Climate Change Around the World

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

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

Climate change is going to affect different nations to different degrees and in different ways. Unfashionable though these terms may be, there will be "winners" as well as "losers."

CAROLYN PUMPHREY, Researcher, Strategic Studies Institute, U.S. Army War College, *Global Climate Change: National Security Implications*, 2008

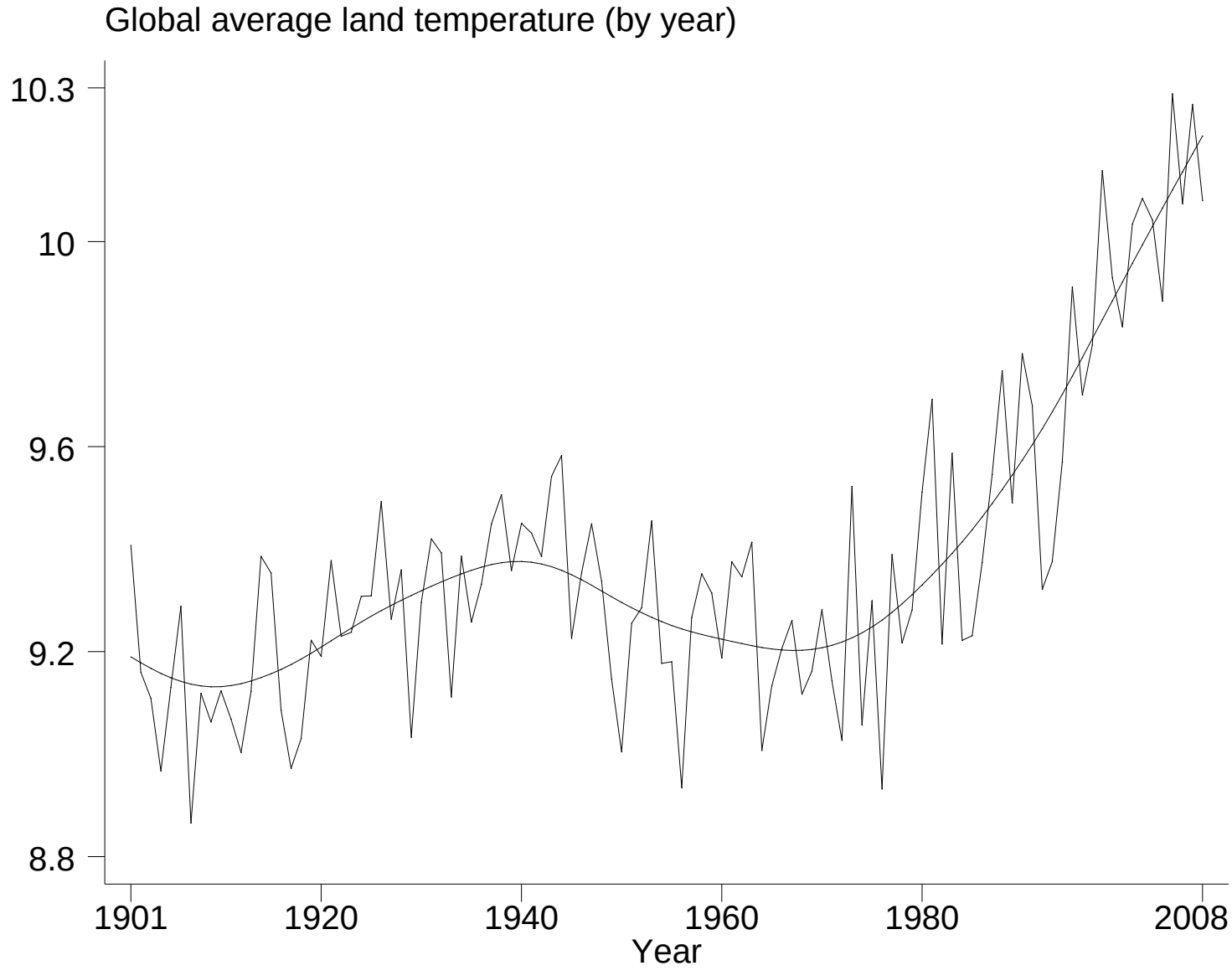
You may agree with — or be provoked by — these statements about climate change.

The project

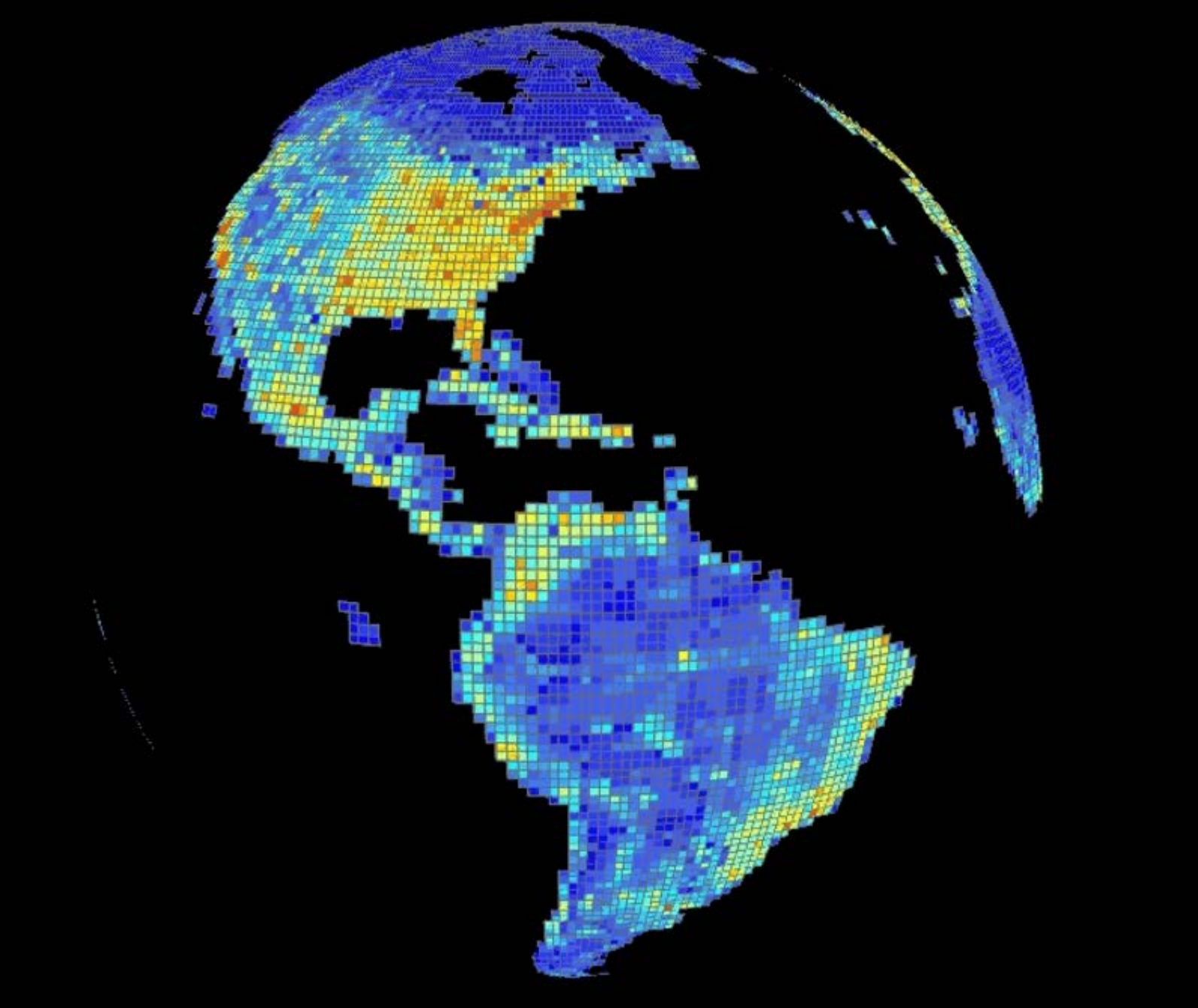
- Construct global model of economy-climate interactions featuring a high degree of geographic resolution ($1^\circ \times 1^\circ$ regions).
- Use the model as a laboratory to quantify the distributional effects of climate change and climate policy.
- If a set of regions imposes a carbon tax (or a quantity restriction on emissions), how does the path of global emissions respond? Which regions gain and which lose, and by how much?

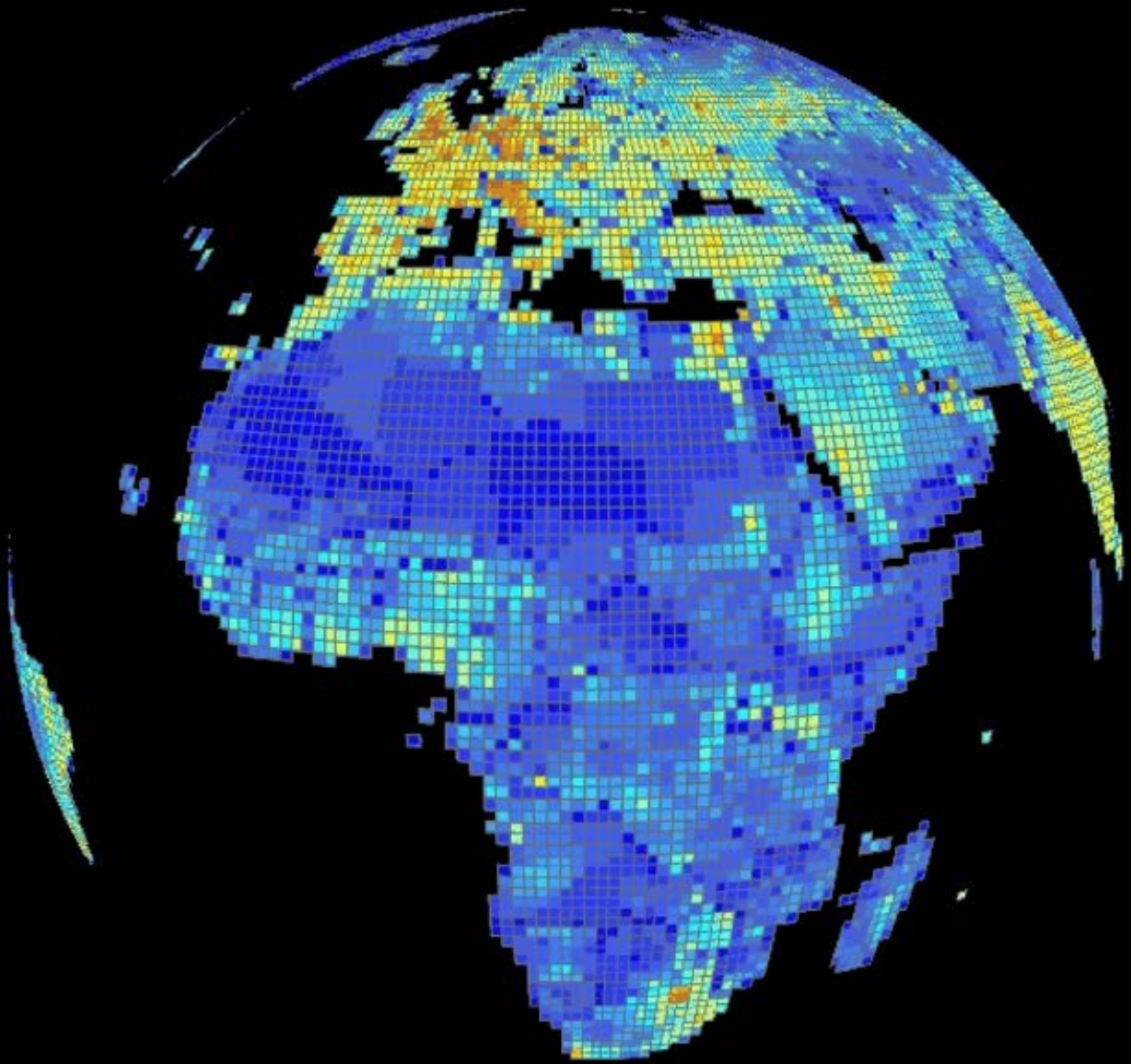
The data

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

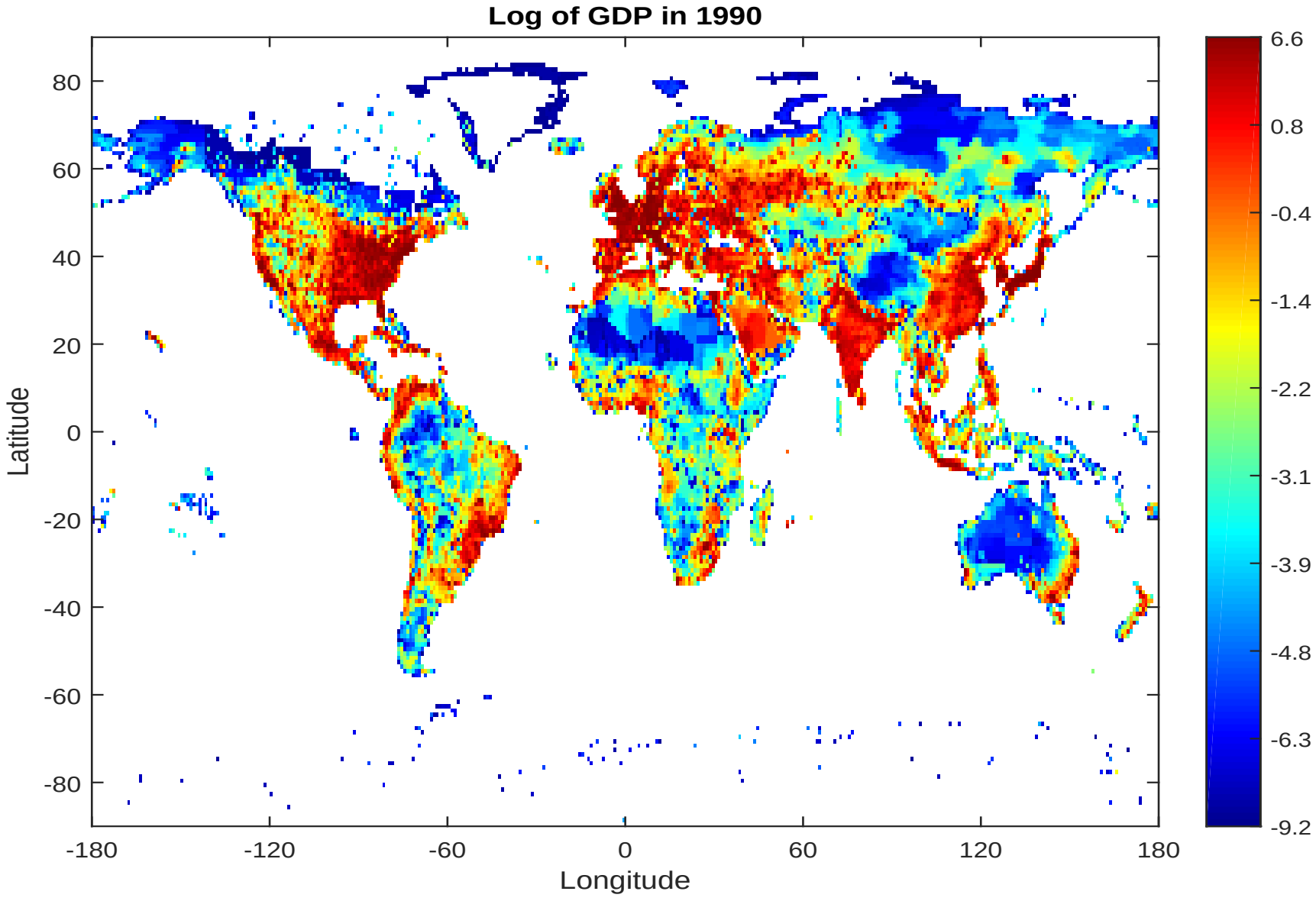

Global average land temperature (by year)
10.3
10
9.6
9.2
8.8
1901
1920
1940
1960
1980
2008
Year

Nordhaus's G-Econ globe with output by regions

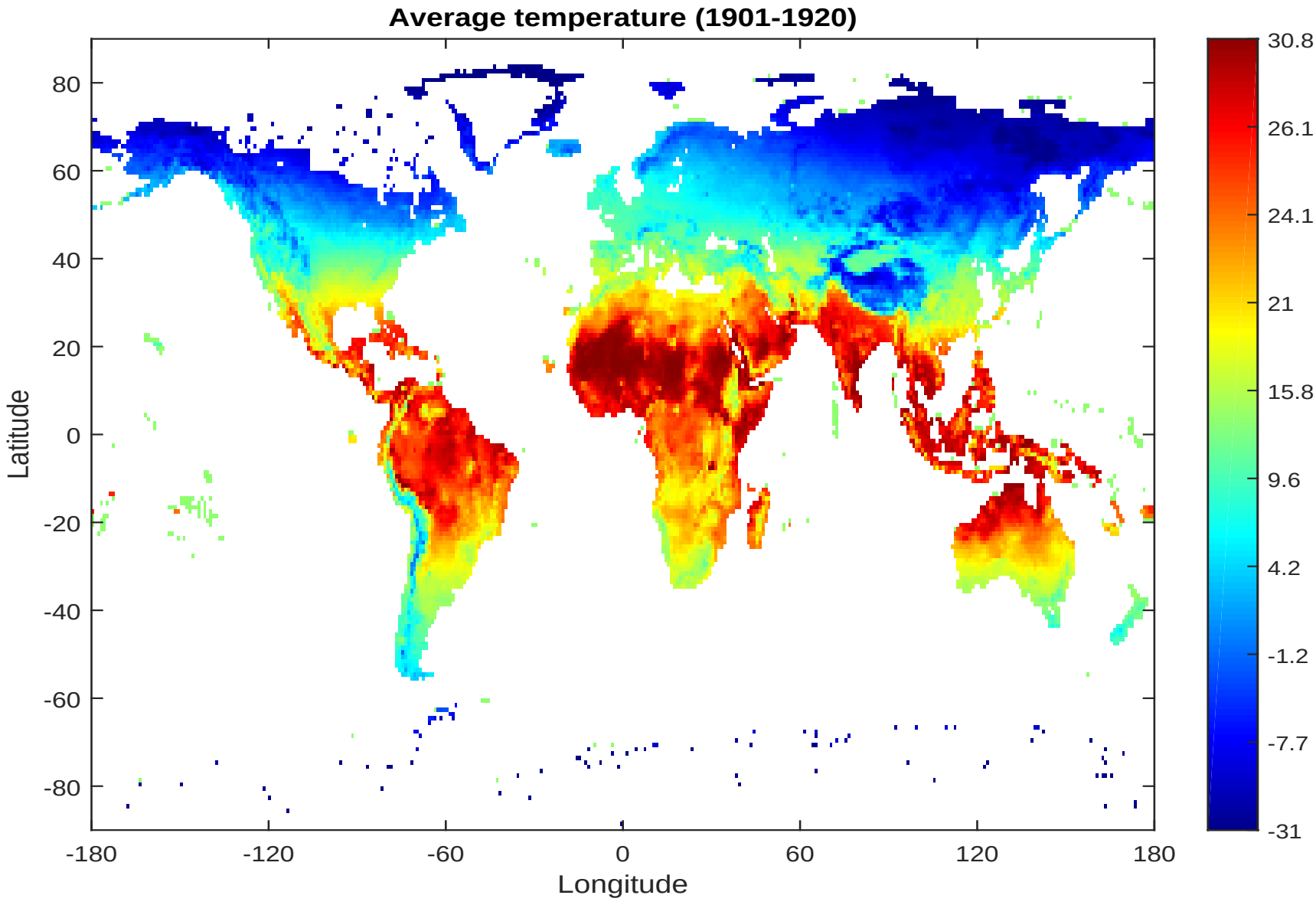




same data on our map


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
0.8
-0.4
-1.4
-2.2
-3.1
-3.9
-4.8
-6.3
-9.2

temperature map of the world


Average temperature (1901-1920)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
30.8
26.1
24.1
21
15.8
9.6
4.2
-1.2
-7.7
-31

Natural-science background I: the climate

- What determines the earth's surface temperature, T_s?
- Energy balance: "energy in" = "energy out".
- With no atmosphere (treat the Earth as a "blackbody"):

$$\pi R^2 \times (1 - \alpha) I = 4\pi R^2 \times \sigma T_s^4,$$

  where I is the solar flux intensity, α is Earth's albedo, R is the Earth's radius, and σ is the Stefan-Boltzmann constant.
- T_s is the "price" that equilibrates the two energy flows.
- Plug in the constants and solve for T_s: Earth too cold by 30 degrees.

Natural-science background I: the climate (cont'd)

- The (single) layer model with an opaque atmosphere.
- Short-wave solar radiation penetrates the atmosphere, but long-wave radiation emitted by the Earth's surface does not.
- *Energy balance for the atmosphere*:
  energy radiated by surface $=$
  $2 \times$ energy radiated by atmosphere (depends on T_a^4).
- *Energy balance for the surface*:
  incoming solar energy $+$ energy radiated by atmosphere $=$
  energy radiated by surface (depends on T_s^4).
- Solve the two equations for T_s and T_a: Earth's surface too warm by 18 degrees.

Natural-science background I: the climate (cont'd)

- The atmosphere is semi-opaque: only part of it consists of greenhouse gases which trap long-wave radiation.
- "Forcing", F, from CO_2 in the atmosphere (relative to pre-industrial) is:

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

where $S = 840\text{GtC}$ 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 feedbacks not present in the (simple) layer model. $\lambda \approx 3 \pm 1.5$ 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: 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!
- 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.

Some relevant background from past work

- Model development:
  - a number of our earlier papers on this can be viewed as "pilot studies" for present work
  - in particular, Golosov, Hassler, K, and Tsyvinski (GHKT; *Econometrica*, 2014) develops simple one-sector DSGE setting.
- Build present structure on earlier insights: one-region version of present model very close to GHKT.

Overview for remainder of talk

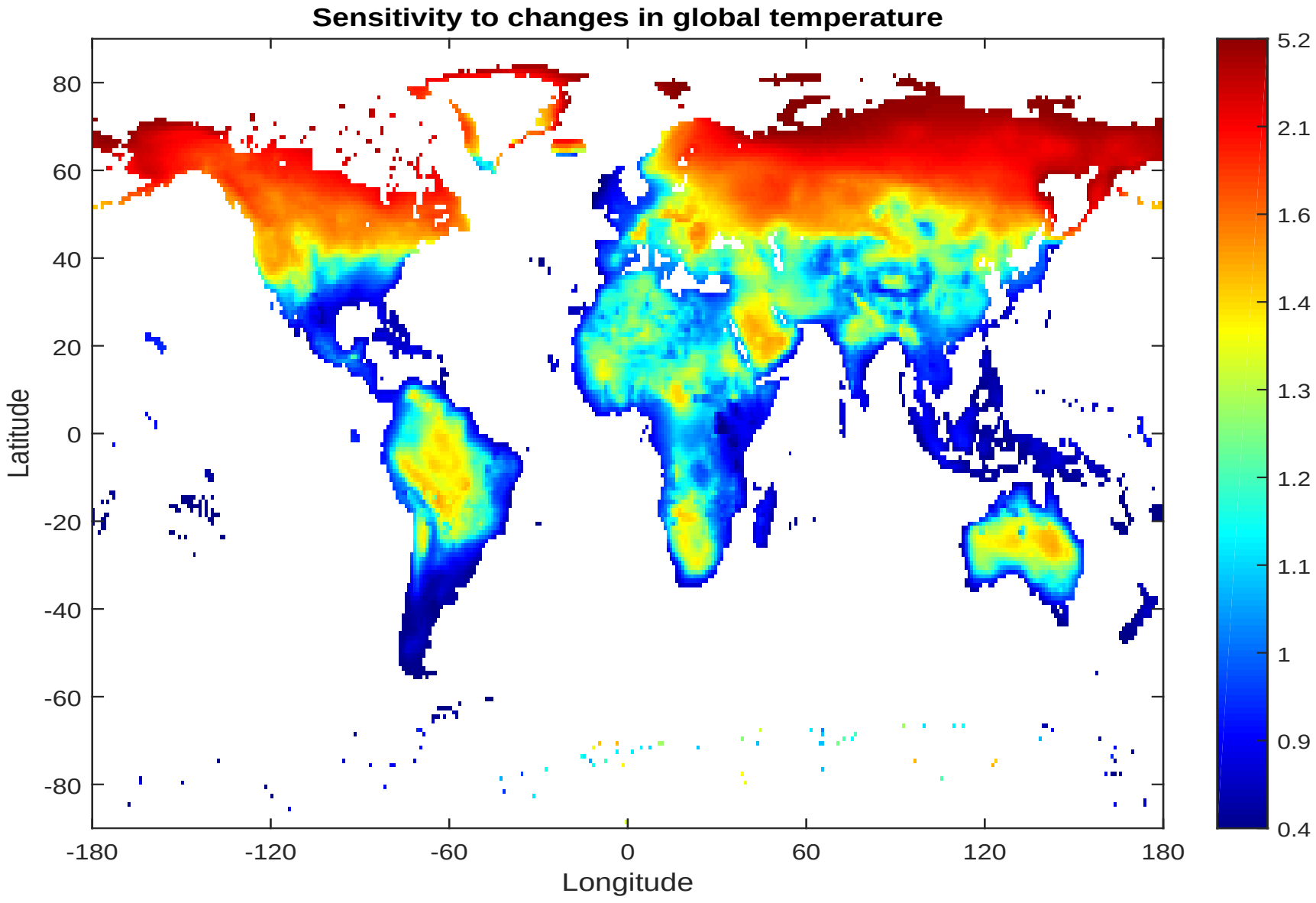
1. our climate modeling
2. our damage specification
3. economic model
4. calibration, computation
5. results
6. conclusions, future

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 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 coefficent (linear structure; standard).
- With help of climate scientists, use runs of (highly) complex climate models into the future to estimate sensitivities.

global map with estimated sensitivities: how much temperature goes up everywhere if T rises by one degree

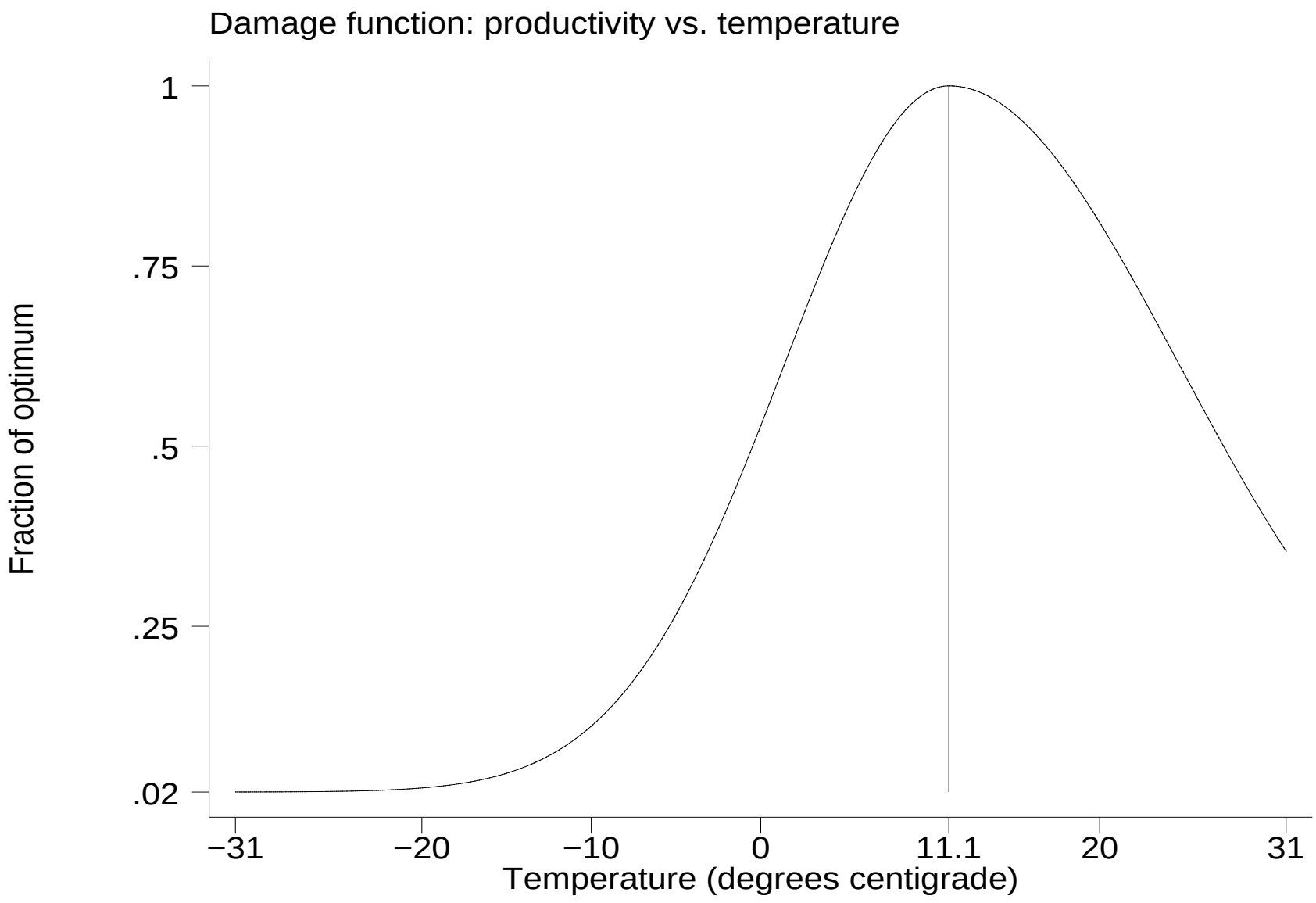

Sensitivity to changes in global temperature
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
5.2
2.1
1.6
1.4
1.3
1.2
1.1
1
0.9
0.4

Our damage specification

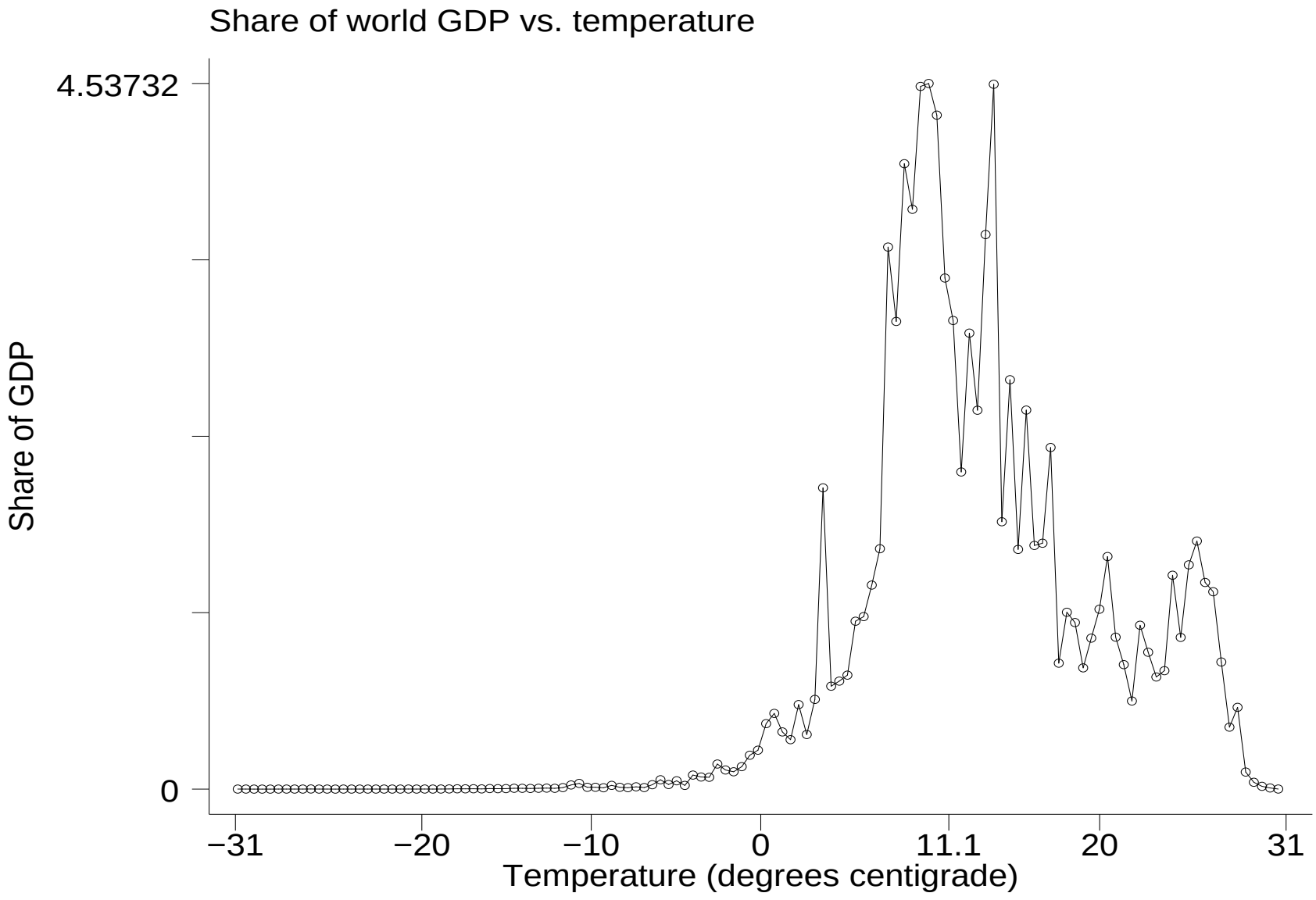
What are the damages in region ℓ as a result of global warming?

- Damage measurements: overall, weakest part of quantitative climate-economy models, especially for regional damages.
- Our approach: formulate a damage function *D of local temperature* that is: common across all ℓ; like Nordhaus's, a TFP drag; and U-shaped, with three parameters. . .
- . . . which are estimated to match, when aggregated across all ℓ, the global damages estimated by Nordhaus:
  - Nordhaus's formulation: convex
  - three points used: at 1 degree centigrade, 0.3% output drag; at 2.5, 1.8%; and at 5, 6.8%.
  - Nordhaus's global estimates not much different from those of others (IPCC has recent summary).
- Desmet and Rossi-Hansberg (2014) also use a common U-shape in a spatial application.

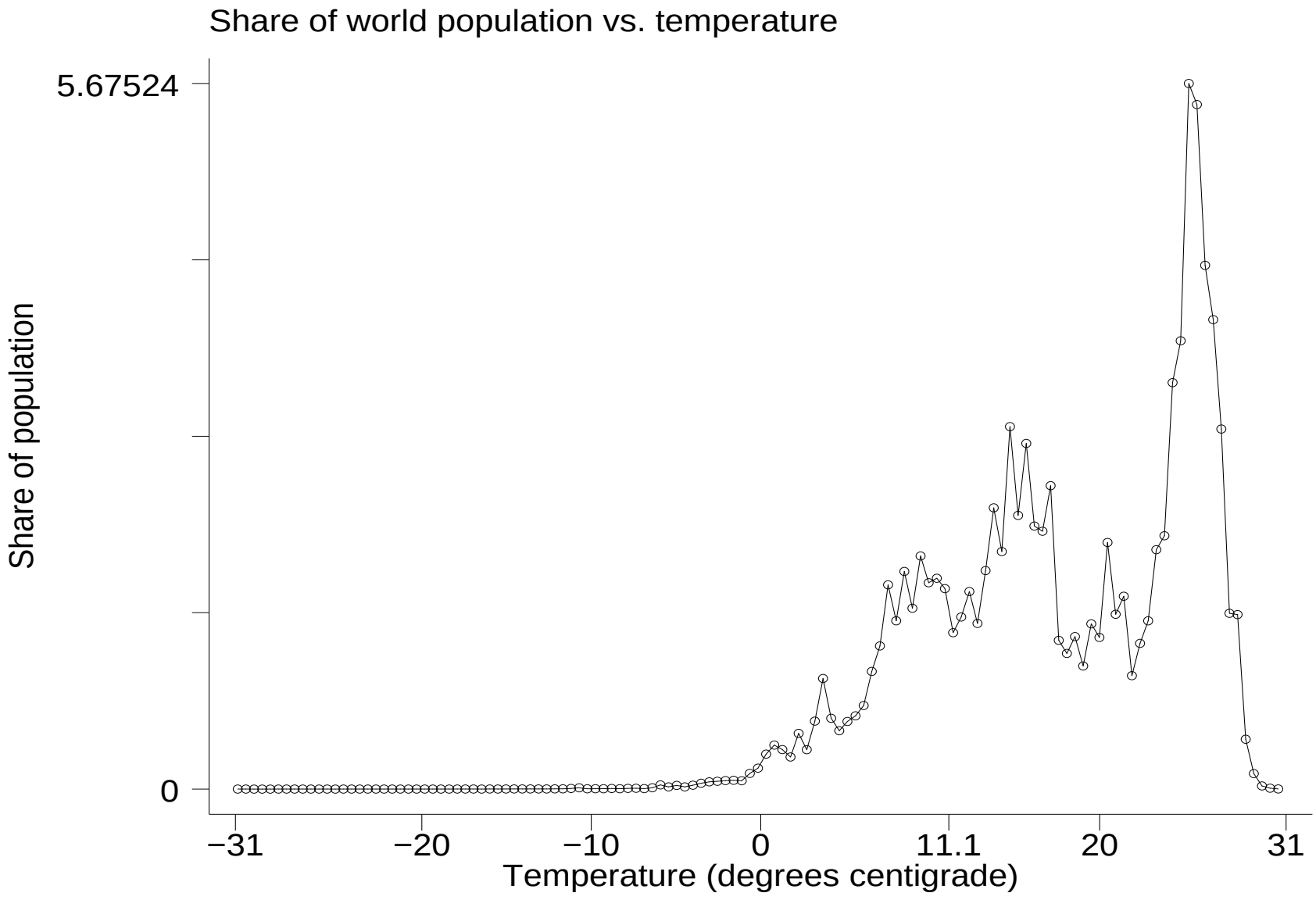
picture of 1 minus estimated U-shaped damage function, as function of local temperature


Damage function: productivity vs. temperature
Fraction of optimum
1
.75
.5
.25
.02
−31
−20
−10
0
11.1
20
31
Temperature (degrees centigrade)

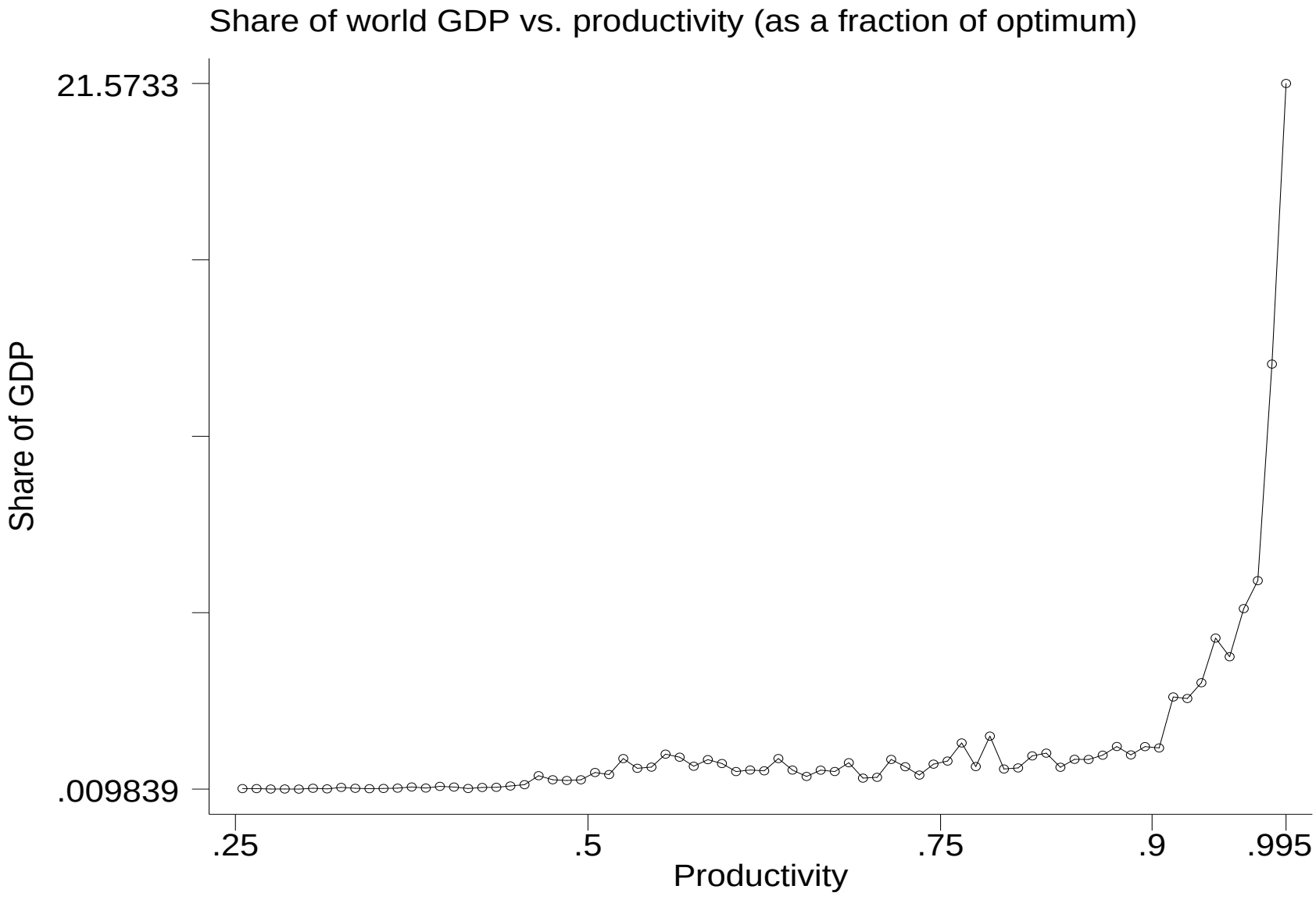
gdp distribution across temperatures (you see that most output is near the optimum)


Share of world GDP vs. temperature
4.53732
0
Share of GDP
−31
−20
−10
0
11.1
20
31
Temperature (degrees centigrade)

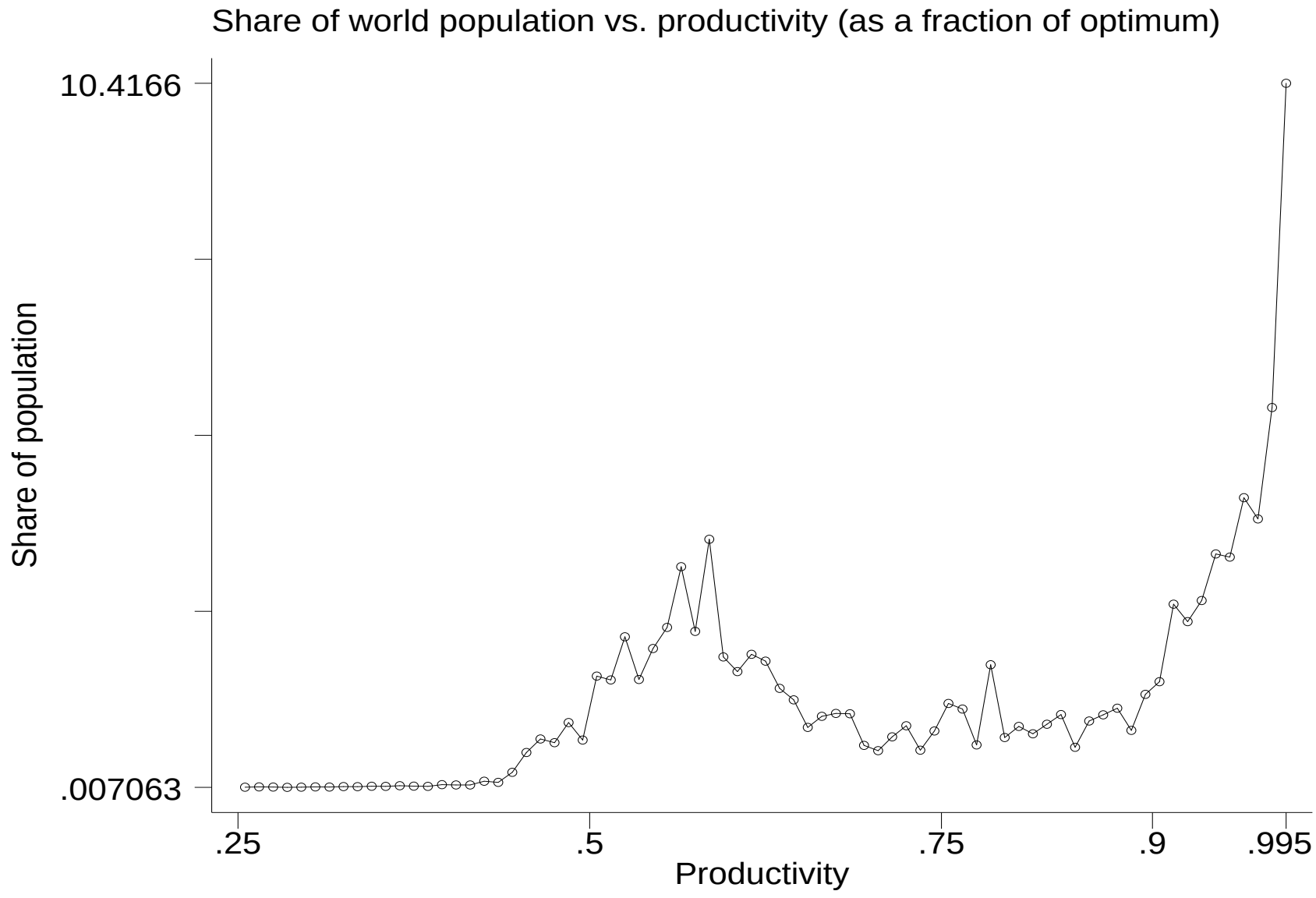
population distribution across temperatures (similar graph, but less concentrated near optimum)


Share of world population vs. temperature
5.67524
0
Share of population
−31
−20
−10
0
11.1
20
31
Temperature (degrees centigrade)

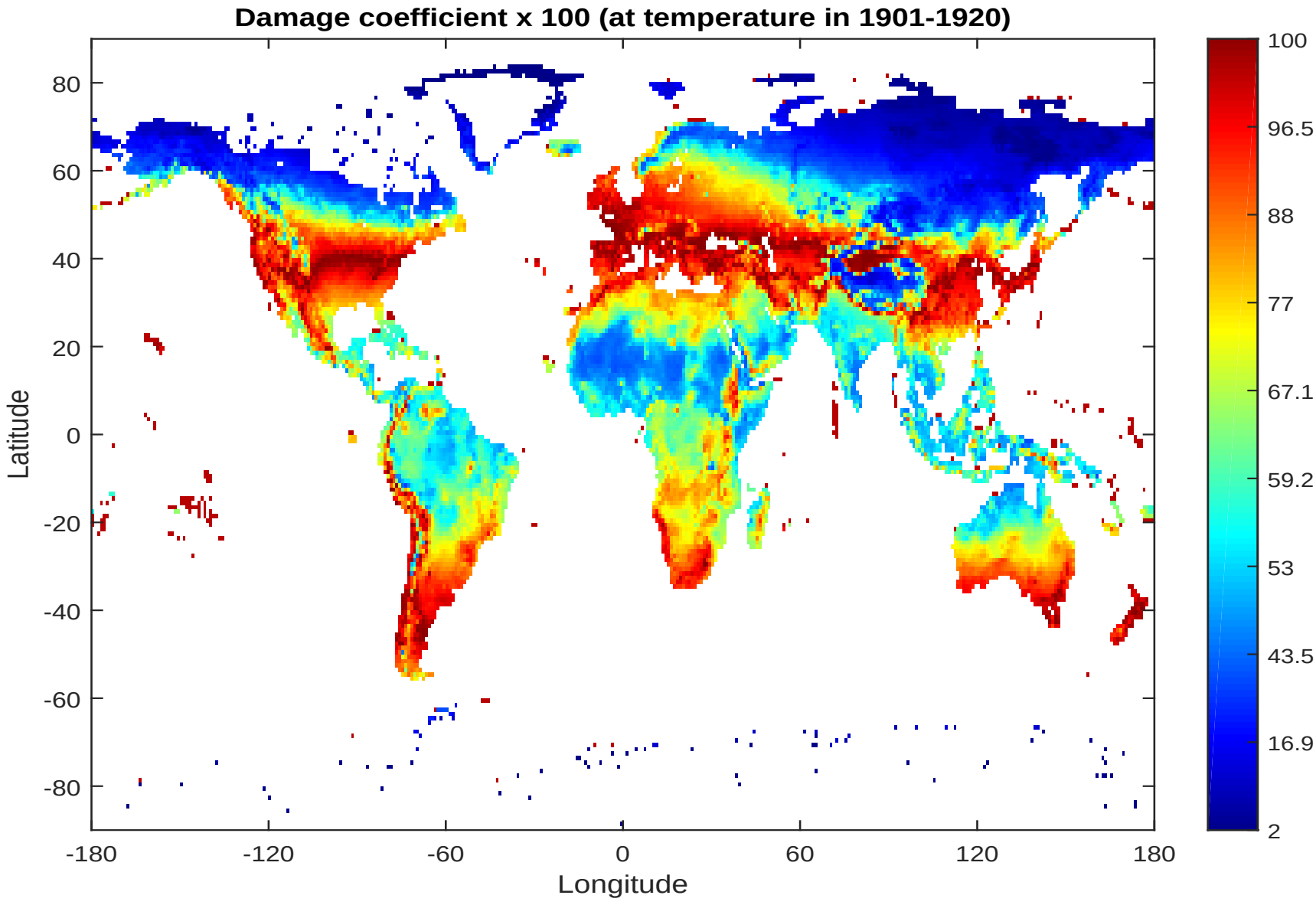
gdp distribution across 1 minus damages


Share of world GDP vs. productivity (as a fraction of optimum)
21.5733
.009839
Share of GDP
.25
.5
.75
.9
.995
Productivity

population distribution across 1 minus damages


Share of world population vs. productivity (as a fraction of optimum)
10.4166
.007063
Share of population
.25
.5
.75
.9
.995
Productivity

global map with 1 minus damage coefficients


Damage coefficient x 100 (at temperature in 1901-1920)
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
-180
-120
-60
0
60
120
180
100
96.5
88
77
67.1
59.2
53
43.5
16.9
2

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 tech.
- Market structure: two cases.
  - Autarky (regions only linked via emission externality).
  - Unrestricted borrowing/lending (world interest rate clears market).
- Summary: like Aiyagari (1994) and our previous work, 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

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

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

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

Calibration

- Annual time step, log utility, $\delta = 10\%$, $g = 1\%$, $\beta = 0.985$.
- Production function F is CES in $k^{\alpha}((1-D)AL)^{1-\alpha}$ and Be, with elasticity 0.1 (we do robustness) and $\alpha = 0.36$.
- Initial distribution of region-specific capital and level of productivity chosen to: (1) match regional GDP per capita in 1990 and; (2) equalize MPK across regions.
- Price of coal and B chosen to match: (1) total carbon emissions in 1990; and (2) energy share of 5% along a balanced growth path.
- Green energy replaces coal slowly (logistic).

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

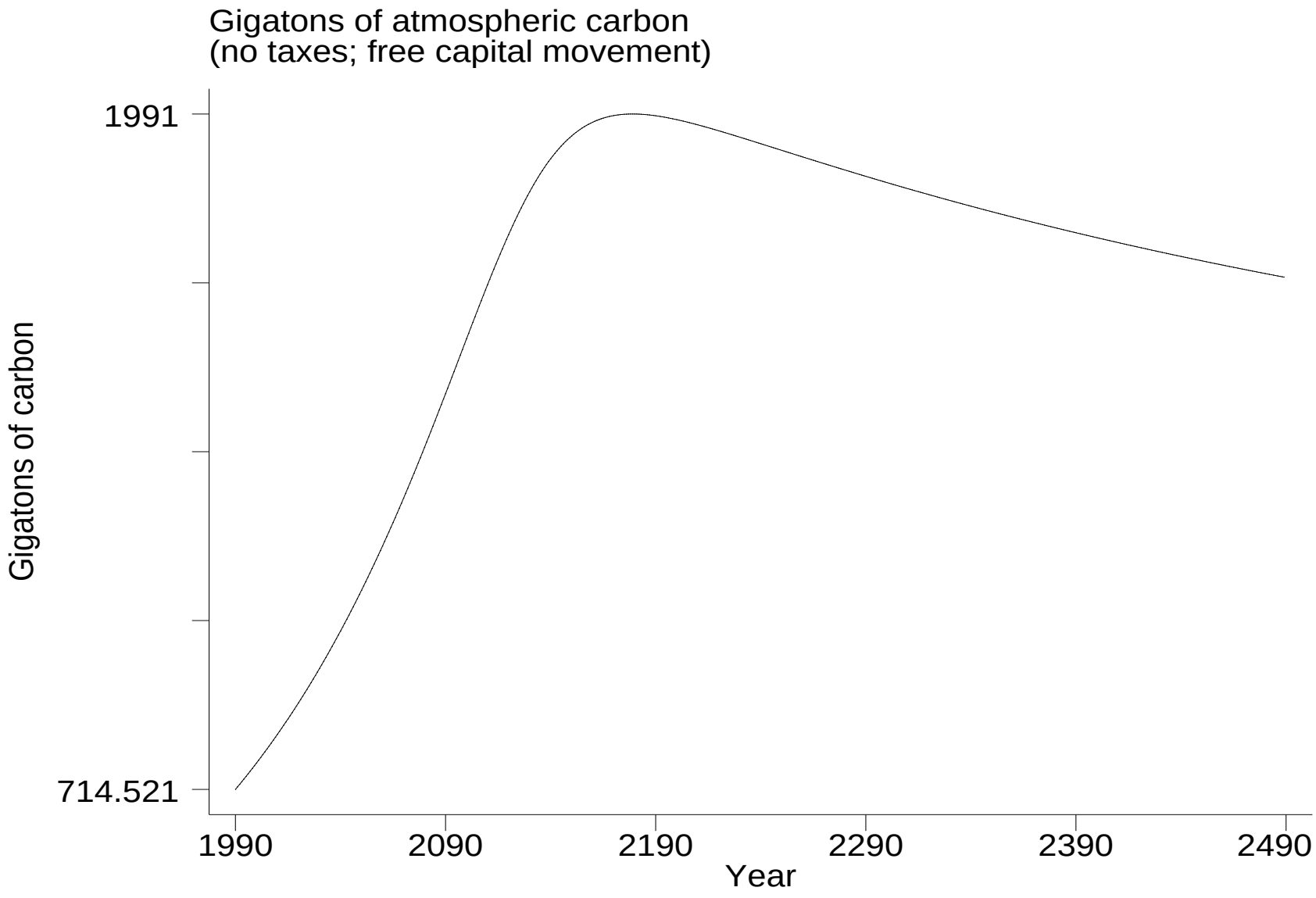
- Laissez-faire.
- Main policy experiment: all regions impose a modest common carbon tax, financed locally (no transfers implied).

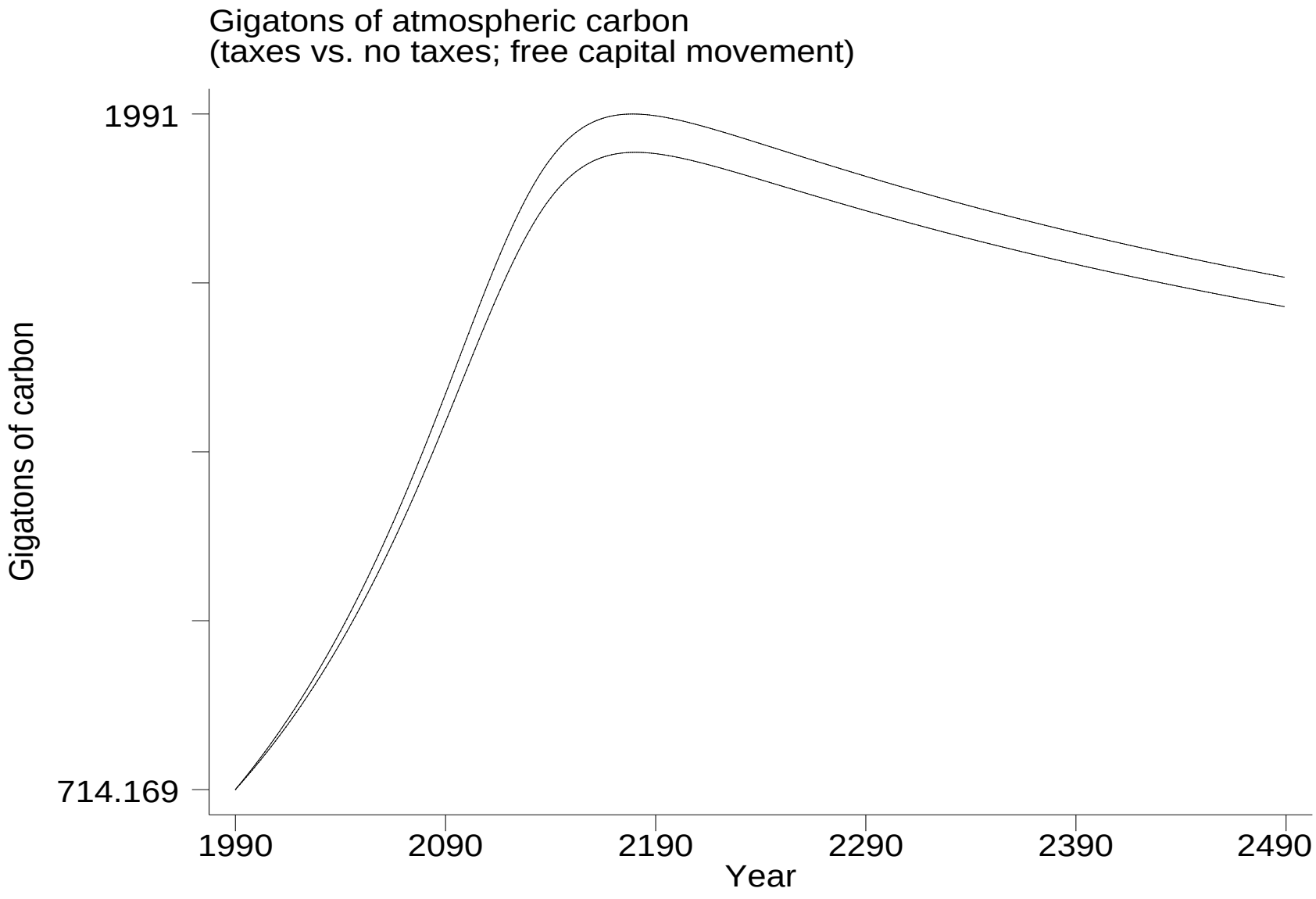
Throughout: focus on relative effects, not aggregates.

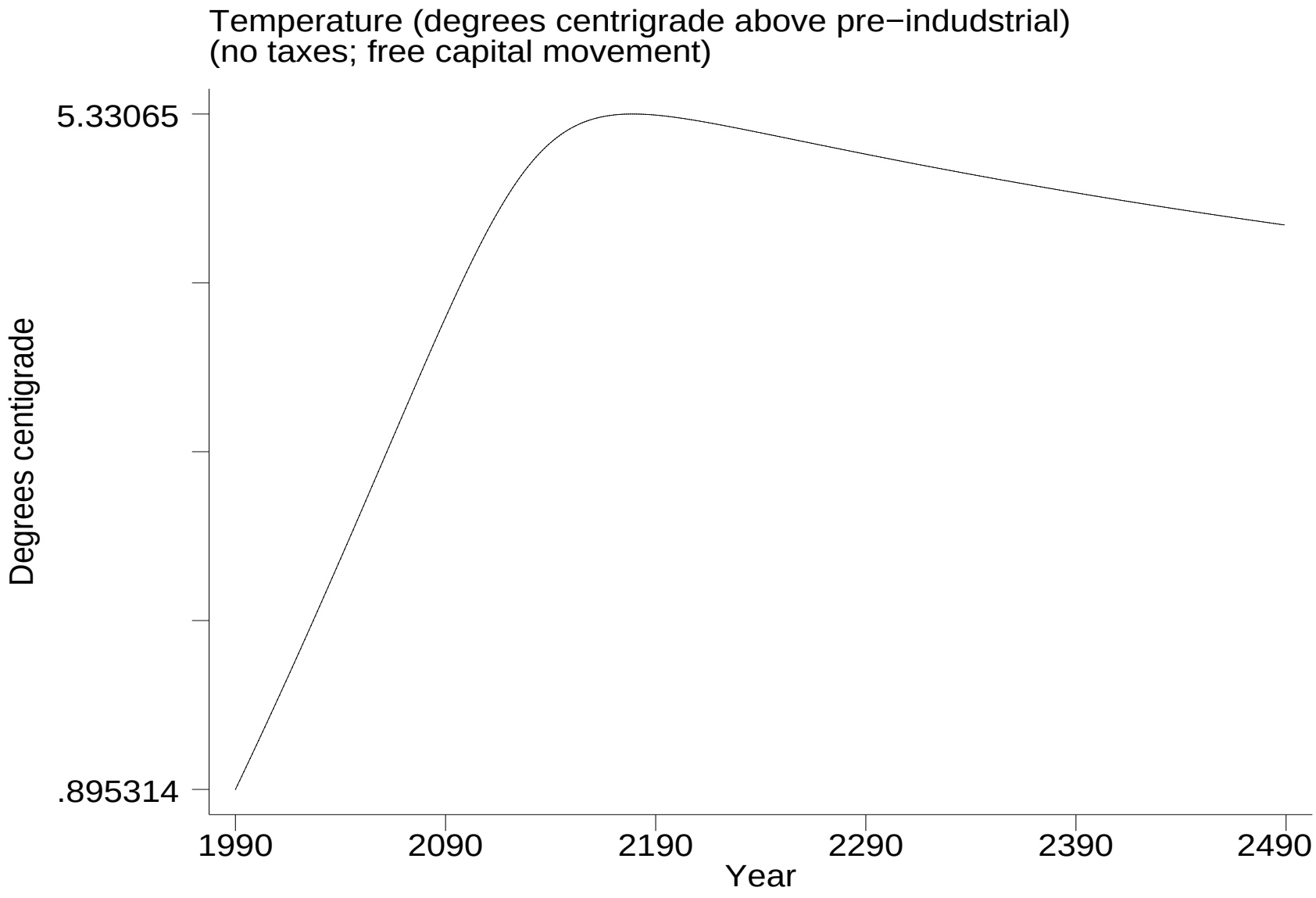
Main findings

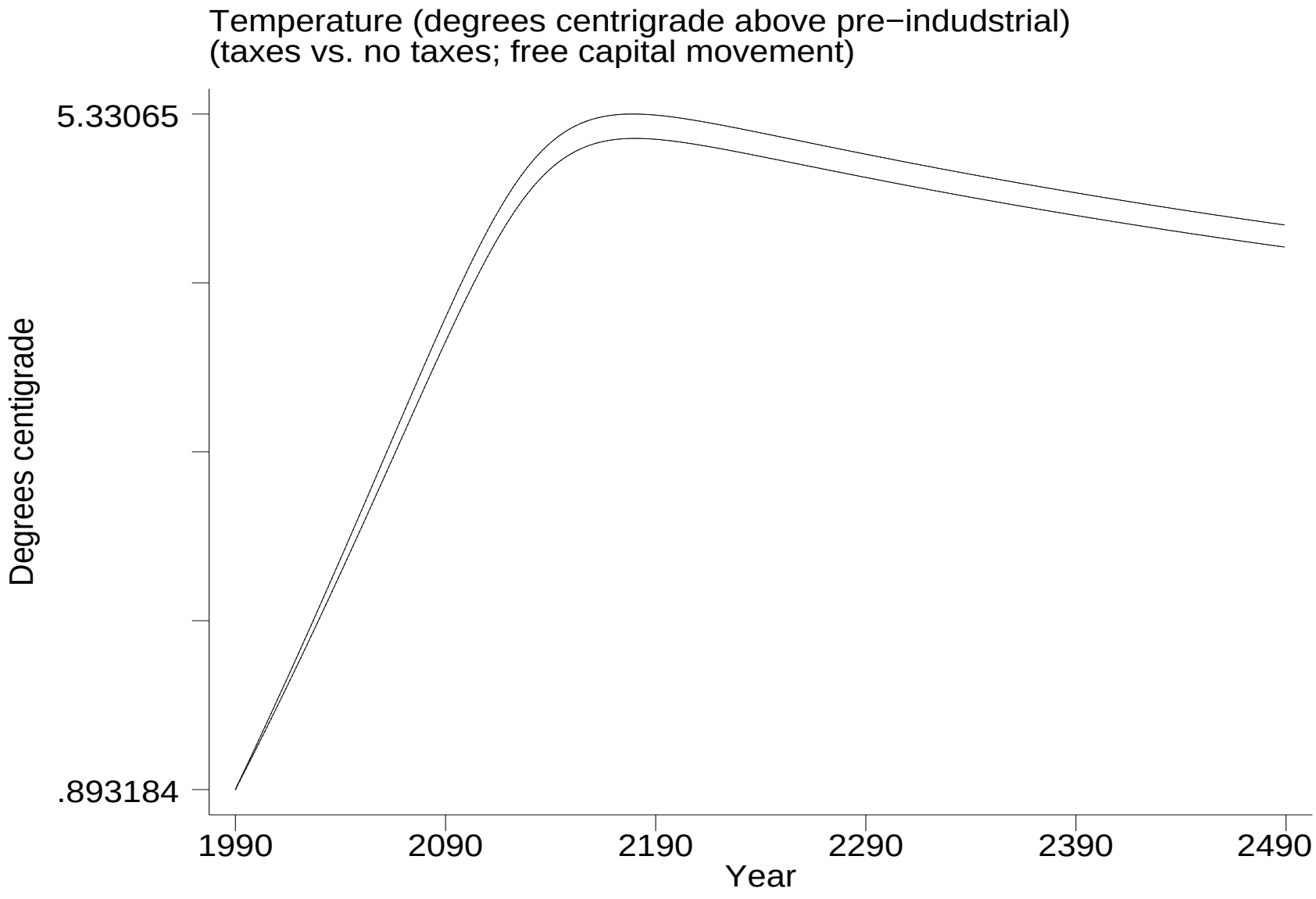
- Climate change affects regions *very* differently. Stakes big at regional level.
- Though a tax on carbon would affect welfare positively in some average sense, there is a large disparity of views across regions (55% of regions gain, while 45% lose).
- Findings almost identical for two extreme market structures (autarky and international capital markets).

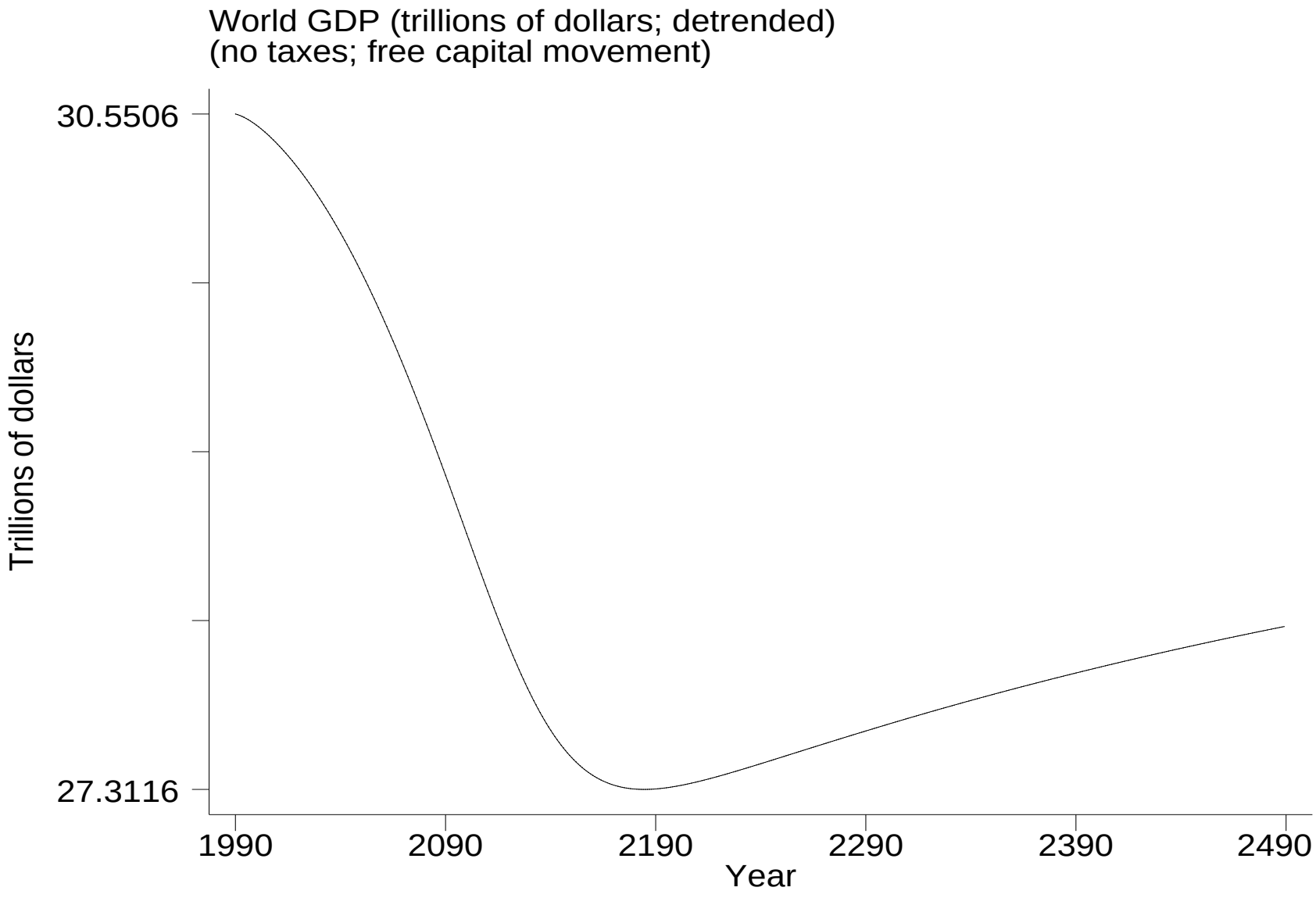
behavior of aggregates over time

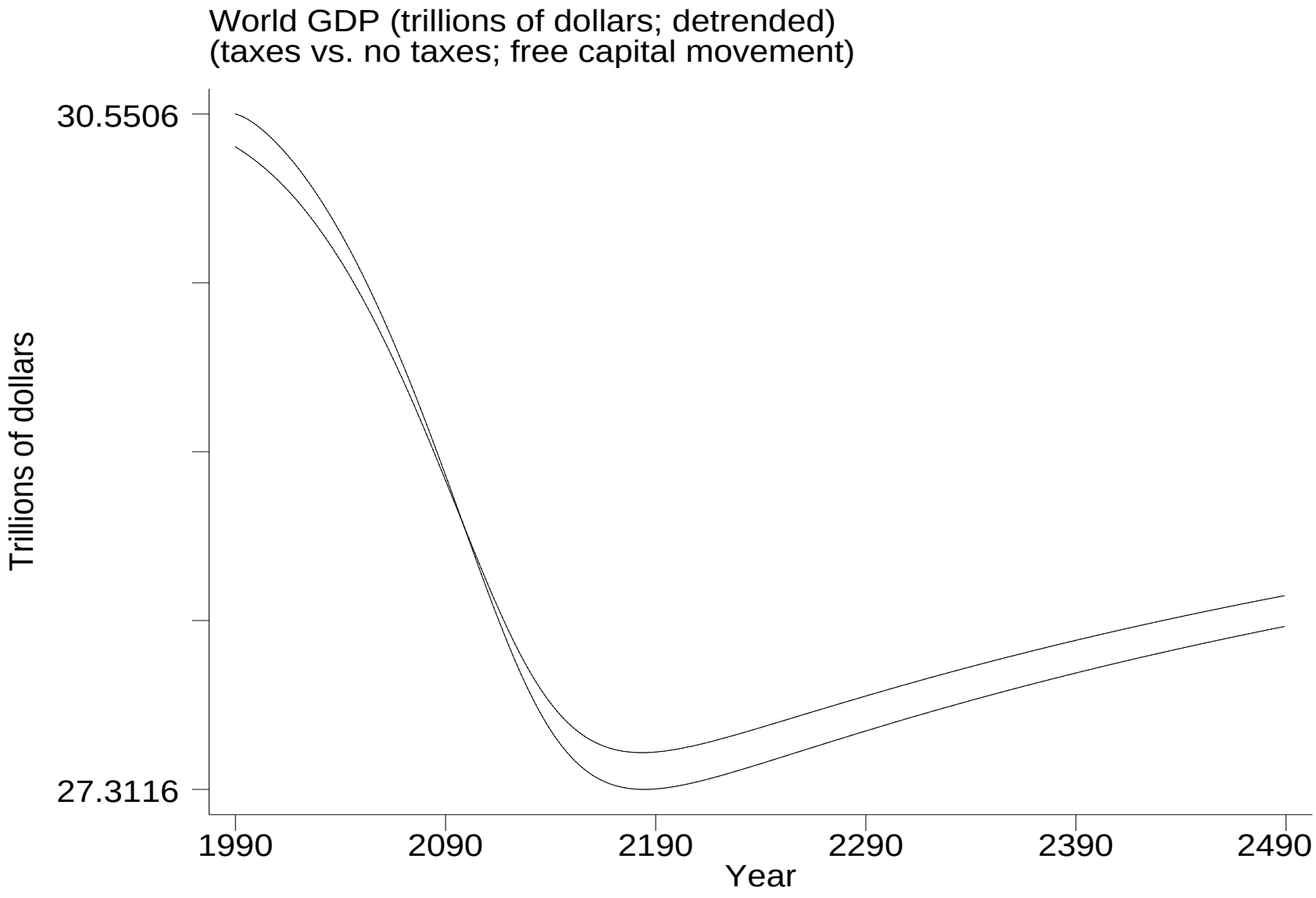

Gigatons of atmospheric carbon
(no taxes; free capital movement)
1991
714.521
Gigatons of carbon
1990
2090
2190
2290
2390
2490
Year

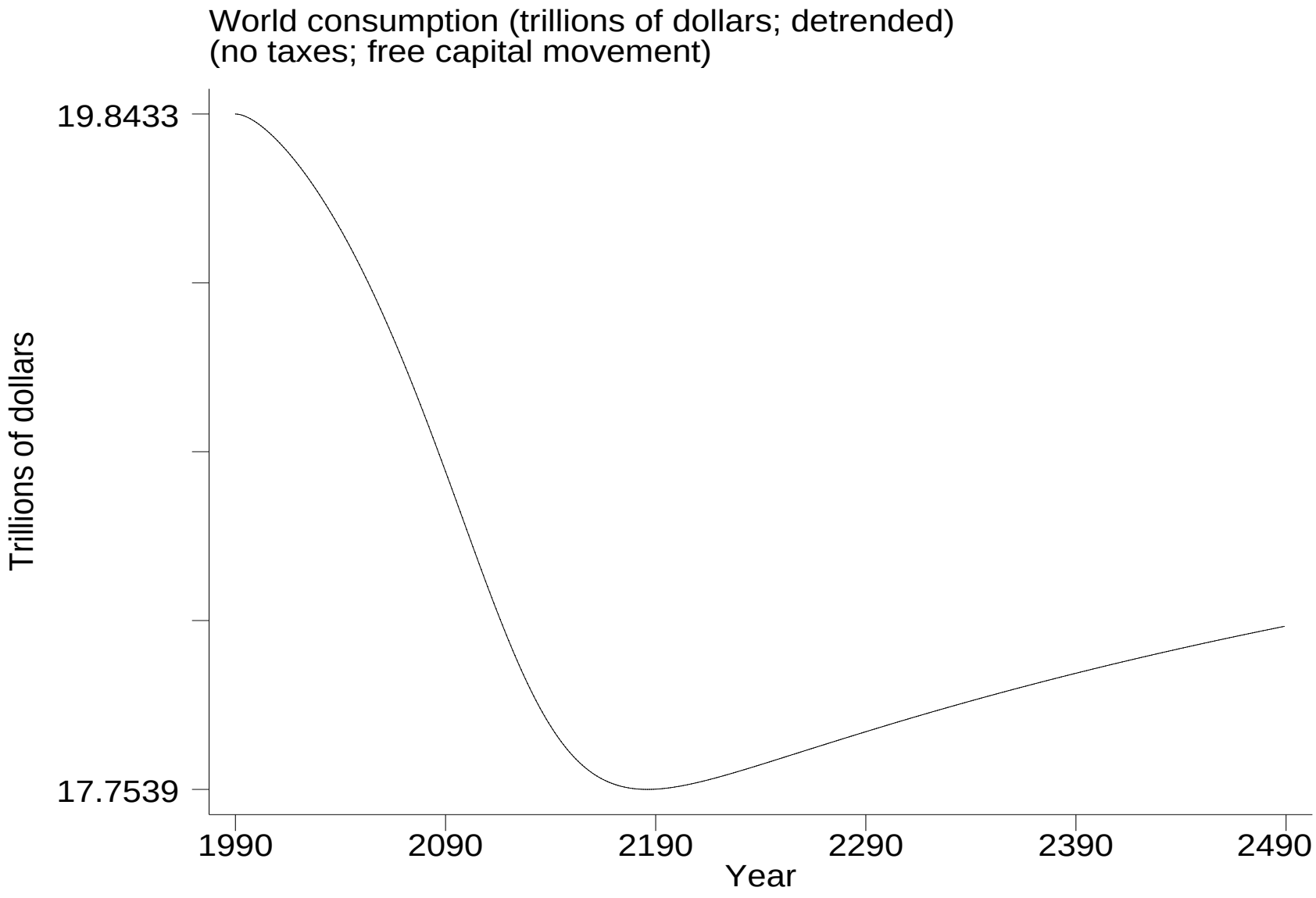

Gigatons of atmospheric carbon
(taxes vs. no taxes; free capital movement)
1991
714.169
Gigatons of carbon
1990
2090
2190
2290
2390
2490
Year

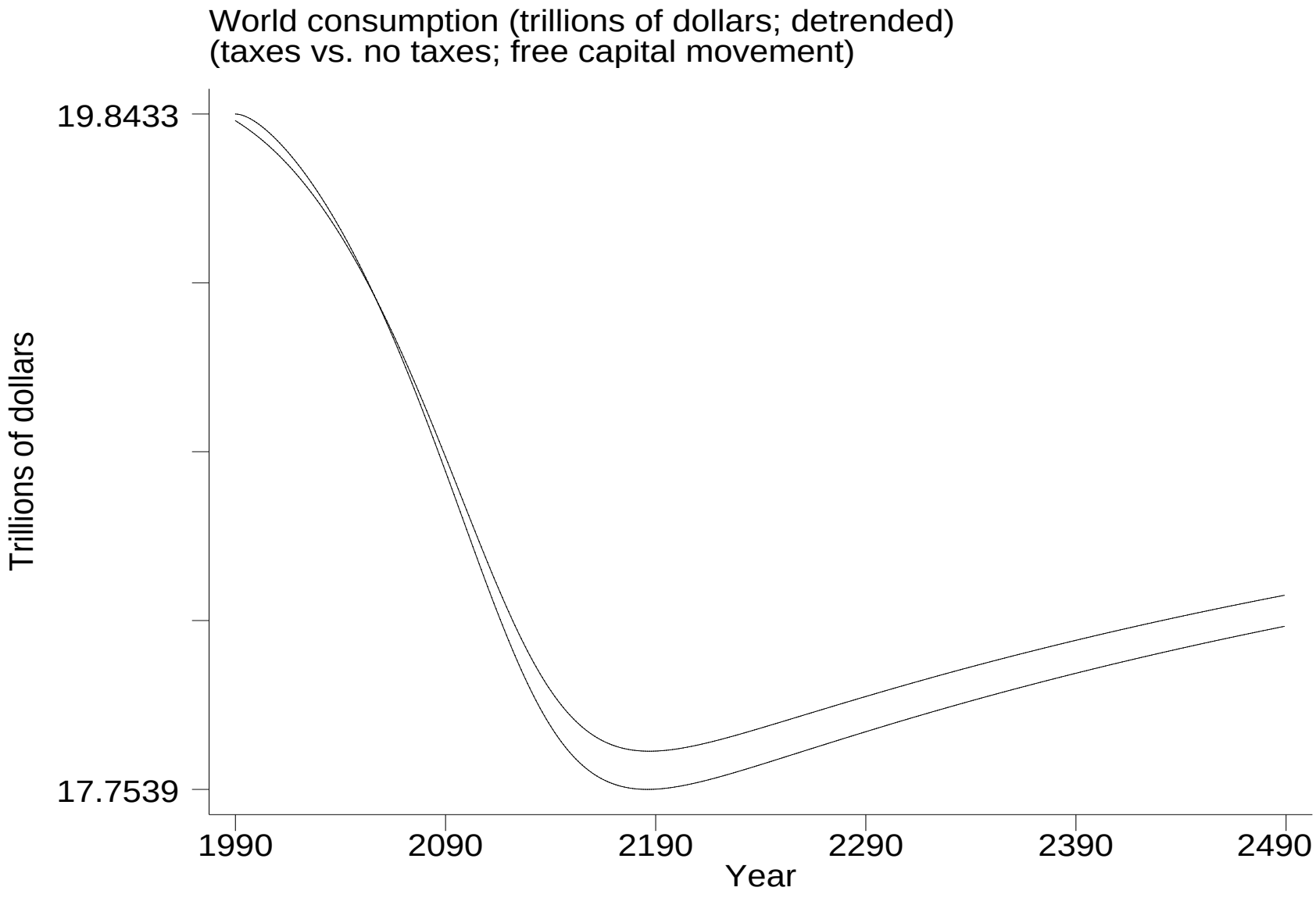

Temperature (degrees centrigrade above pre−indudstrial)
(no taxes; free capital movement)
5.33065
.895314
Degrees centigrade
1990
2090
2190
2290
2390
2490
Year

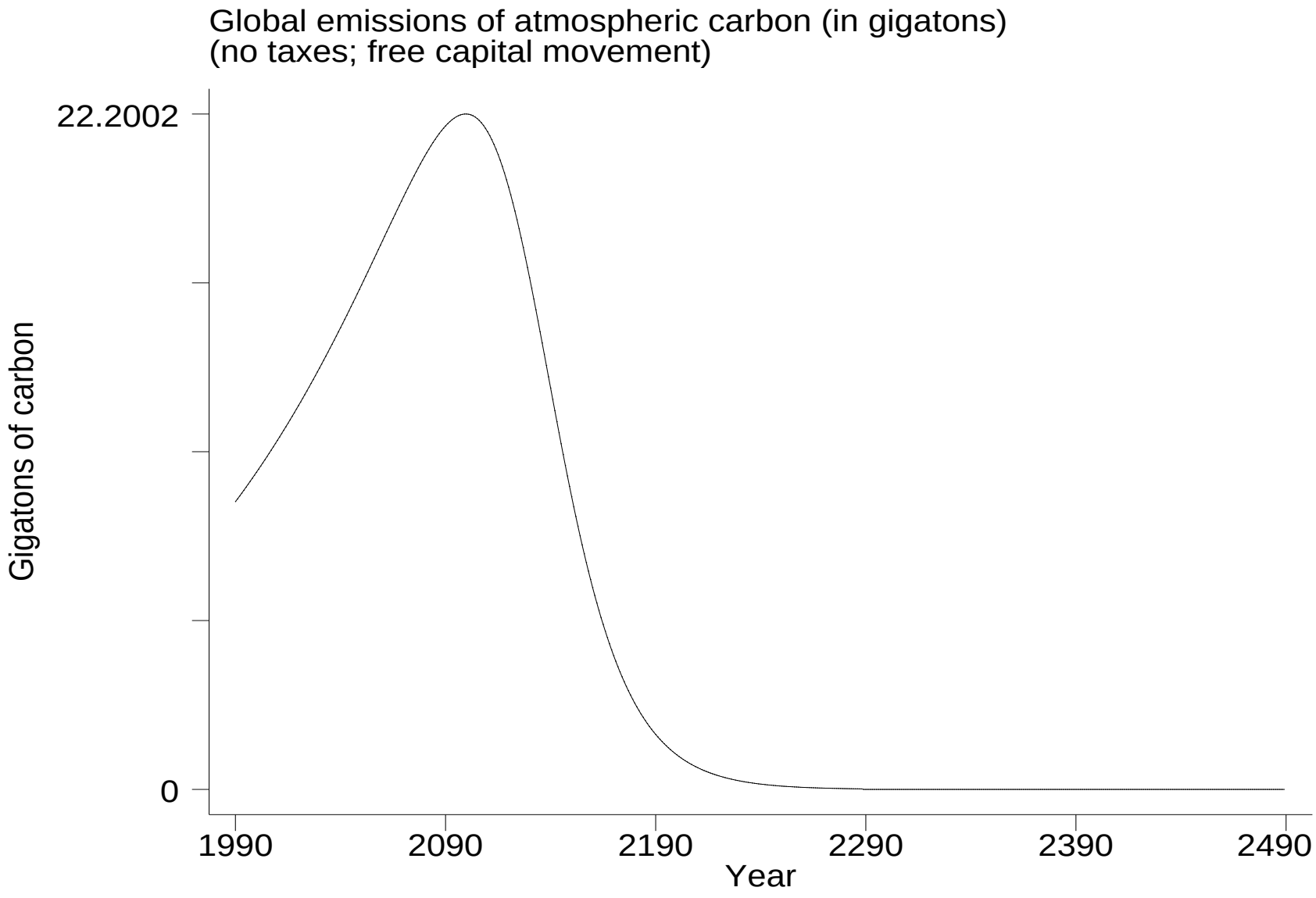

Temperature (degrees centrigrade above pre−indudstrial)
(taxes vs. no taxes; free capital movement)
5.33065
.893184
Degrees centigrade
1990
2090
2190
2290
2390
2490
Year

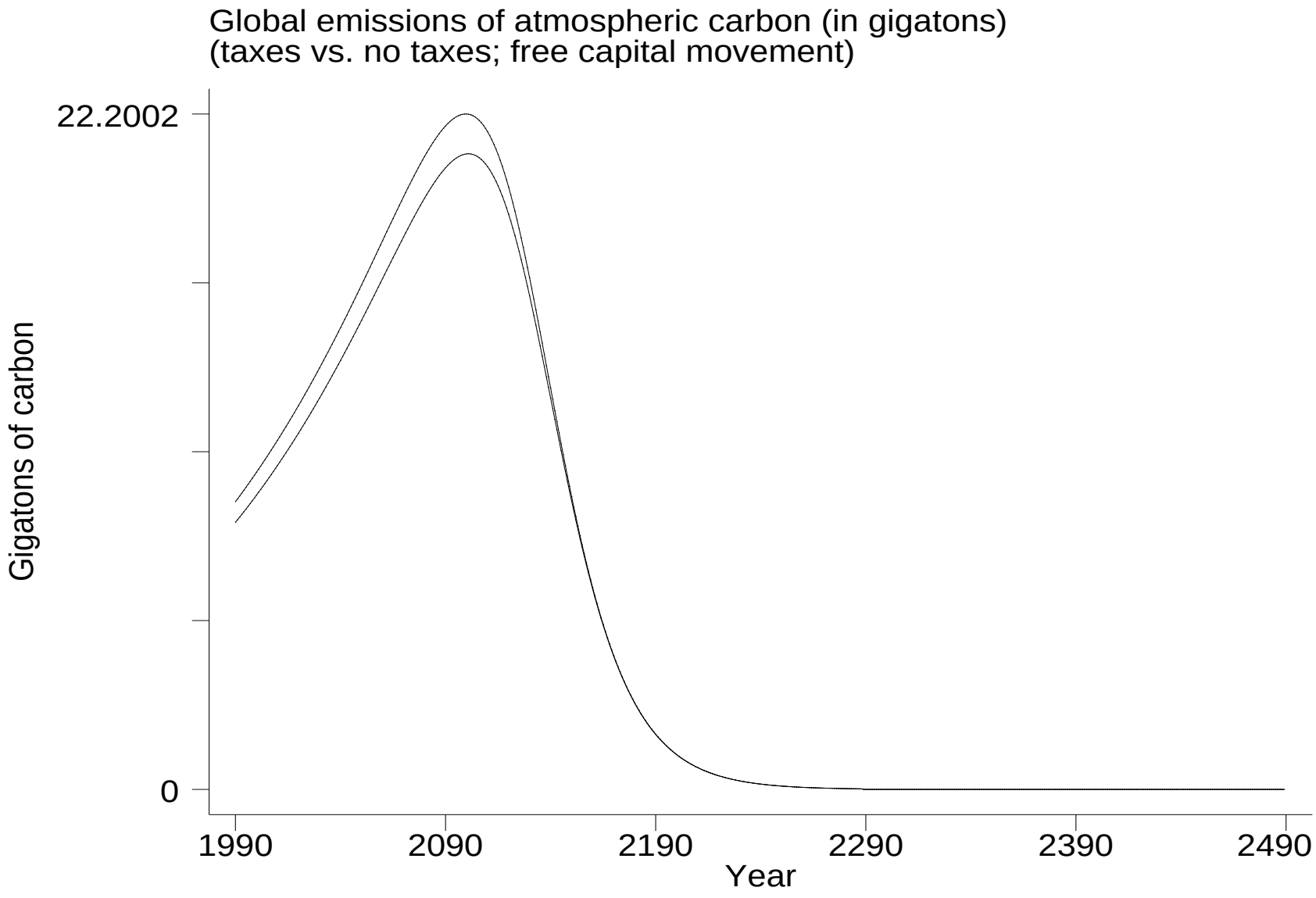

World GDP (trillions of dollars; detrended)
(no taxes; free capital movement)
30.5506
27.3116
Trillions of dollars
1990
2090
2190
2290
2390
2490
Year


World GDP (trillions of dollars; detrended)
(taxes vs. no taxes; free capital movement)
30.5506
27.3116
Trillions of dollars
1990
2090
2190
2290
2390
2490
Year

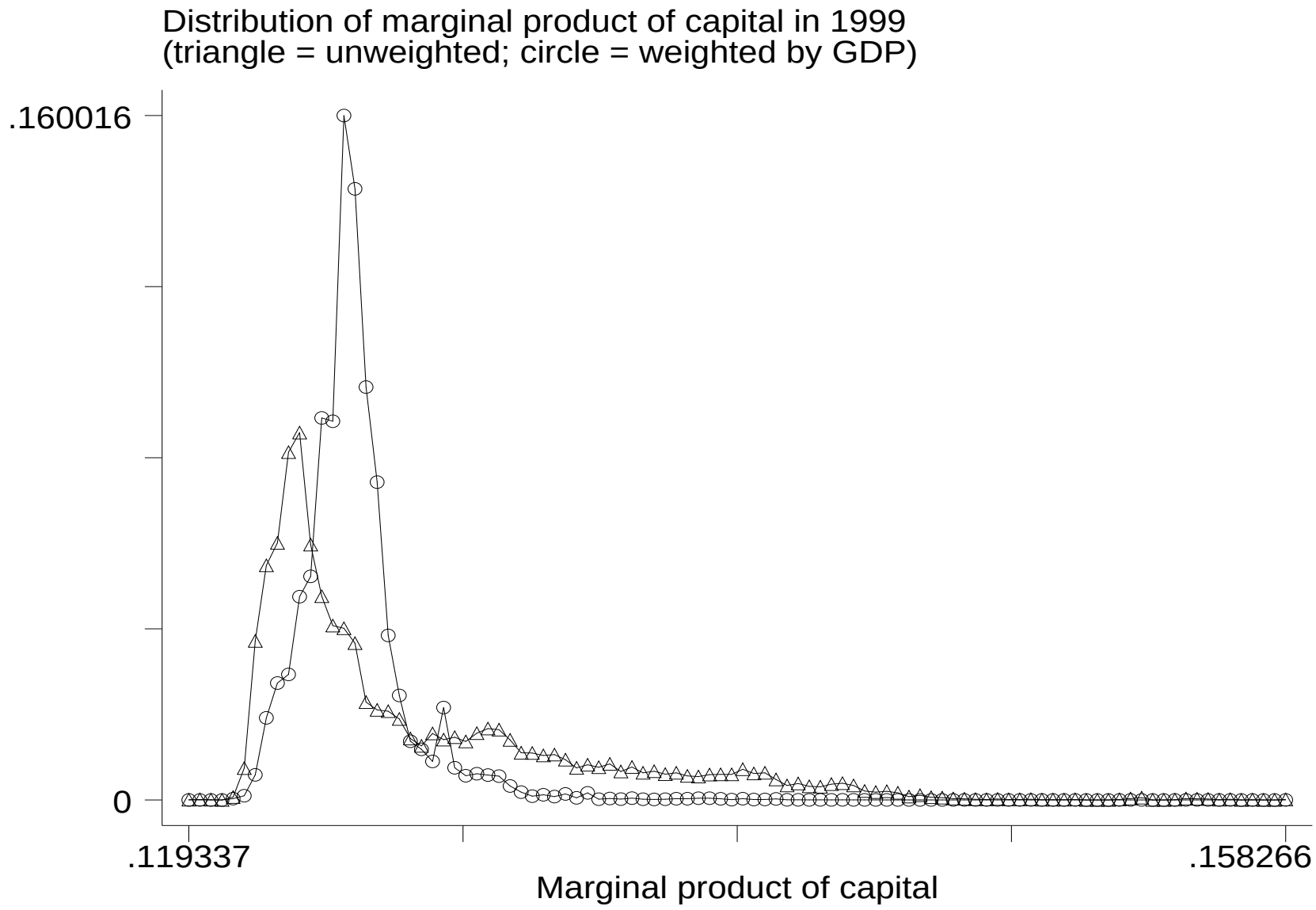

World consumption (trillions of dollars; detrended)
(no taxes; free capital movement)
19.8433
17.7539
Trillions of dollars
1990
2090
2190
2290
2390
2490
Year

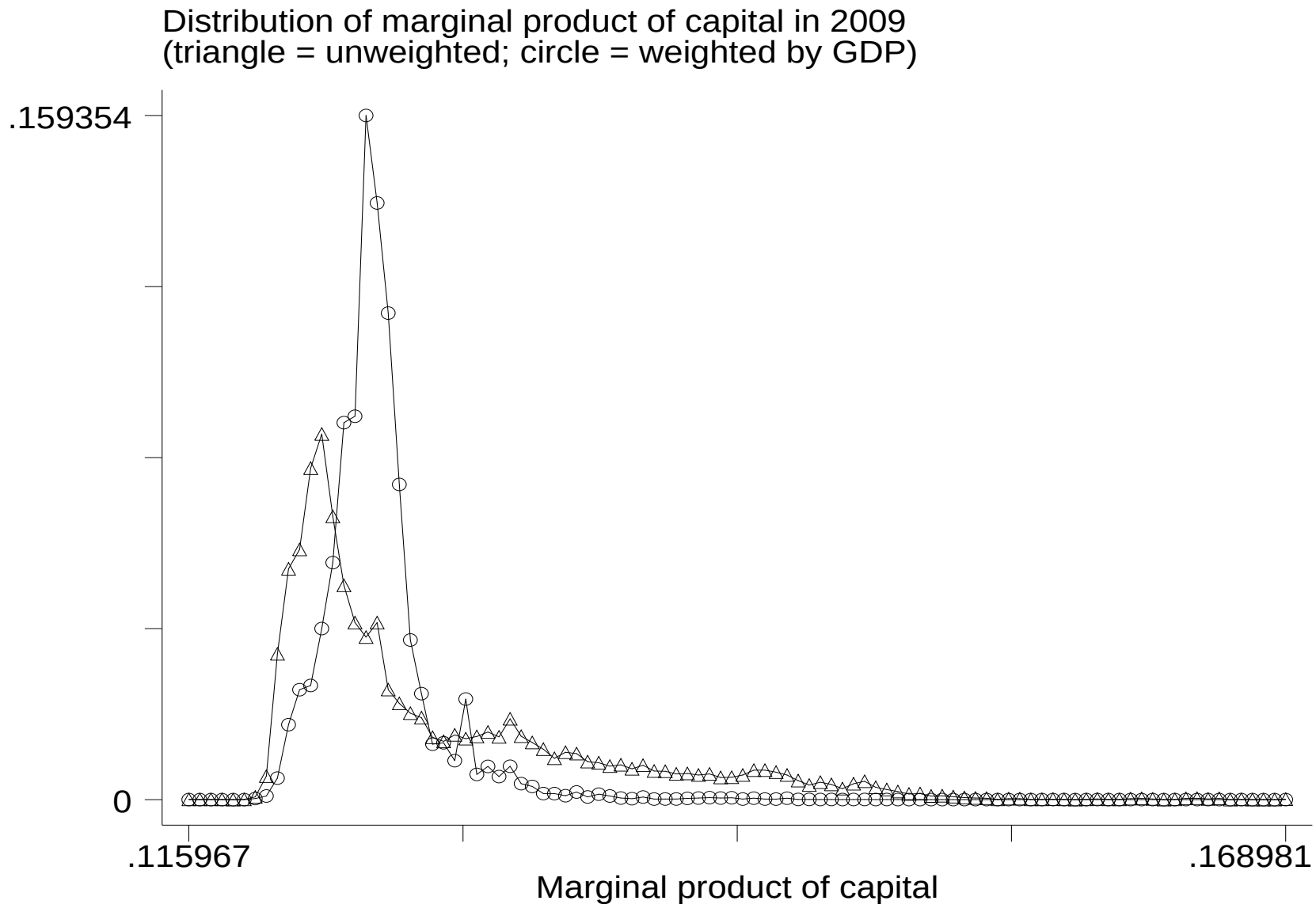

World consumption (trillions of dollars; detrended)
(taxes vs. no taxes; free capital movement)
19.8433
17.7539
Trillions of dollars
1990
2090
2190
2290
2390
2490
Year

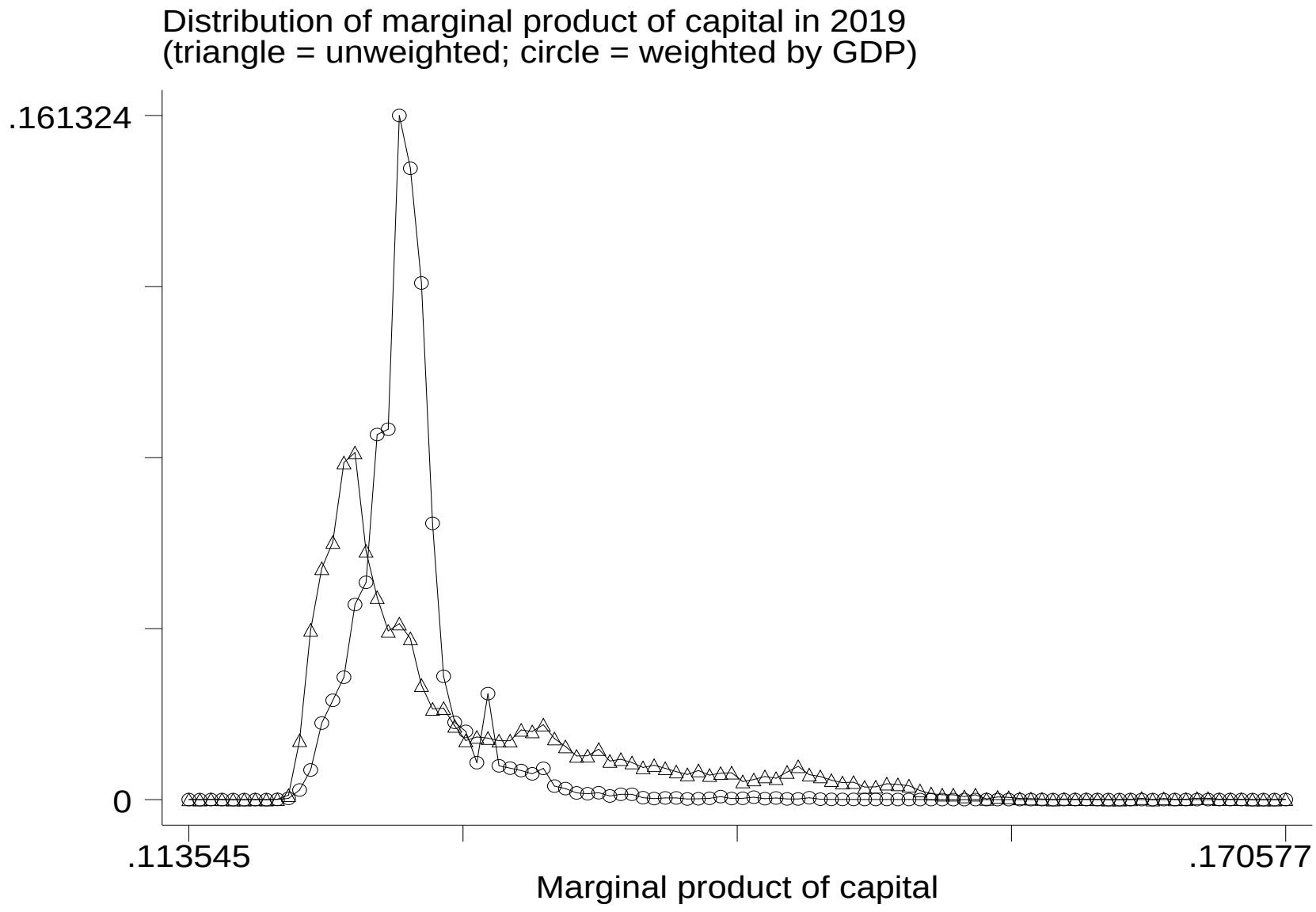

Global emissions of atmospheric carbon (in gigatons)
(no taxes; free capital movement)
22.2002
0
Gigatons of carbon
1990
2090
2190
2290
2390
2490
Year

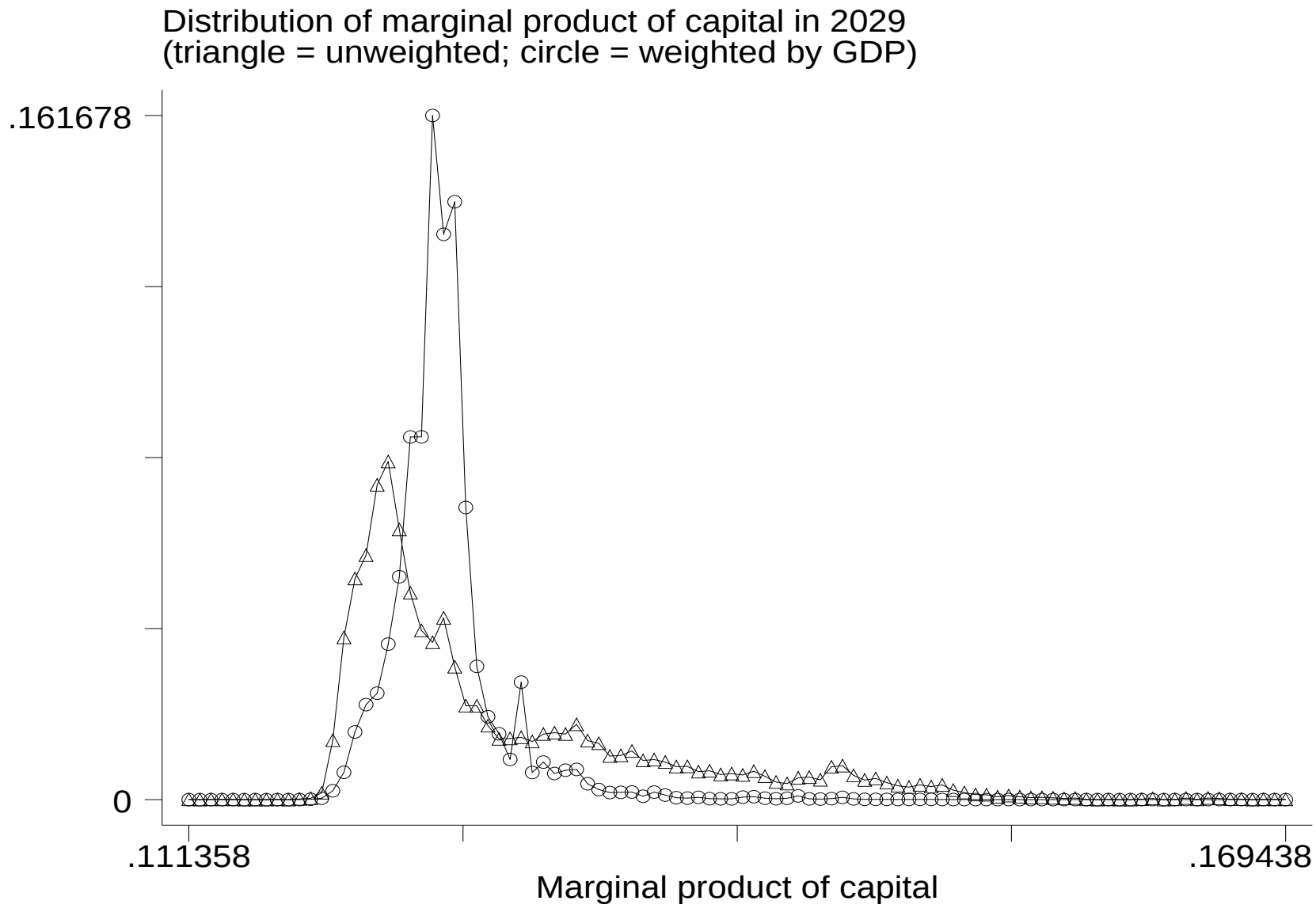

Global emissions of atmospheric carbon (in gigatons)
(taxes vs. no taxes; free capital movement)
22.2002
0
Gigatons of carbon
1990
2090
2190
2290
2390
2490
Year

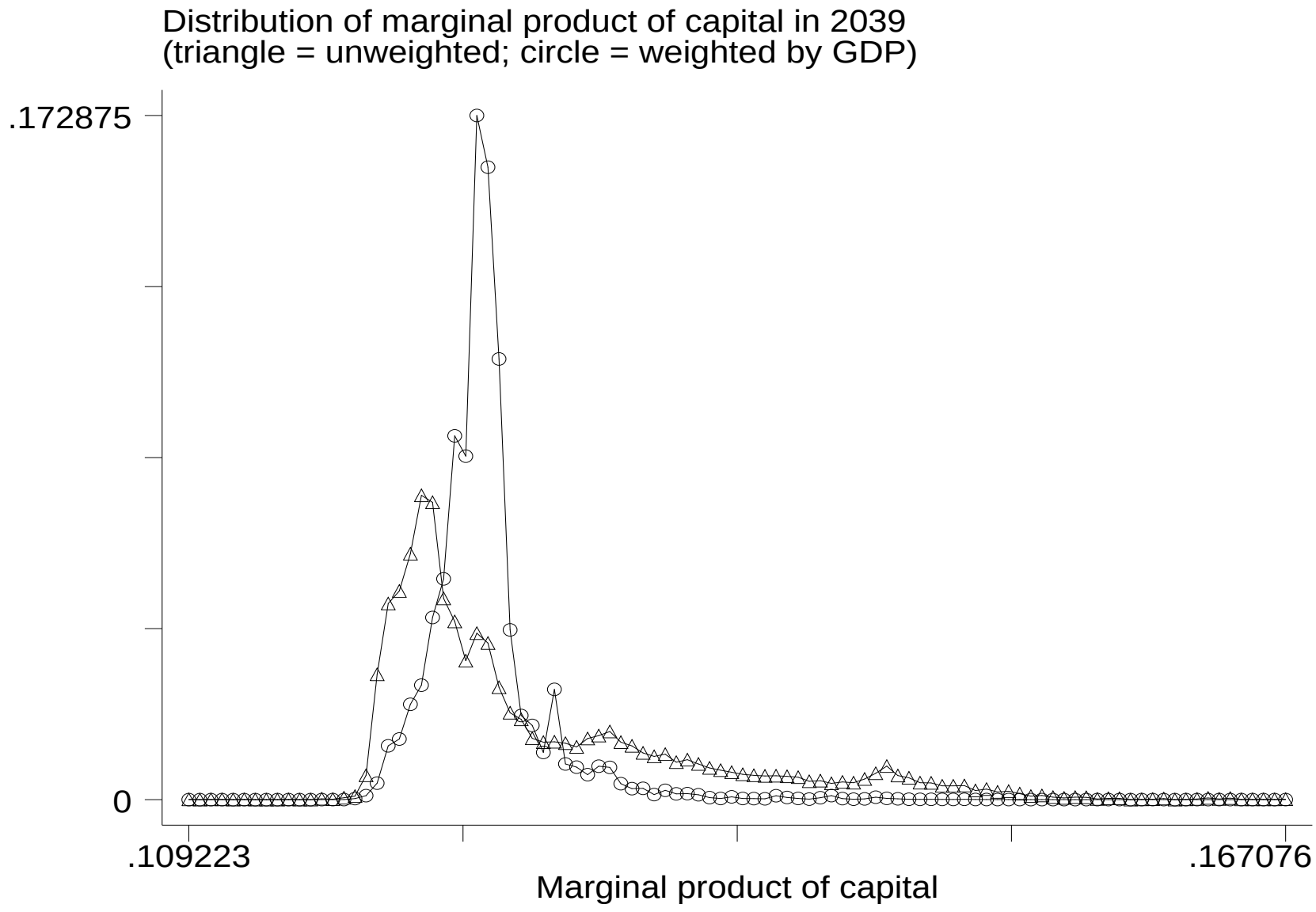
movie: distribution of mpks

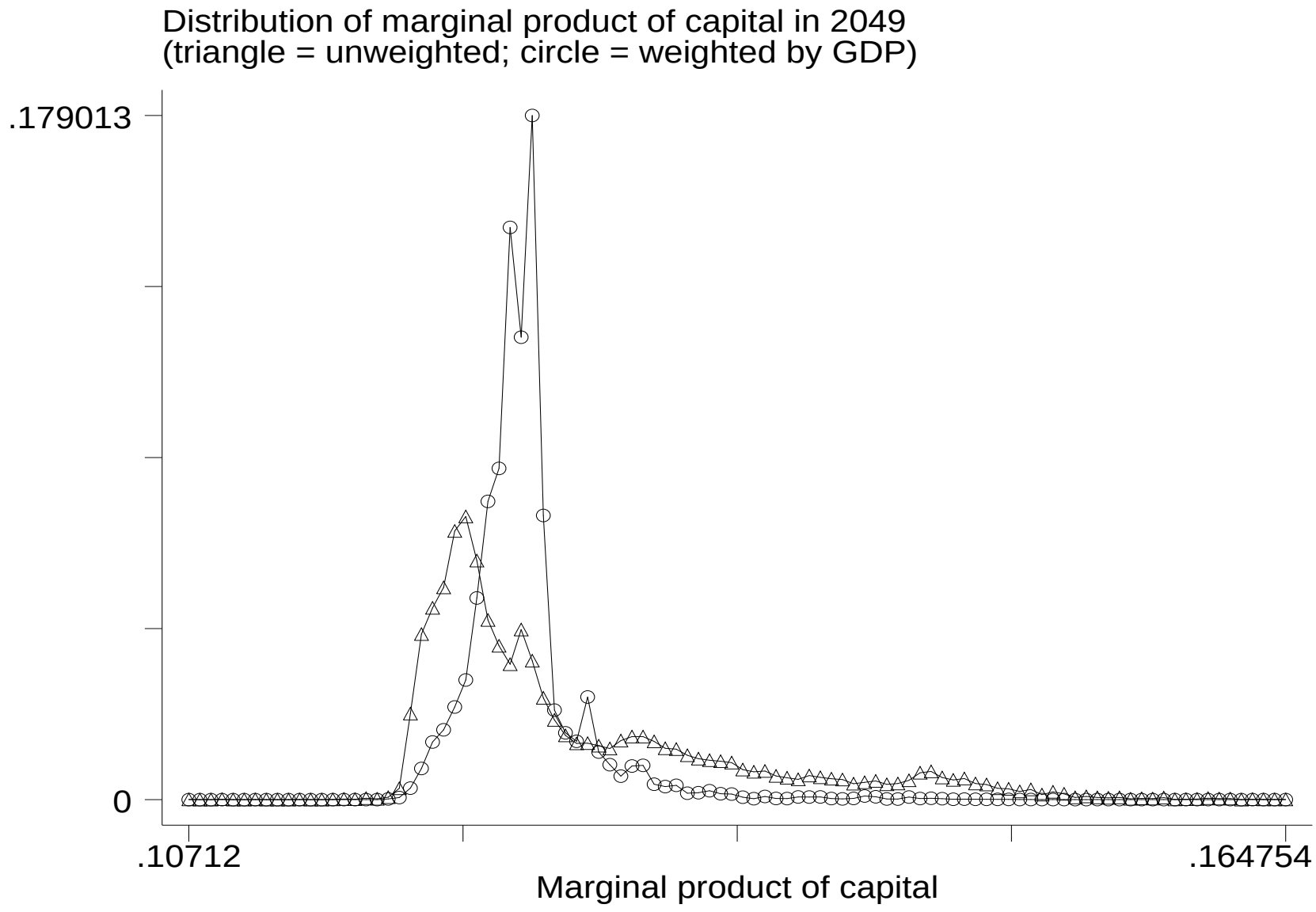

Distribution of marginal product of capital in 1999
(triangle = unweighted; circle = weighted by GDP)
.160016
0
.119337
.158266
Marginal product of capital

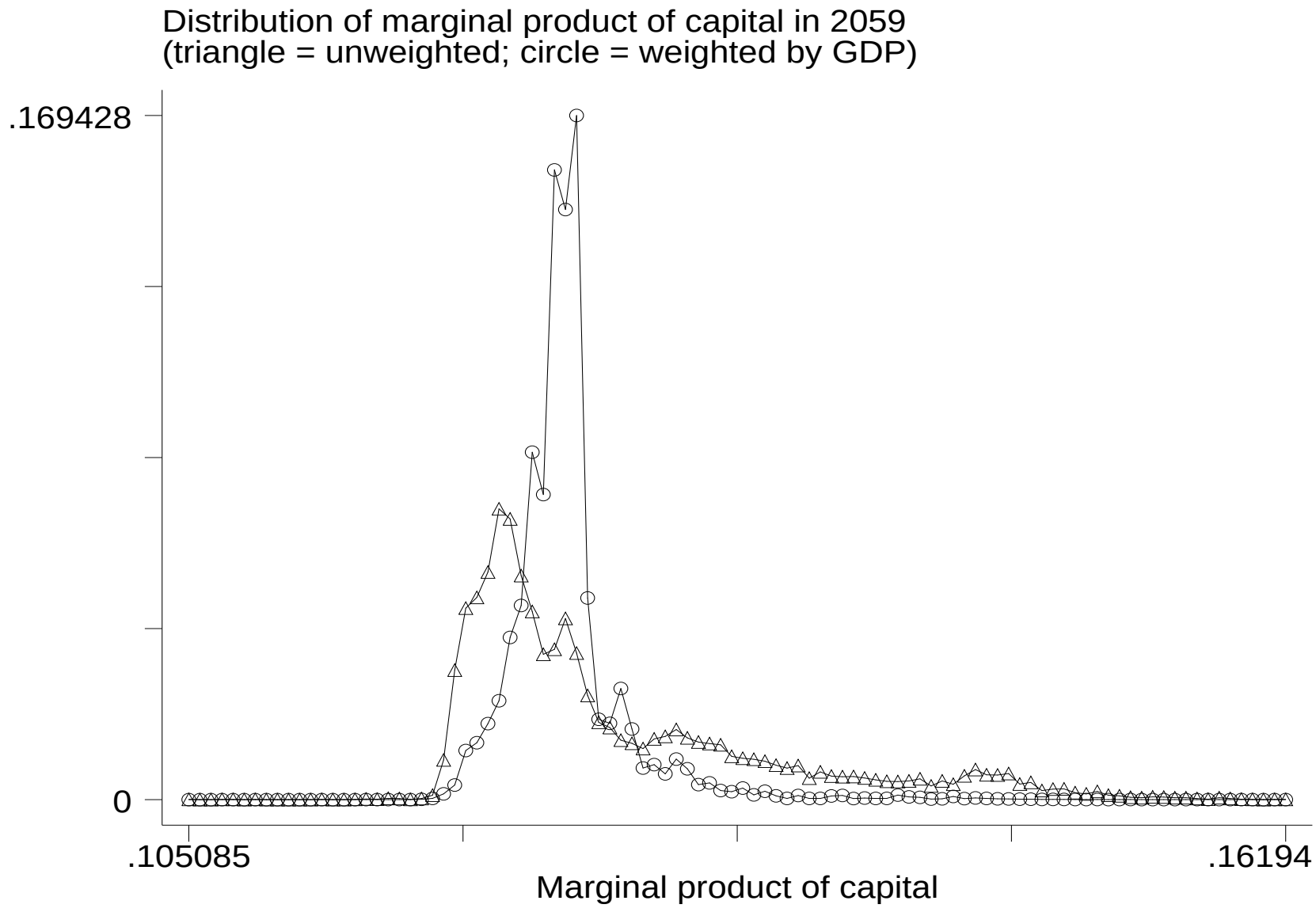

Distribution of marginal product of capital in 2009
(triangle = unweighted; circle = weighted by GDP)
.159354
0
.115967
.168981
Marginal product of capital

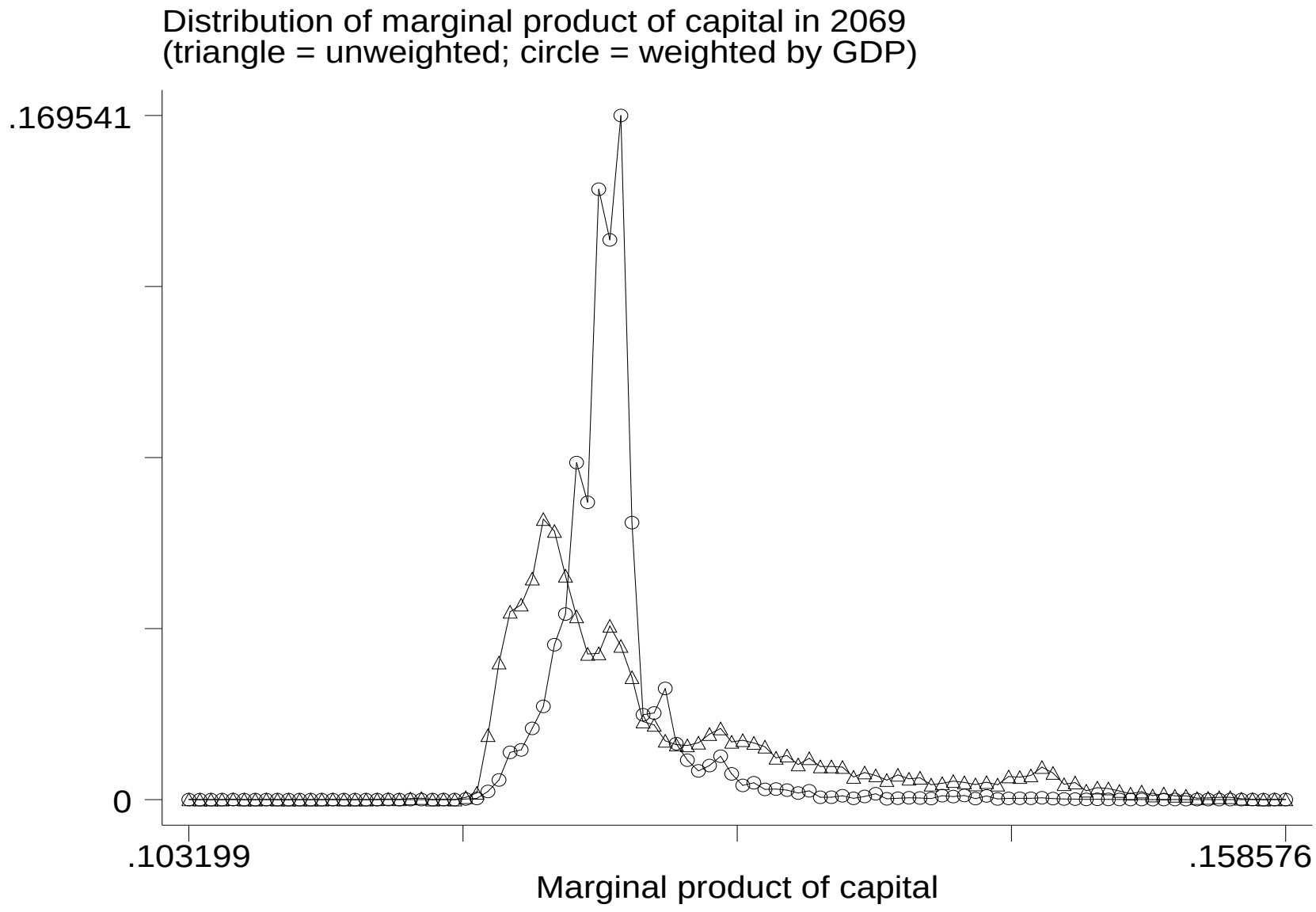

Distribution of marginal product of capital in 2019
(triangle = unweighted; circle = weighted by GDP)
.161324
0
.113545
.170577
Marginal product of capital

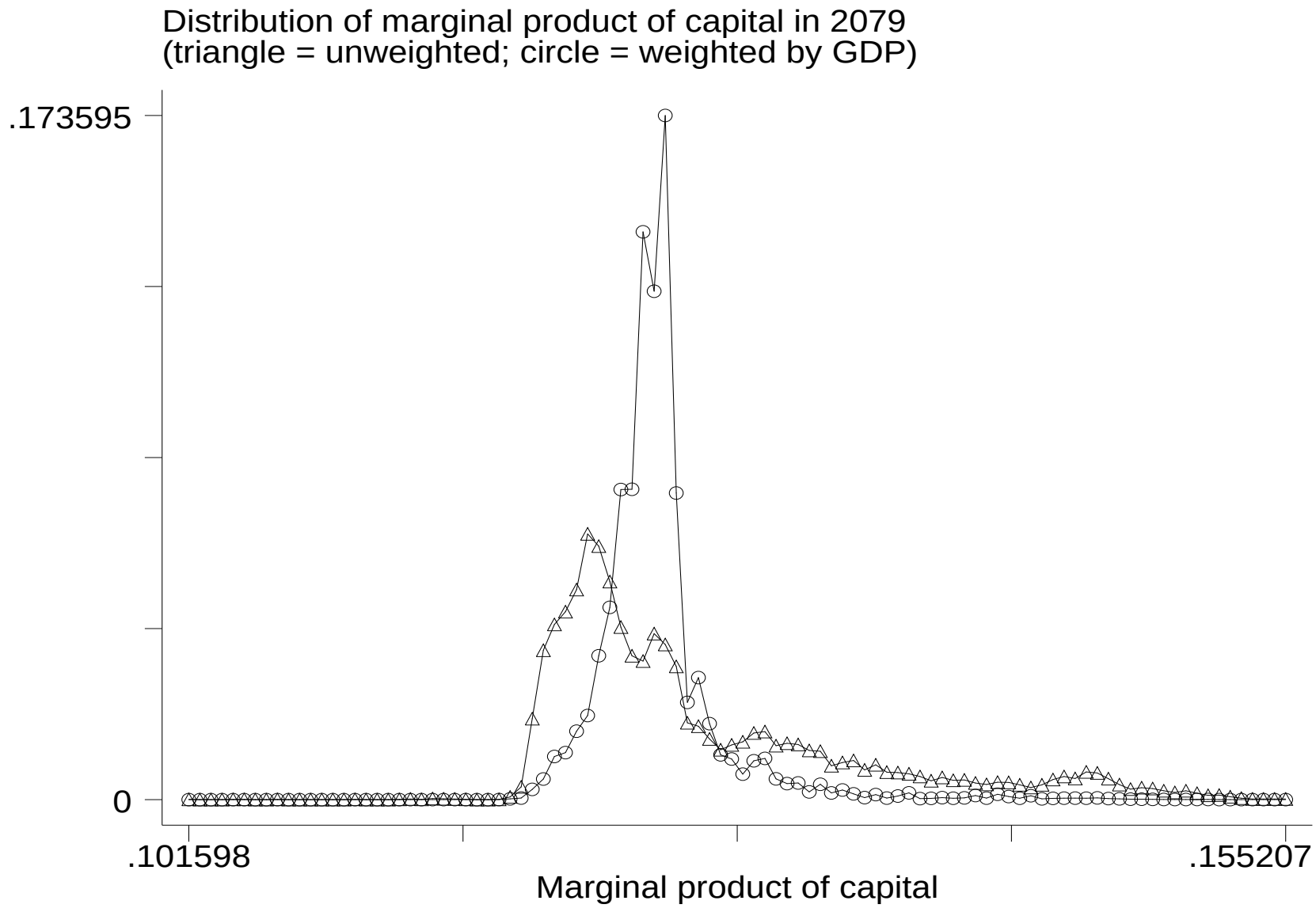

Distribution of marginal product of capital in 2029
(triangle = unweighted; circle = weighted by GDP)
.161678
0
.111358
.169438
Marginal product of capital

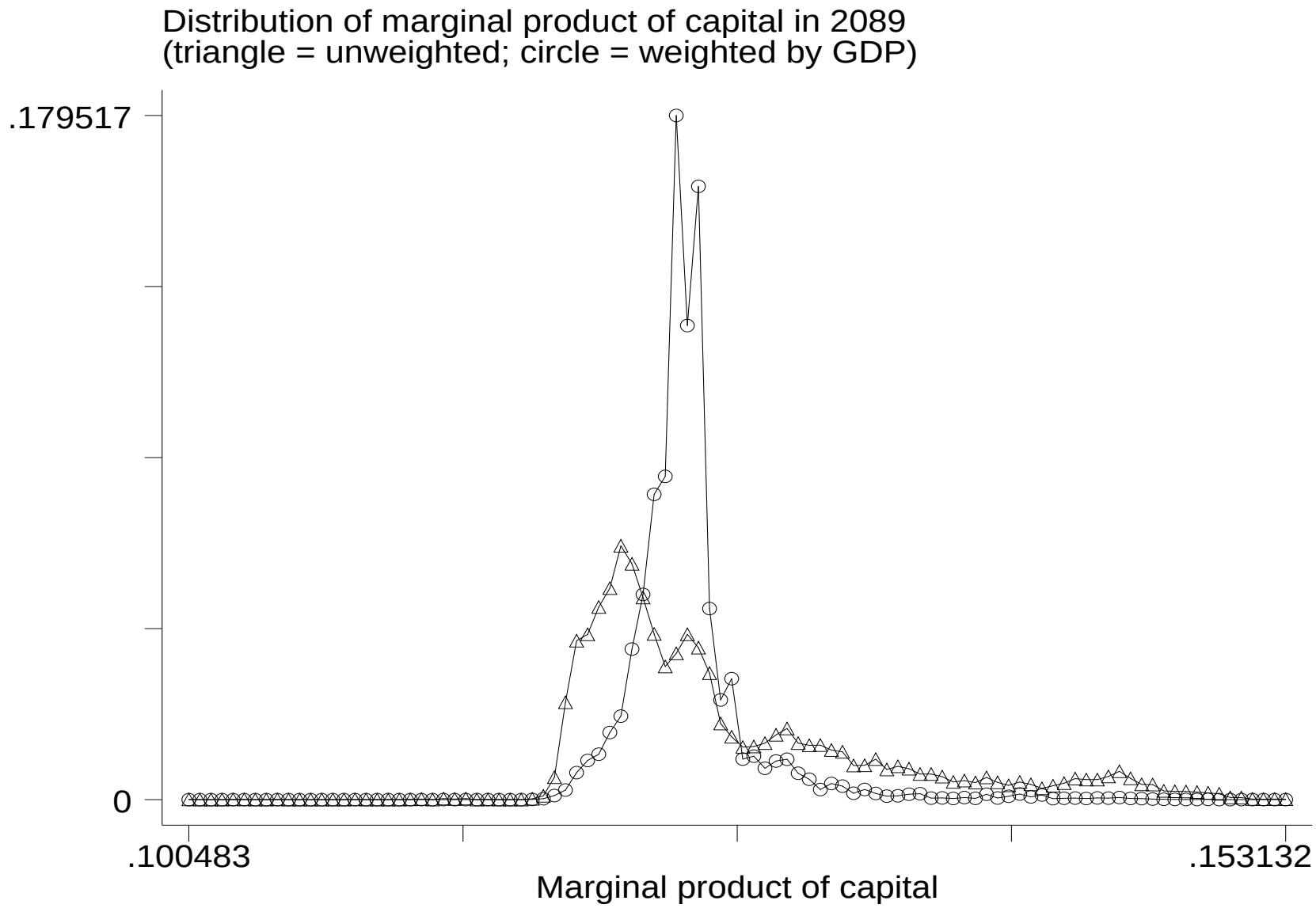

Distribution of marginal product of capital in 2039
(triangle = unweighted; circle = weighted by GDP)
.172875
0
.109223
.167076
Marginal product of capital

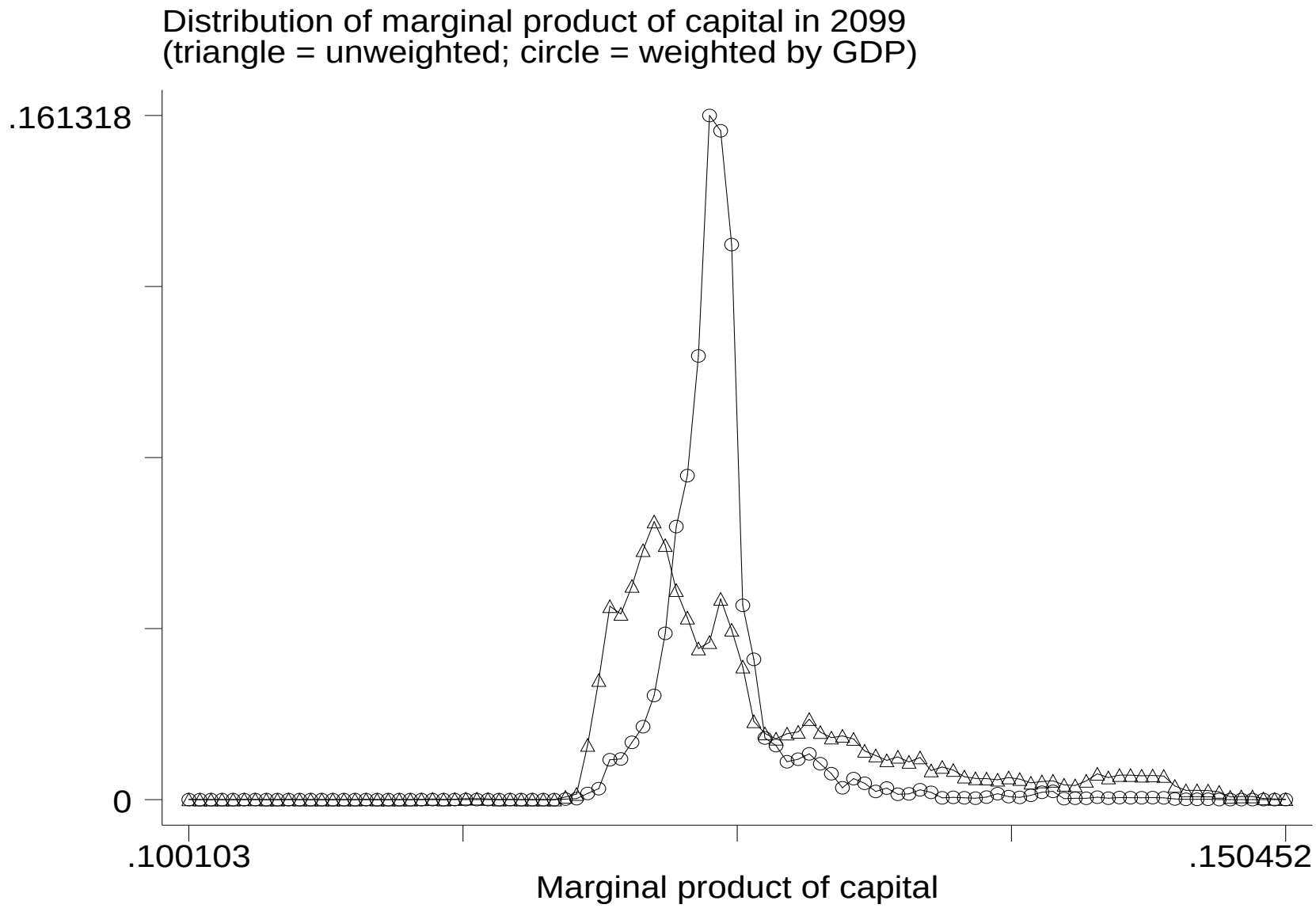

Distribution of marginal product of capital in 2049
(triangle = unweighted; circle = weighted by GDP)
.179013
0
.10712
.164754
Marginal product of capital

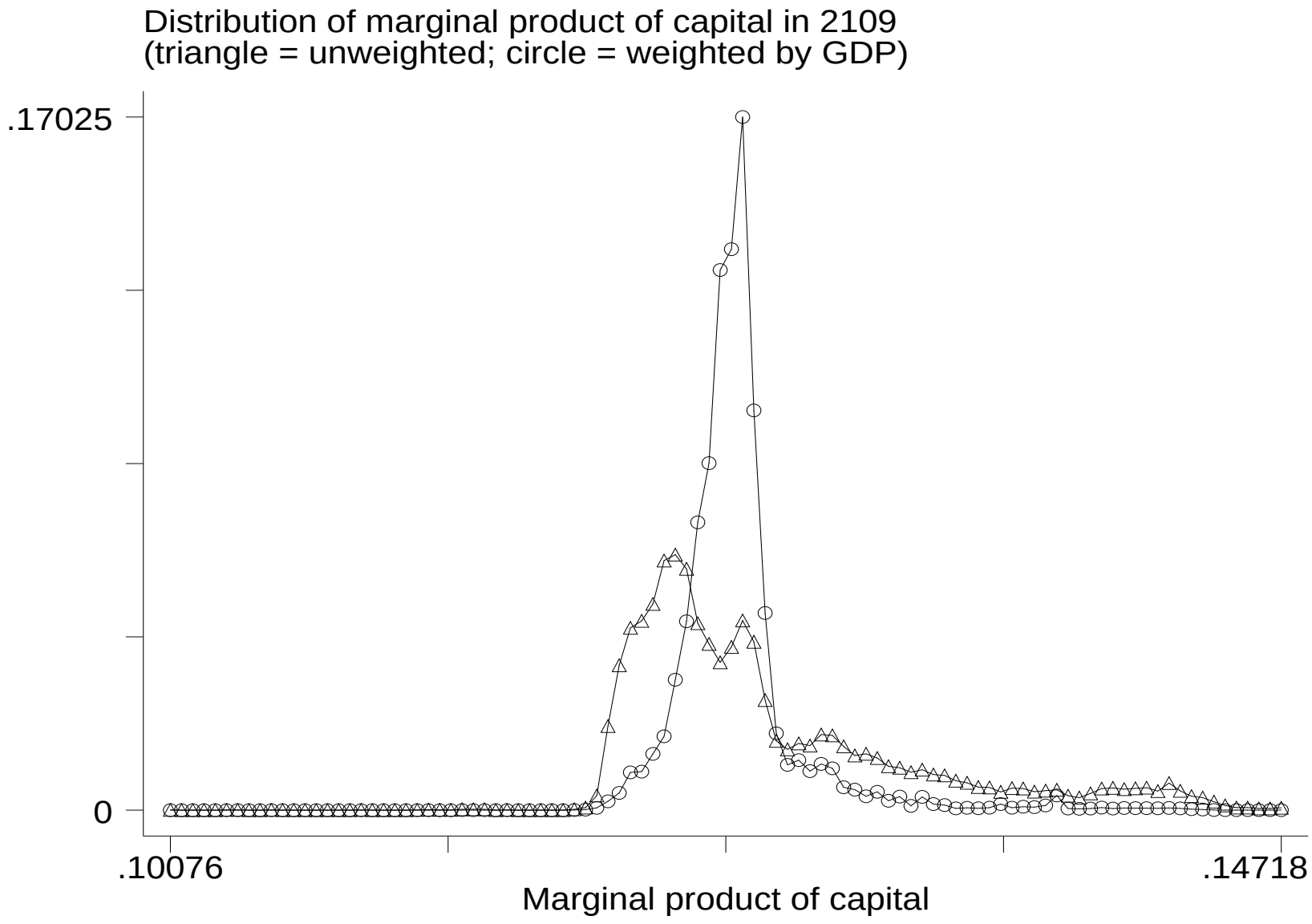

Distribution of marginal product of capital in 2059
(triangle = unweighted; circle = weighted by GDP)
.169428
0
.105085
.16194
Marginal product of capital

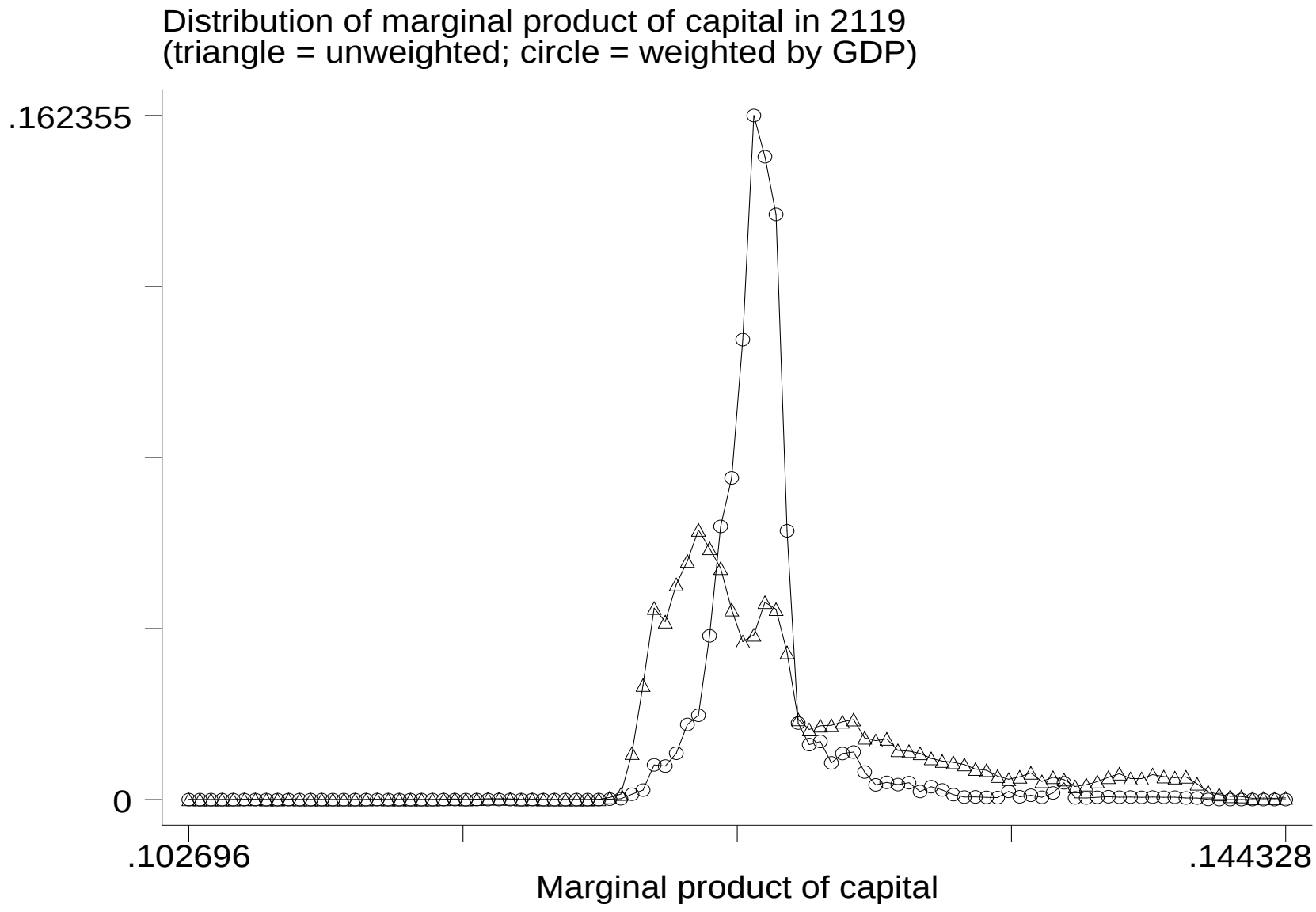

Distribution of marginal product of capital in 2069
(triangle = unweighted; circle = weighted by GDP)
.169541
0
.103199
.158576
Marginal product of capital

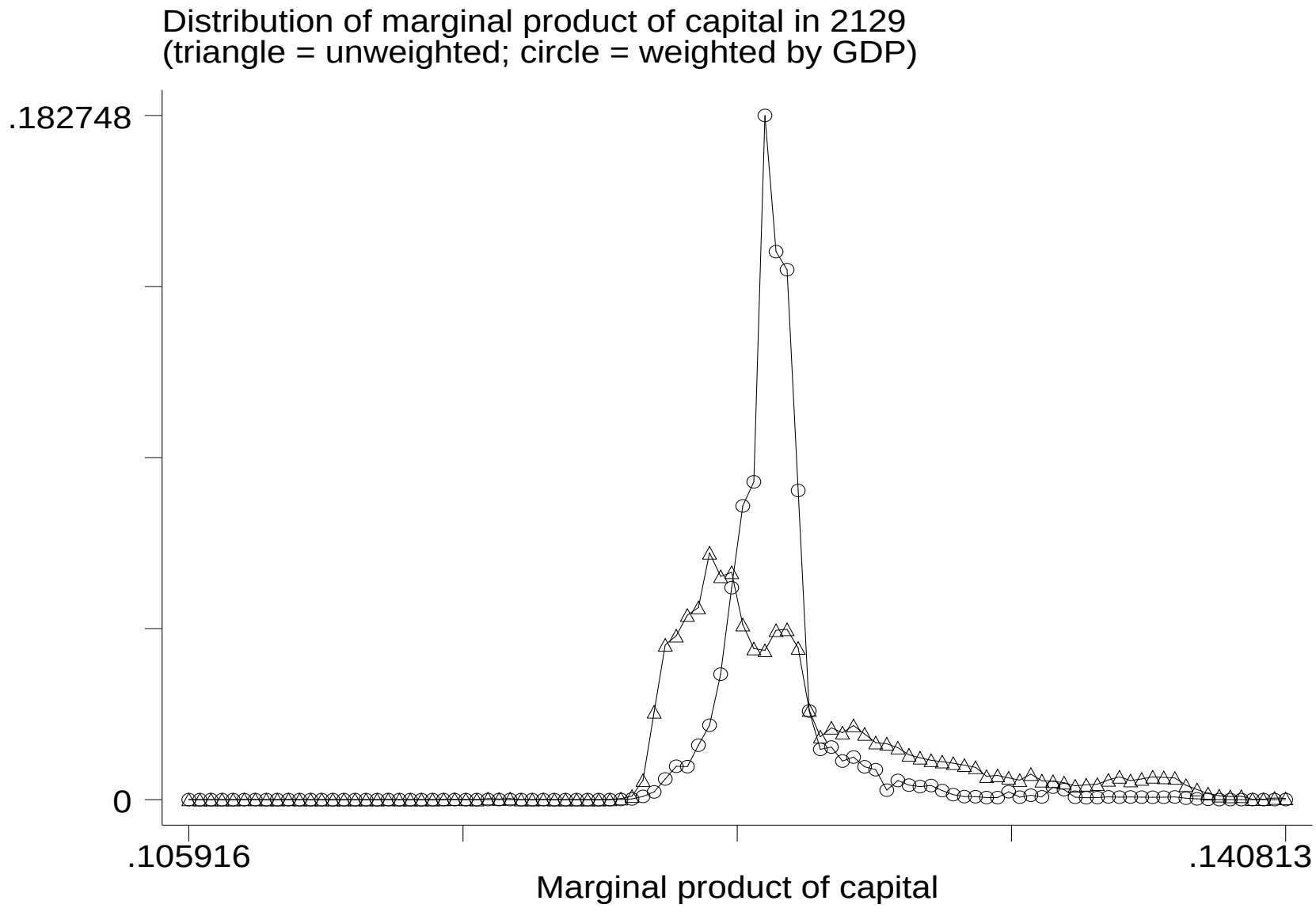

Distribution of marginal product of capital in 2079
(triangle = unweighted; circle = weighted by GDP)
.173595
0
.101598
.155207
Marginal product of capital

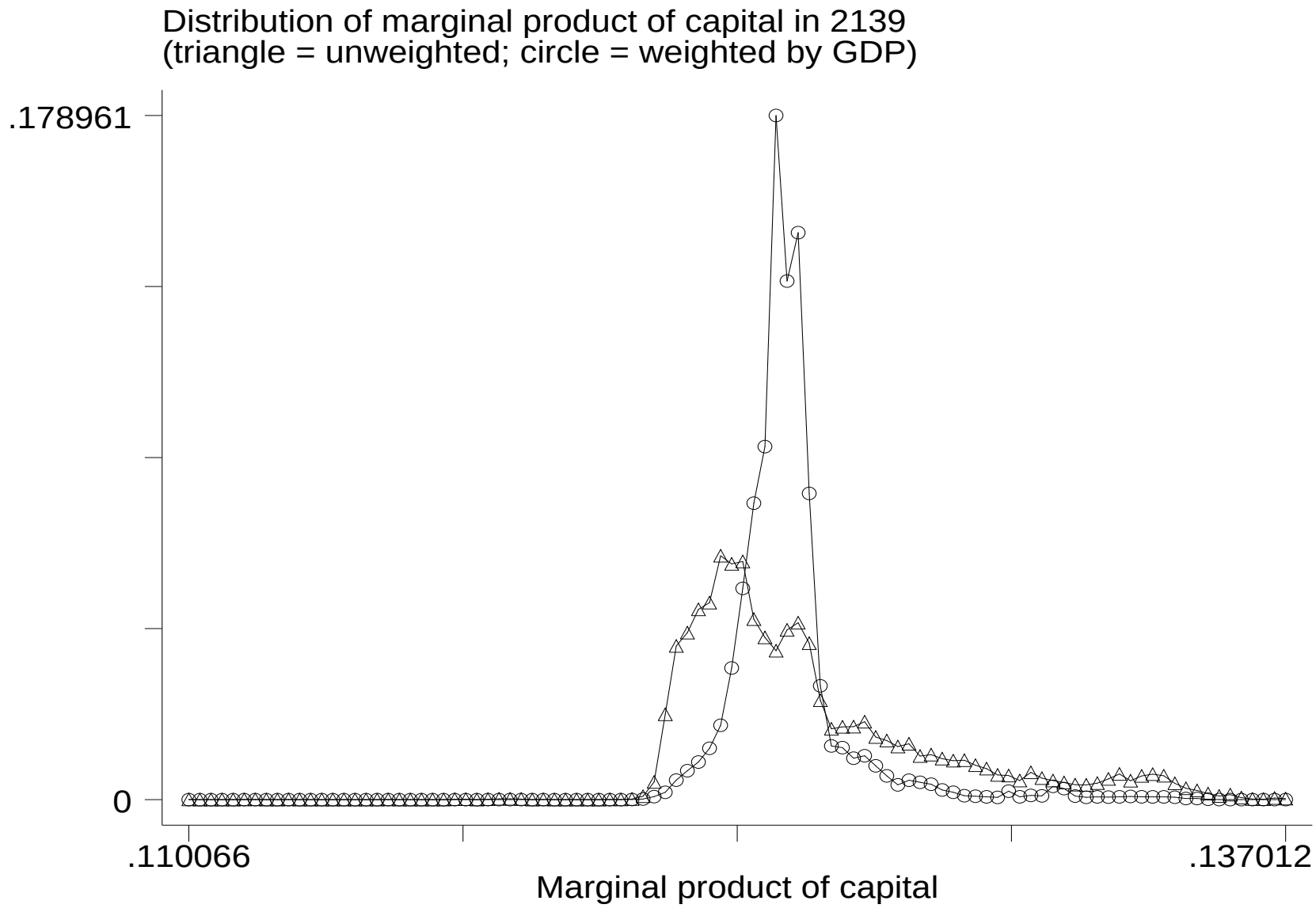

Distribution of marginal product of capital in 2089
(triangle = unweighted; circle = weighted by GDP)
.179517
0
.100483
.153132
Marginal product of capital

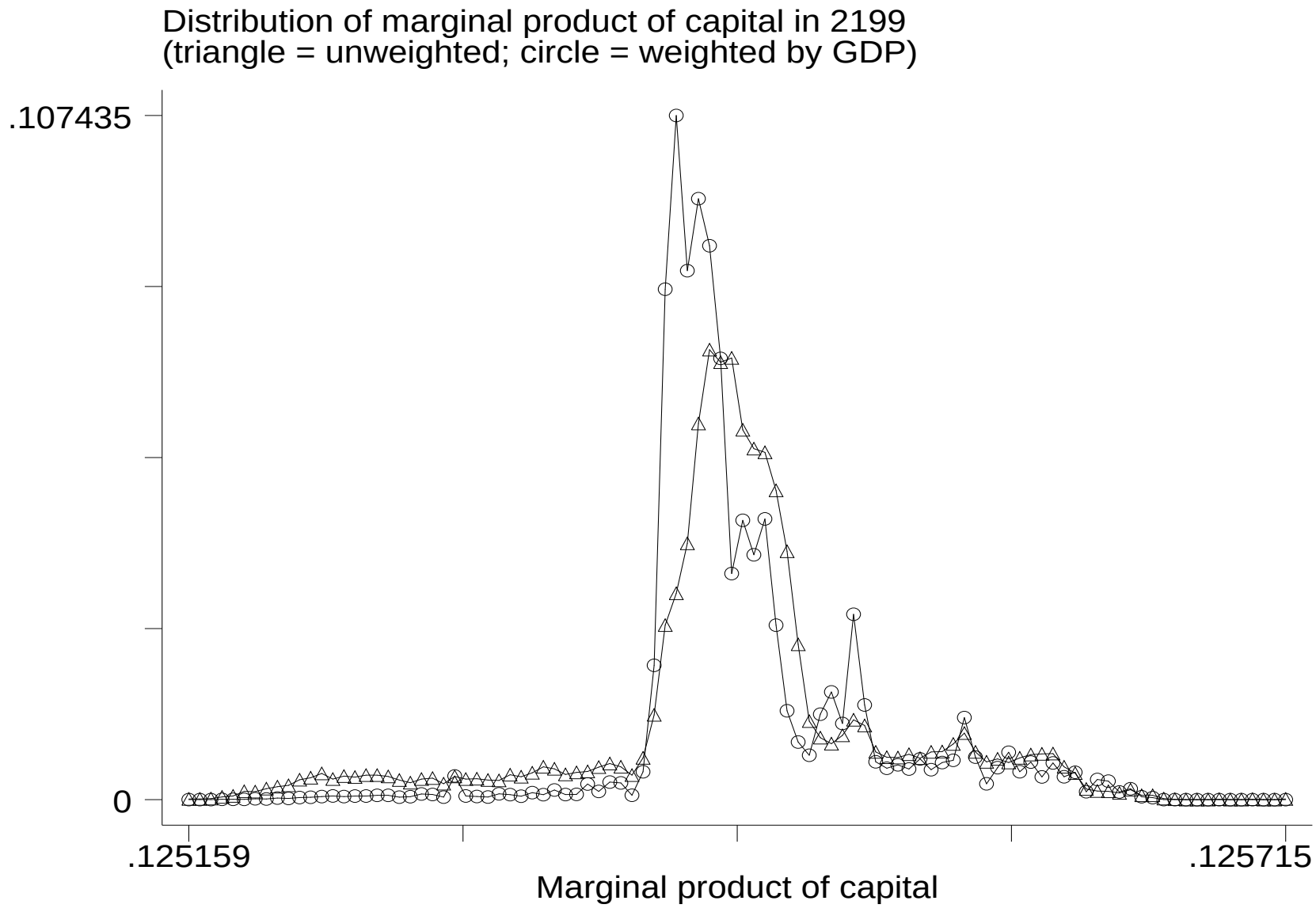

Distribution of marginal product of capital in 2099
(triangle = unweighted; circle = weighted by GDP)
.161318
0
.100103
.150452
Marginal product of capital

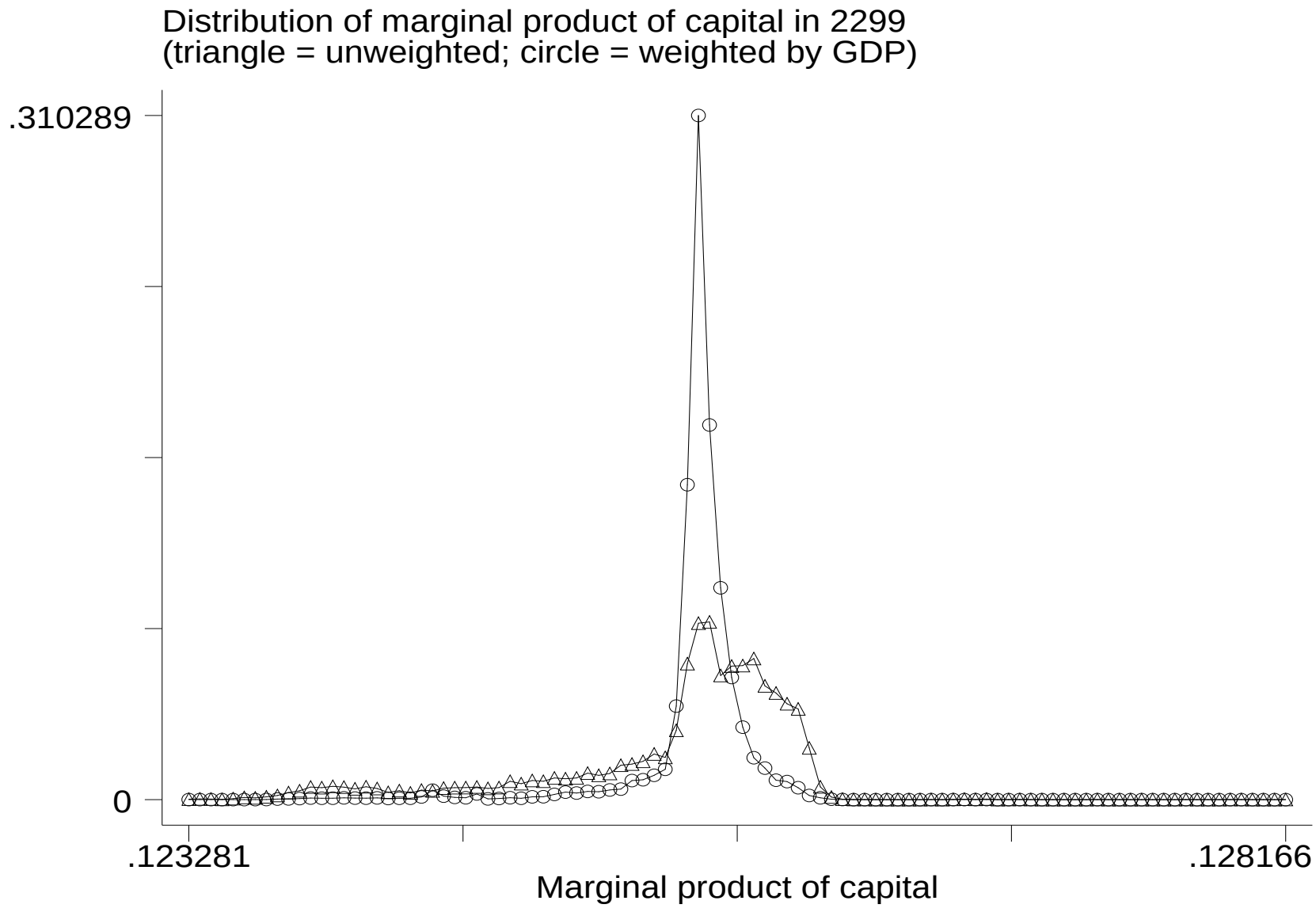

Distribution of marginal product of capital in 2109
(triangle = unweighted; circle = weighted by GDP)
.17025
0
.10076
.14718
Marginal product of capital


Distribution of marginal product of capital in 2119
(triangle = unweighted; circle = weighted by GDP)
.162355
0
.102696
.144328
Marginal product of capital

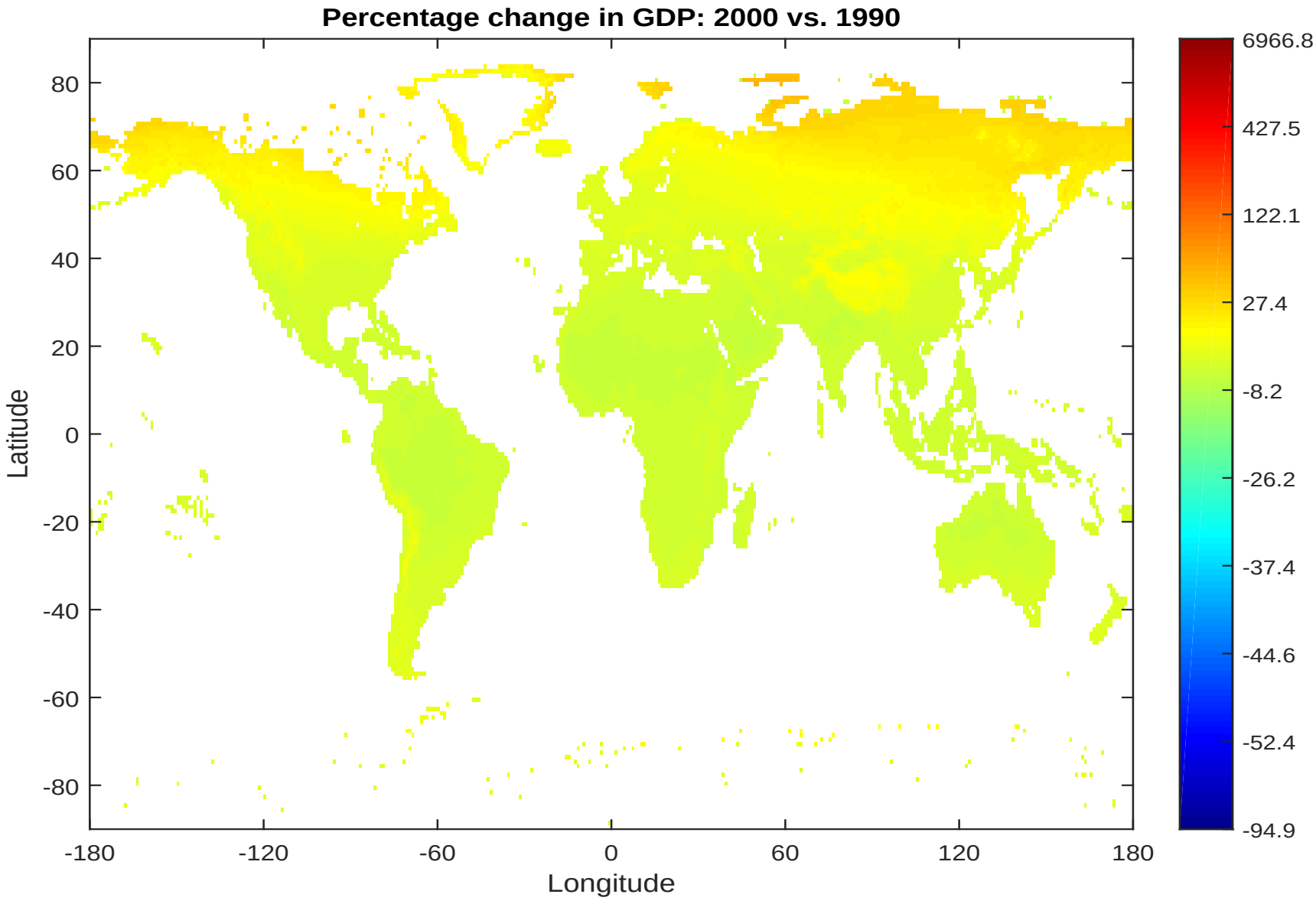

Distribution of marginal product of capital in 2129
(triangle = unweighted; circle = weighted by GDP)
.182748
0
.105916
.140813
Marginal product of capital

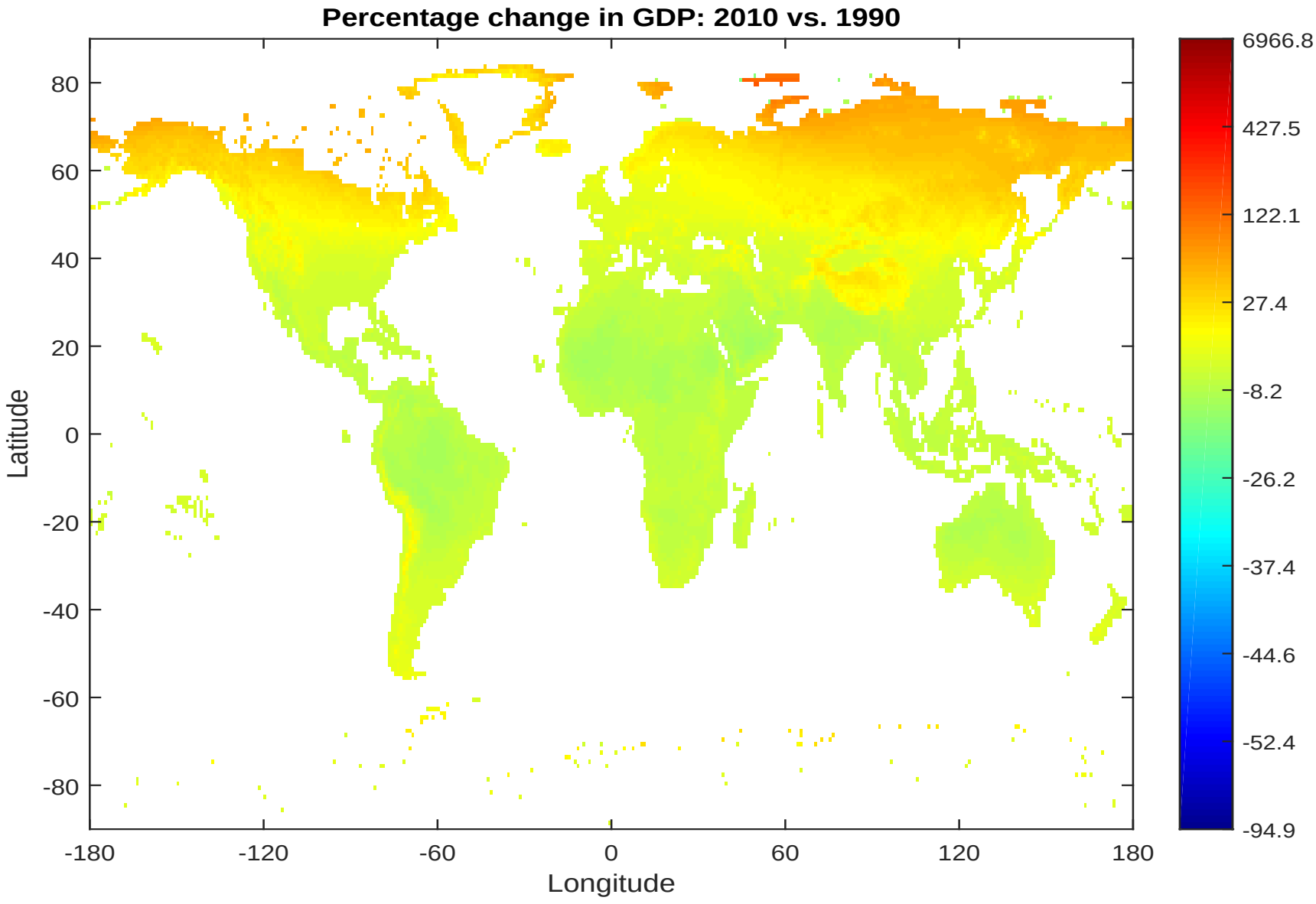

Distribution of marginal product of capital in 2139
(triangle = unweighted; circle = weighted by GDP)
.178961
0
.110066
.137012
Marginal product of capital

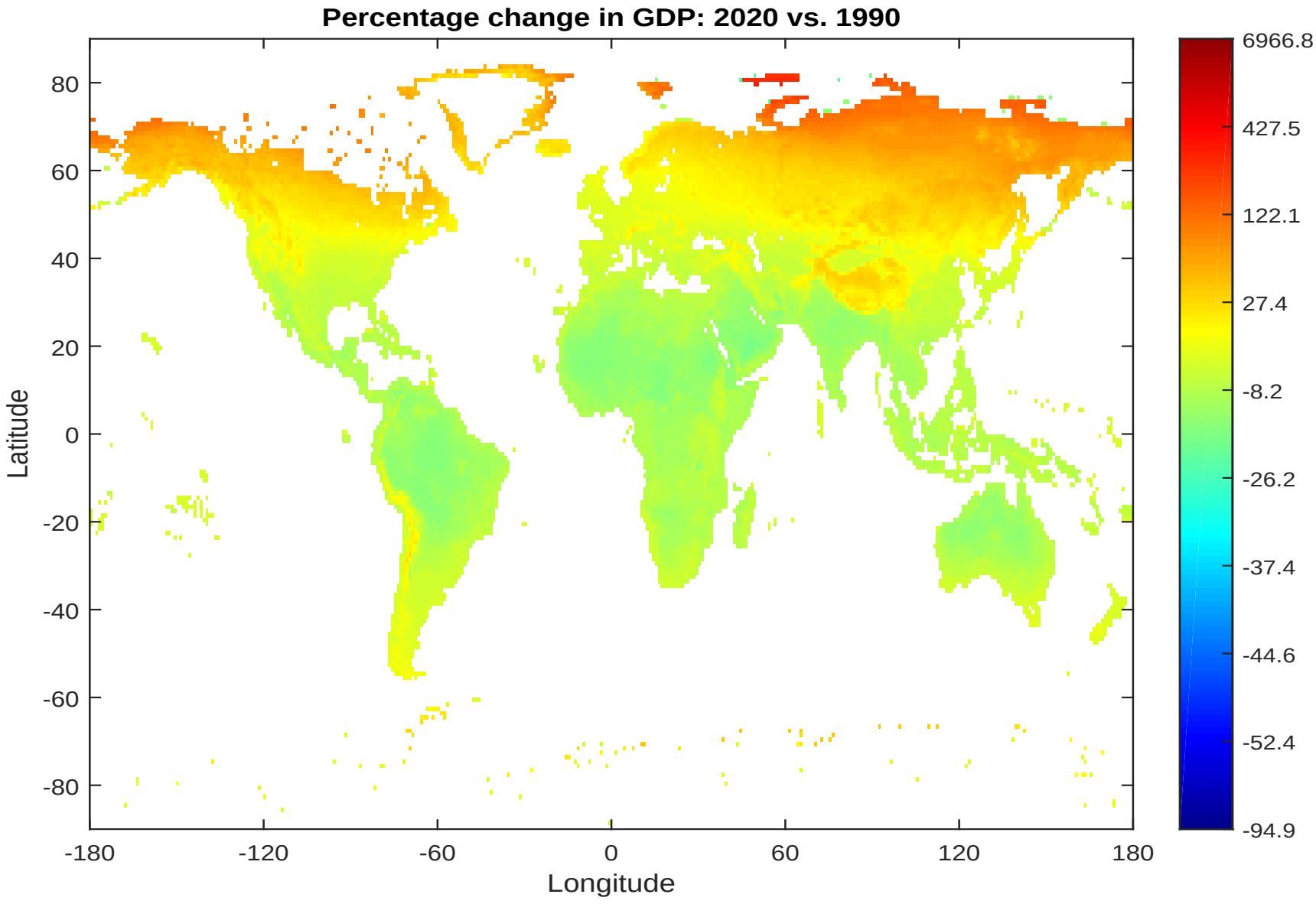

Distribution of marginal product of capital in 2199
(triangle = unweighted; circle = weighted by GDP)
.107435
0
.125159
.125715
Marginal product of capital

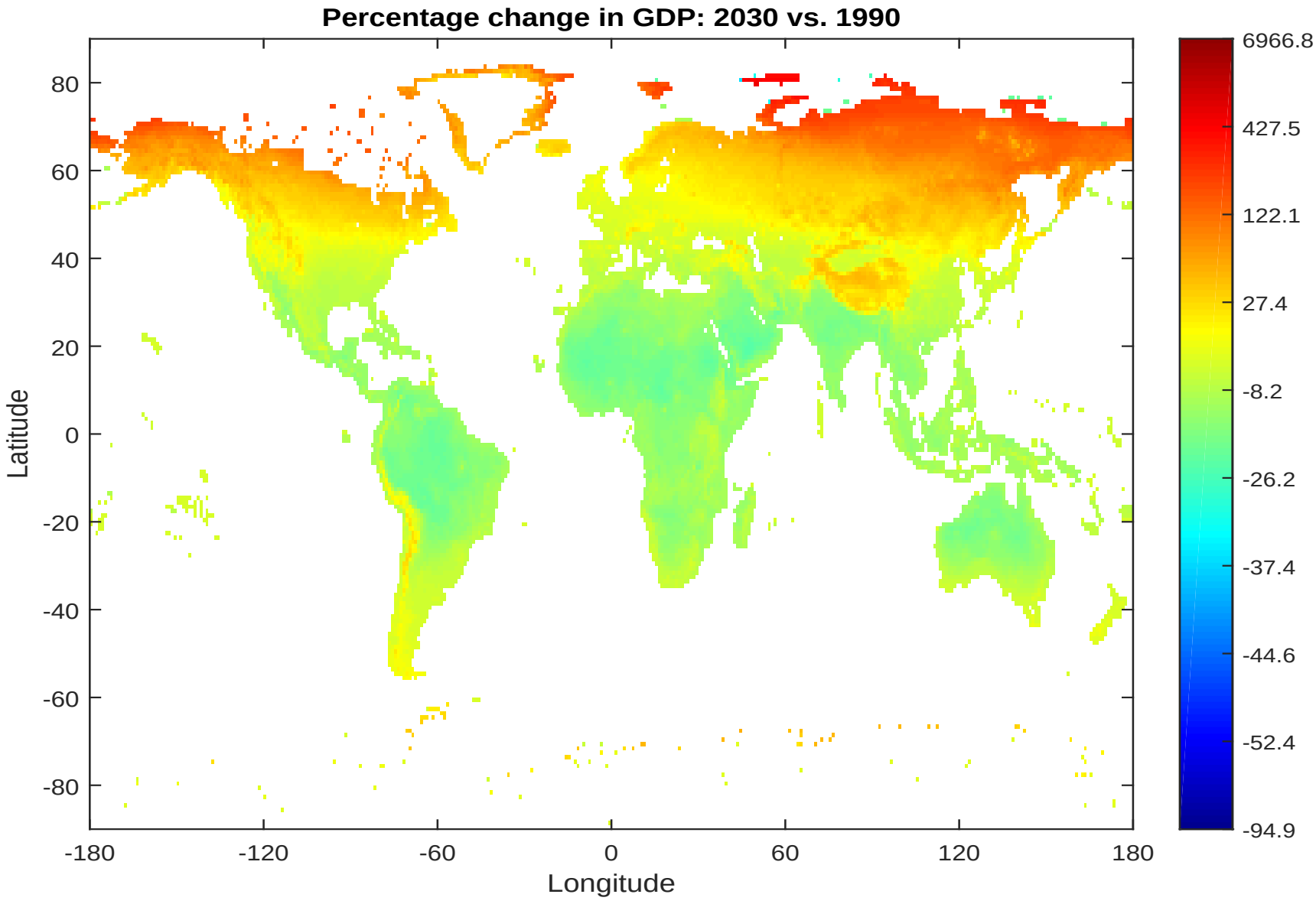

Distribution of marginal product of capital in 2299
(triangle = unweighted; circle = weighted by GDP)
.310289
0
.123281
.128166
Marginal product of capital

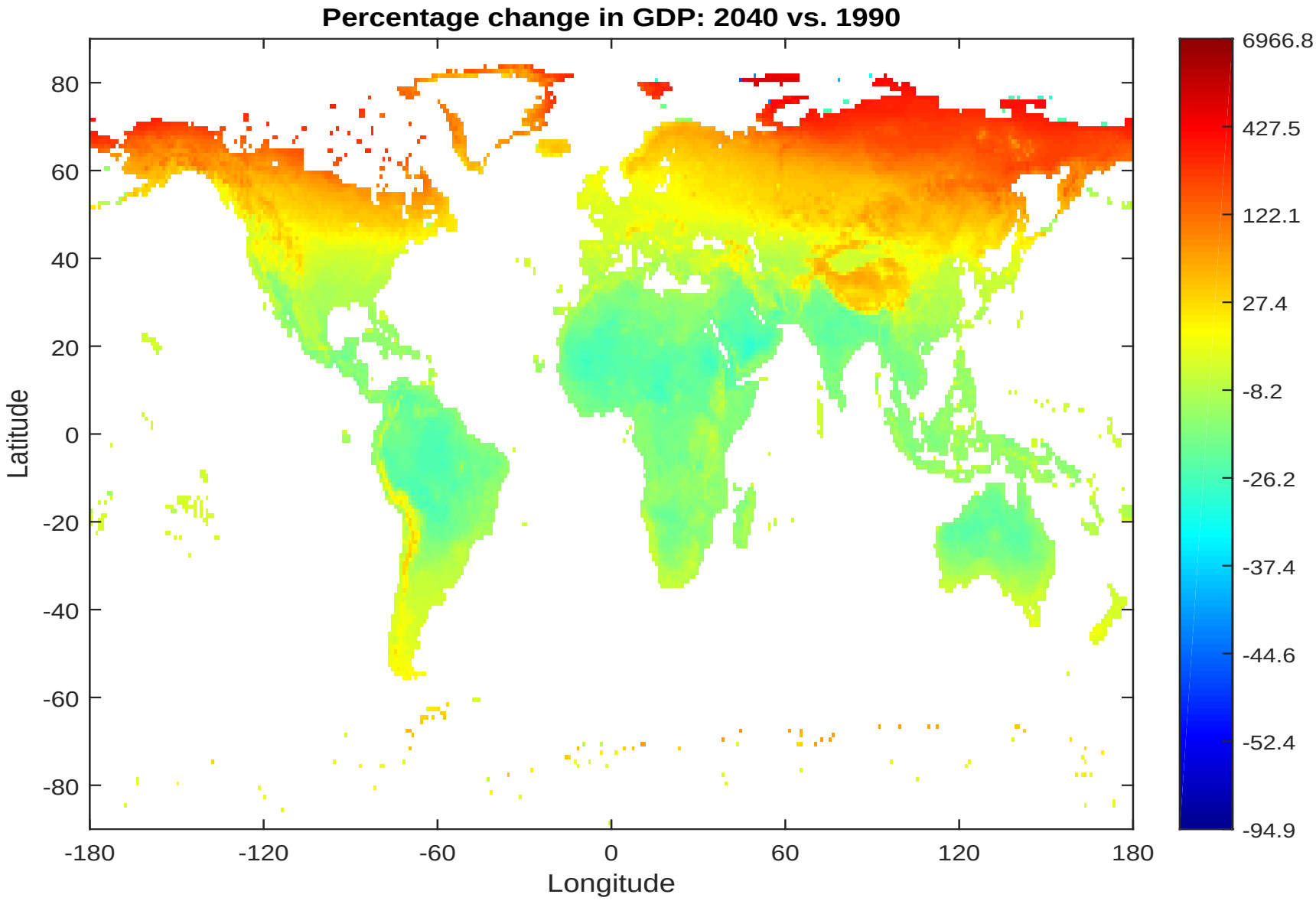
movie: percentage change in gdp, laissez-faire

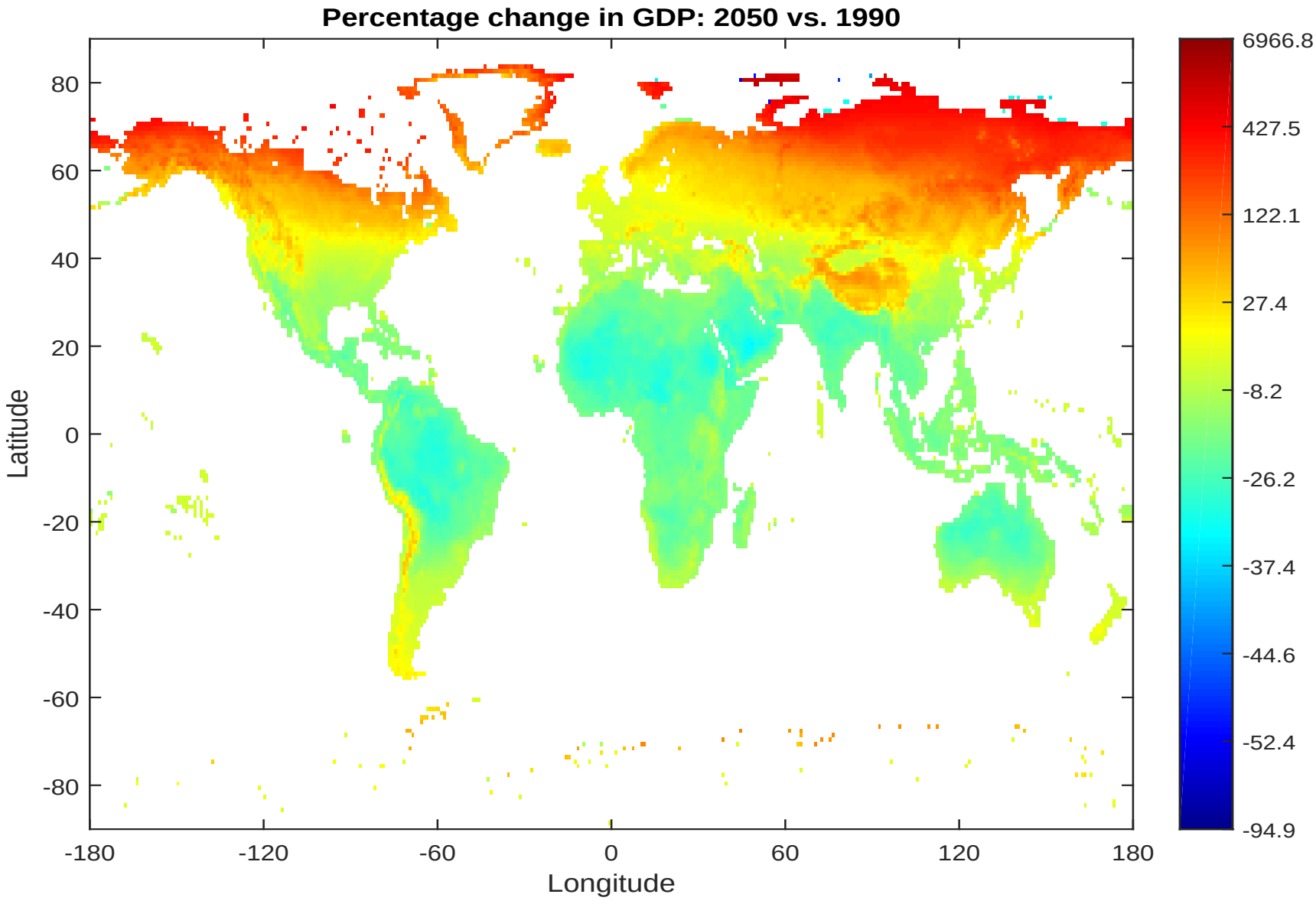

Percentage change in GDP: 2000 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

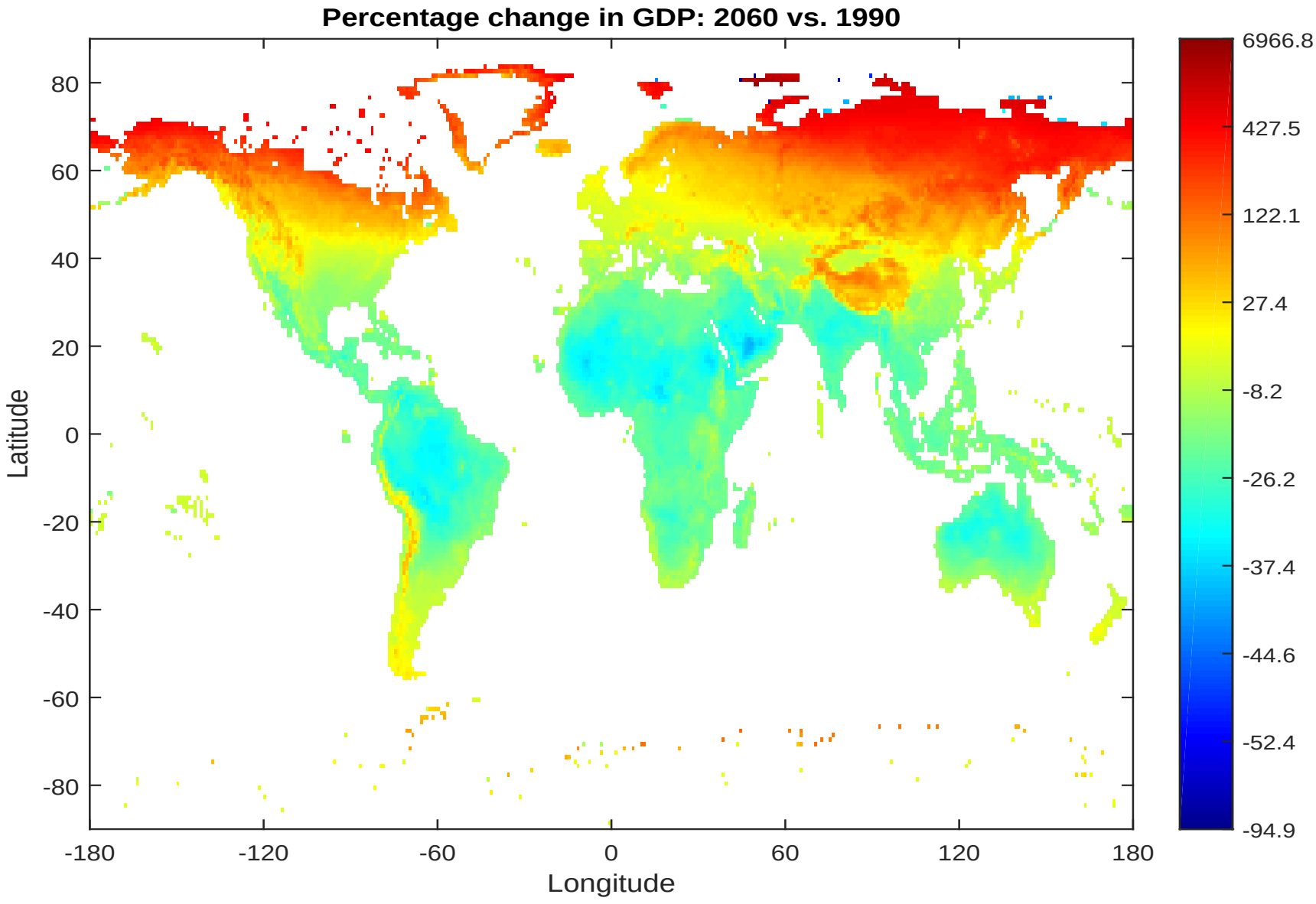

Percentage change in GDP: 2010 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

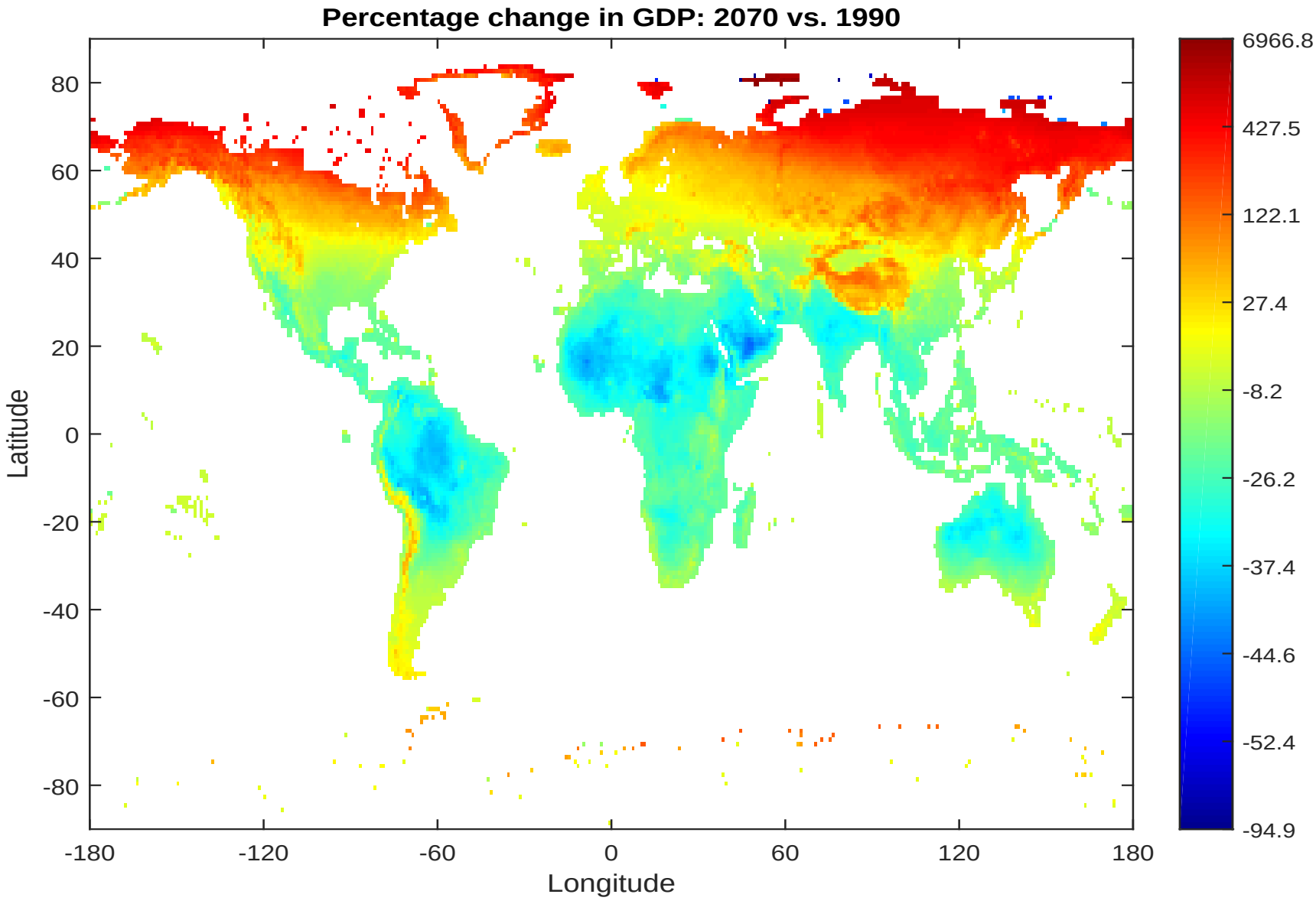

Percentage change in GDP: 2020 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
Longitude
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

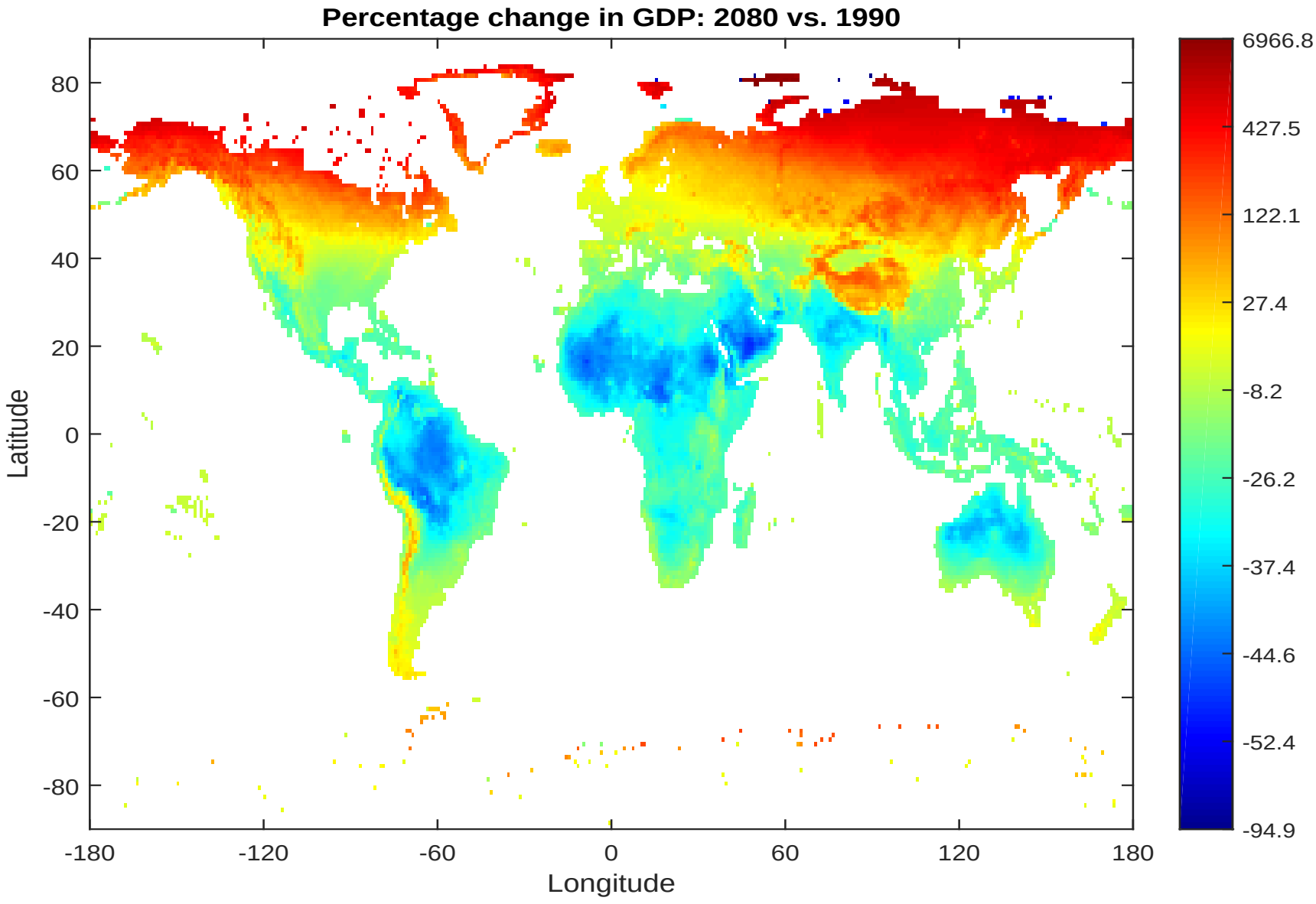

Percentage change in GDP: 2030 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

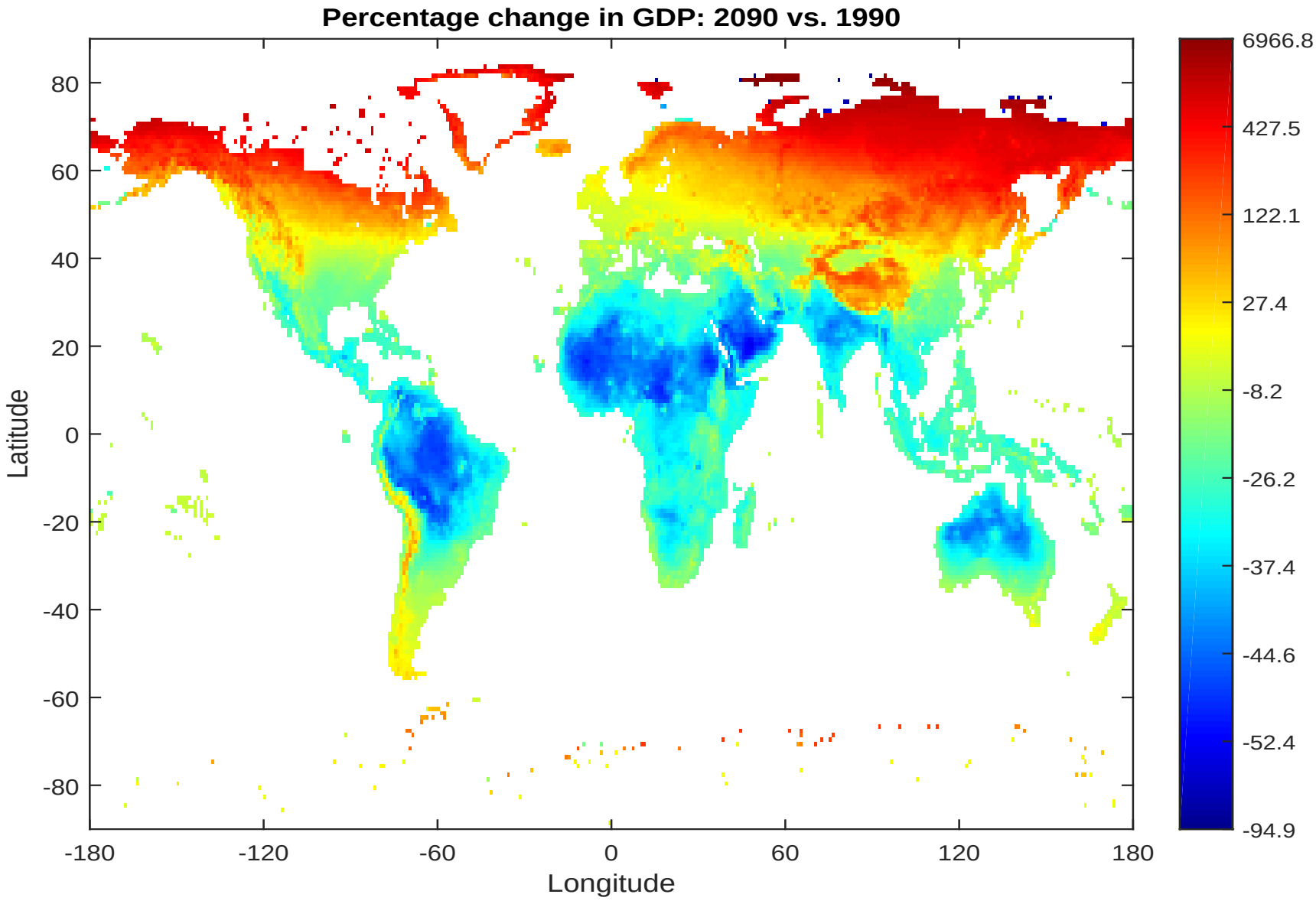

Percentage change in GDP: 2040 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

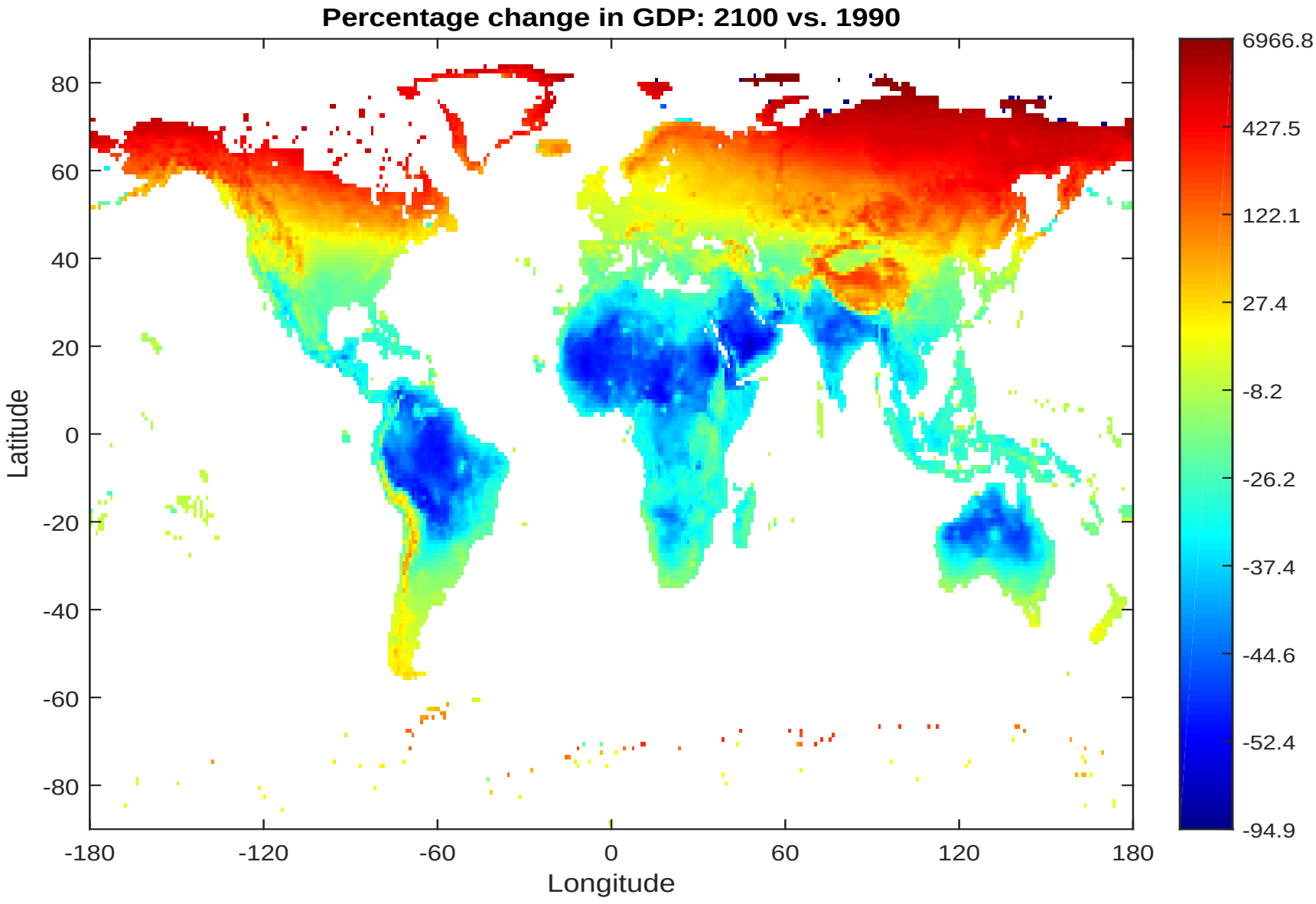

Percentage change in GDP: 2050 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

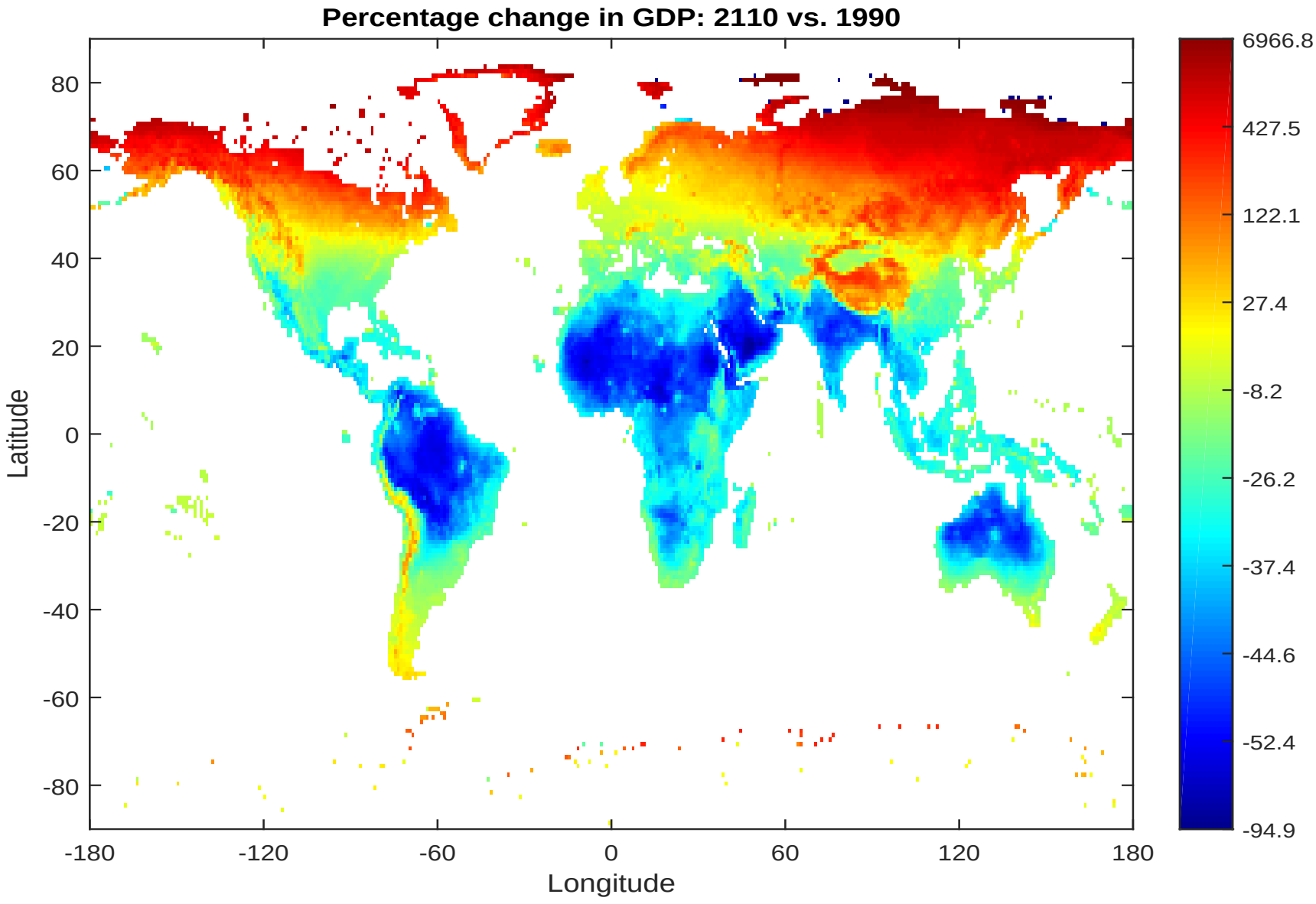

Percentage change in GDP: 2060 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

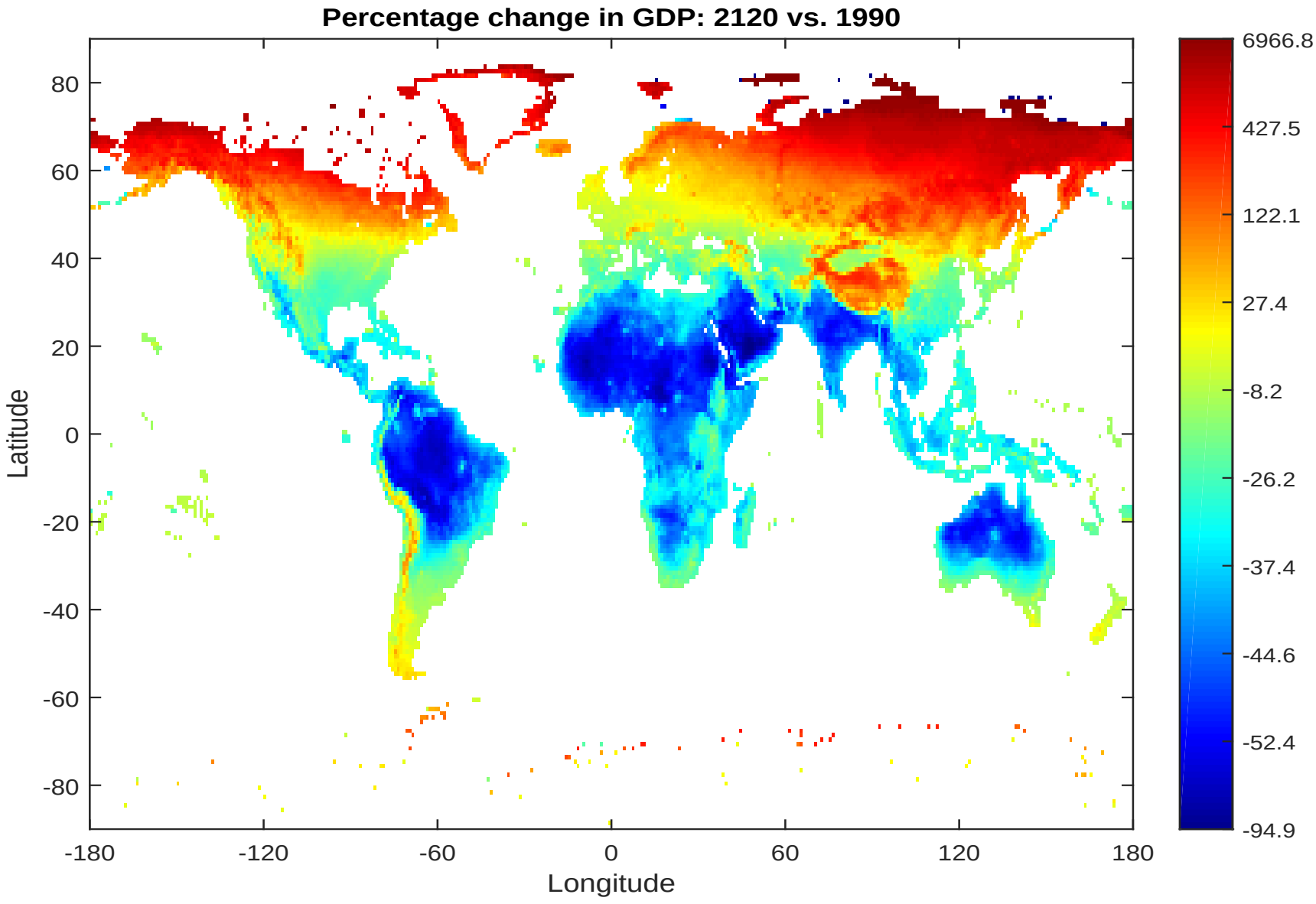

Percentage change in GDP: 2070 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

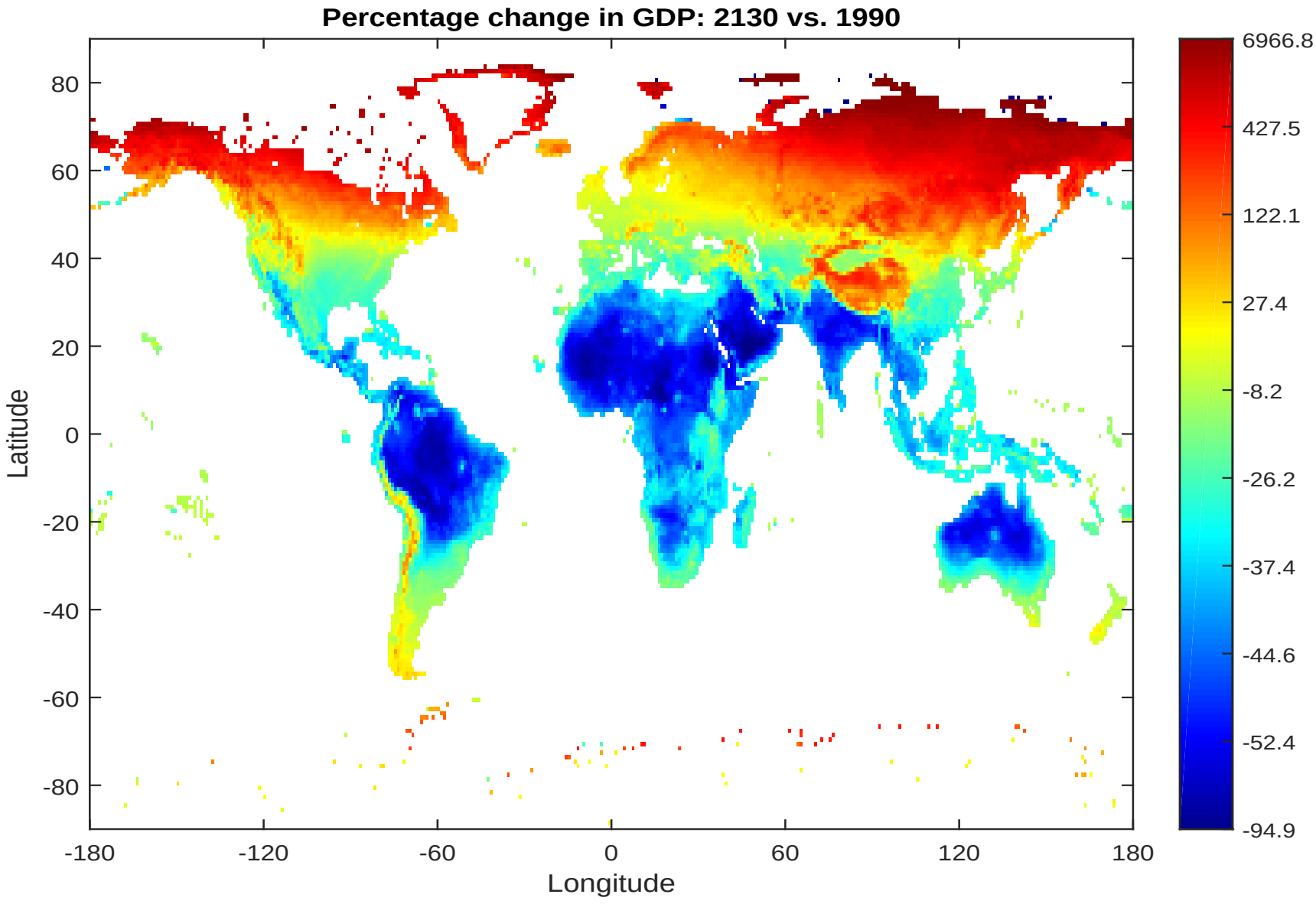

Percentage change in GDP: 2080 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

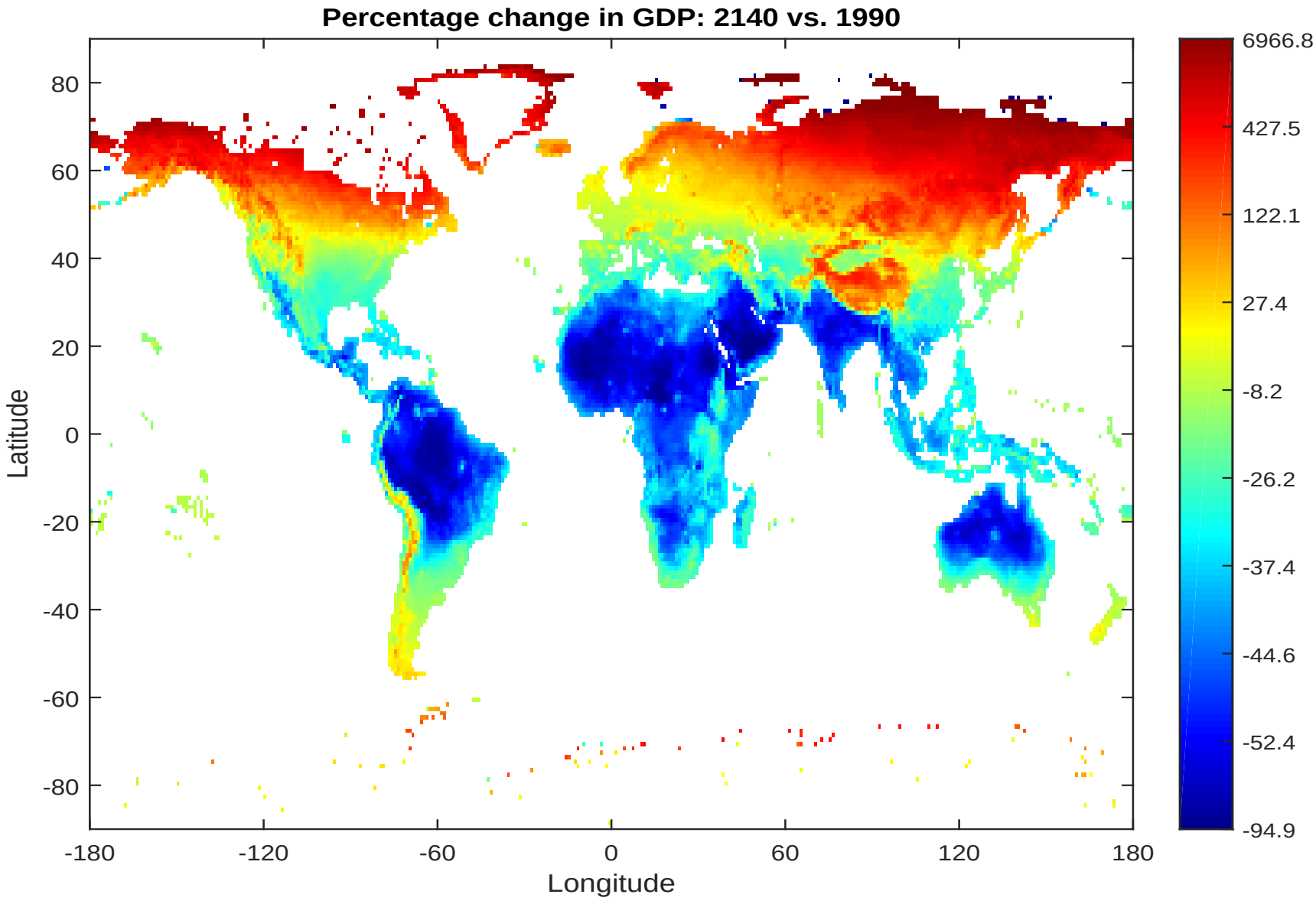

Percentage change in GDP: 2090 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

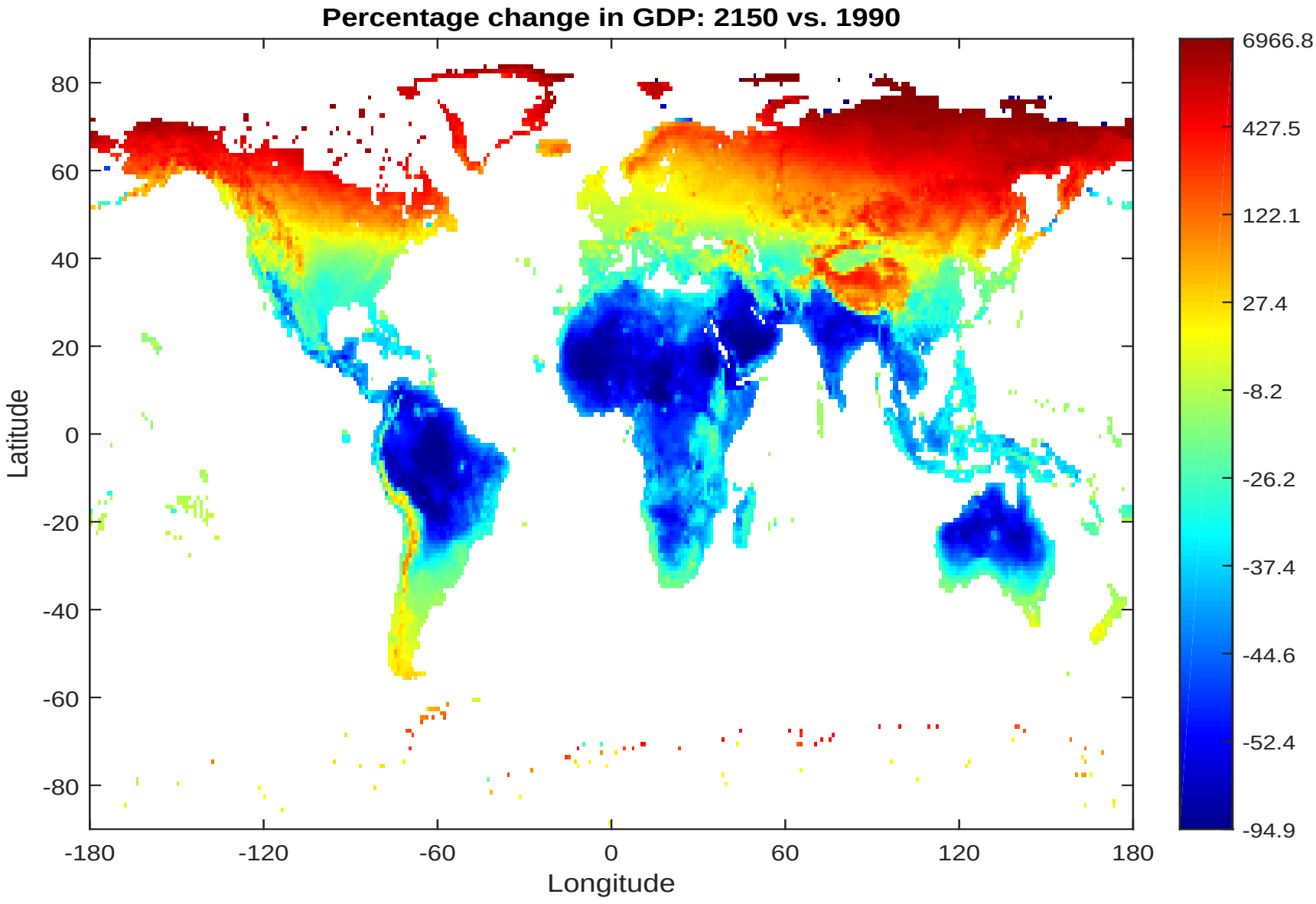

Percentage change in GDP: 2100 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

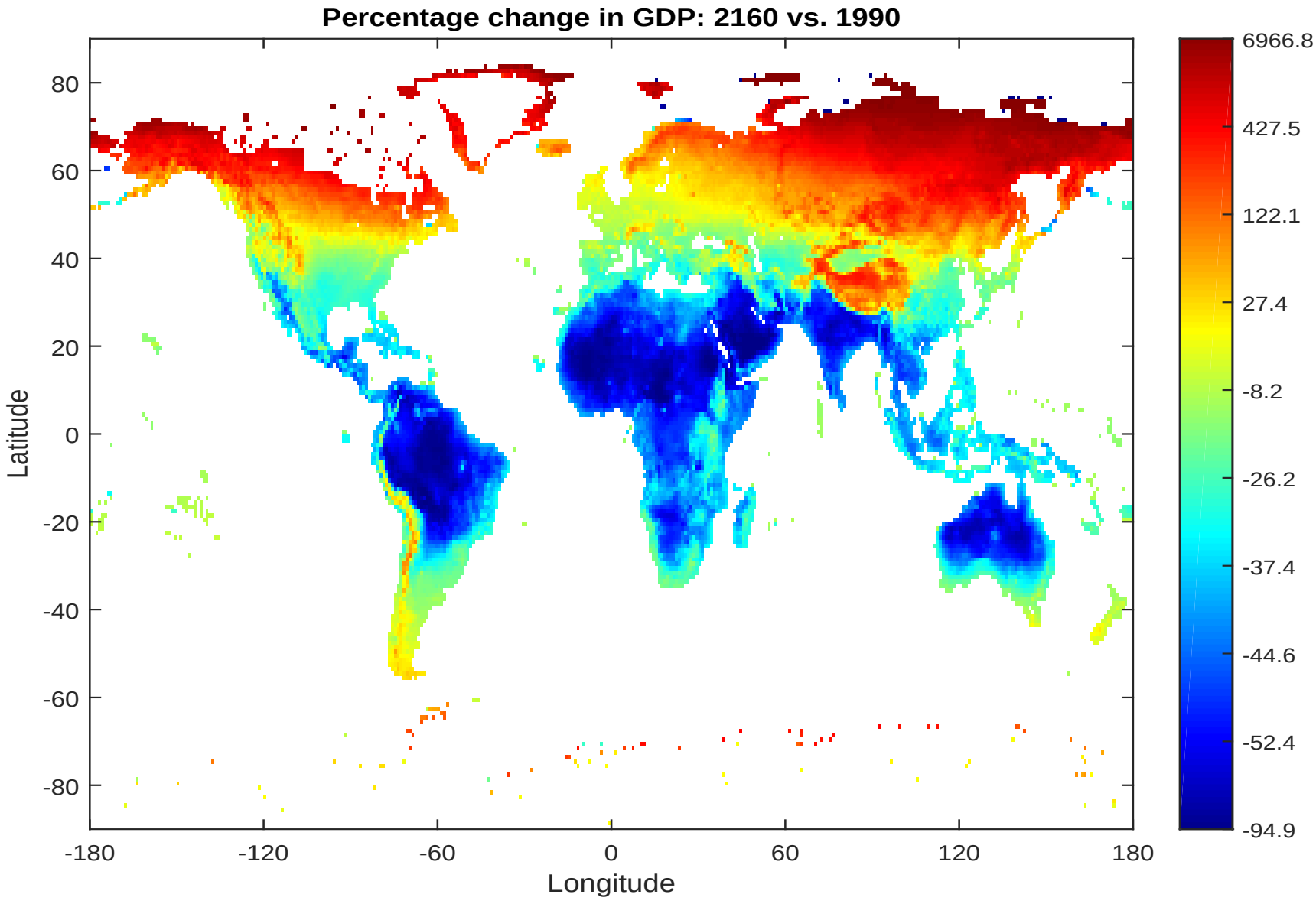

Percentage change in GDP: 2110 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

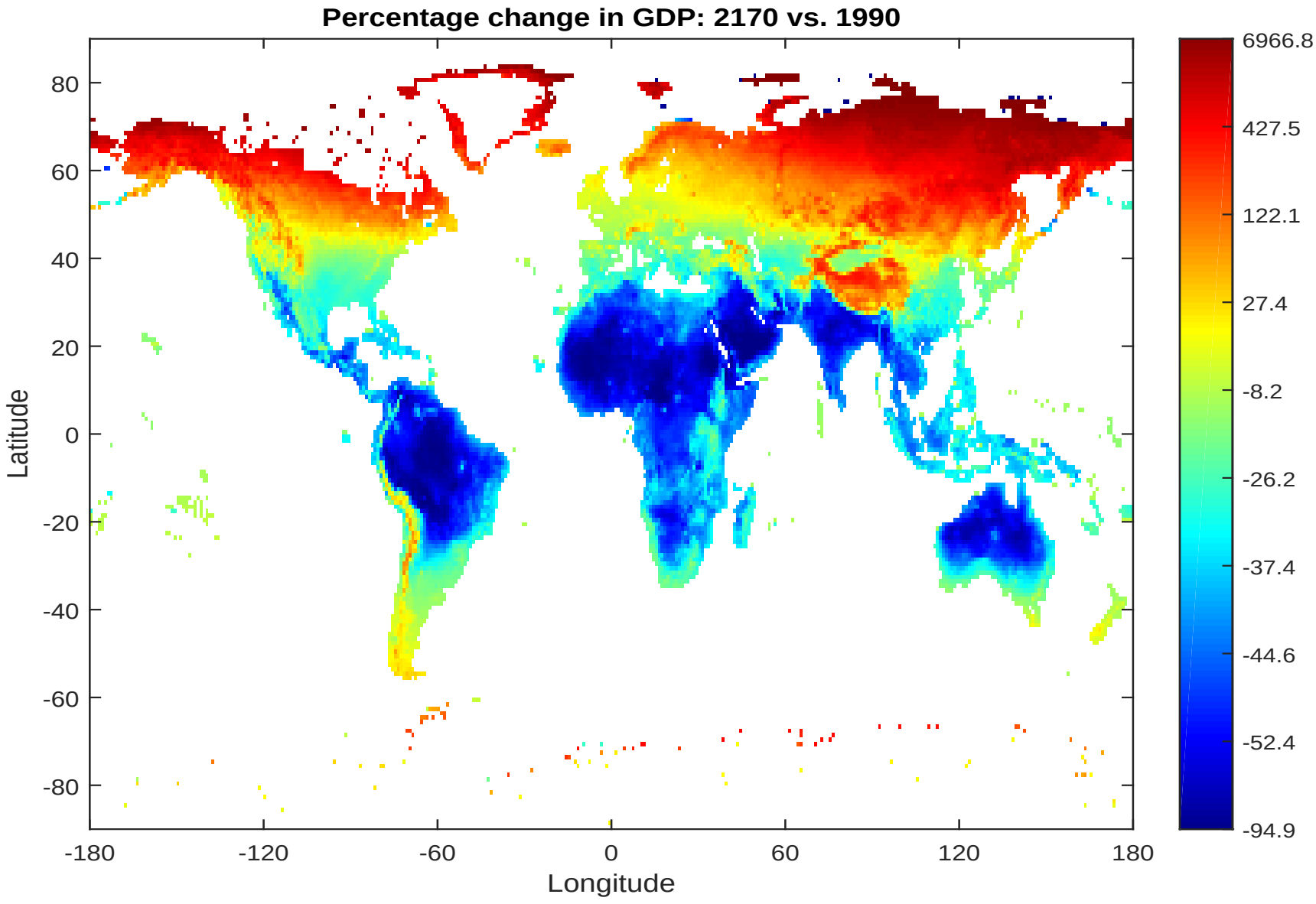

Percentage change in GDP: 2120 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

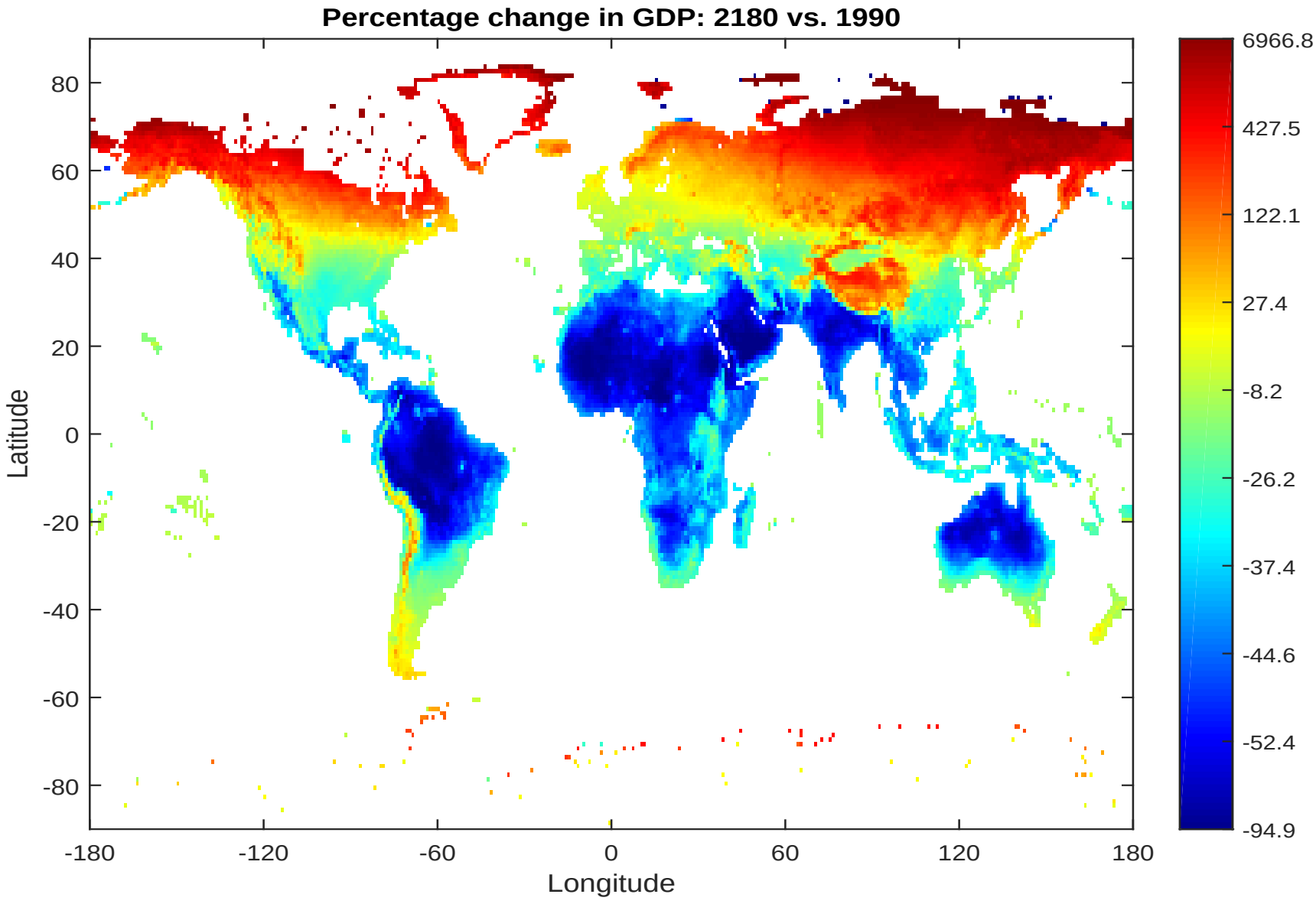

Percentage change in GDP: 2130 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

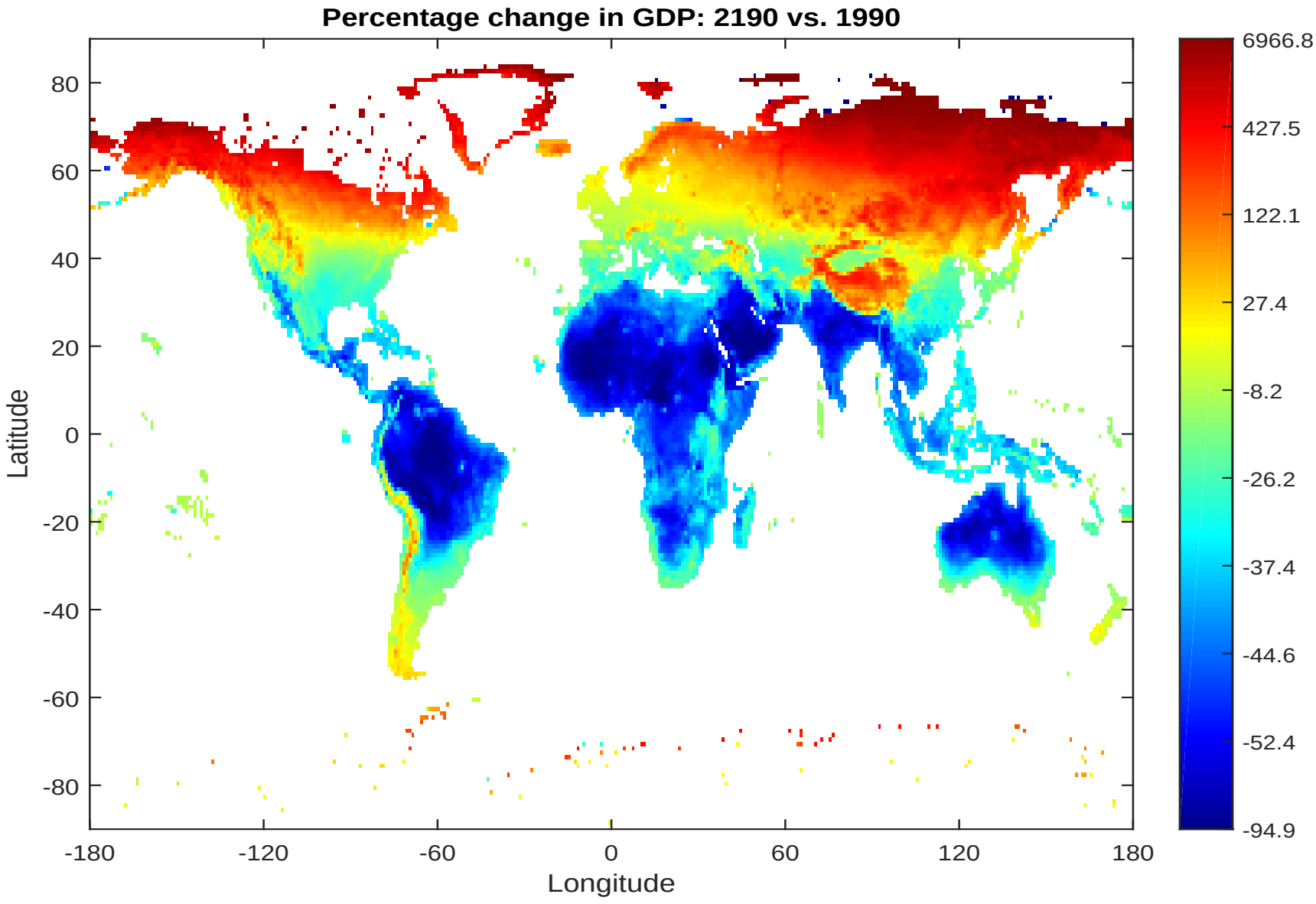

Percentage change in GDP: 2140 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

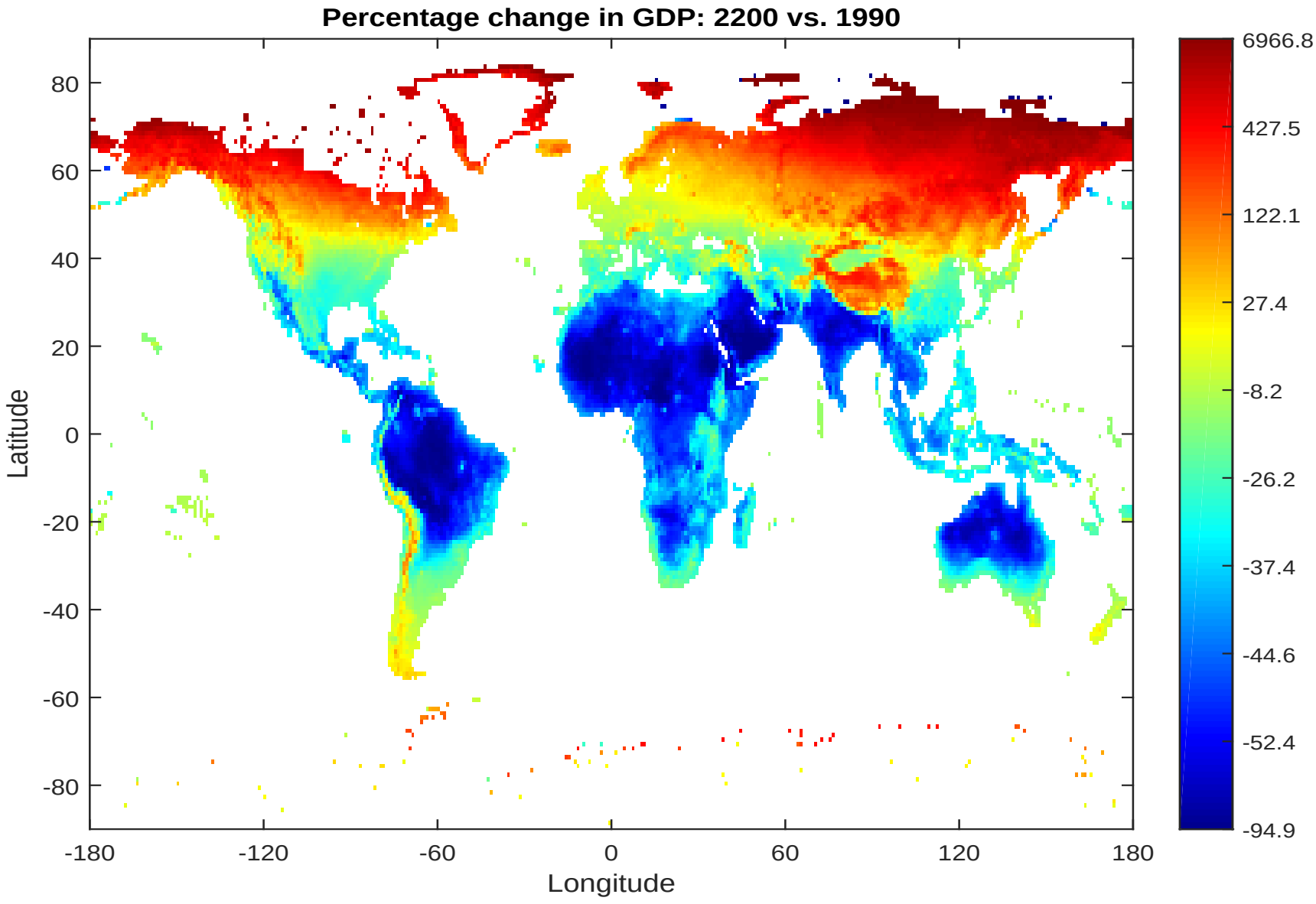

Percentage change in GDP: 2150 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9


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
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

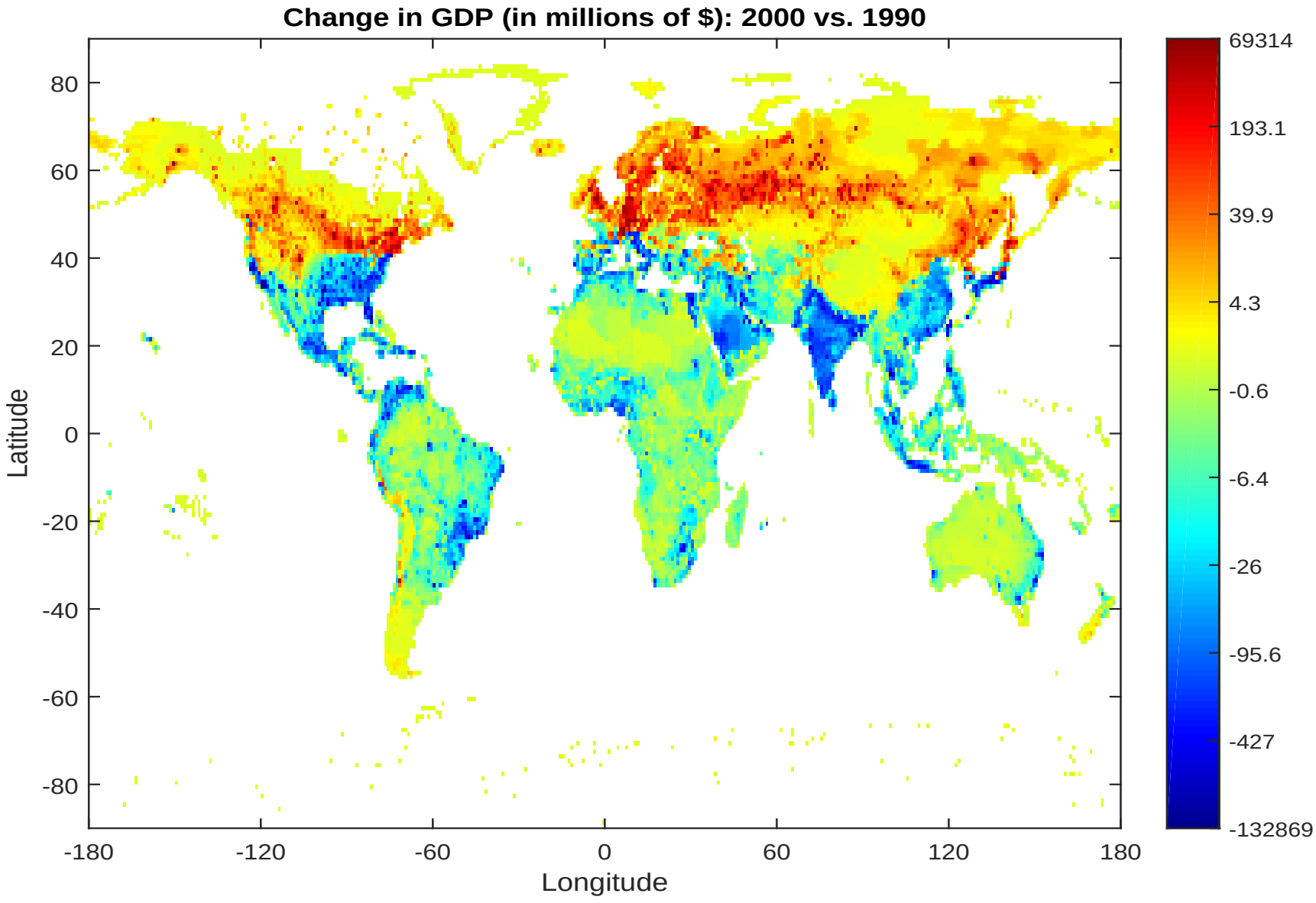

Percentage change in GDP: 2170 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

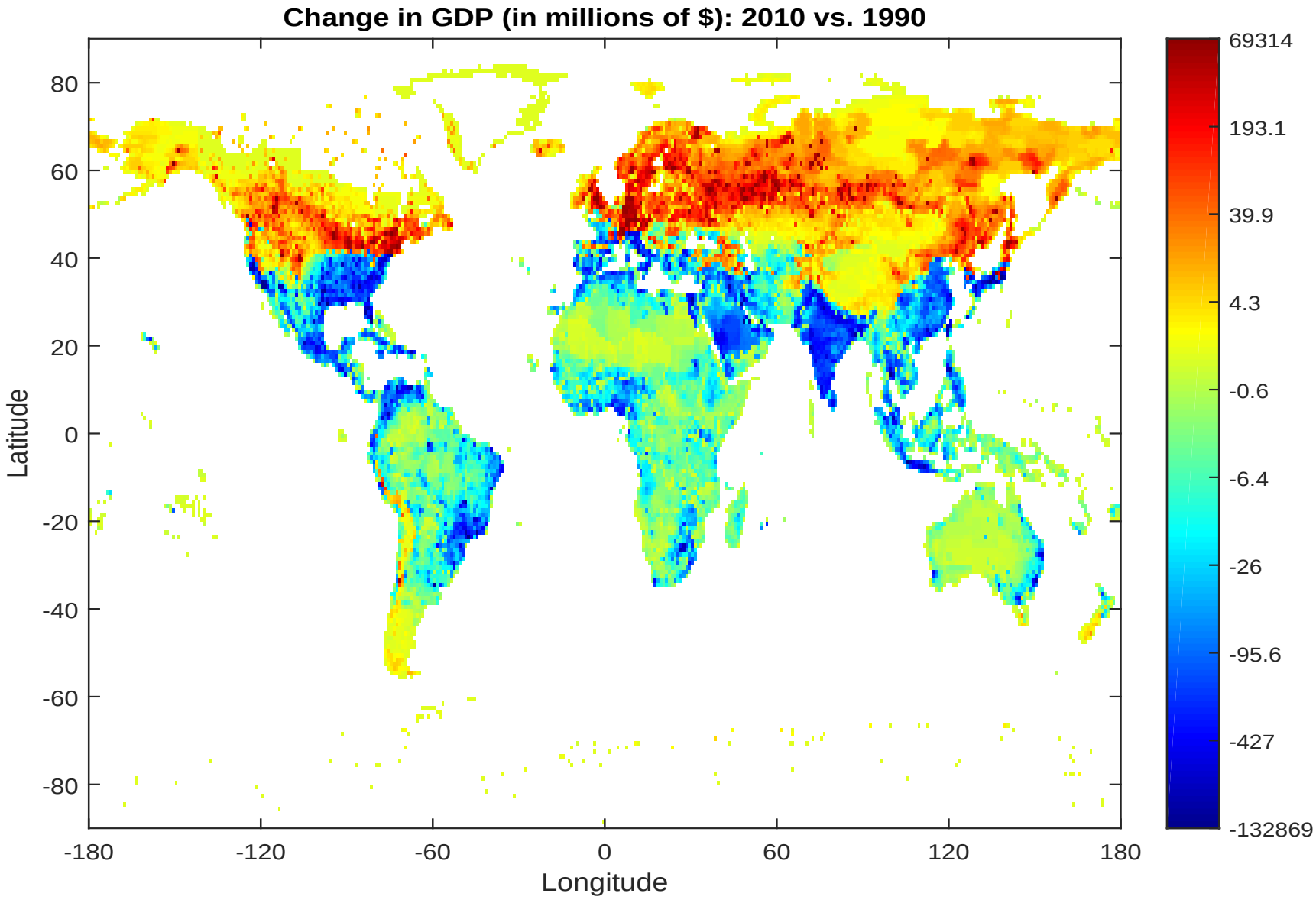

Percentage change in GDP: 2180 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

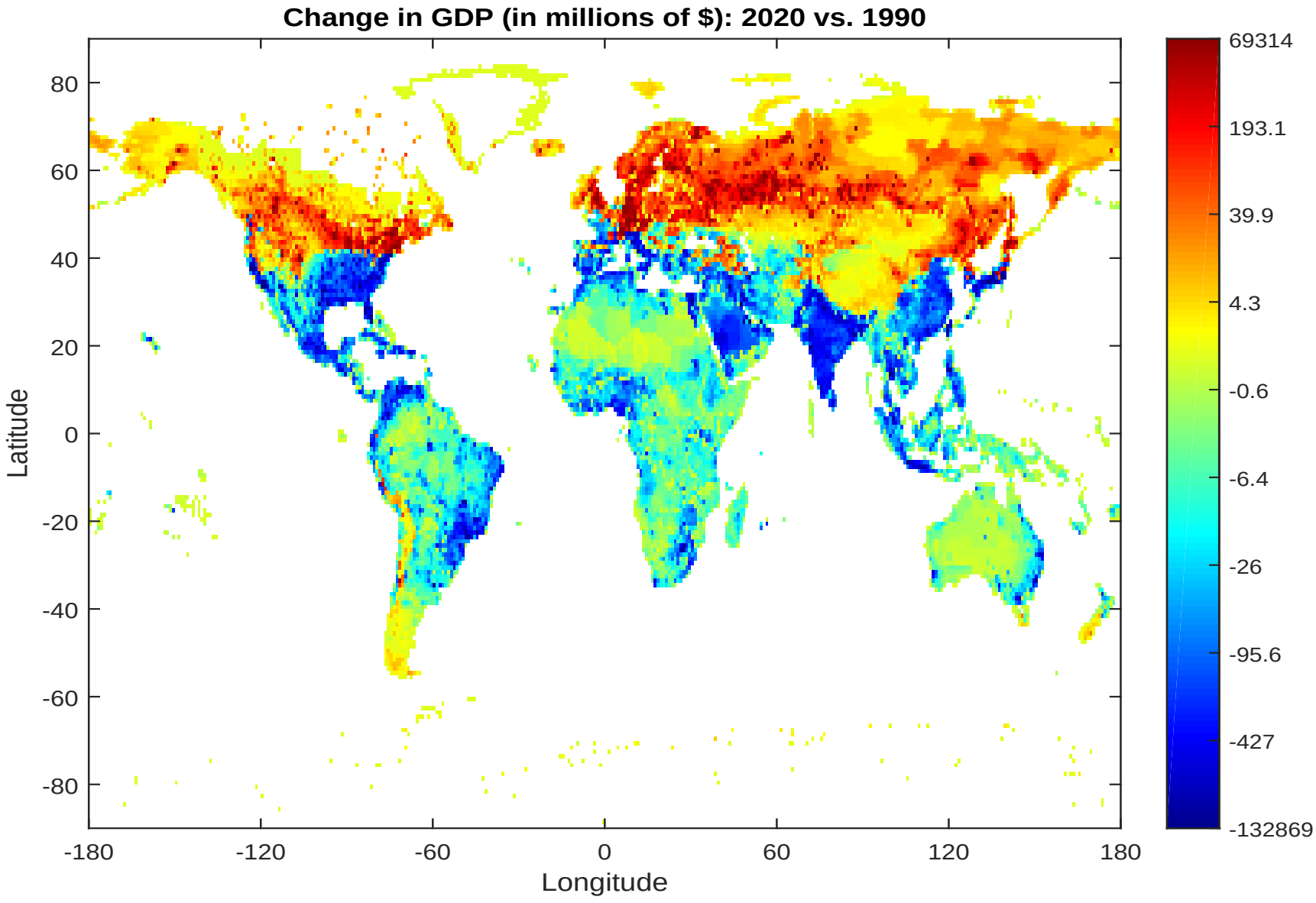

Percentage change in GDP: 2190 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

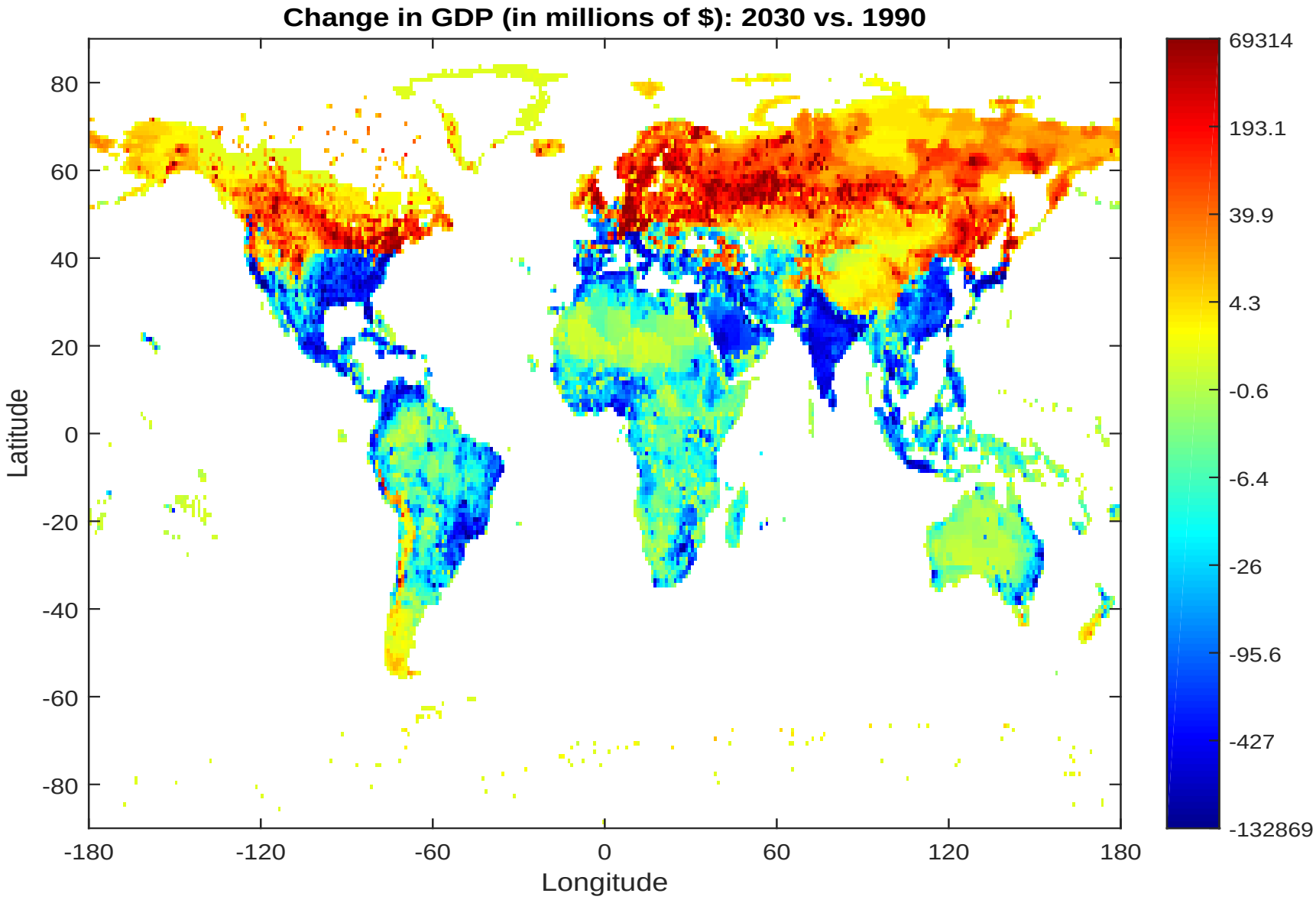

Percentage change in GDP: 2200 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6966.8
427.5
122.1
27.4
-8.2
-26.2
-37.4
-44.6
-52.4
-94.9

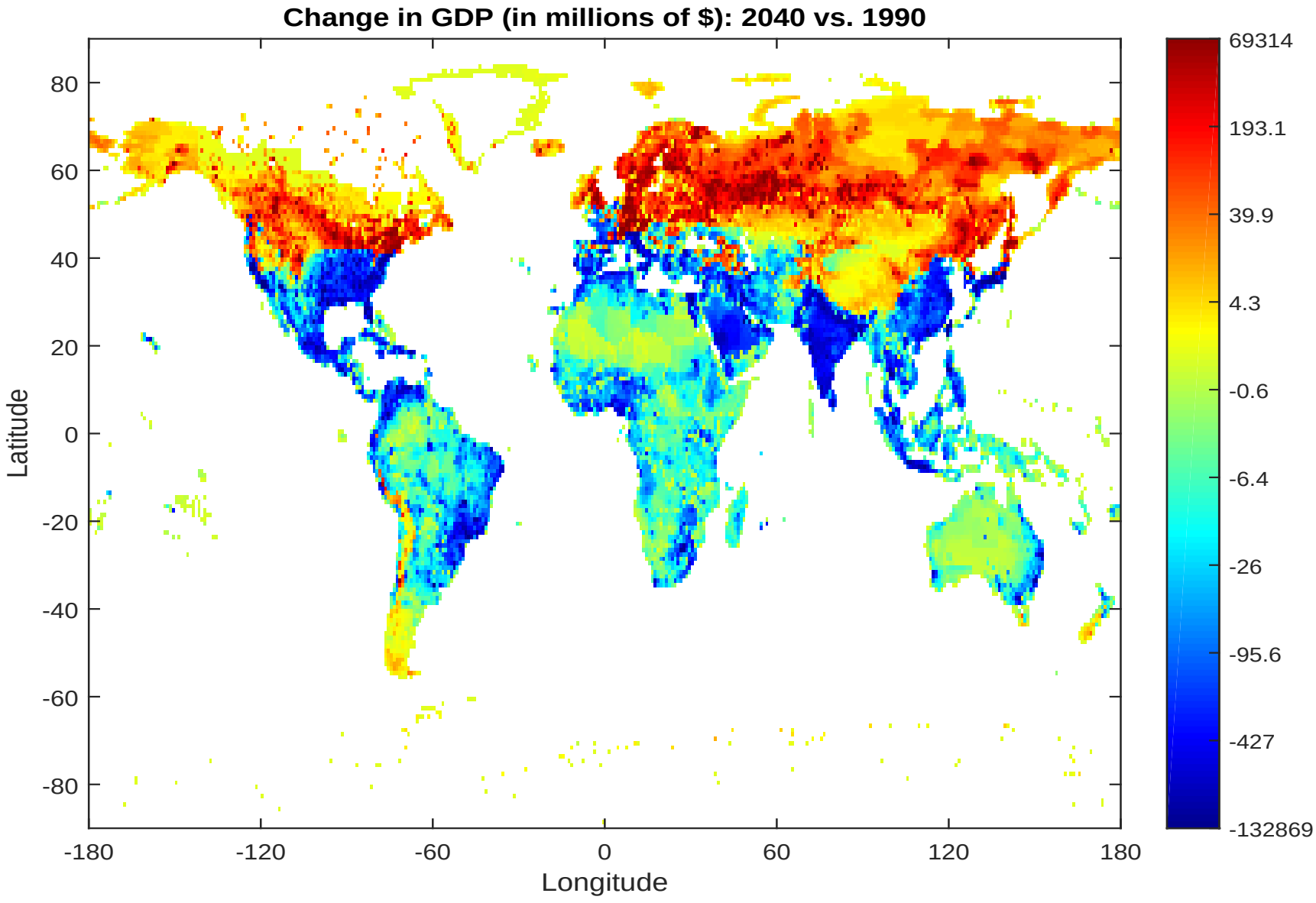
movie: level change in gdp, laissez-faire

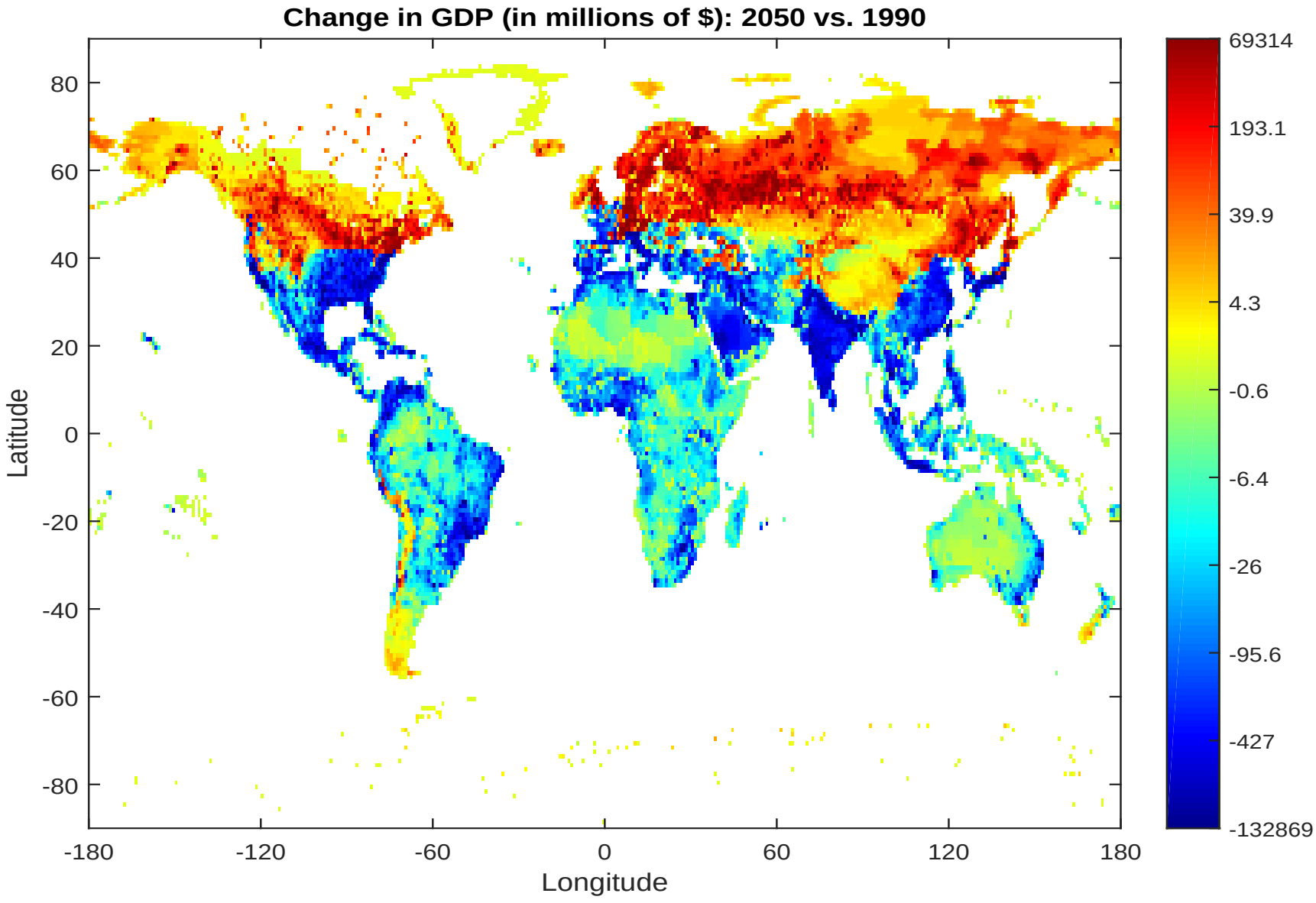

Change in GDP (in millions of $): 2000 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

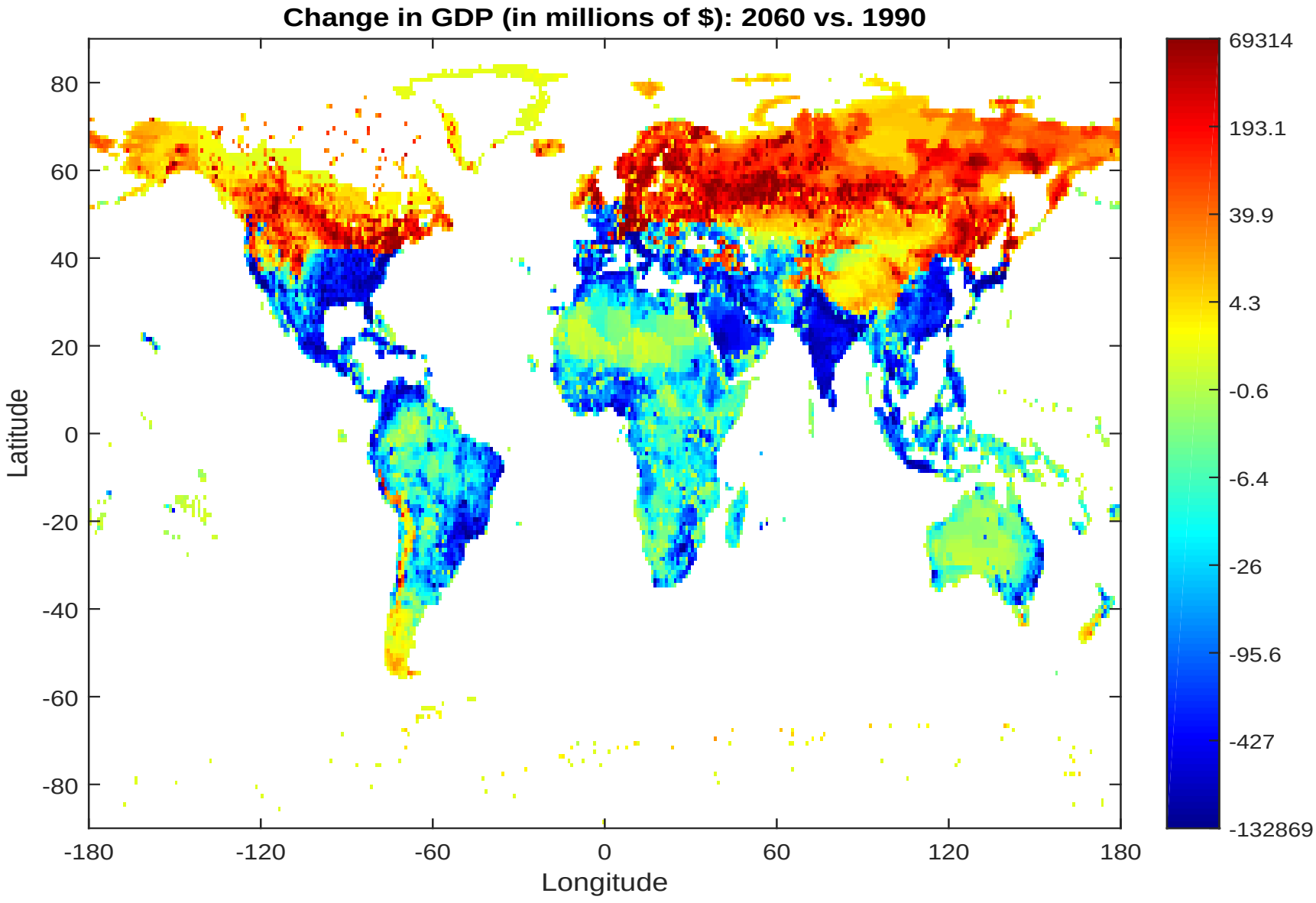

Change in GDP (in millions of $): 2010 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

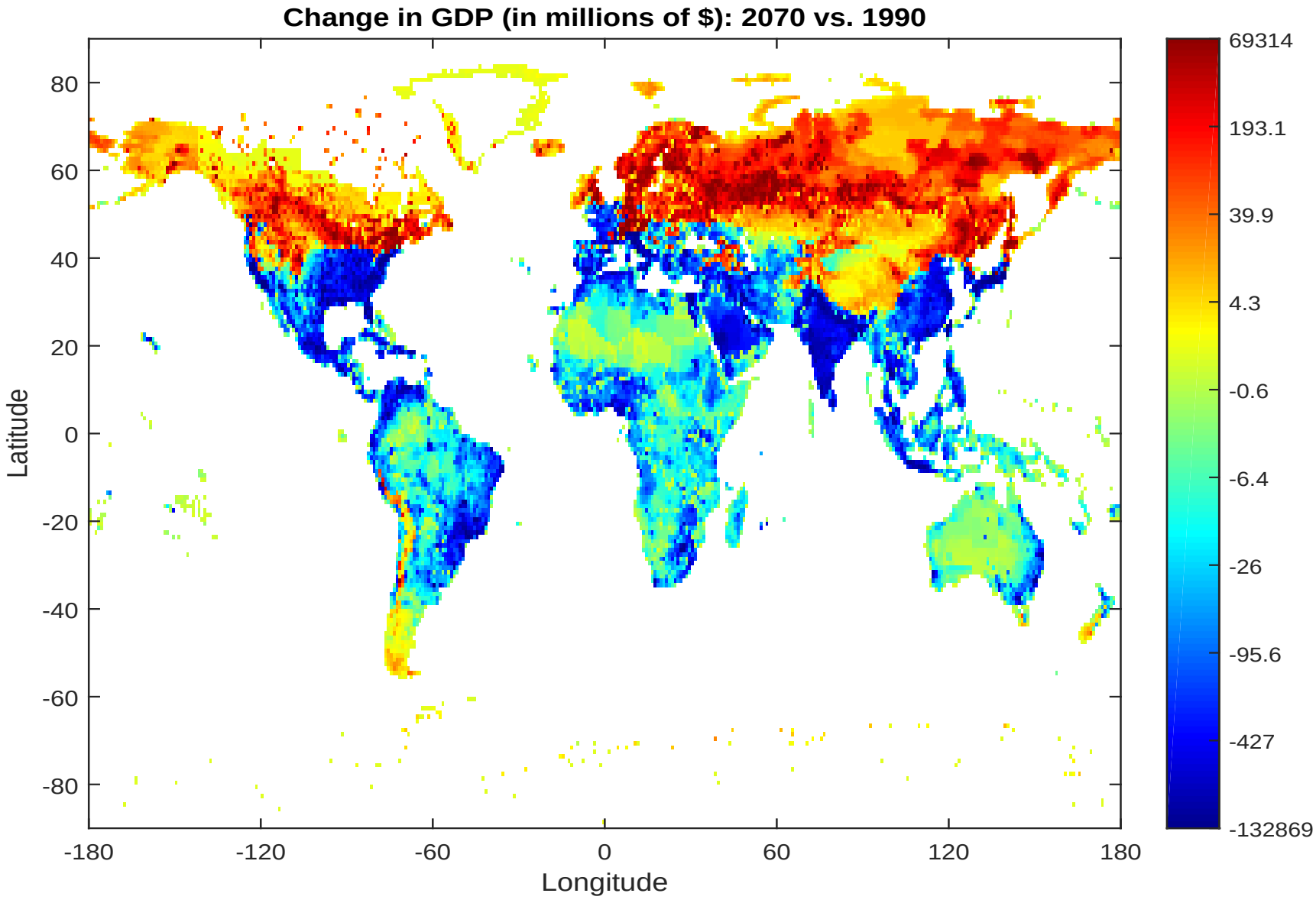

Change in GDP (in millions of $): 2020 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

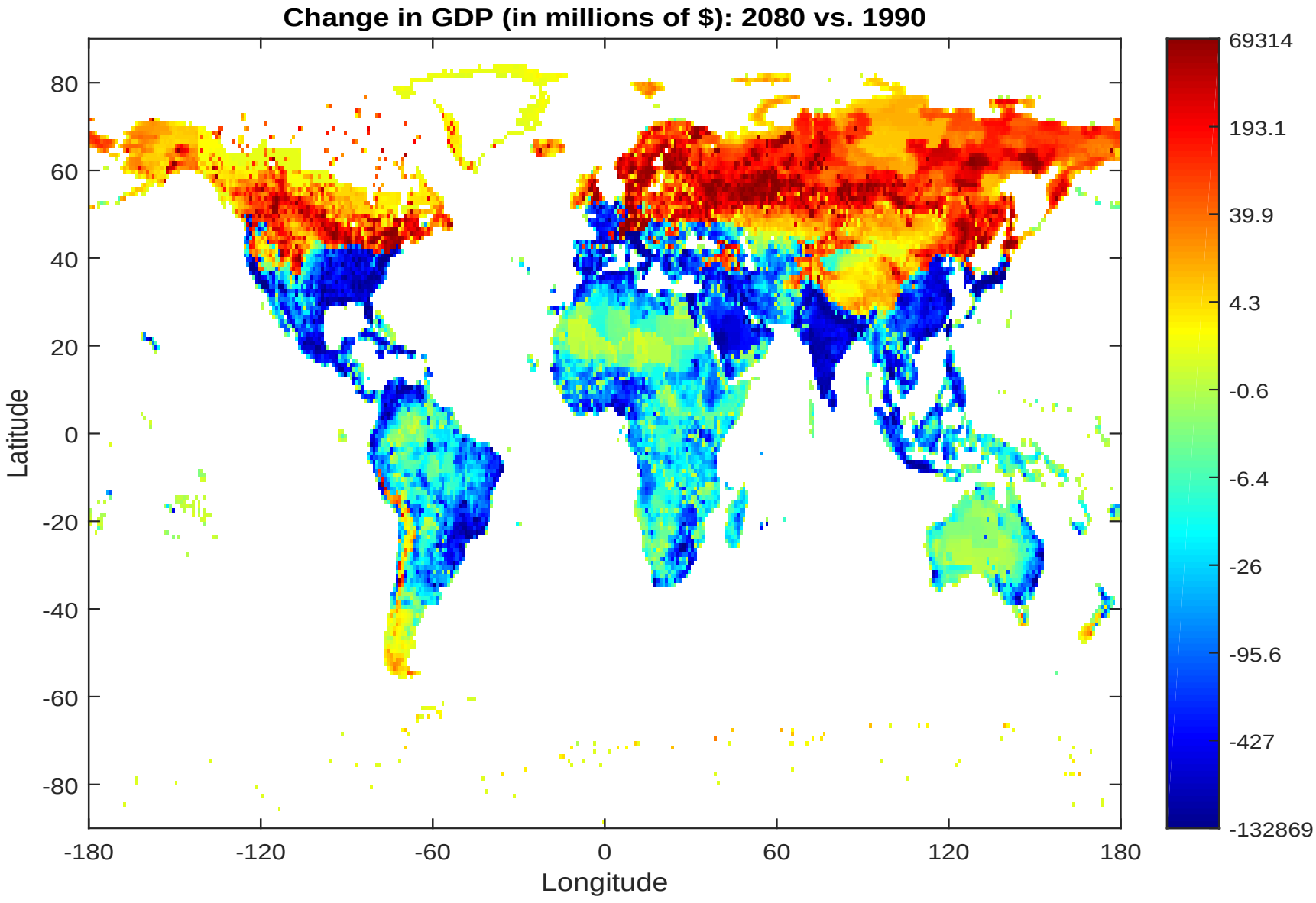

Change in GDP (in millions of $): 2030 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

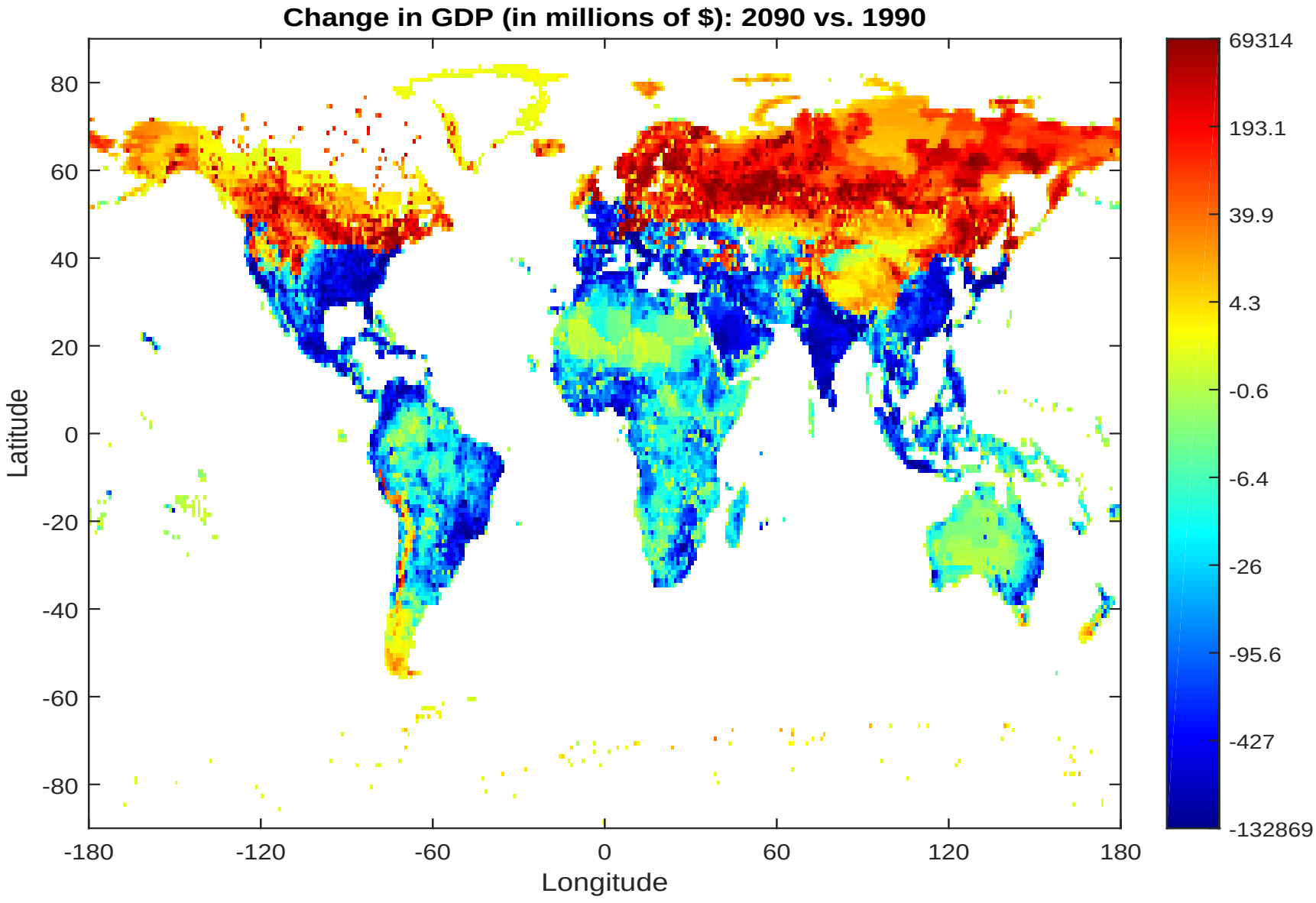

Change in GDP (in millions of $): 2040 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

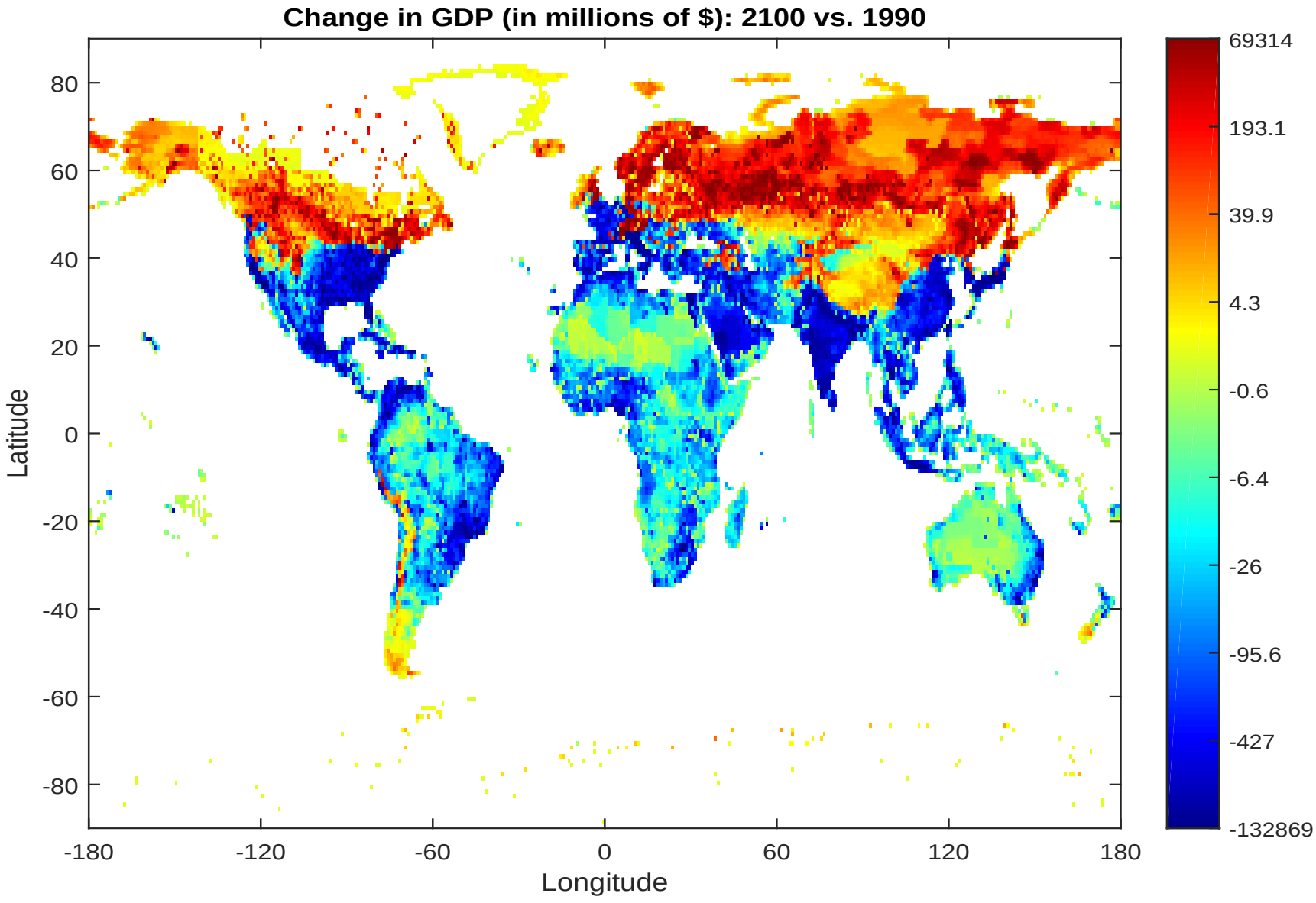

Change in GDP (in millions of $): 2050 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

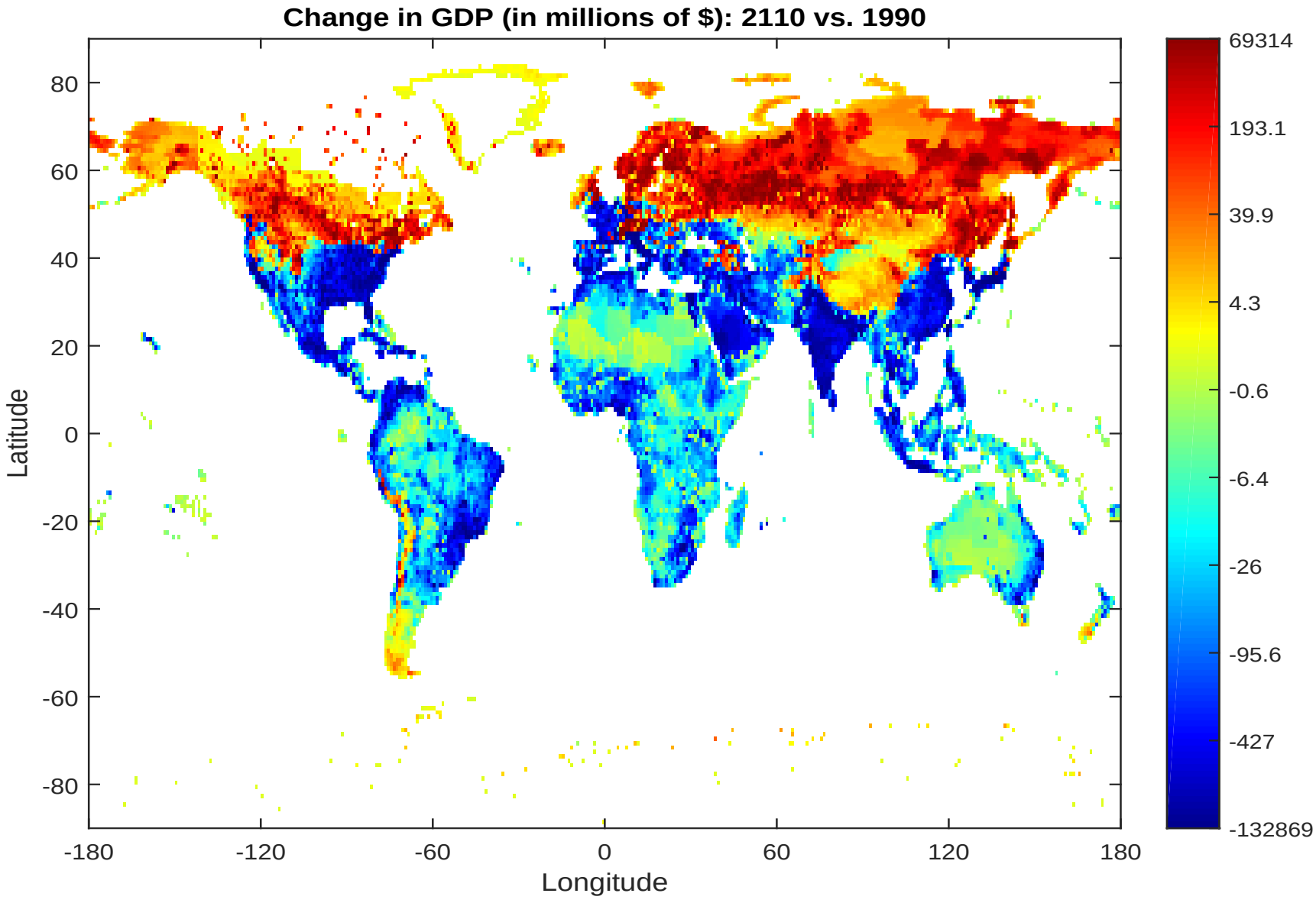

Change in GDP (in millions of $): 2060 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

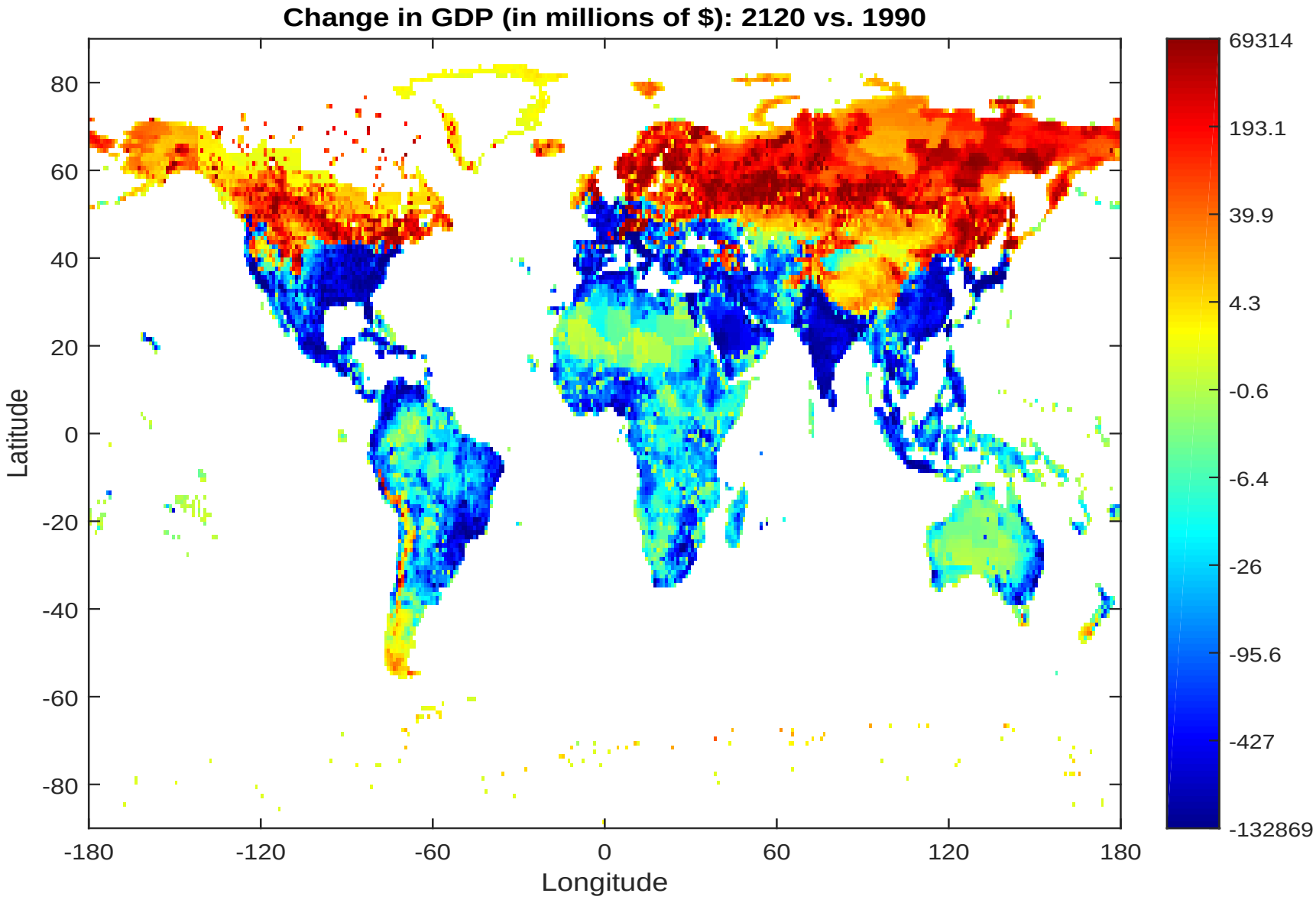

Change in GDP (in millions of $): 2070 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

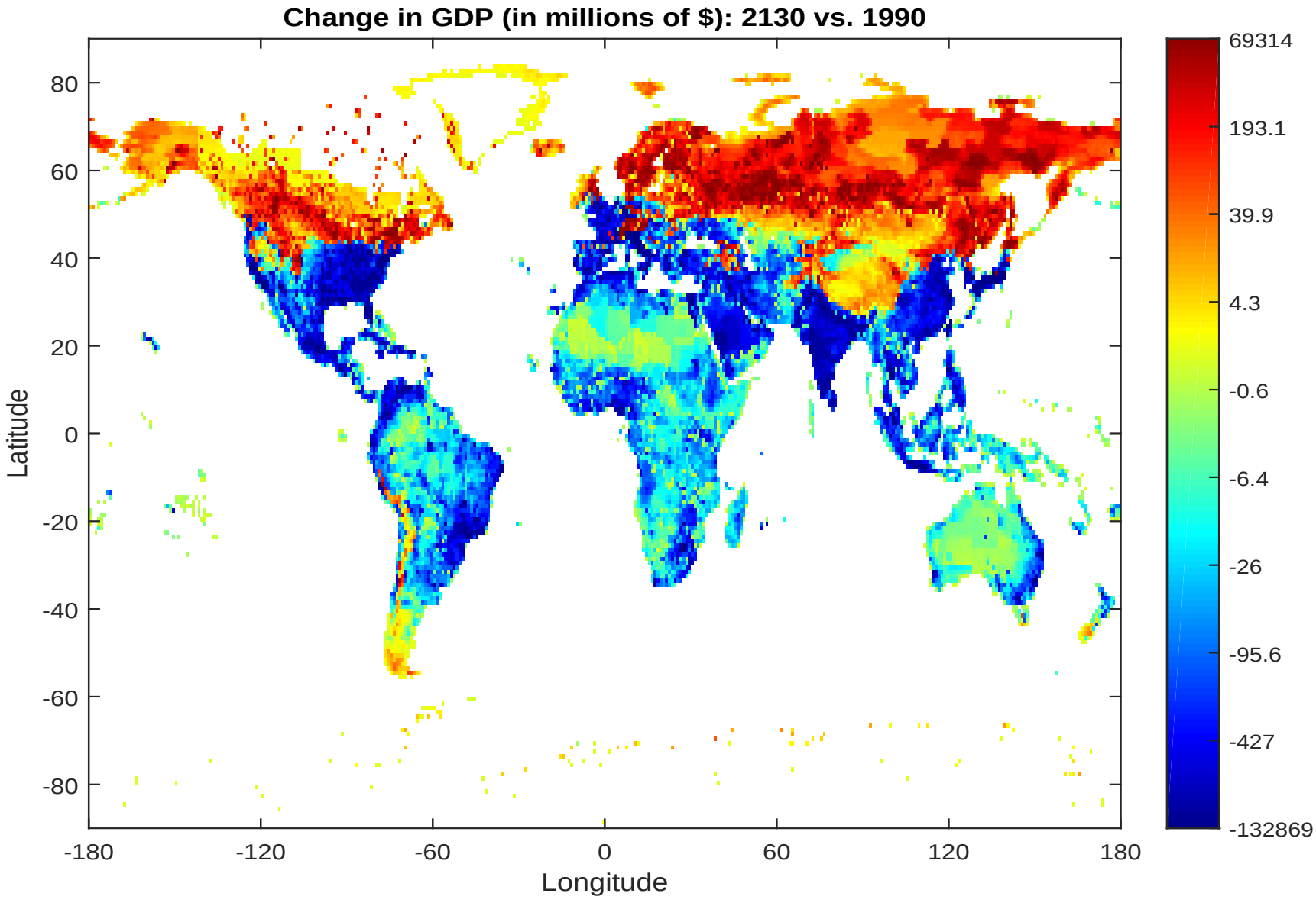

Change in GDP (in millions of $): 2080 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

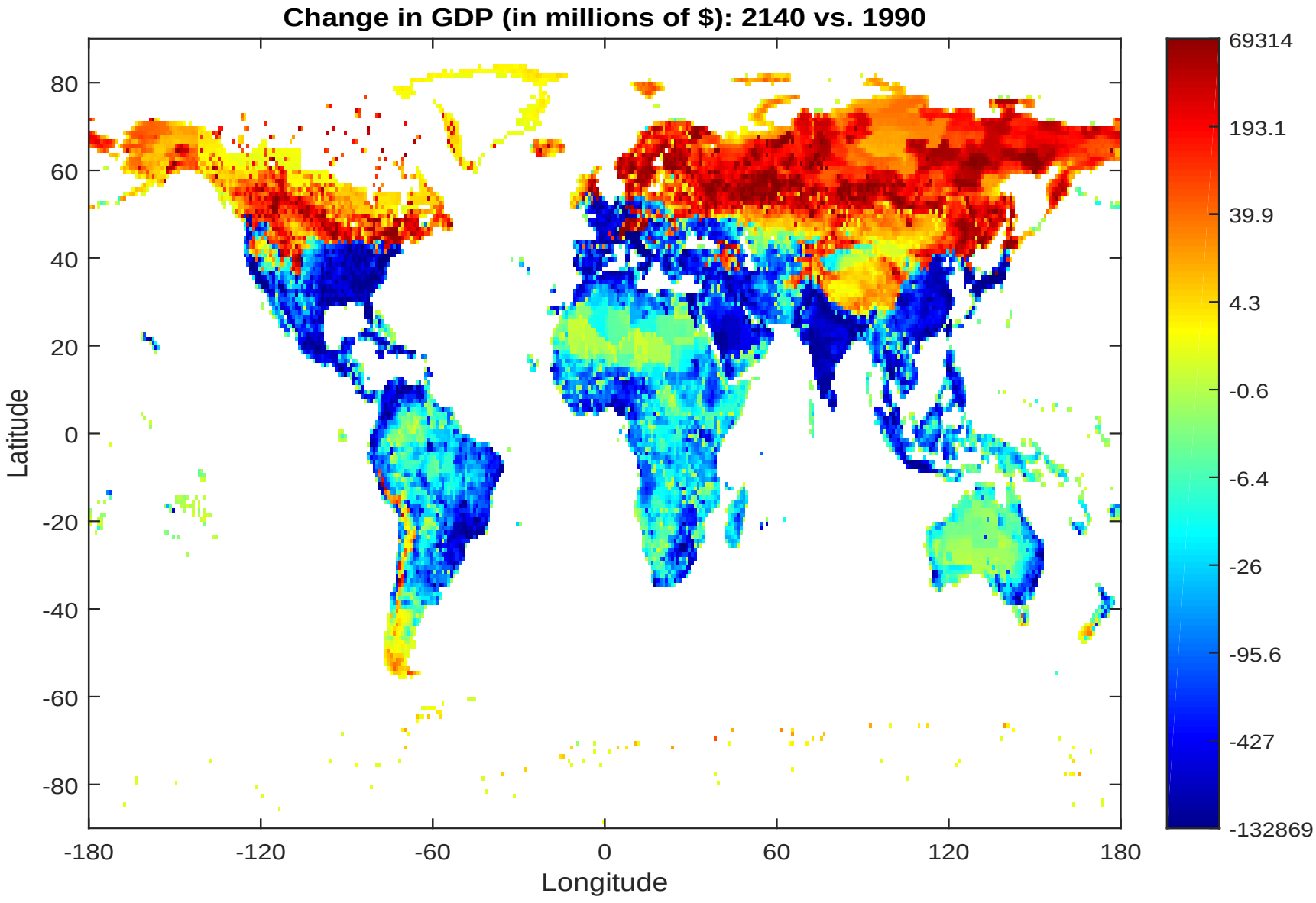

Change in GDP (in millions of $): 2090 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

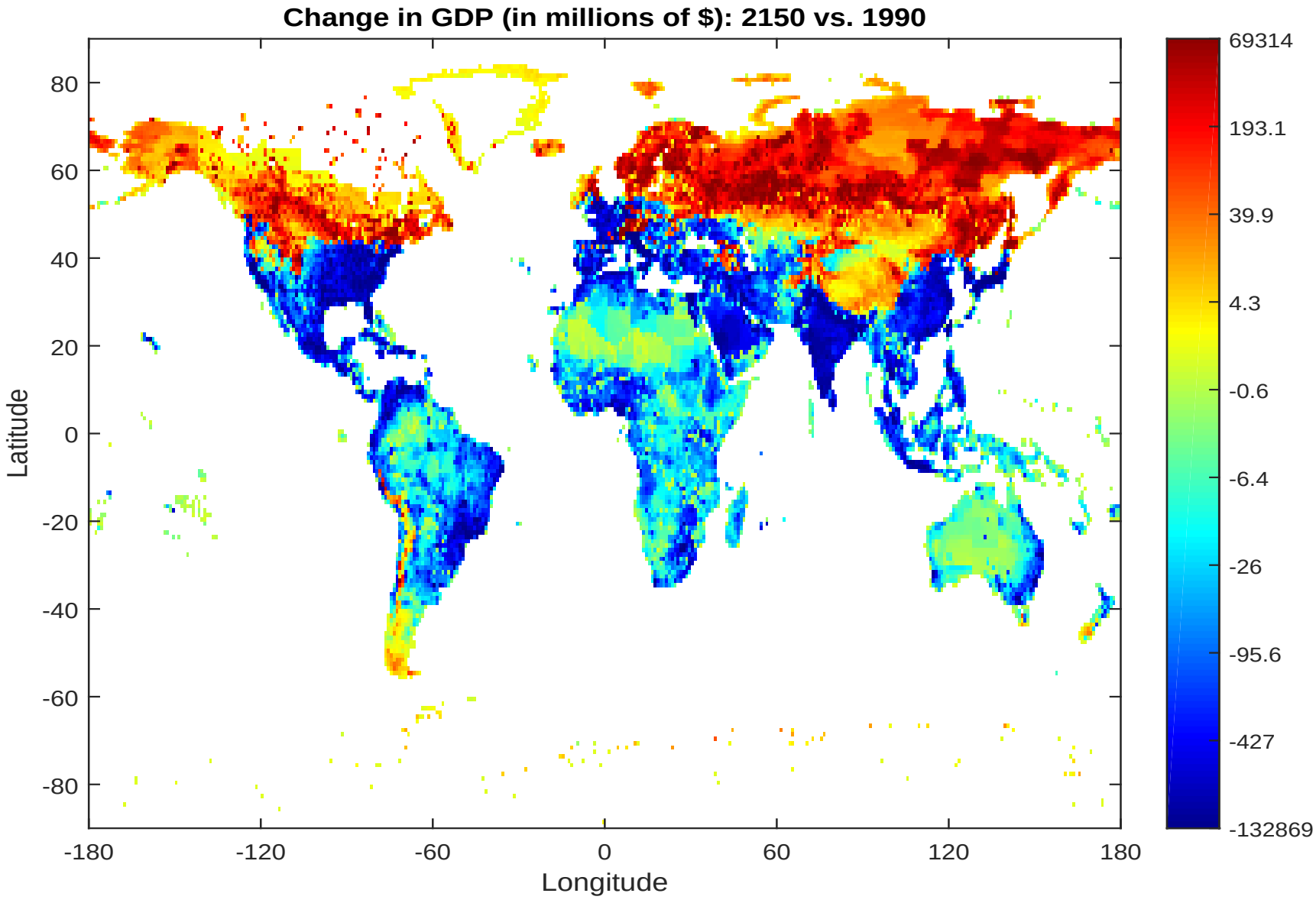

Change in GDP (in millions of $): 2100 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

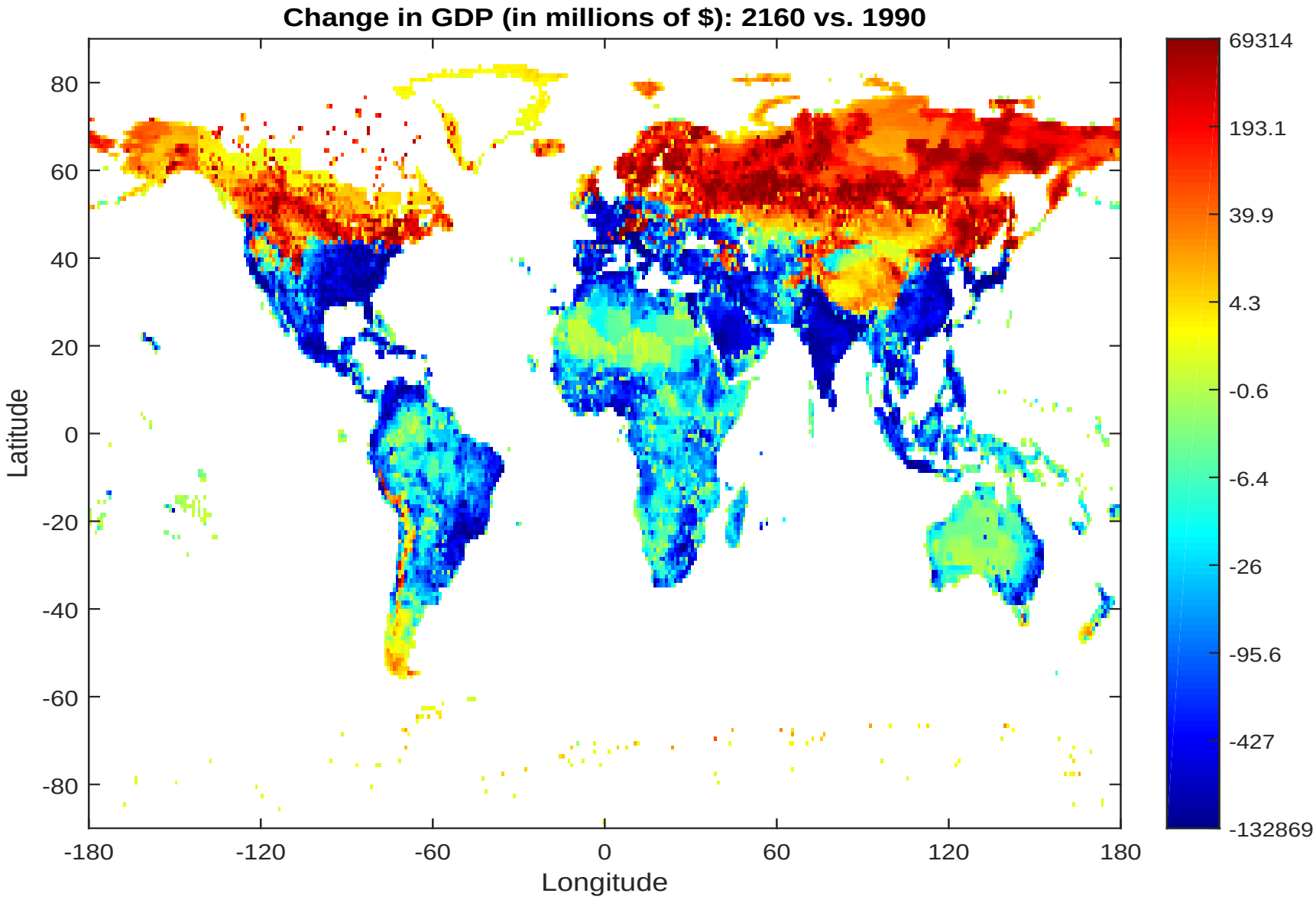

Change in GDP (in millions of $): 2110 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

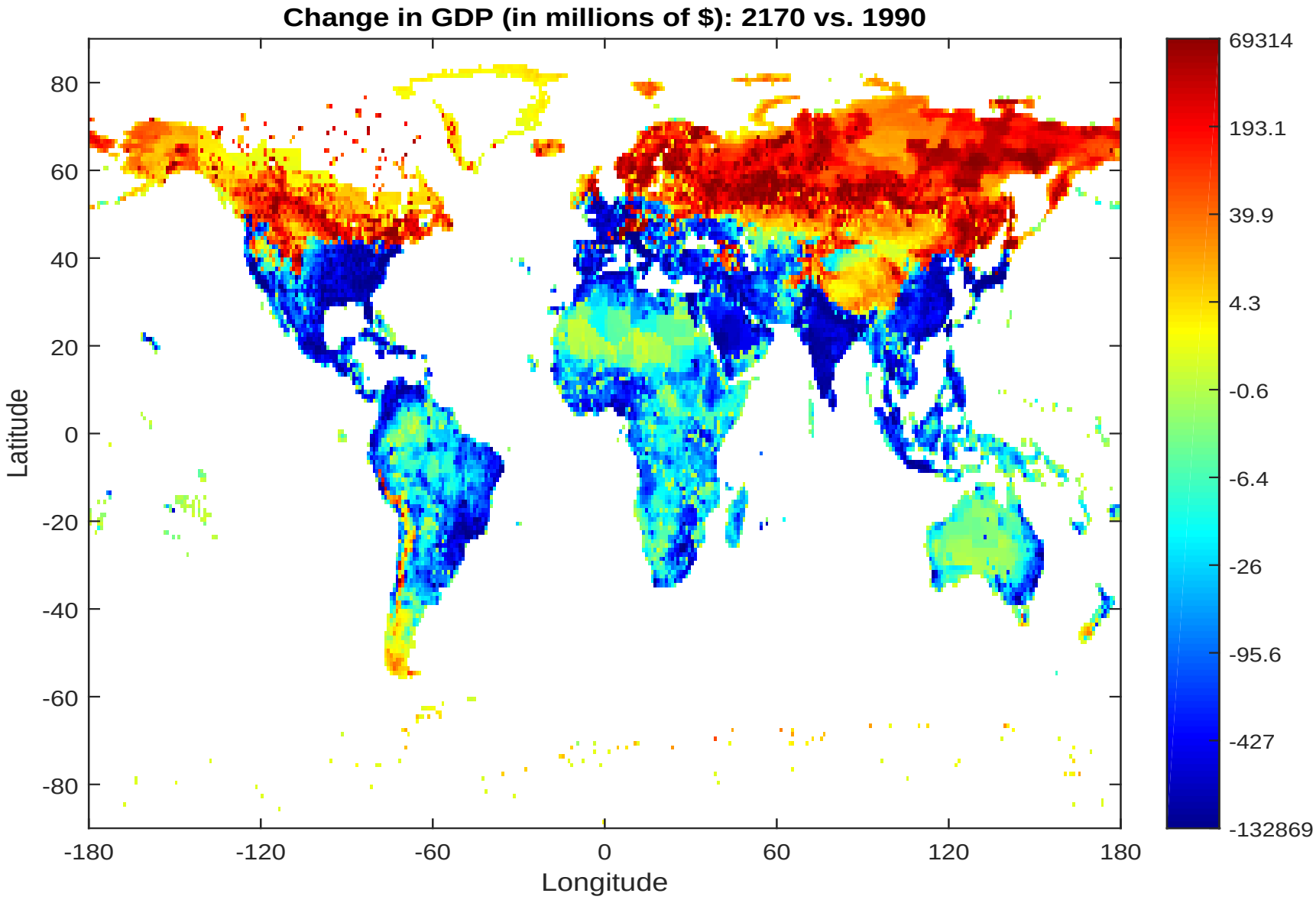

Change in GDP (in millions of $): 2120 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

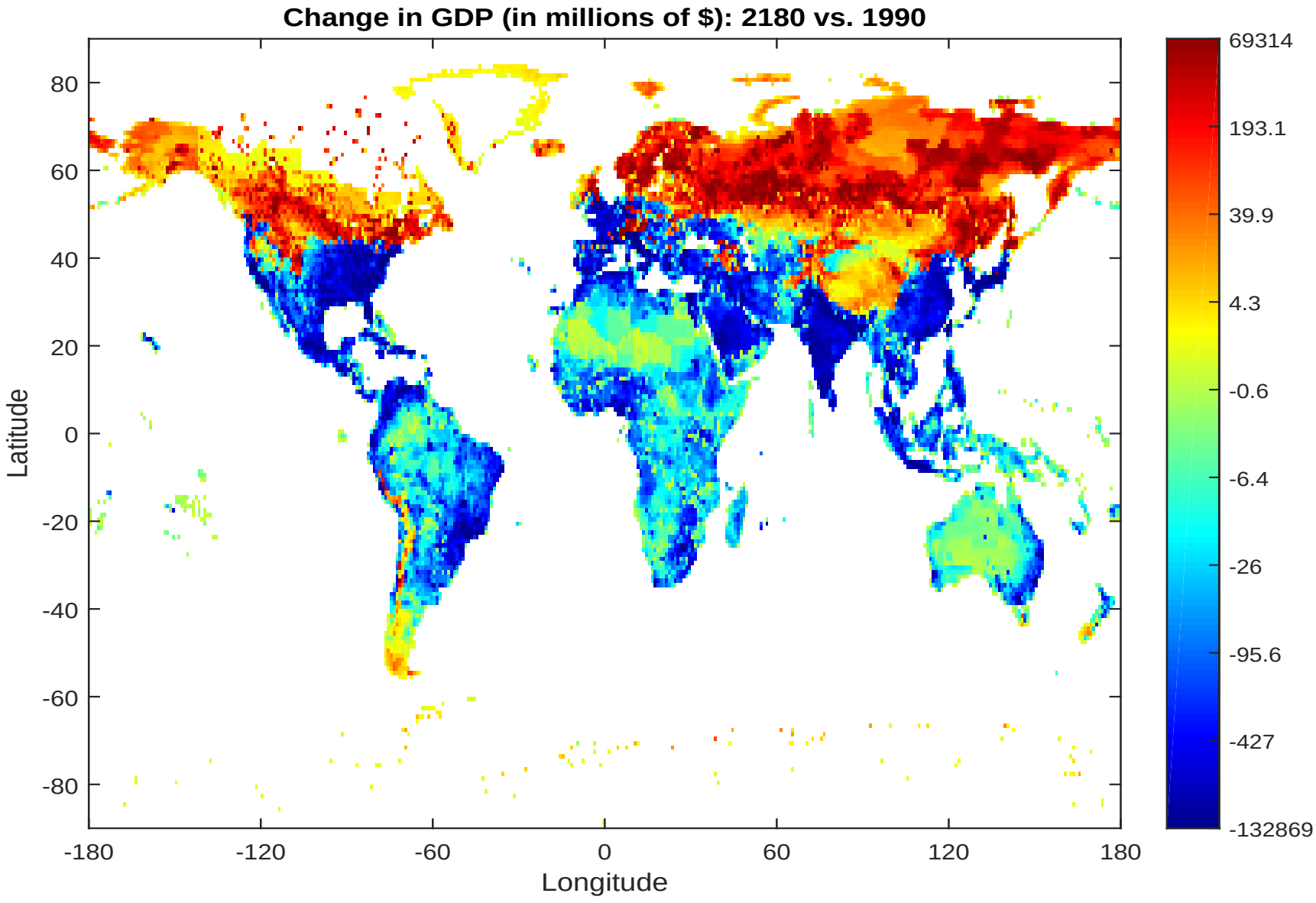

Change in GDP (in millions of $): 2130 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

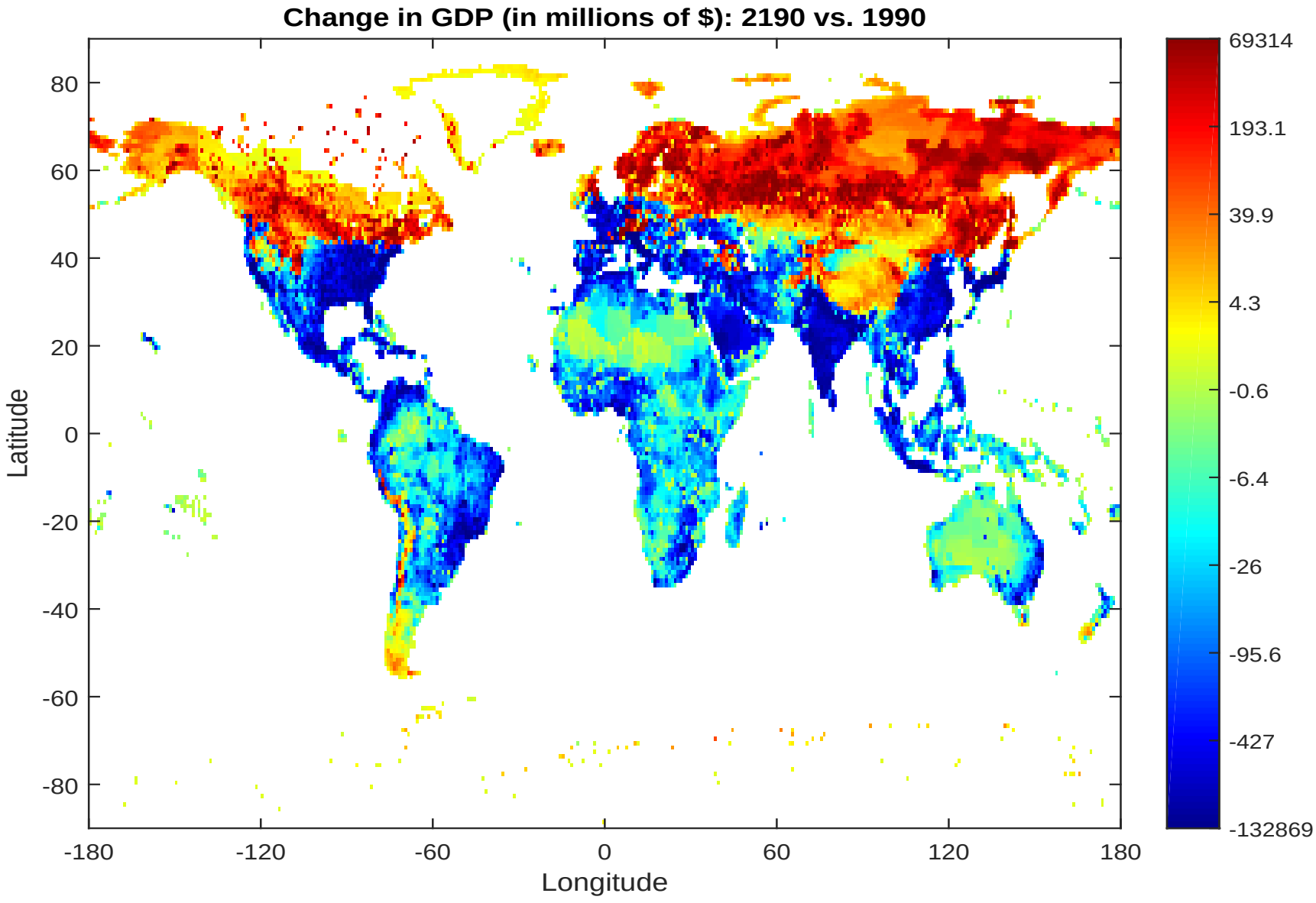

Change in GDP (in millions of $): 2140 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

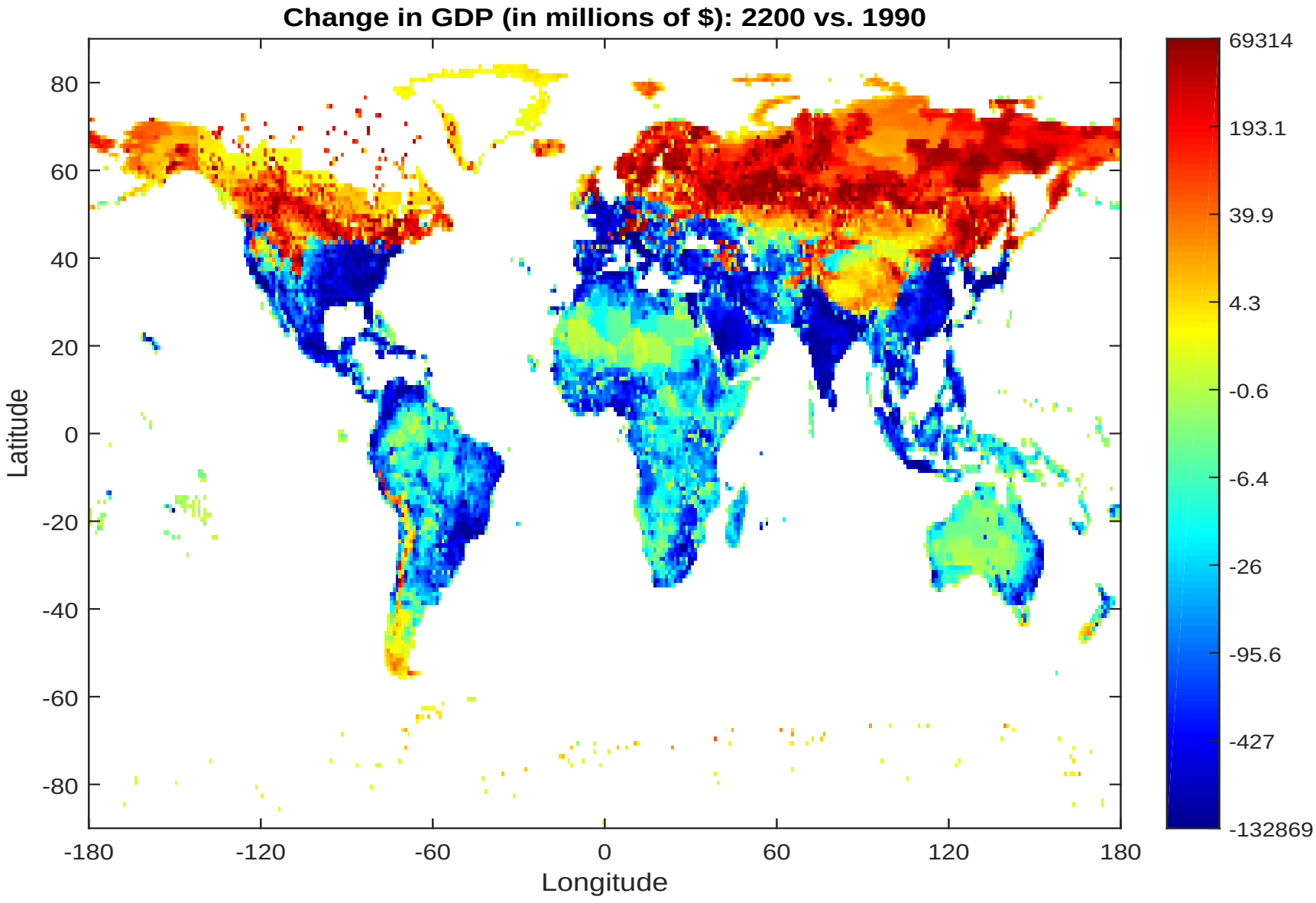

Change in GDP (in millions of $): 2150 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869


Change in GDP (in millions of $): 2160 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

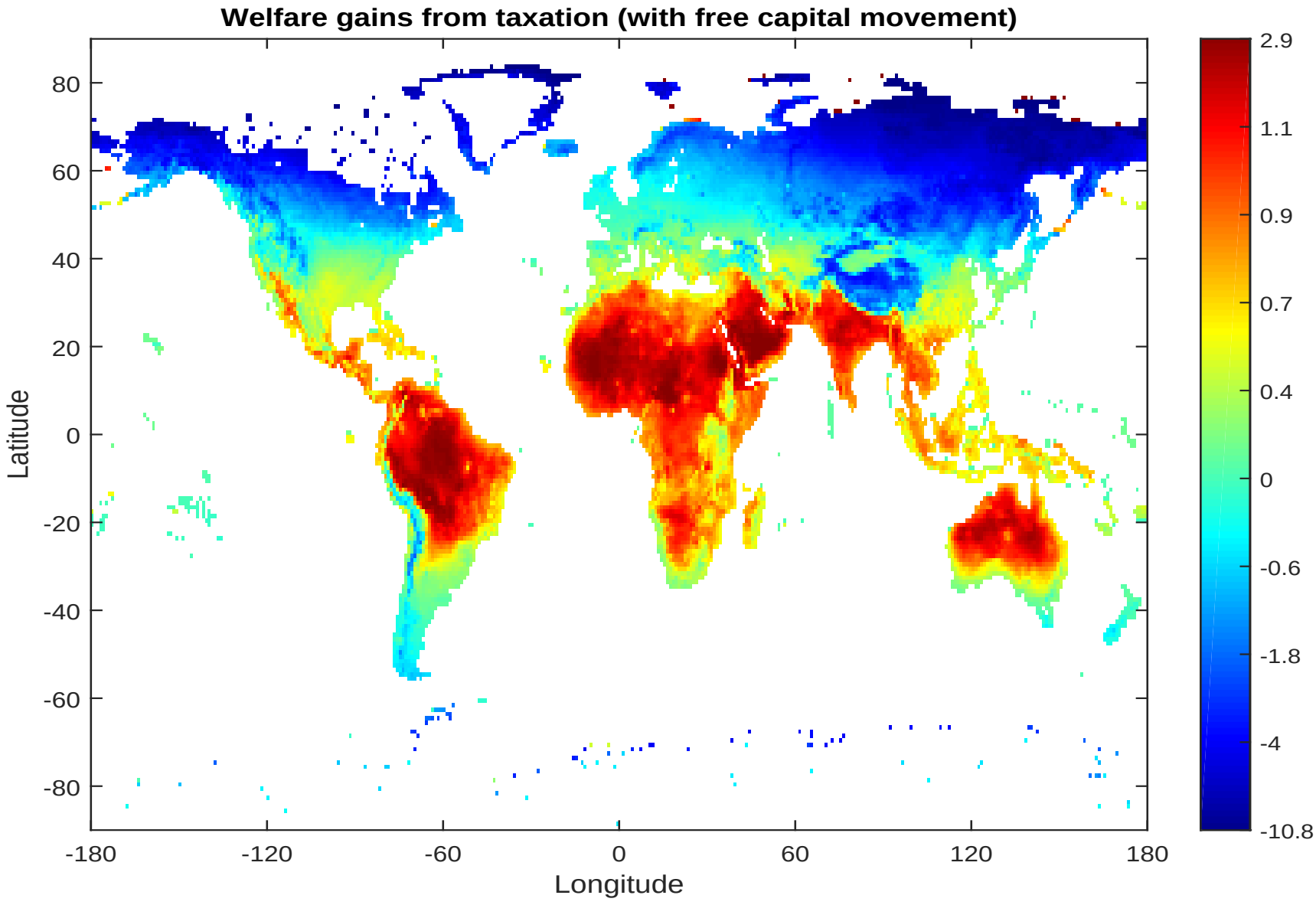

Change in GDP (in millions of $): 2170 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

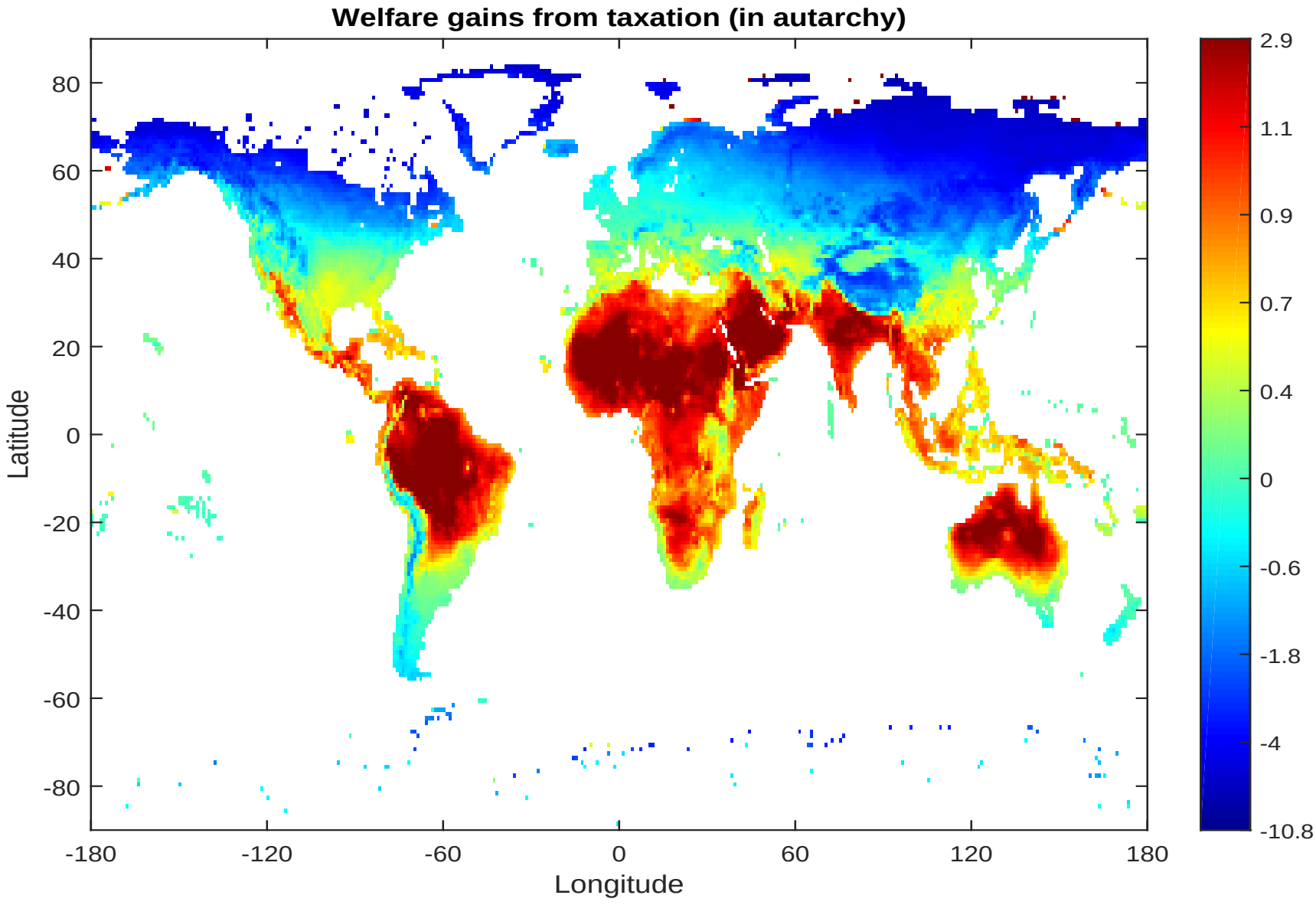

Change in GDP (in millions of $): 2180 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

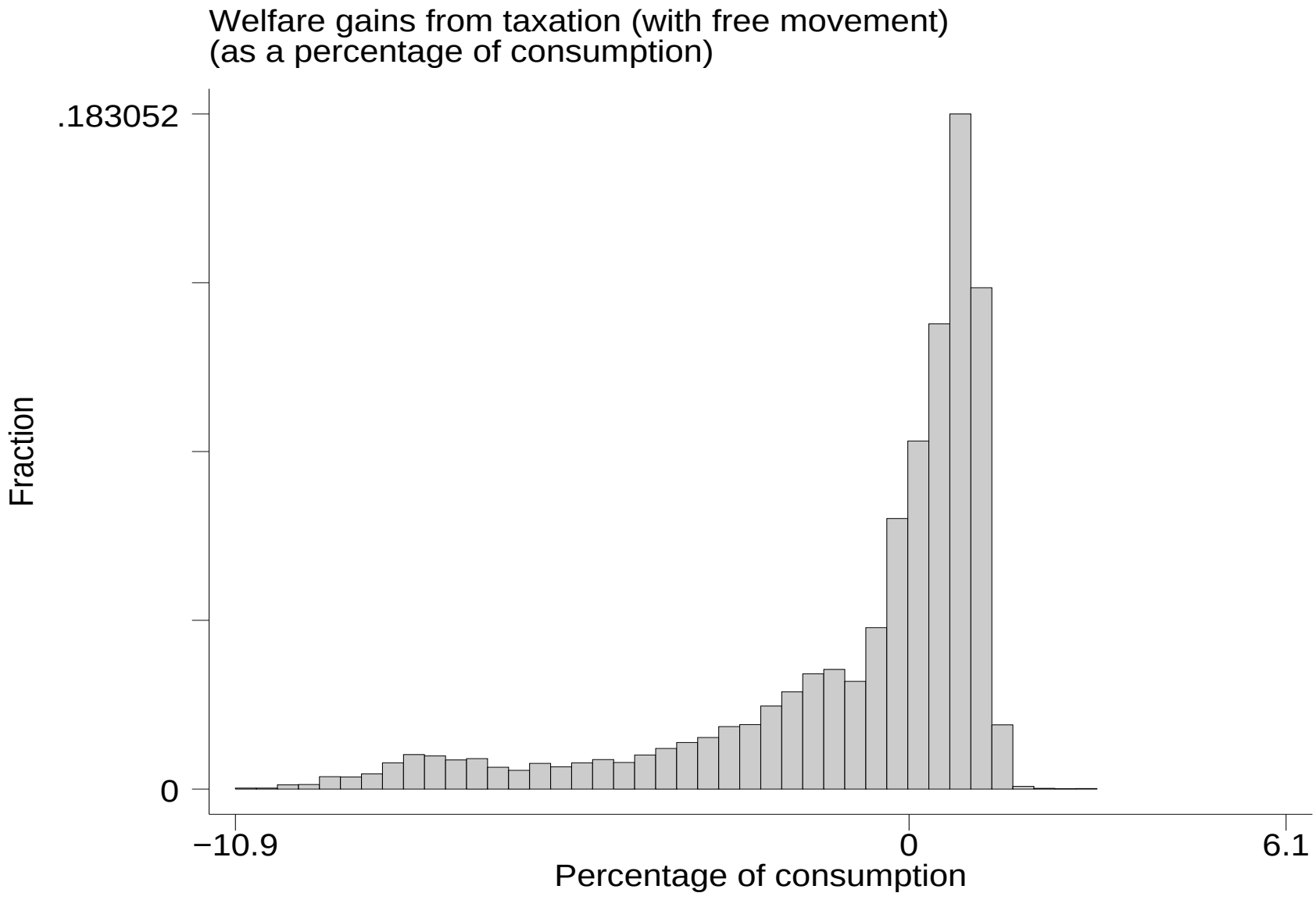

Change in GDP (in millions of $): 2190 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

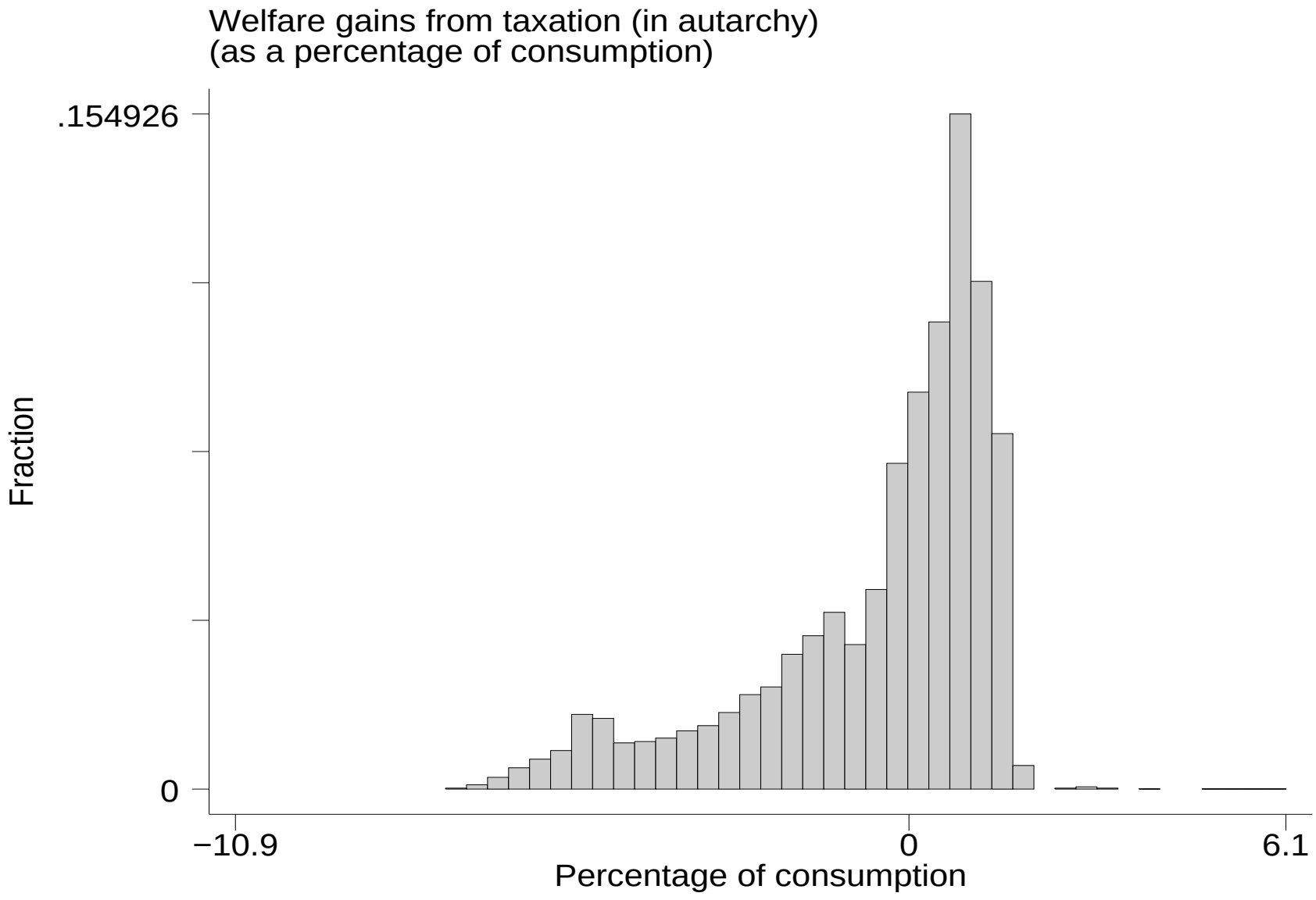

Change in GDP (in millions of $): 2200 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
69314
193.1
39.9
4.3
-0.6
-6.4
-26
-95.6
-427
-132869

pictures: map (and histogram) of winners and losers from tax, full equalization (then autarky)


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
2.9
1.1
0.9
0.7
0.4
0
-0.6
-1.8
-4
-10.8


Welfare gains from taxation (in autarchy)
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
2.9
1.1
0.9
0.7
0.4
0
-0.6
-1.8
-4
-10.8

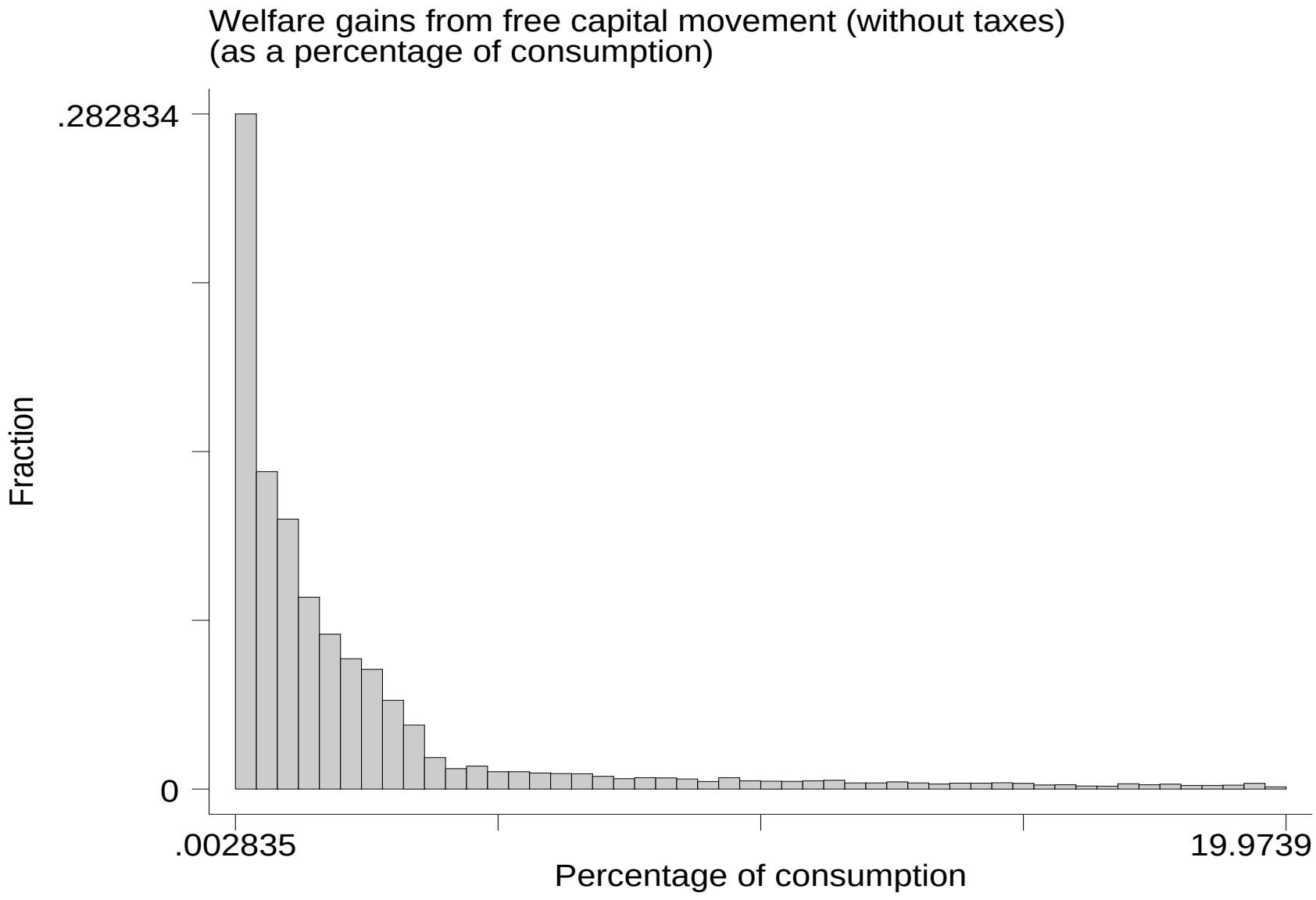

Welfare gains from taxation (with free movement)
(as a percentage of consumption)
.183052
0
Fraction
−10.9
0
6.1
Percentage of consumption


Welfare gains from taxation (in autarchy)
(as a percentage of consumption)
.154926
0
Fraction
−10.9
0
6.1
Percentage of consumption

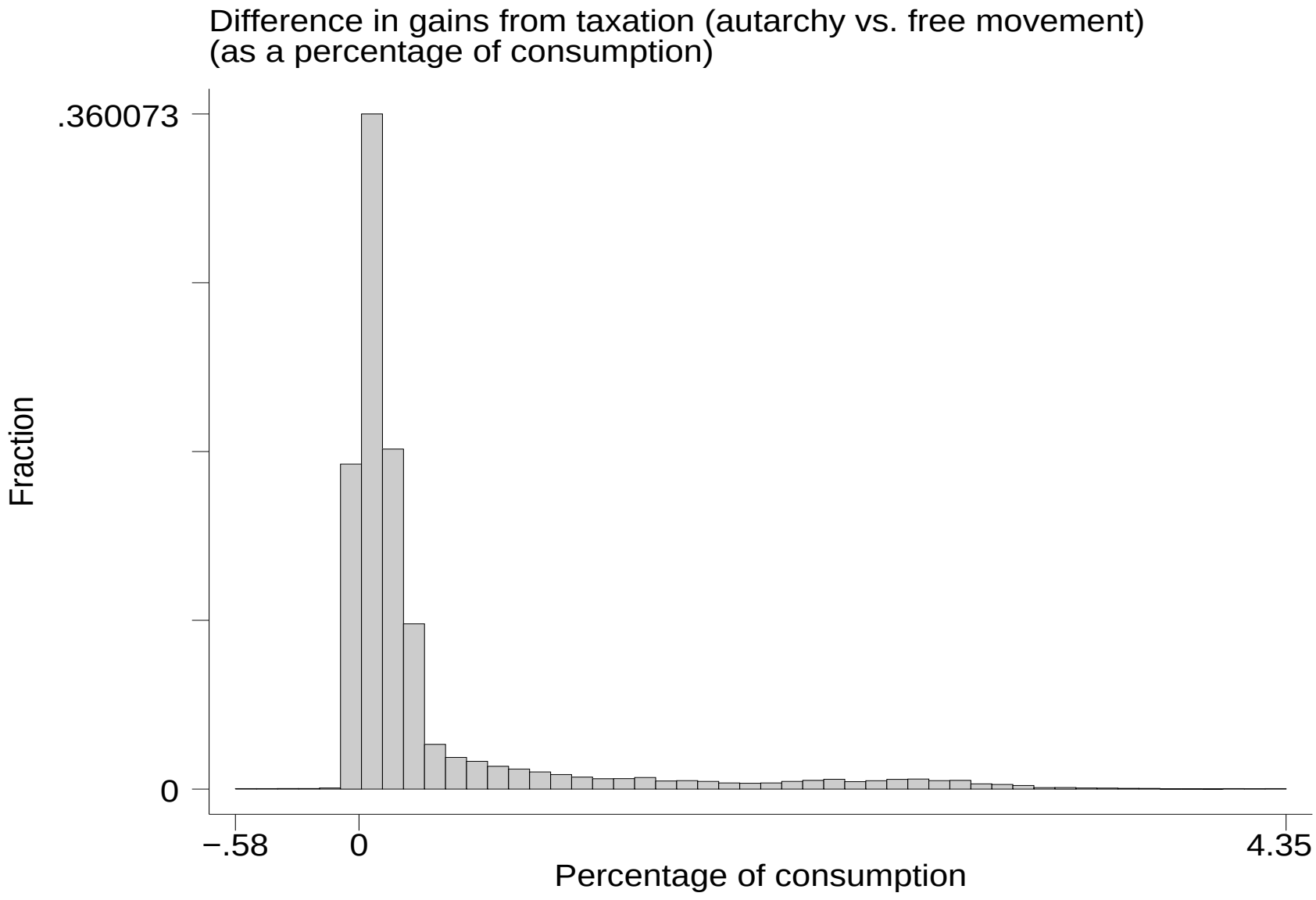
Welfare changes from tax: summary measures

- One region = one vote: 55% gain.
- One person = one vote: 83% gain.
- One dollar = one vote: 65% gain.
- Average gain across all regions: -0.81% (of consumption).
- Average gain weighted by regional GDP: 0.14%.
- Average gain weighted by regional population: 0.46%.
- World consumption path: gain of 0.03%.

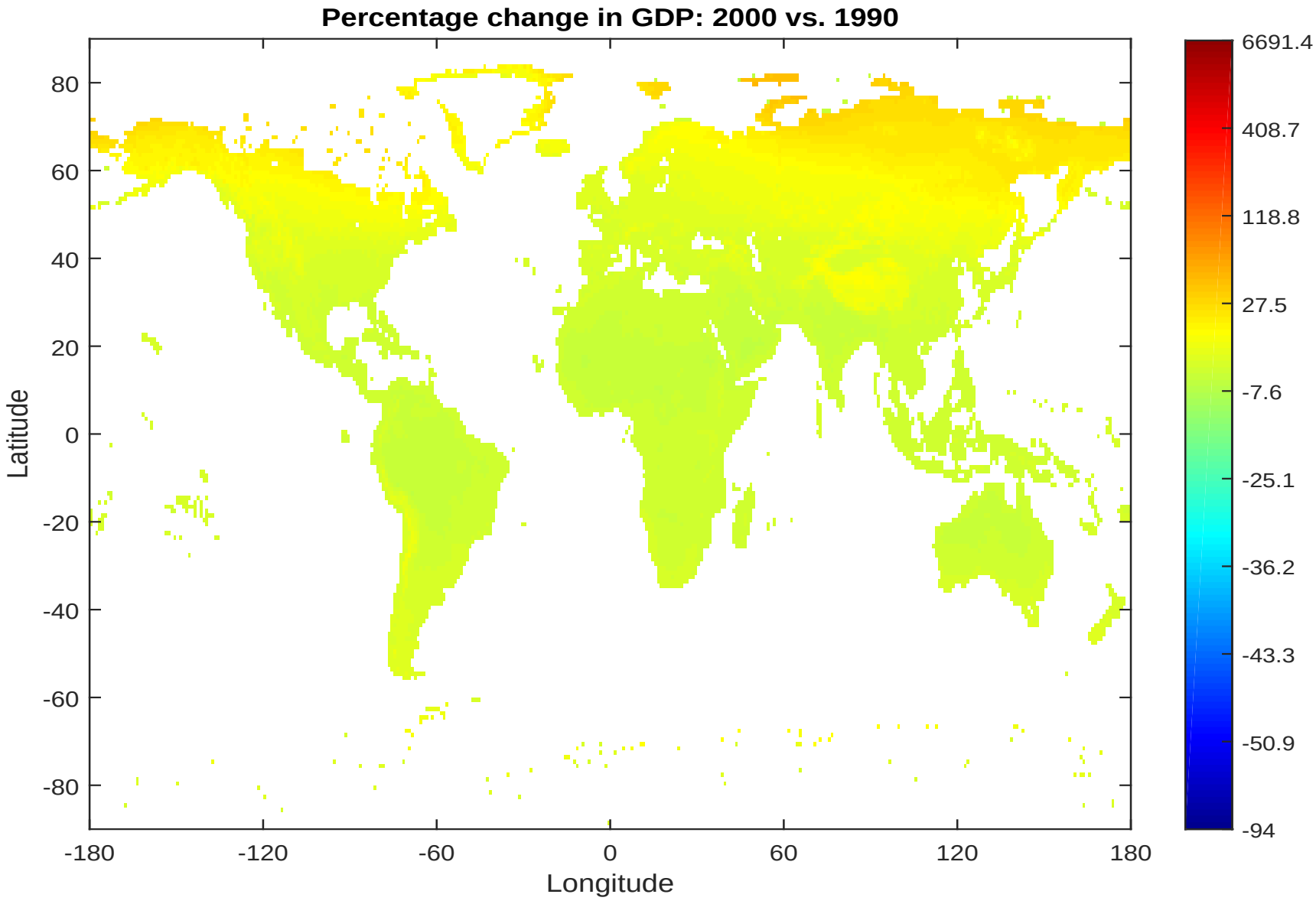
picture: welfare gains from free capital movements (laissez-faire)

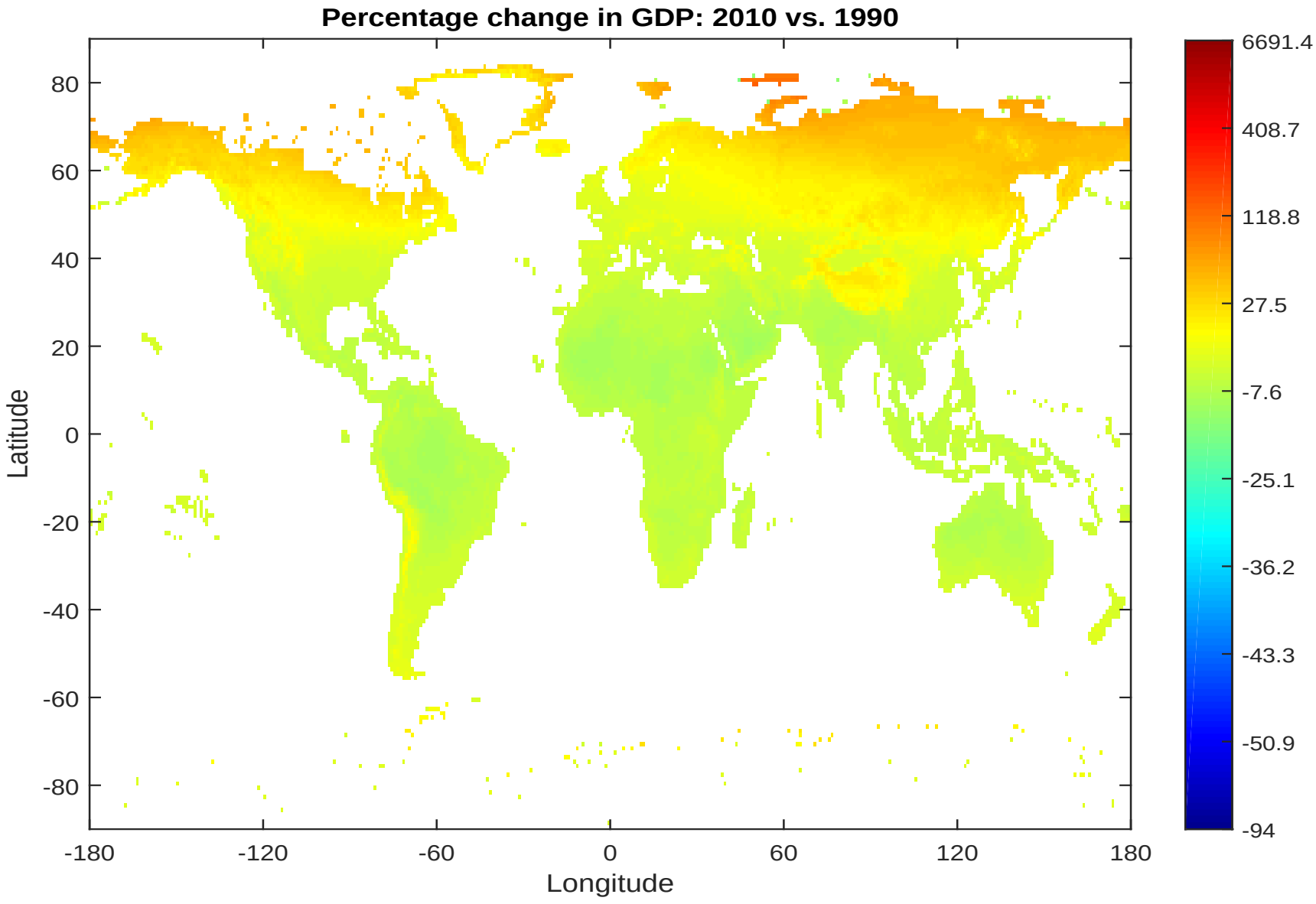

Welfare gains from free capital movement (without taxes)
(as a percentage of consumption)
.282834
0
Fraction
.002835
19.9739
Percentage of consumption

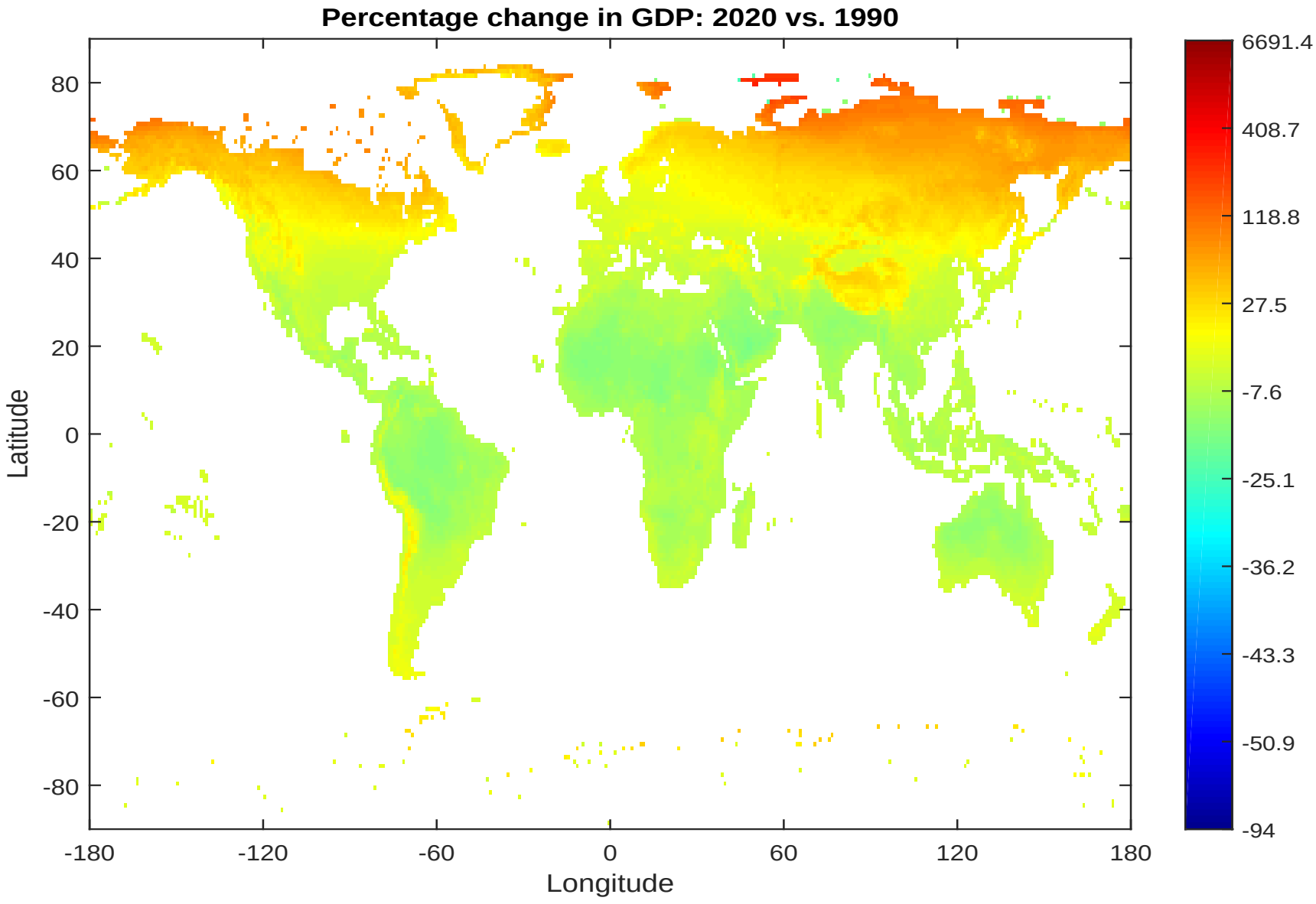
picture: differences in gains from taxation (autarky vs. free capital movements)

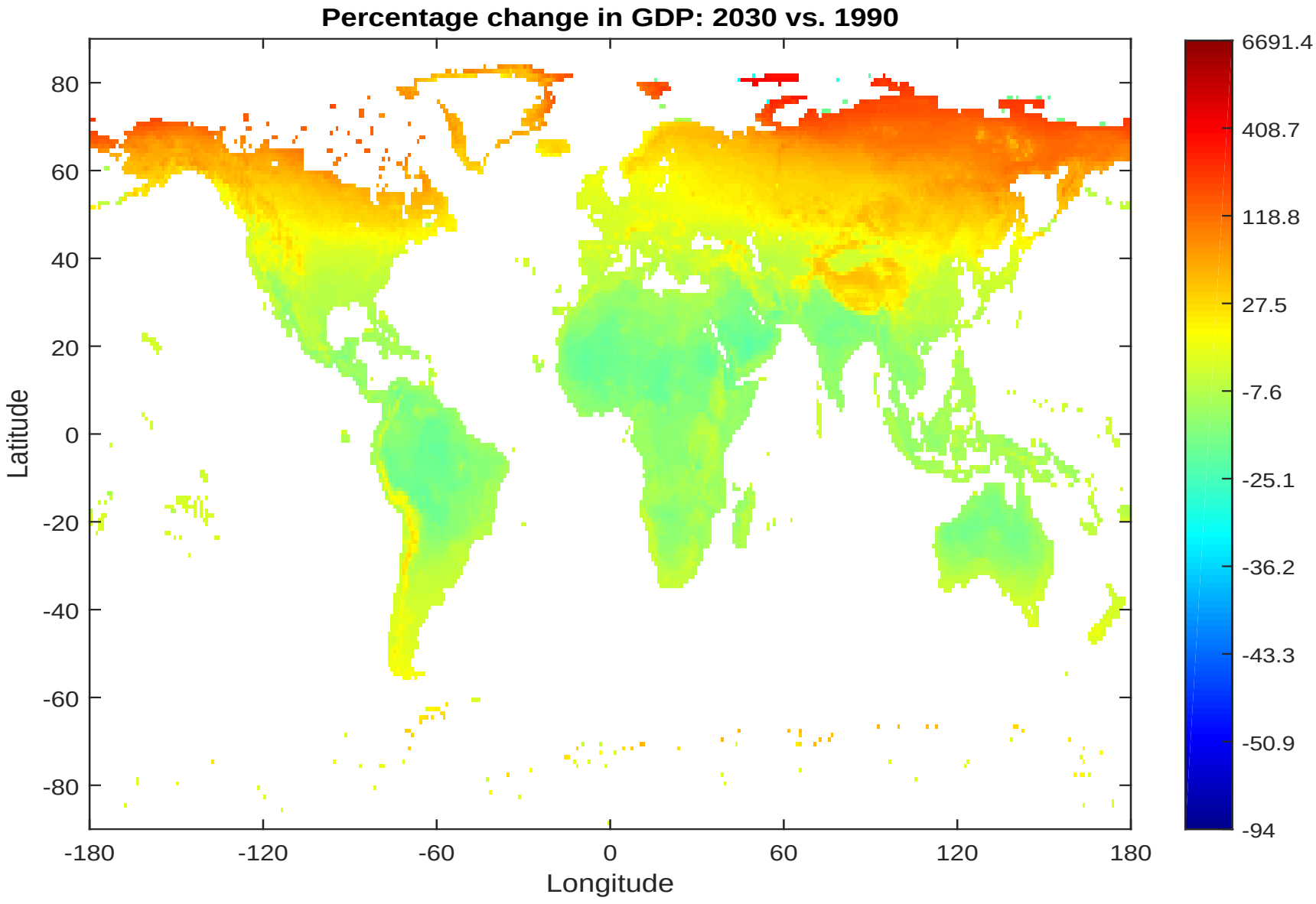

Difference in gains from taxation (autarchy vs. free movement)
(as a percentage of consumption)
.360073
0
Fraction
−.58
0
4.35
Percentage of consumption

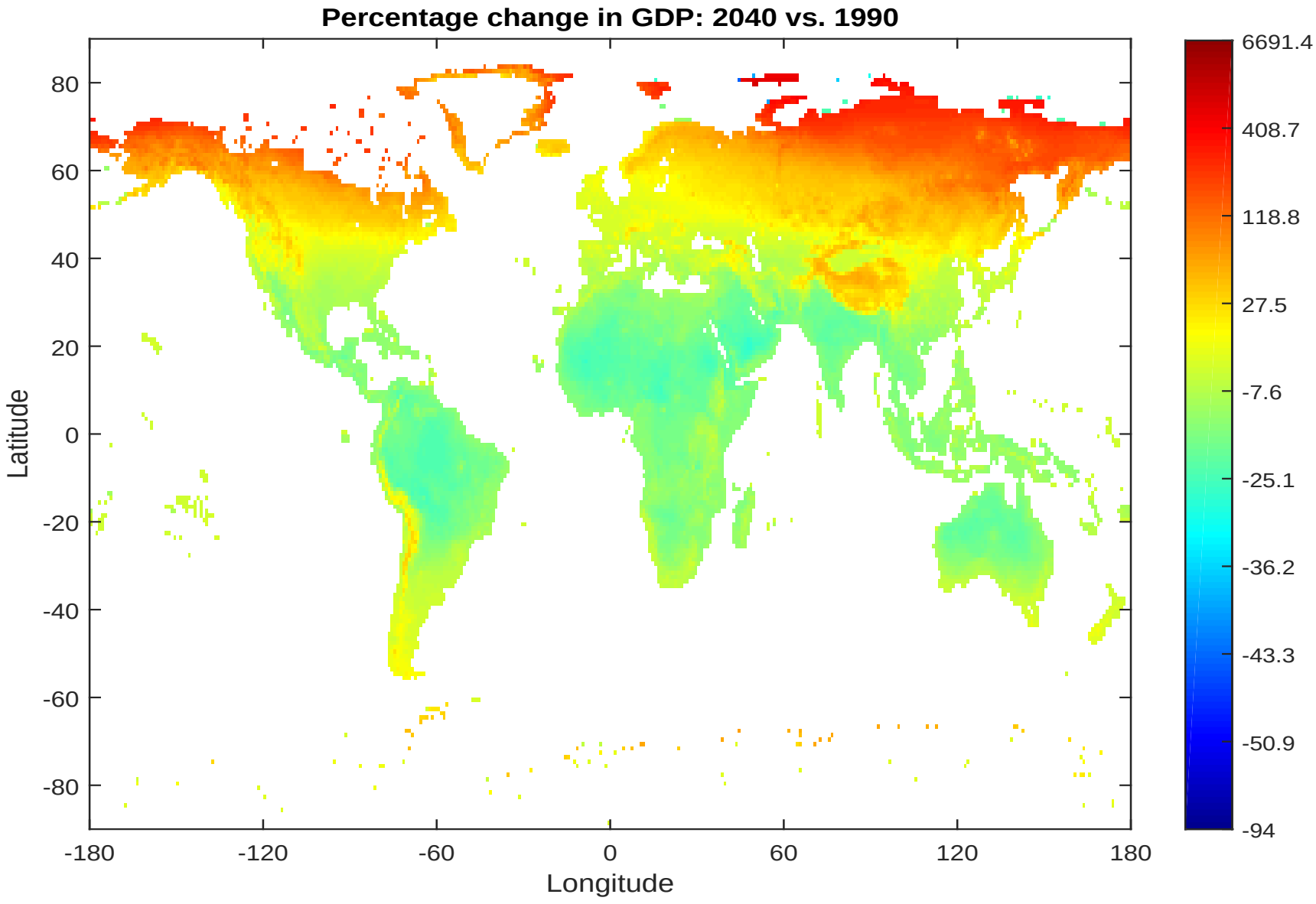
movie: percentage change in gdp, taxes

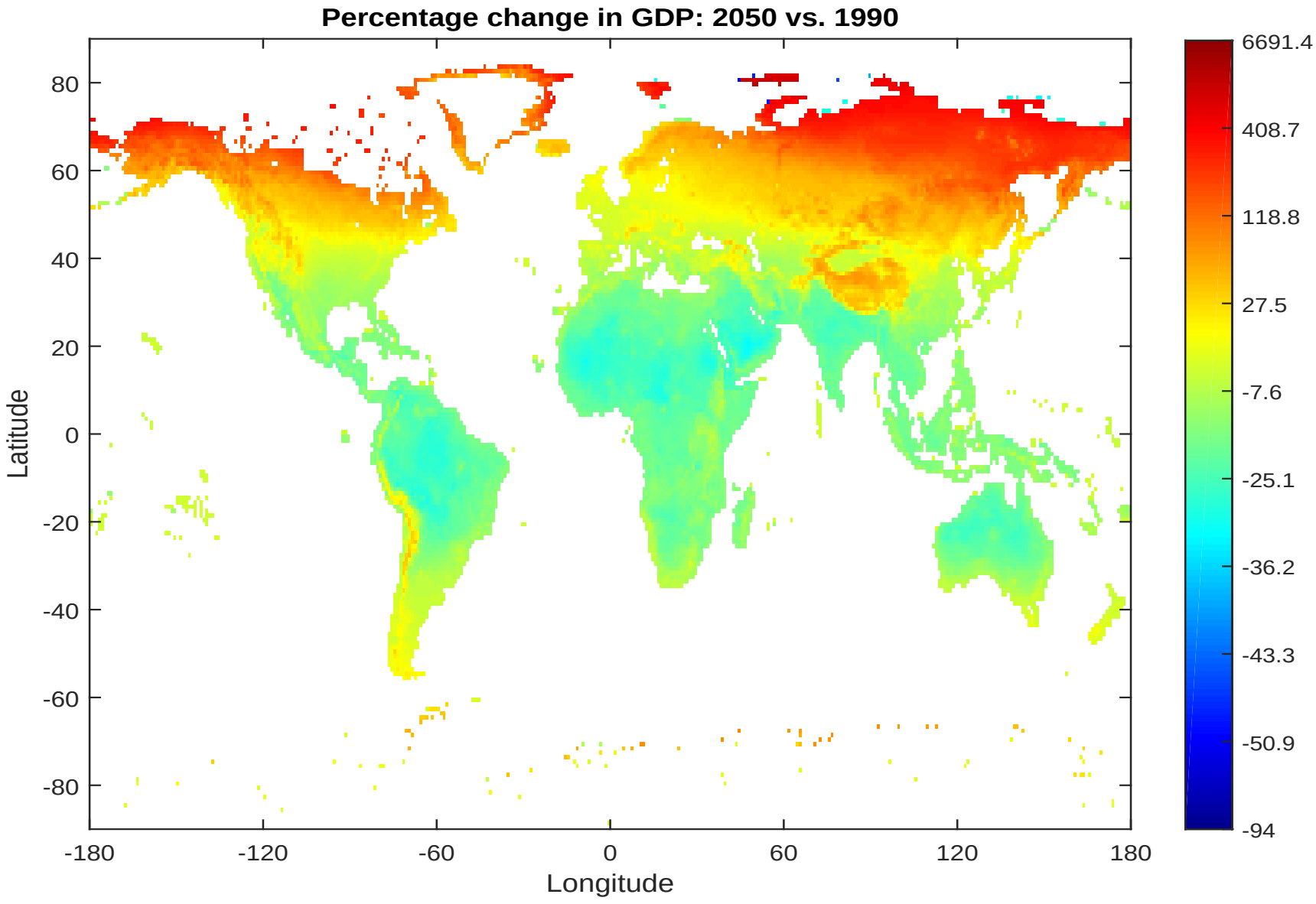

Percentage change in GDP: 2000 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94

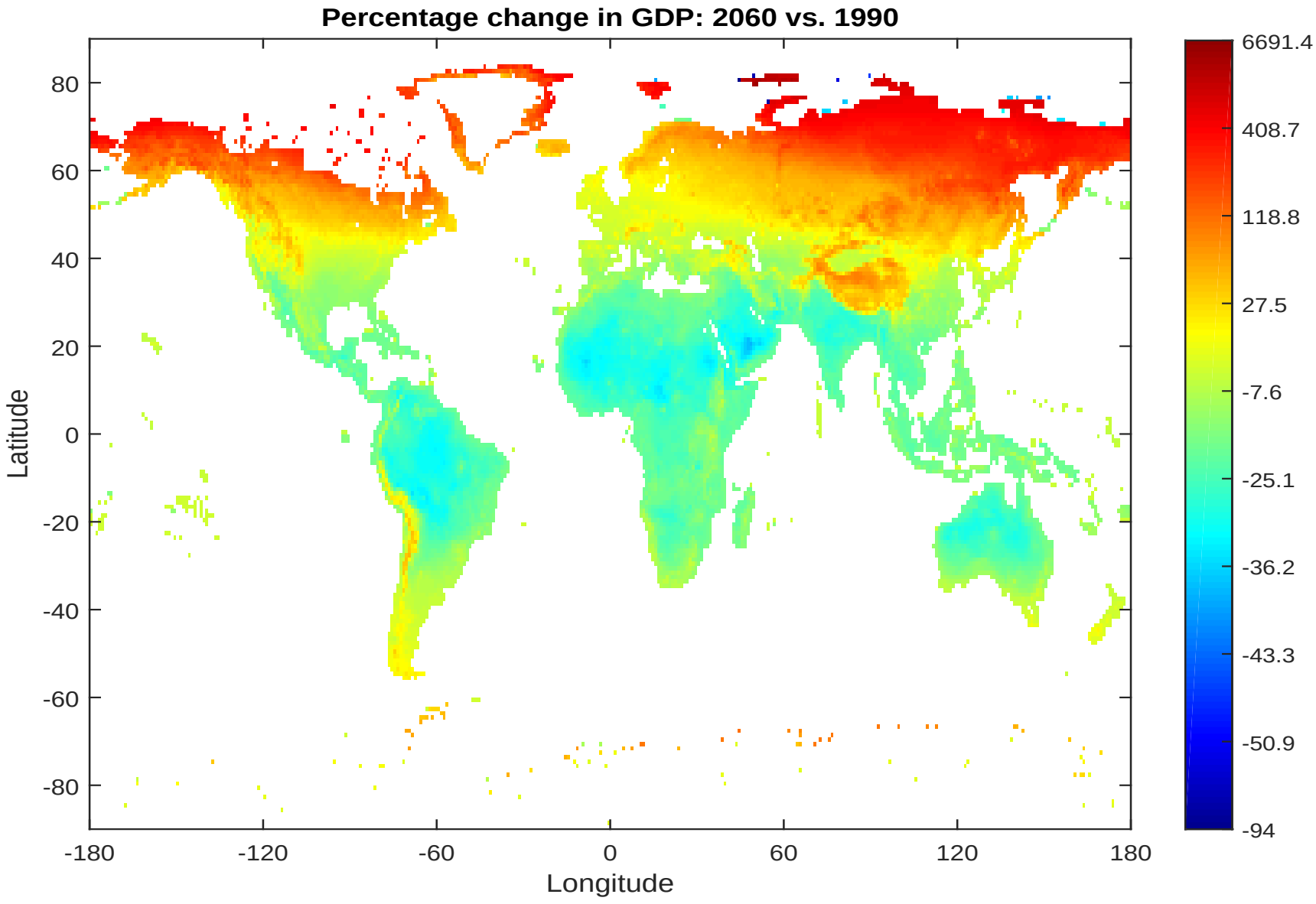

Percentage change in GDP: 2010 vs. 1990
Latitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
Longitude
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
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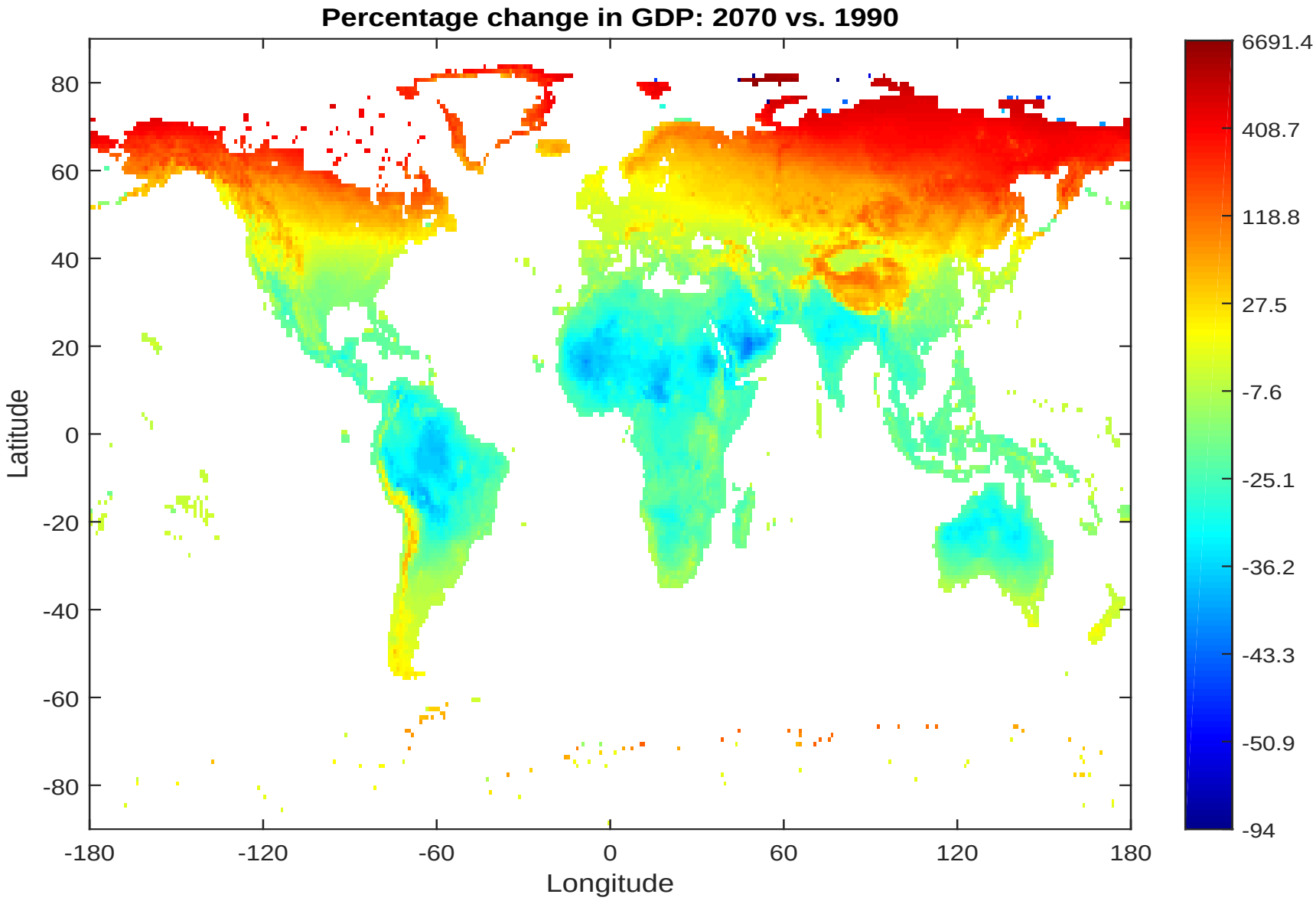
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
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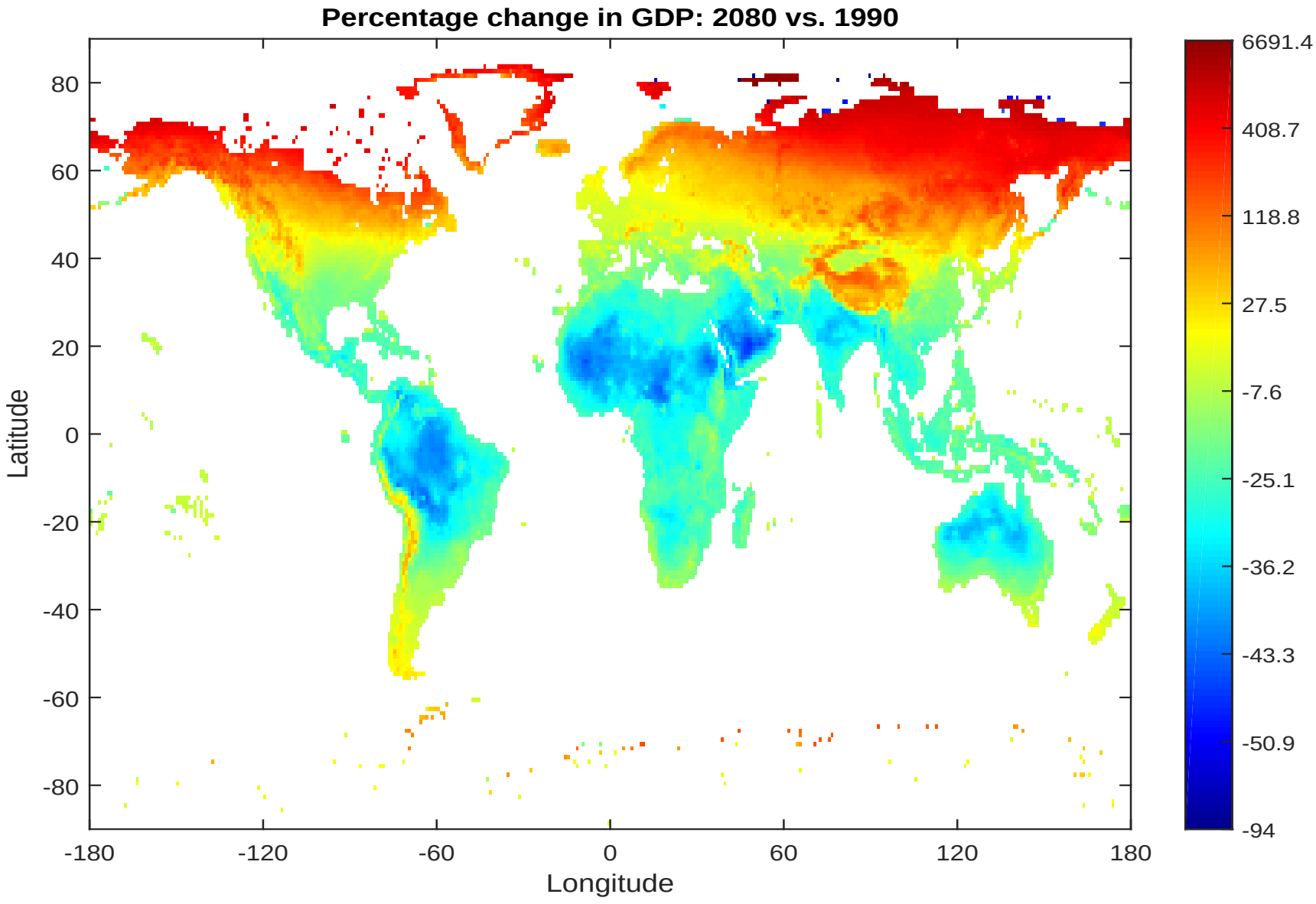
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
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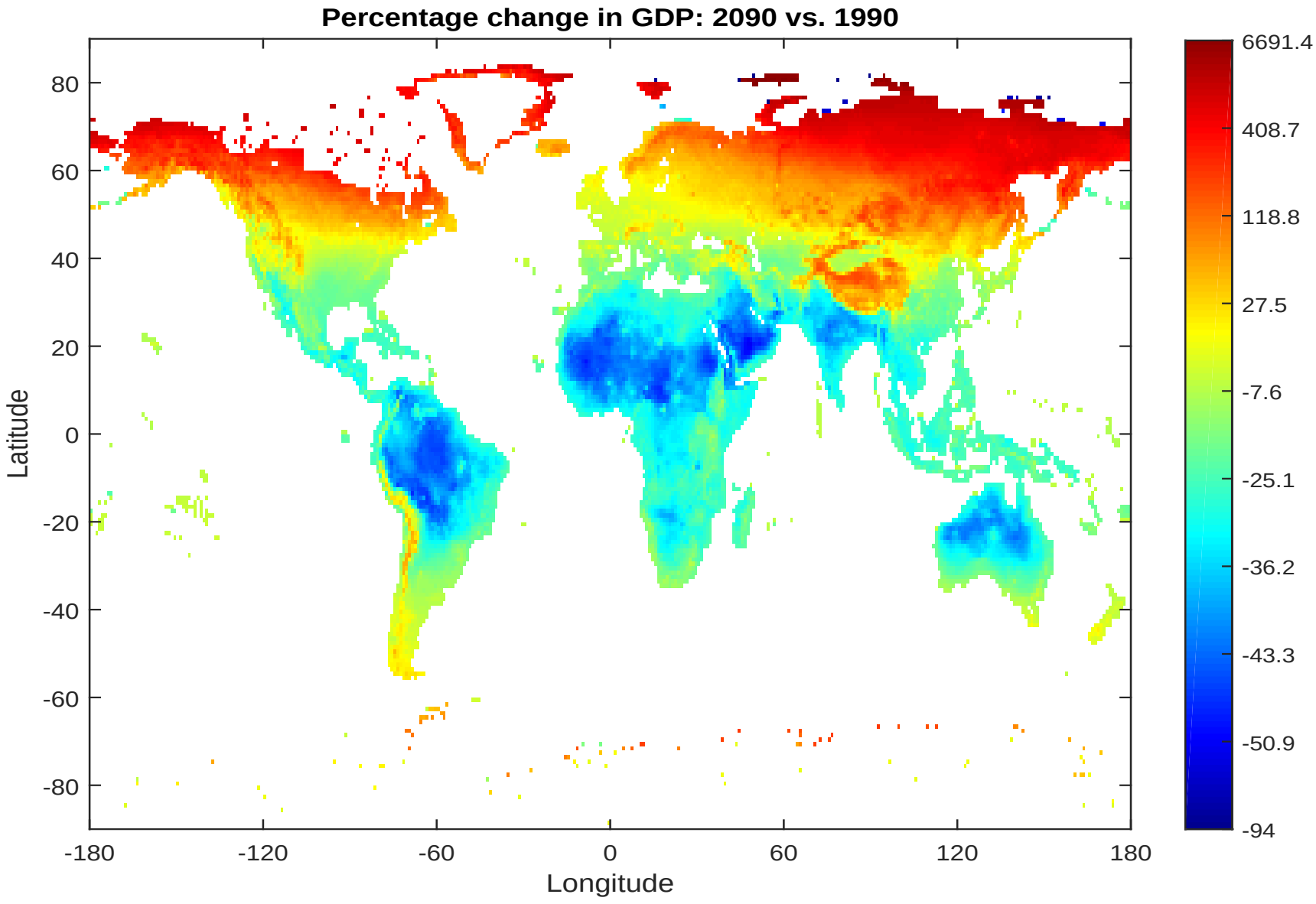
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
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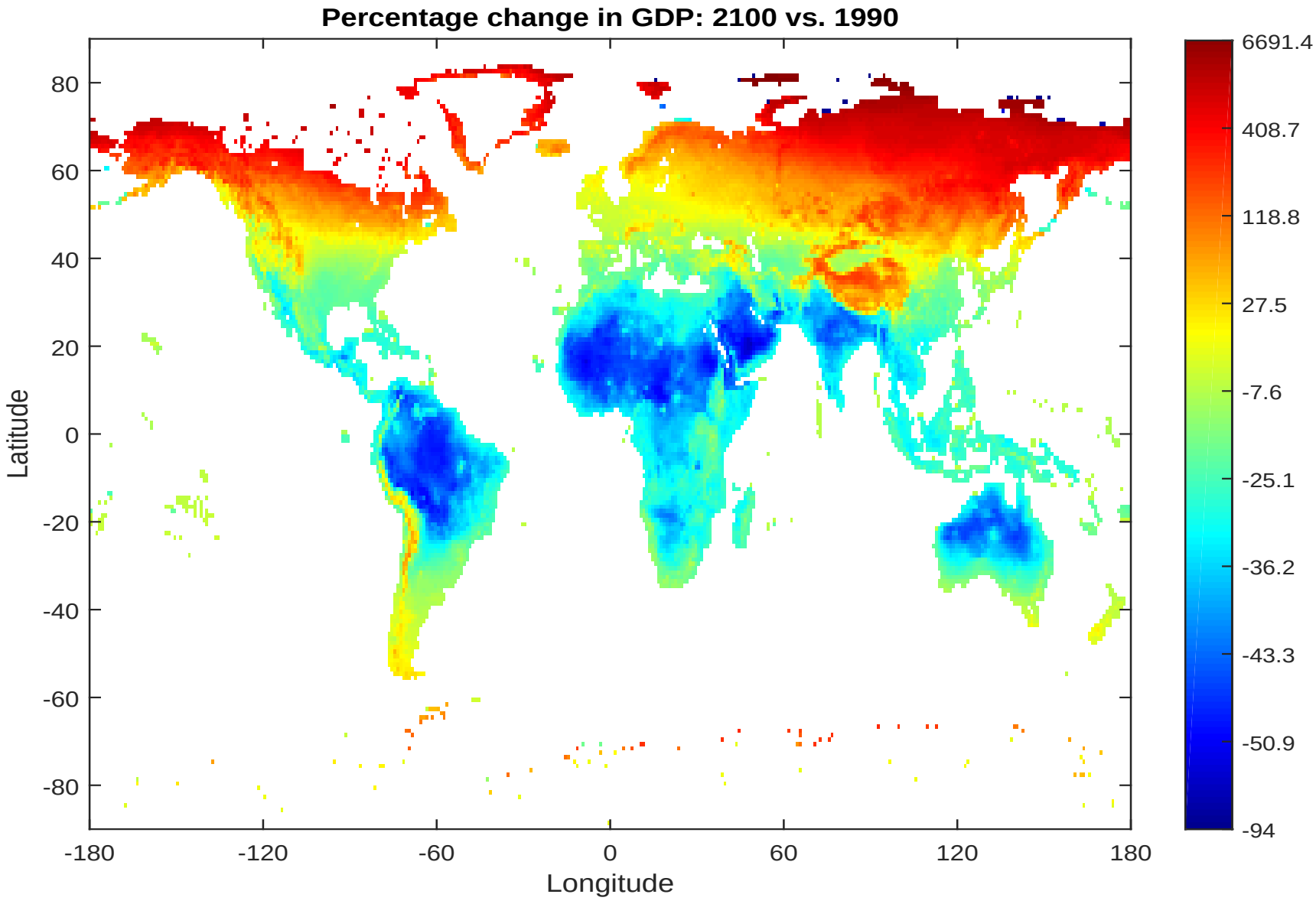
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
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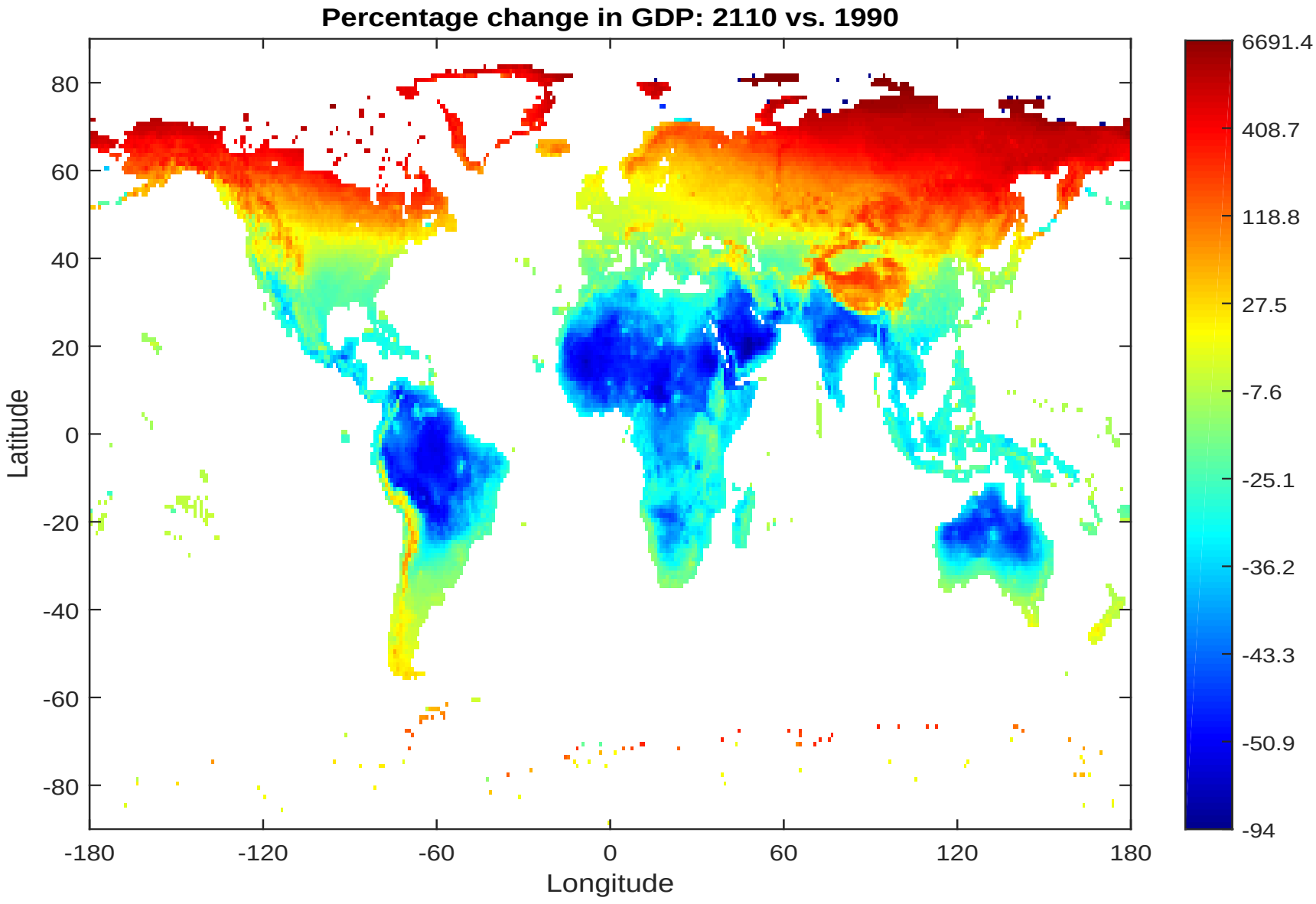
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


Percentage change in GDP: 2110 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
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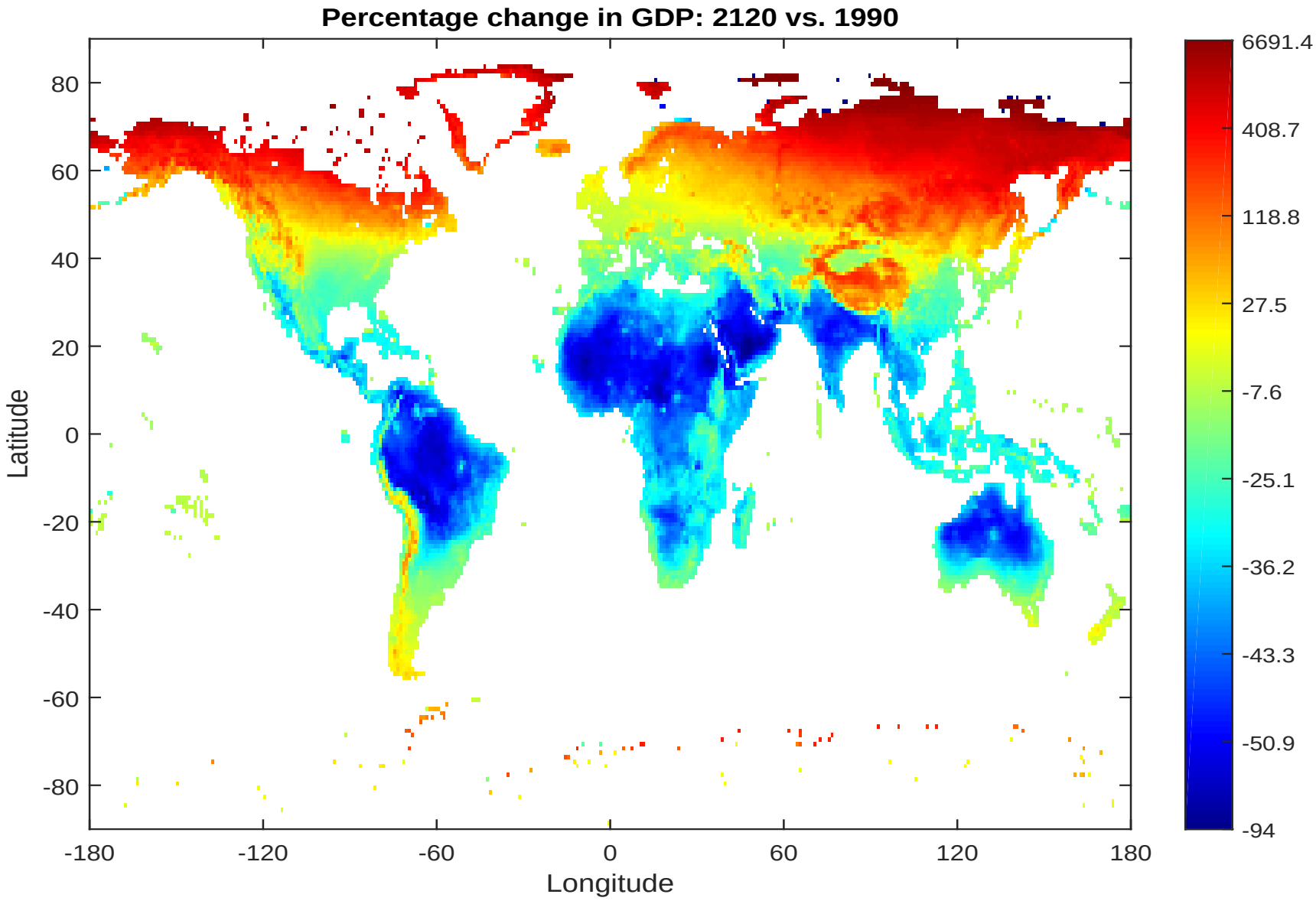
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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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118.8
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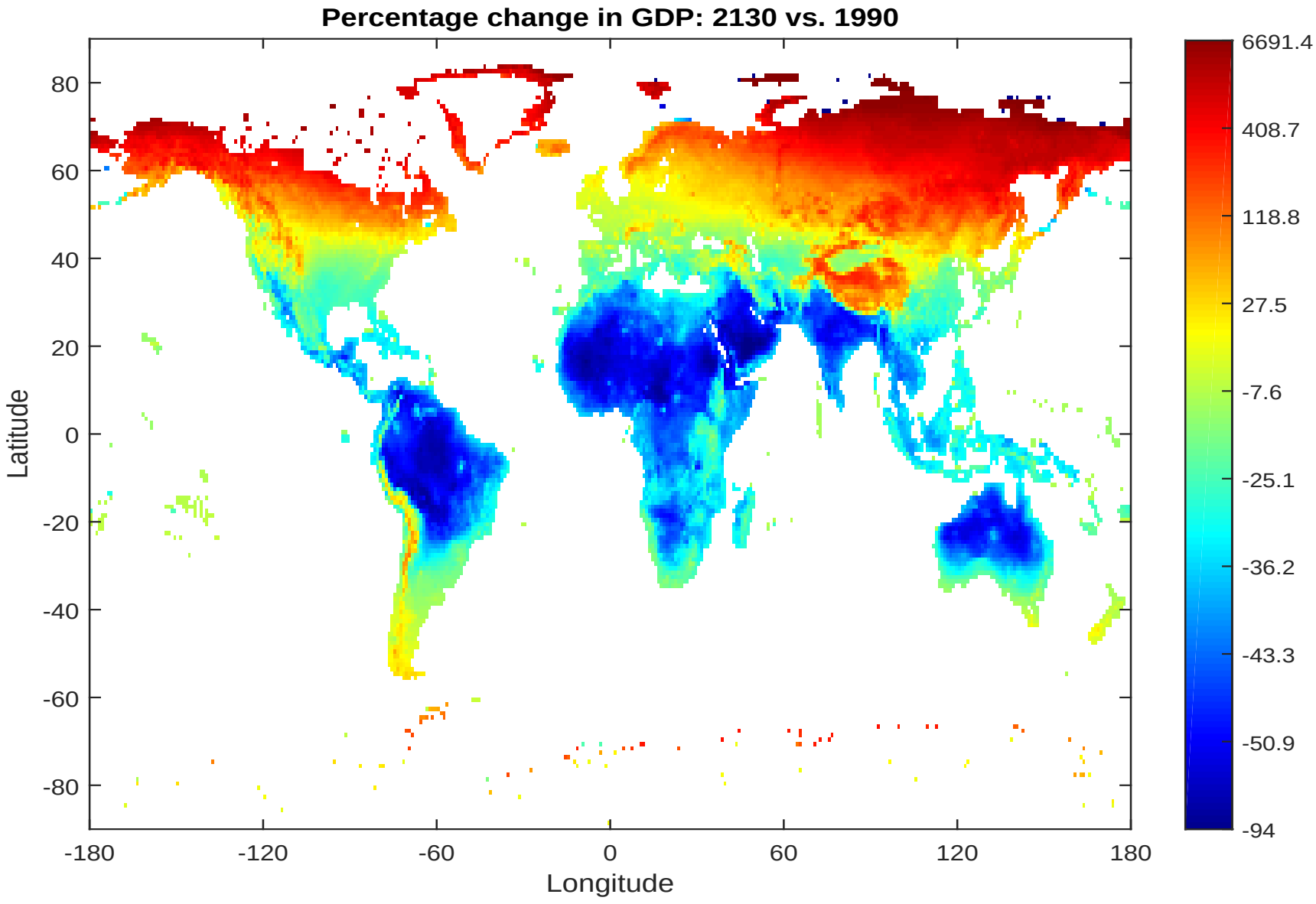
-7.6
-25.1
-36.2
-43.3
-50.9
-94


Percentage change in GDP: 2130 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
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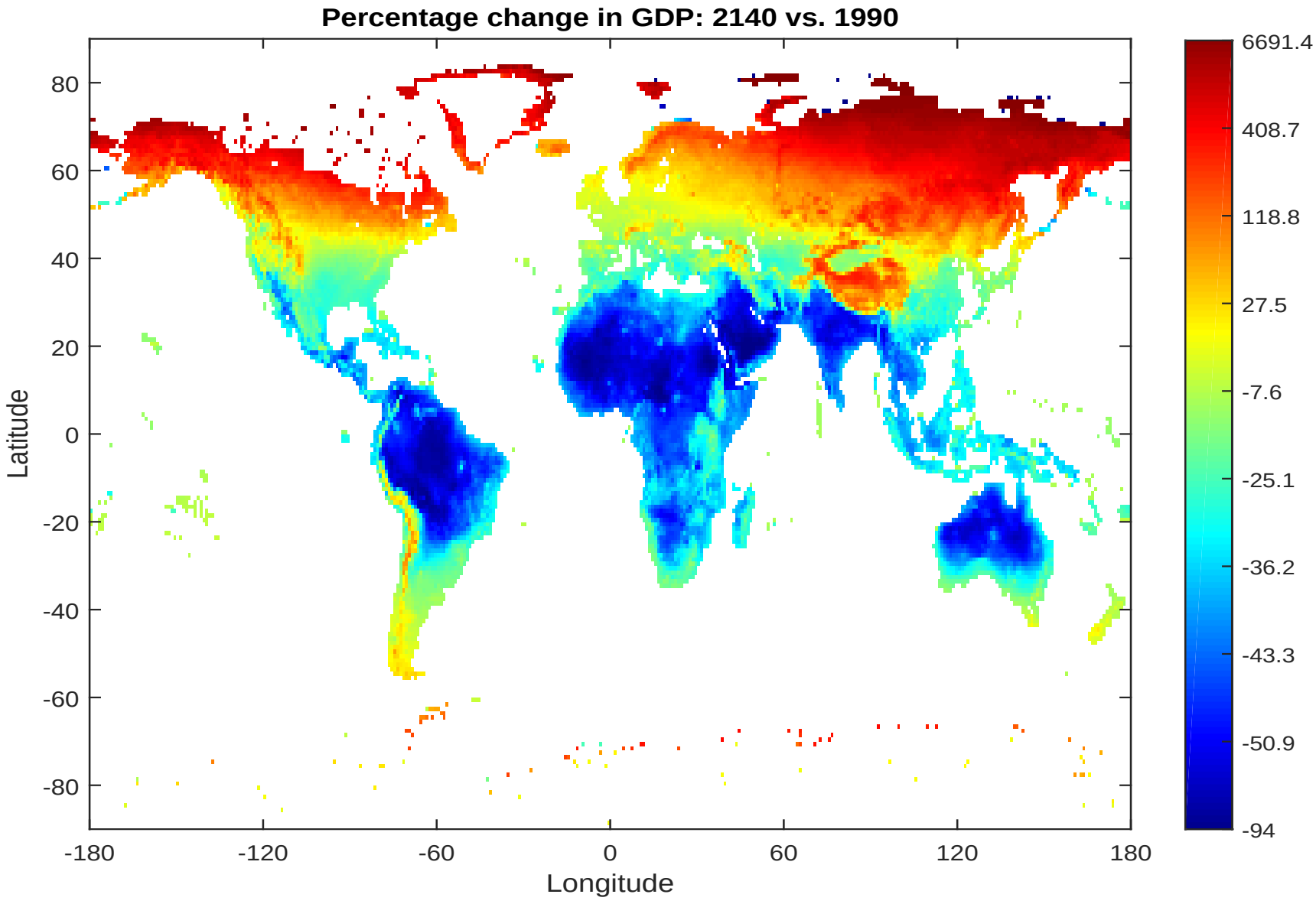
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


Percentage change in GDP: 2140 vs. 1990
Latitude
80
60
40
20
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-20
-40
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-80
-180
-120
-60
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60
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Longitude
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118.8
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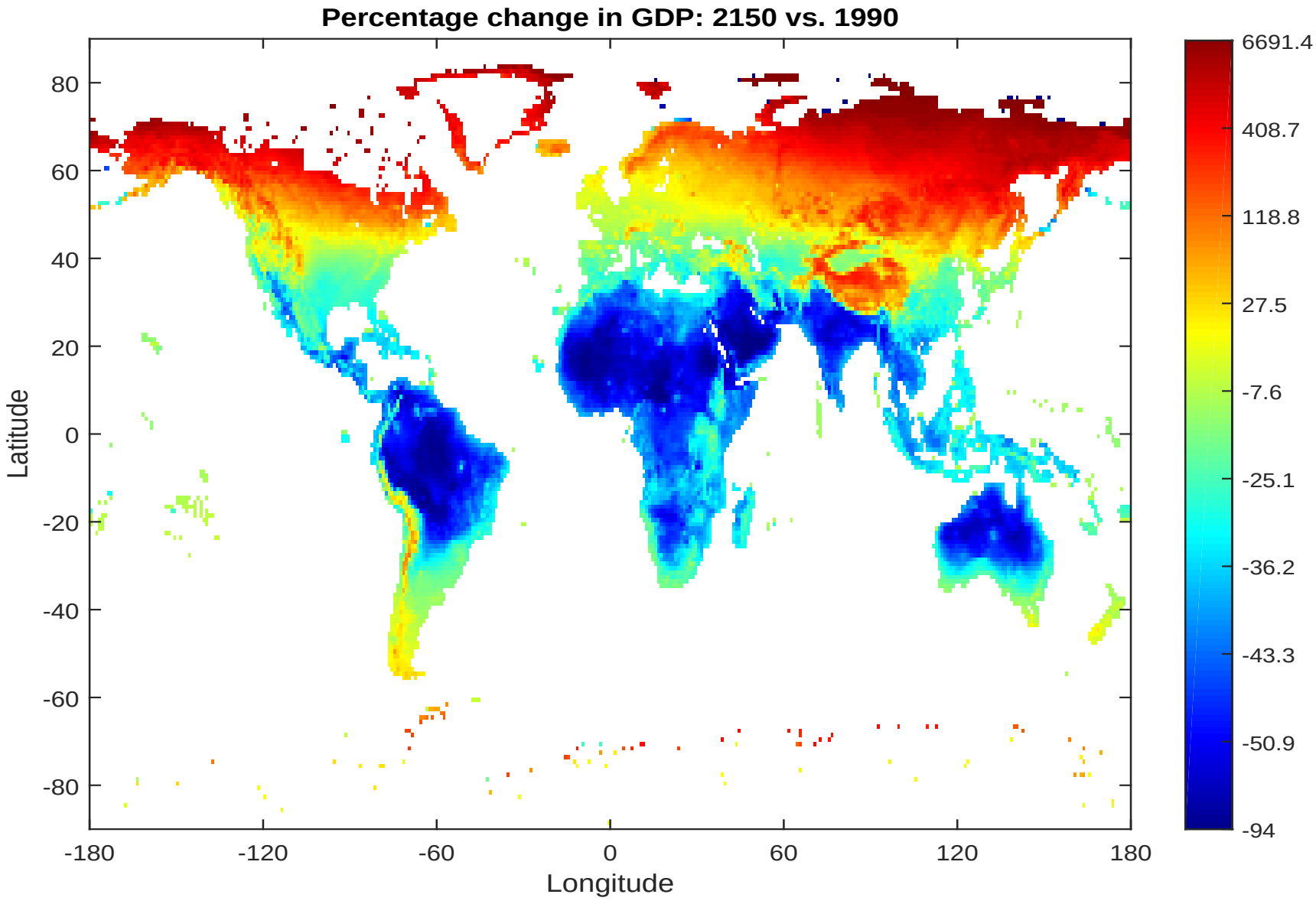
-7.6
-25.1
-36.2
-43.3
-50.9
-94


Percentage change in GDP: 2150 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
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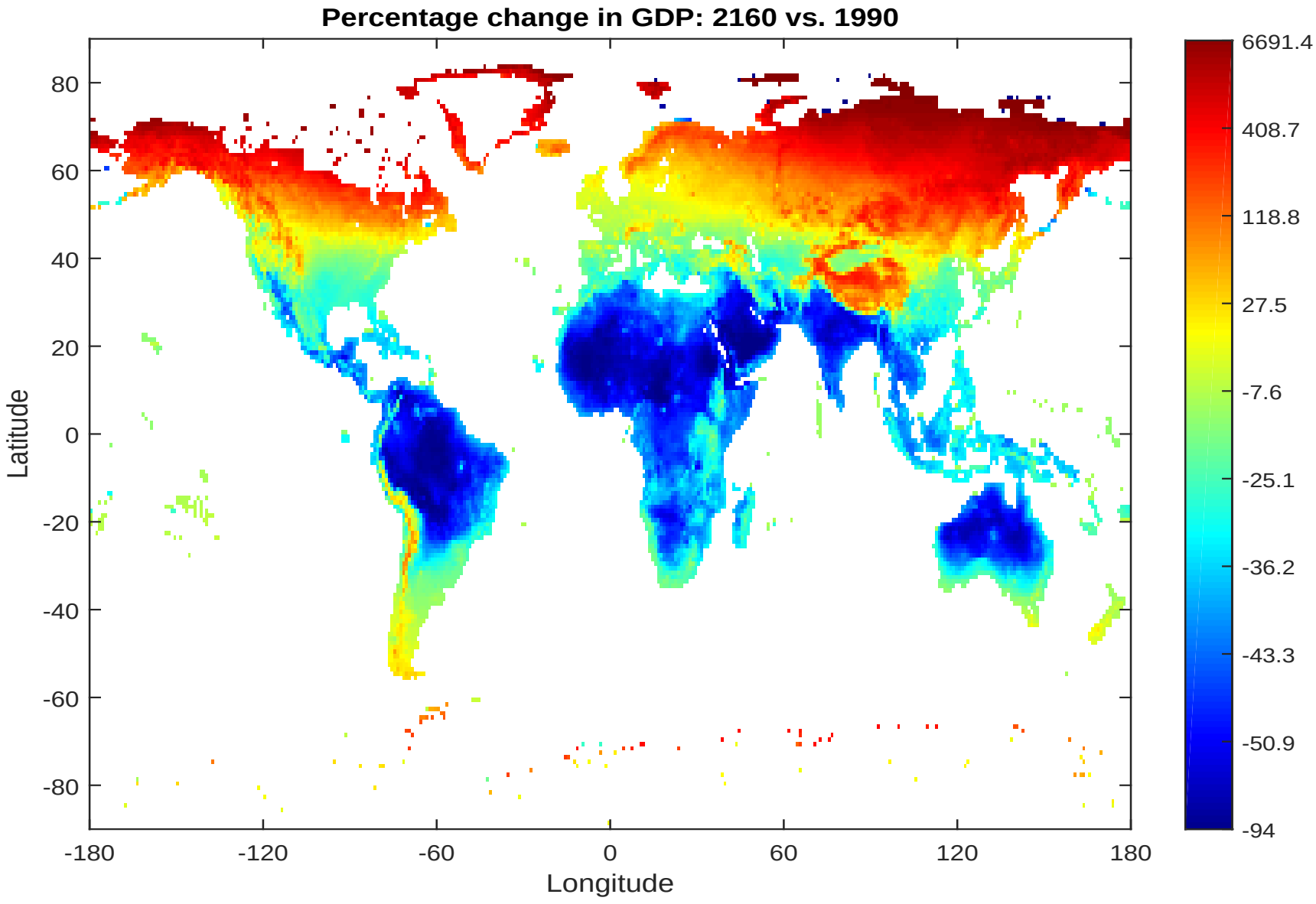
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
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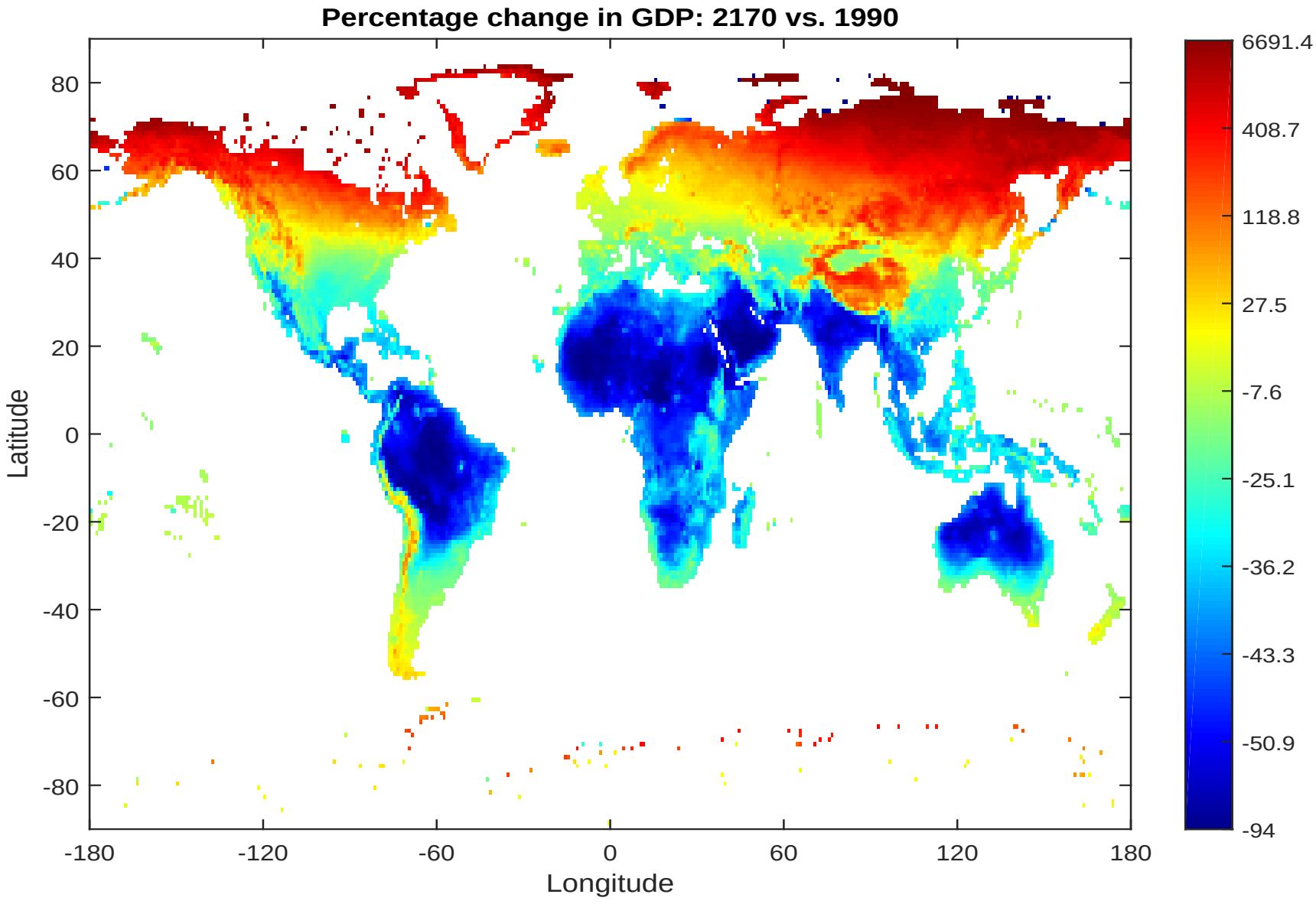
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


Percentage change in GDP: 2170 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
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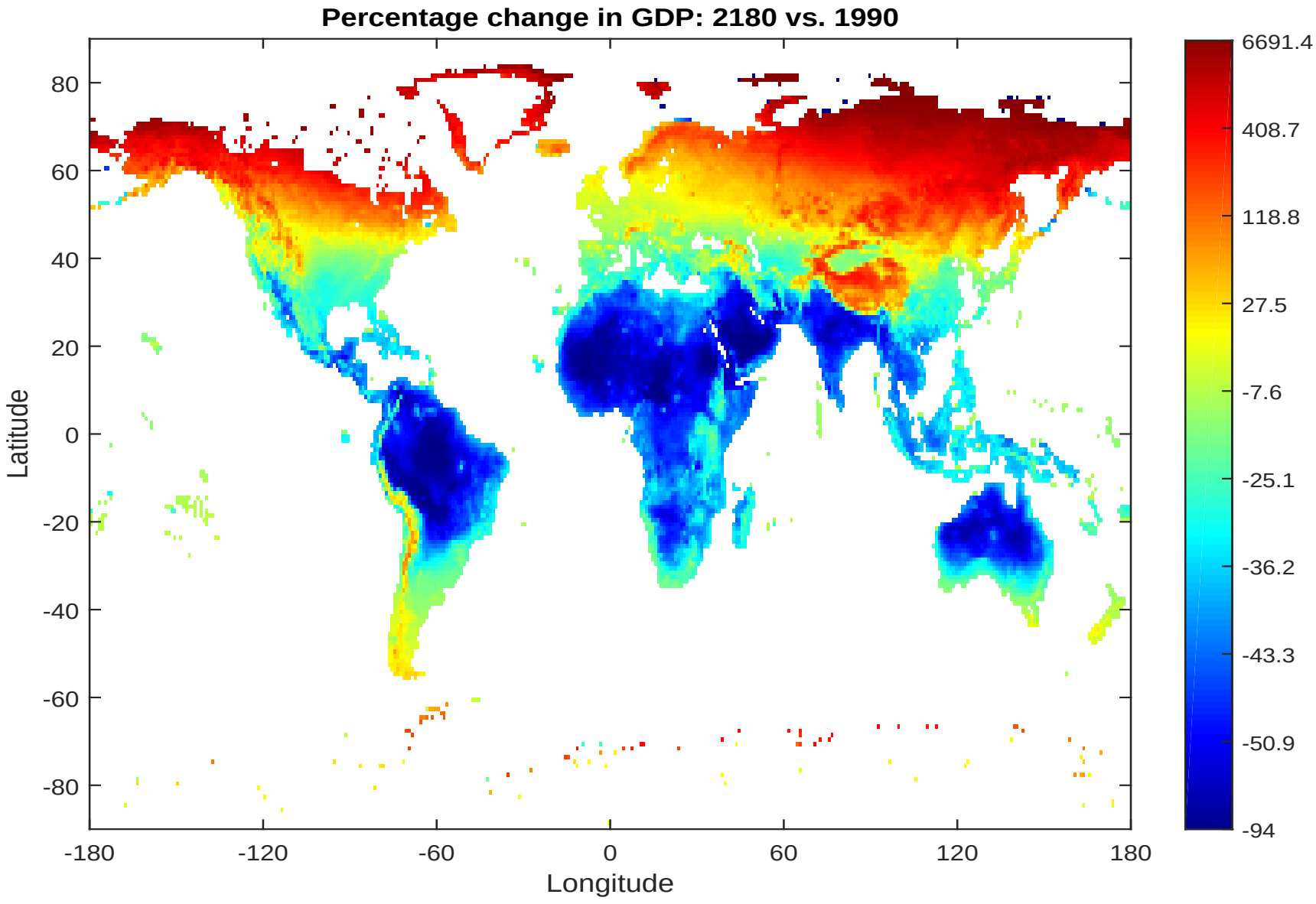
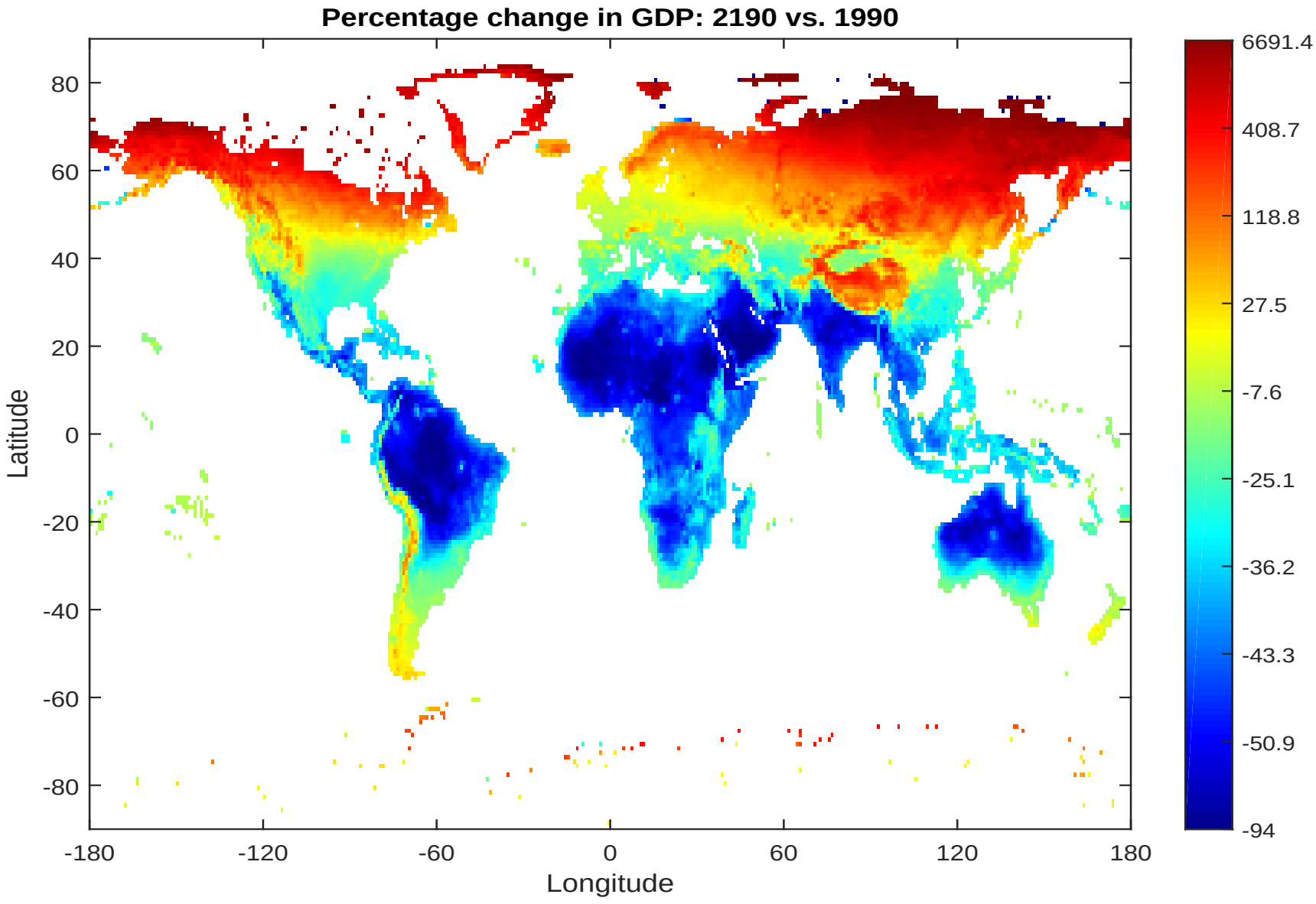
-36.2
-43.3
-50.9
-94


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
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


Percentage change in GDP: 2190 vs. 1990
Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
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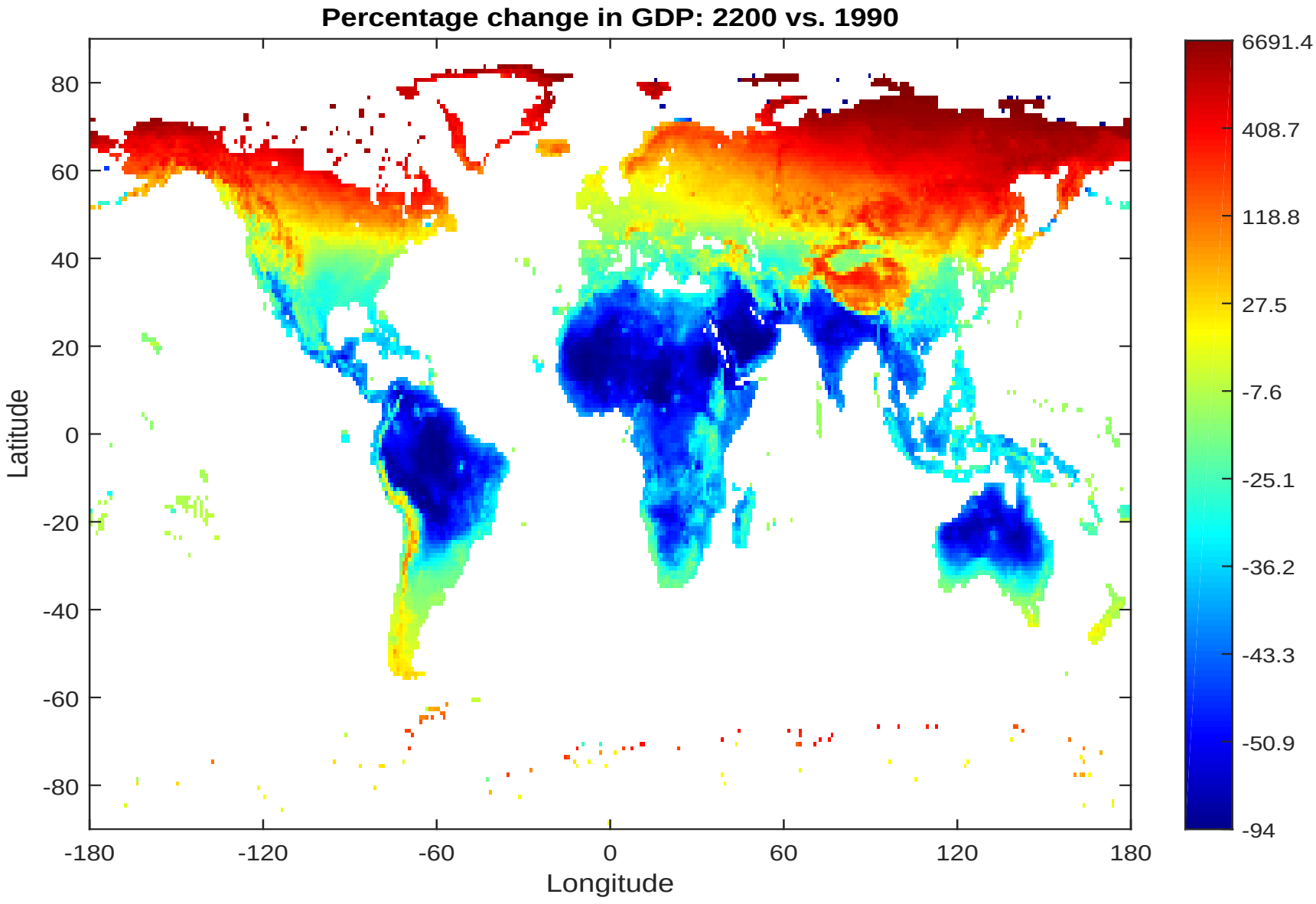
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94


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
6691.4
408.7
118.8
27.5
-7.6
-25.1
-36.2
-43.3
-50.9
-94

Conclusions

Take-away:

- 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.

Some caveats

- On one hand, damages "too local" and symmetric: no common aggregate damages. There are potentially such effects:
  - world technology development (level or growth) can be impacted;
  - biodiversity, ocean acidification, . . . ;
  - spillovers through trade, migration, tourism, . . .
- On other hand, maybe not enough regional heterogeneity yet (rural vs. urban, manufacturing vs. agriculture, . . .).

Near-future follow-up

Within present model/paper:

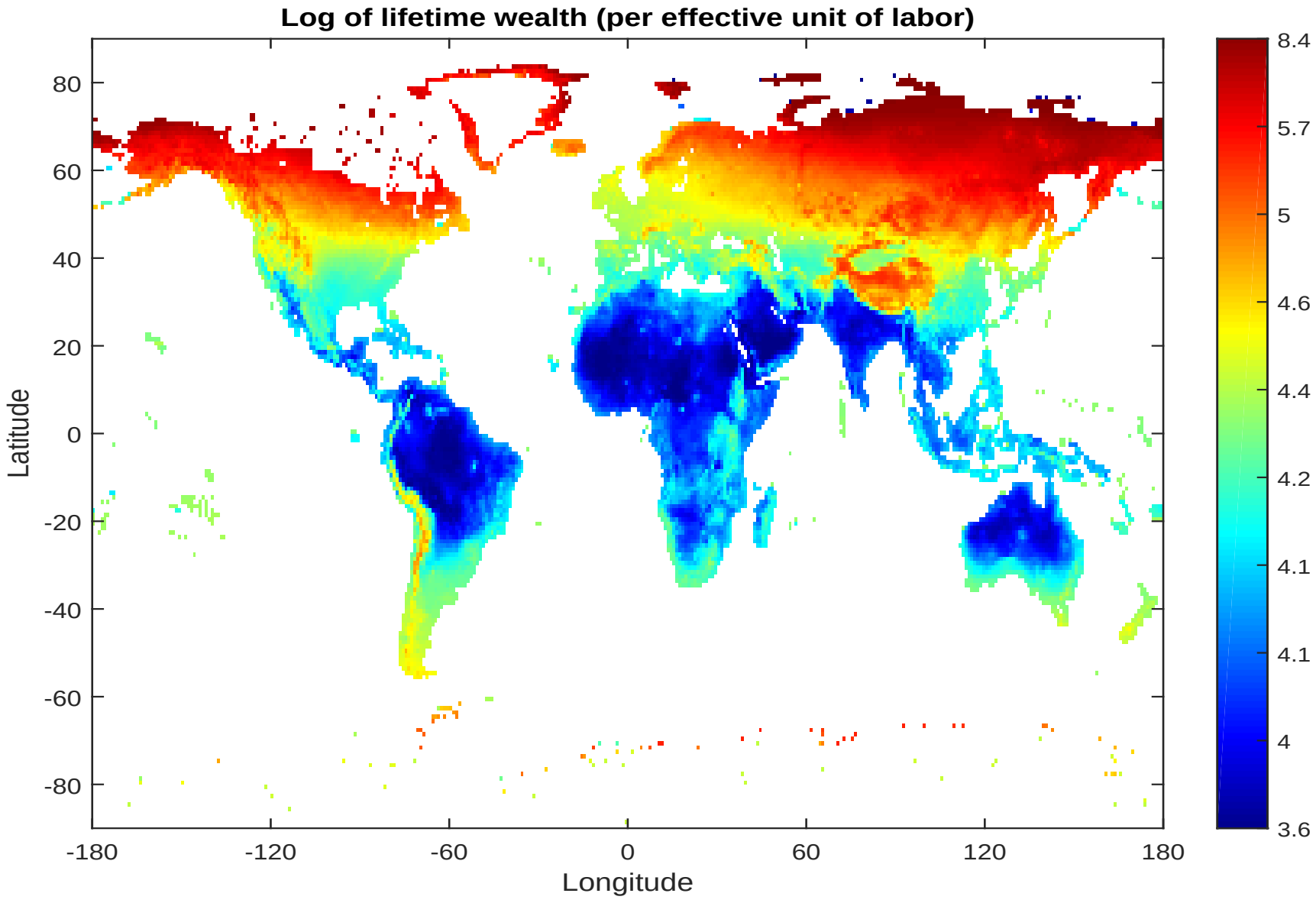
- Heterogeneous taxes (results for tax in U.S. and China only).
- How does climate change influence migration pressure at borders? Easy to compute. (PICTURE!)
- Sea-level rise and coastal damages (straightforward to incorporate).

Applications:

- Temperature shocks; can be problematic at higher Ts because of extreme weather events (programming under way).
- Rising volatility as globe warms.
- Agricultural sector and food supplies (includes adding precipitation).
- ...

Welfare changes from tax: summary measures

- One region = one vote: 55% gain (vs. 55%)
- One person = one vote: 62% gain (vs. 83%).
- One dollar = one vote: 70% gain (vs. 65%)
- Average gain across all regions: -0.18% (vs. -0.81%).
- Average gain weighted by GDP: 0.04% (vs. 0.14%).
- Average gain weighted by population: 0.12% (vs. 0.46%).
- World consumption path: gain of 0.007% (vs. 0.03%).
- 3% of regions in U.S. gain (vs. 42%).
- 7% of regions in China gain (vs. 30%).
- 62% of regions in ROW gain (vs. 57%).


Log of 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
8.4
5.7
5
4.6
4.4
4.2
4.1
4.1
4
3.6