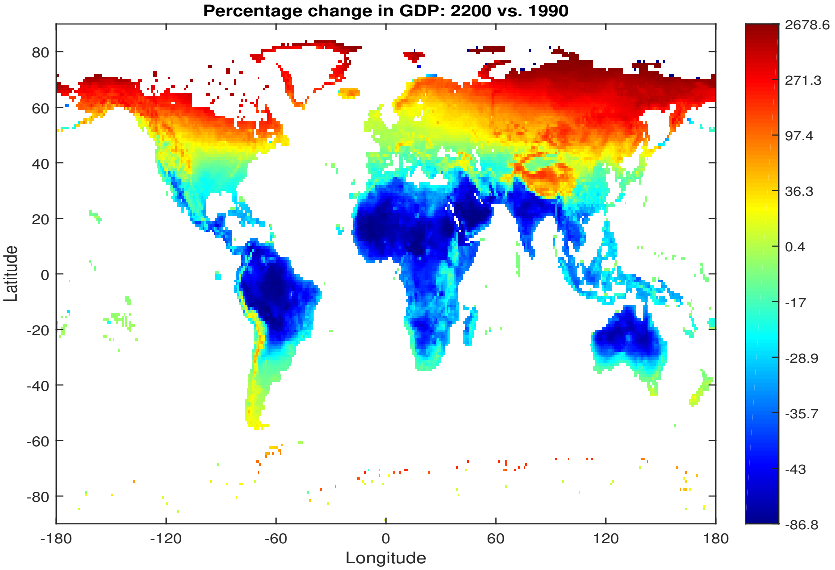
## Percentage change in GDP: 2170 vs. 1990

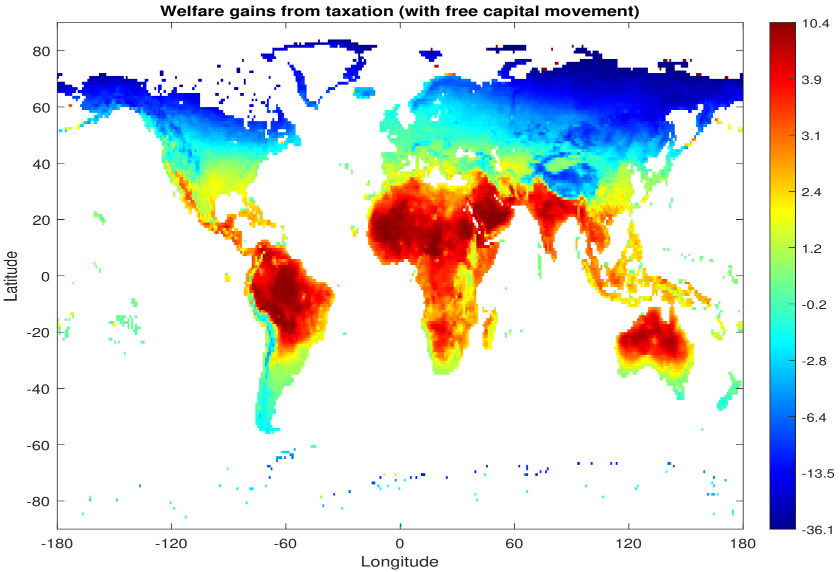



Percentage change in GDP: 2180 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8



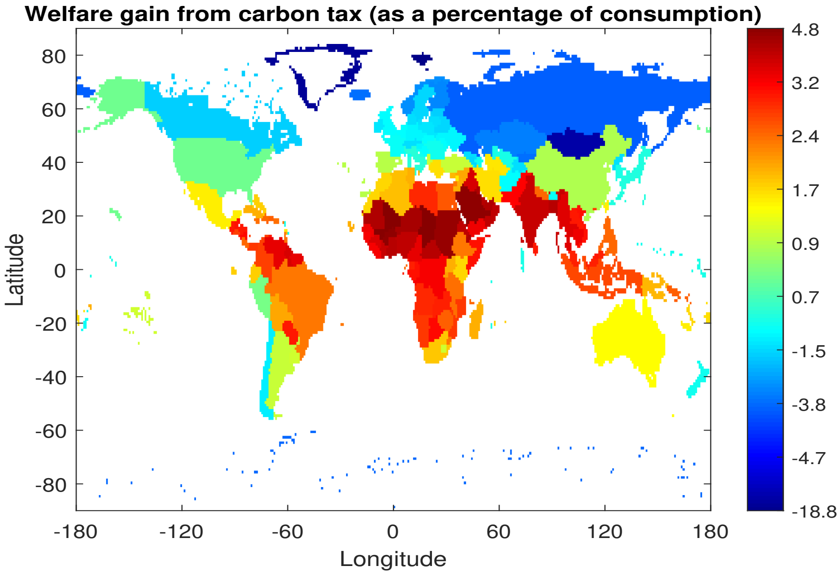
Percentage change in GDP: 2190 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2678.6
271.3
97.4
36.3
0.4
-17
-28.9
-35.7
-43
-86.8


Percentage change in GDP: 2200 vs. 1990
Latitude
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

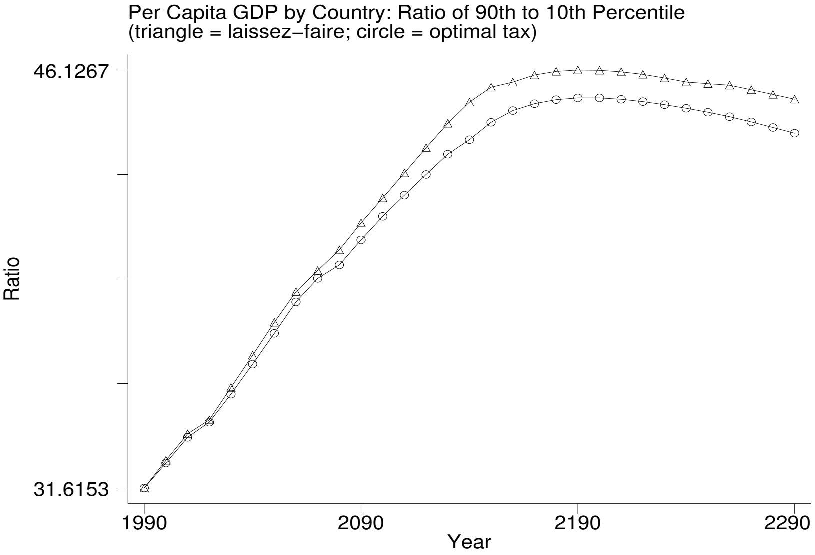

Welfare gains from taxation (with free capital movement)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
10.4
3.9
3.1
2.4
1.2
-0.2
-2.8
-6.4
-13.5
-36.1

# 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: $-2.1\%$ (of consumption).
- Average gain weighted by regional GDP: 0.6%.
- Average gain weighted by regional population: 1.7%.
- World consumption path: gain of 0.4%.



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


Per Capita GDP by Country: Ratio of 90th to 10th Percentile
(triangle = laissez–faire; circle = optimal tax)
46.1267
31.6153
Ratio
1990
2090
2190
2290
Year

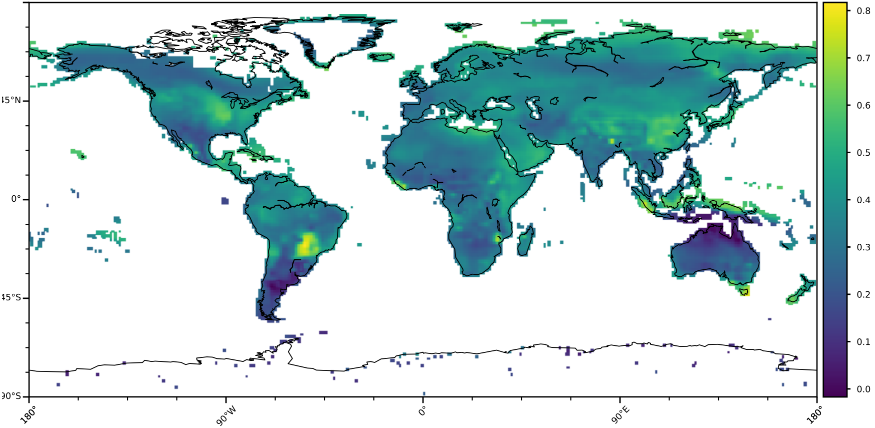
# Takeaways

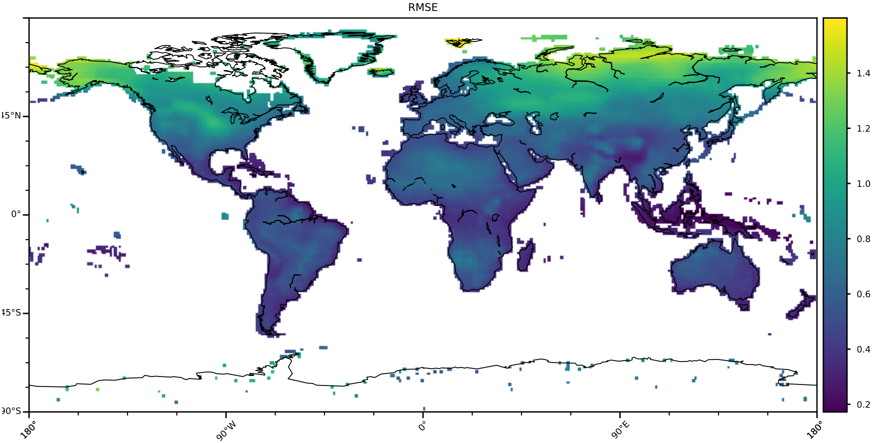
- Results from our model: climate change is about relative effects much more than about average effects!
- In particular, large disagreements about climate policy (so large transfer payments needed to compensate the losers).
- Methodological insight: we thought the market structure (because it admits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

# Building on the platform

- Damages "too local"—no common aggregate damages such as sea-level rise or effects of climate change on ecosystems.
- More heterogeneity in regional damages: rural vs. urban and/or manufacturing vs. agriculture, with separate *U*-shapes.
- More margins of spatial adaptation, such as migration, retaining forward-looking consumption-savings decisions.
- Weather as well as climate: "two-way coupling" of the economic model with NorESM2 (joint with Jenny Bjordal and Trude Storelvmo).
  - No need to simplify geophysics.
  - Gain access to a rich set of "stochastic" weather variables (extreme temperatures, precipitation, wind) on which damages can depend.
  - Use model to study institutions for sharing climate-related risks.

AR1




RMSE
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
1.4
1.2
1.0
0.8
0.6
0.4
0.2

# Computing equilibrium, with weather

- Agents form expectations of future weather using an approximation of dynamics in NorESM2.
- Iterate backwards to obtain agents' decision rules based on approximate expectations.
- Simulate forwards using decision rules and *actual* dynamics of NorESM2.
- Find a fixed point in parameters describing the approximate expectations.
- Methodological challenges:
  - Nonlinear chaotic dynamics vs. stochastic shocks.
  - Timing: economic model runs at annual time step, NorESM2 at half-hourly time step.
- Stay tuned!