How Much Will Global Warming Cool Global Growth?

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Motivation: Wide Divergence in Climate-GDP Projections

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- Prevailing literature: modest impacts
  - Nordhaus (2007): 2.5% of global GDP from 3°C warming by 2100
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  - IPCC (2014): 0.2 to 2% from 2°C of warming
- Prominent exception: very large effects
  - Burke, Hsiang, Miguel (2015): 23% of global GDP by 2100
  - Climate change reduces incomes by $>$ 80% in 50% of countries

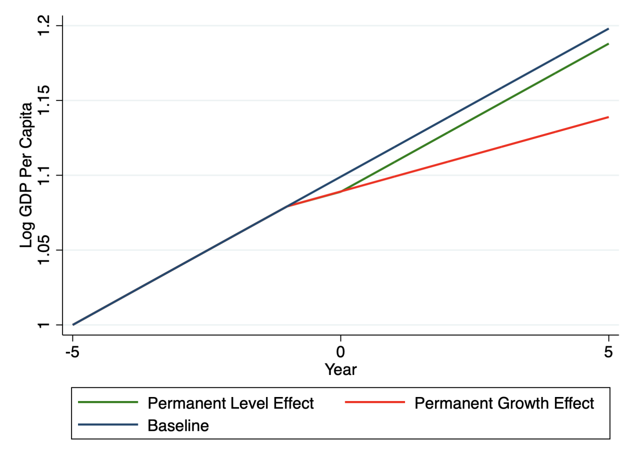
Motivation: Damage estimates are highly influential

- Academic macro papers with a climate damage component
  - e.g. Golosov et al. (2014 ECMA), Acemoglu et al. (2016 JPE), Barrage (2019, REStud)
- Social cost of carbon estimates
  - US EPA Interagency Working Group (Greenstone et al. 2013), Moore & Diaz (2015 Nature CC), Ricke et al. (2018 Nature CC), Burke & Diffenbaugh (2019 PNAS)
- Policy institutions
  - IPCC, EPA, World Bank, IMF, OECD
- Advocacy groups & popular press
  - Cato Institute, Sunrise Movement, Foreign Affairs, New Yorker

Motivation: Why impact estimates diverge

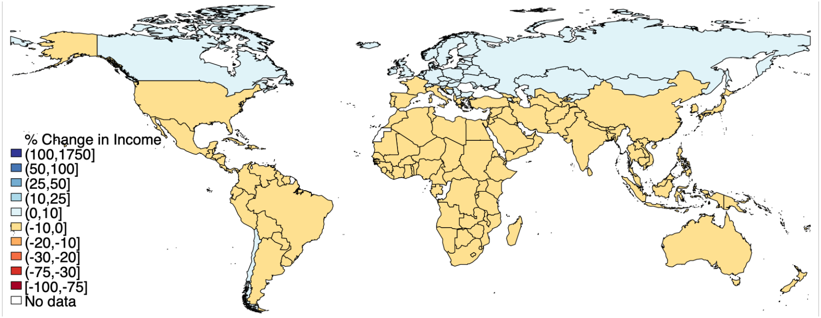
Does a permanent ↑ in temperature affect long-run growth or levels?

Figure: Effects of Permanent Temperature Change in Year 0



Climate change impacts: permanent level effects

Figure: Percent Change in Annual Income in 2099



Source: Example Using Permanent Level Effect Estimates

Climate change impacts: permanent growth effects

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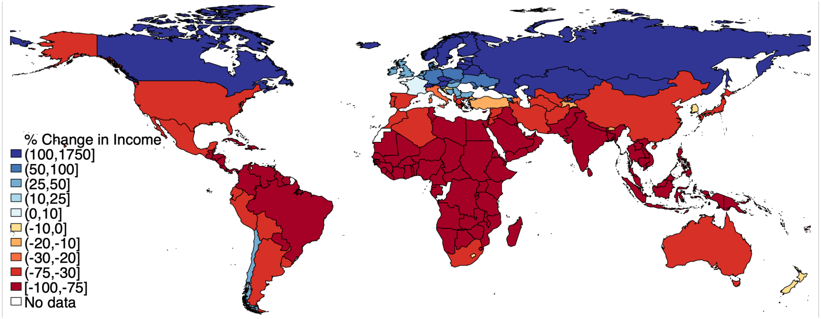

Source: Burke, Hsiang, & Miguel (2015)

Key Challenge - Interpreting a Temperature IRF

Figure: Impact of a *Temporary* Temperature Shock in Year 0

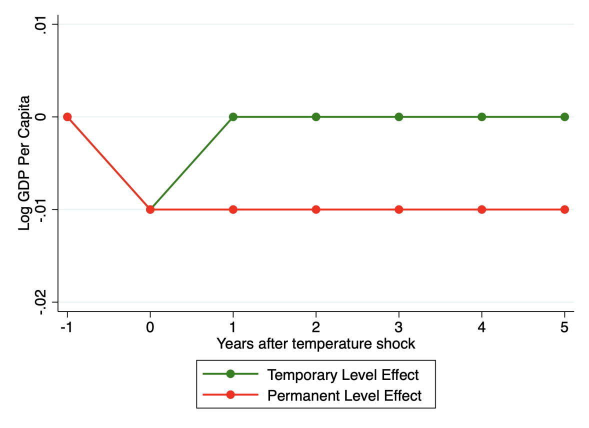

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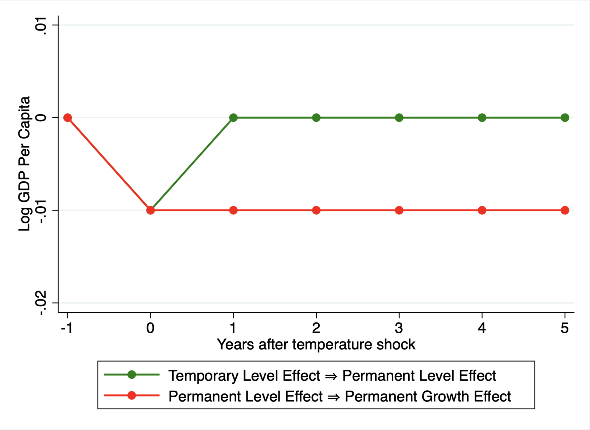
Figure: Implications of *Temporary* Shock for Projecting *Permanent* Shock



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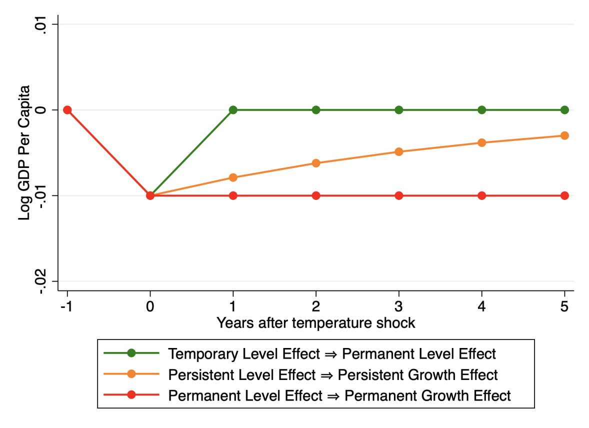
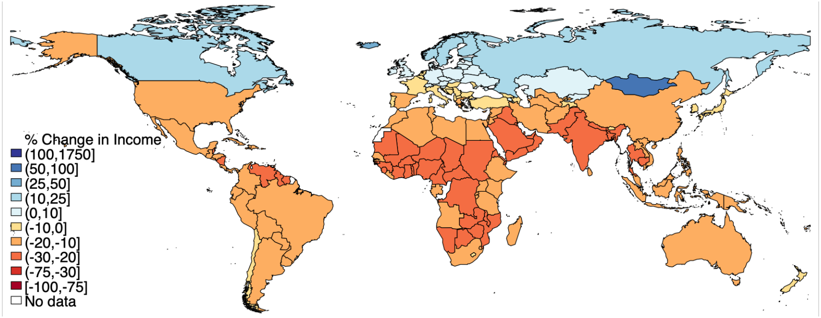


This Paper

- Theory and evidence for why country growth rates should not permanently diverge
- Dynamic panel estimates of the temperature-GDP relationship
- Projections of future climate change impacts based on empirical persistence of temperature effects

Results Preview: Our Projections

Figure: Percent Change in Annual Income in 2099



Key caveat: not a comprehensive welfare estimate

- Non-market damages (e.g. mortality, civil conflict)
  - e.g. Hsiang, Burke, & Miguel (2013), Carleton et al. (2022)
- Non-temperature effects (e.g. hurricanes, coastal flooding)
  - e.g. Desmet et al. (2021), Balboni (2021), Fried (2022)
- Tipping points
  - e.g. Lemoine & Traeger (2016), Dietz et al. (2021)
- Uncertainty and risk aversion
  - e.g. Weitzman (2009), Traeger (2014), Barnett, Brock, & Hansen (2020), Lemoine (2021), Nath et al. (2022)
- Adaptation
  - e.g. Moscona & Sastry (2021), Cruz & Rossi-Hansberg (2021)

Related Literature

- Panel and time-series estimates of temperature and output
  - Country-level data: Dell, Jones, & Olken (2012); Burke, Hsiang, & Miguel (2015); Acevedo et al. (2020); Berg, Curtis, & Mark (2021); Newell, Prest, & Sexton (2021); Bastien-Olvera, Granella, & Moore (2022)
  - Subnational data: Colacito, Hoffman, & Phan (2019); Burke & Tanutama (2019)

- Empirical climate-GDP projections informed by growth models
  - Kahn et al. (2019); Kalkuhl & Wenz (2020); Casey, Fried, & Goode (2022)

Outline

A Stylized Model of Global Growth

- Domestic production draws on domestic and international technology
- In the absence of shocks, countries converge to parallel TFP growth paths with a stationary distribution of relative TFP levels
- Speed of convergence (or of recovery from shocks) is increasing in the degree of international knowledge spillovers
- Countries have permanently divergent growth paths if and only if there are *zero* international knowledge spillovers

A Stylized Model of Global Growth

- Productivity in each country draws on domestic and international technologies, with varying levels of domestic efficiency μ_i:

$$Q_{it} \propto \cdot \mu_{it} \cdot \left(Q_{it-1}\right)^{1-\omega} \left(Q^*_{t-1}\right)^{\omega}.$$

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- μ_i of frontier countries drives global technological progress:

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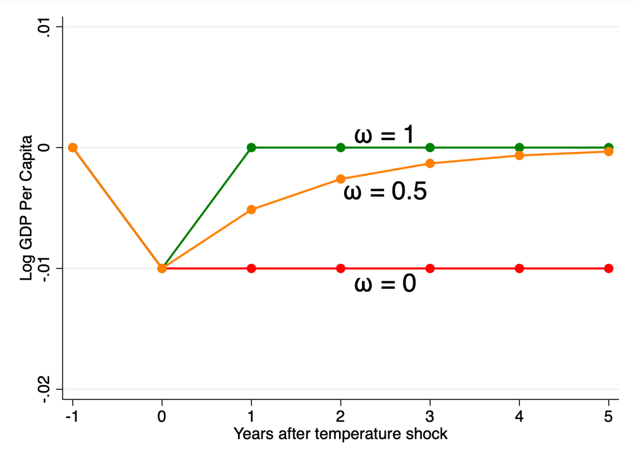
- Each country's per capita income is proportional to its productivity:

$$Y_{it}/L_{it} \propto \cdot M_{it}^{\frac{1}{\sigma-1}} \cdot Q_{it}.$$

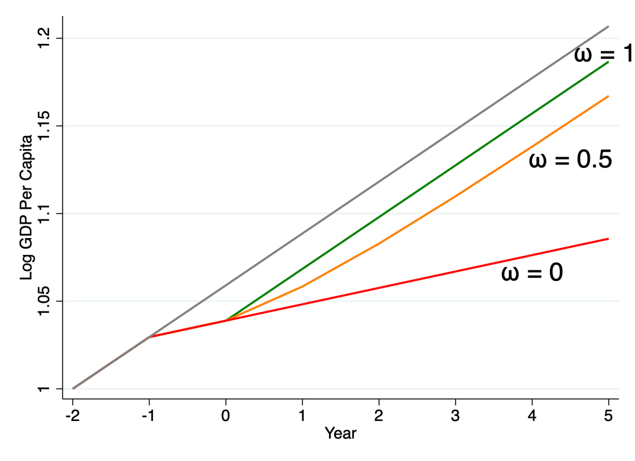
Comparative Statics - Transitory Shock to μ_i

Figure: Effects of a Transitory Temperature Shock to μ_i in Year 0



Comparative Statics - Permanent Shock to μ_i

Figure: Effects of Permanent Temperature Shock Starting in Year 0



A three part case for global growth spillovers ($0 < \omega < 1$)

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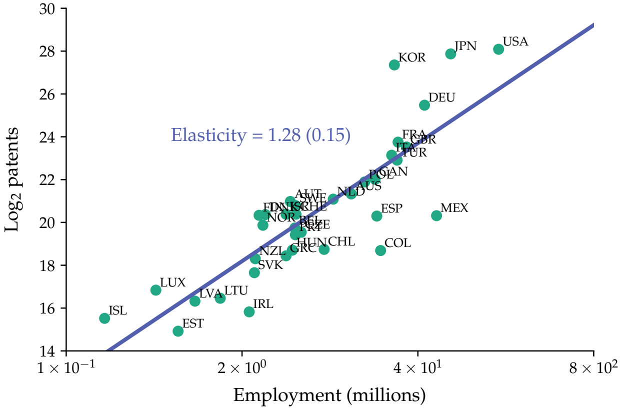
1. Rich countries grow at similar rates despite innovation differences
2.
3.

1. Bigger countries innovate more ...

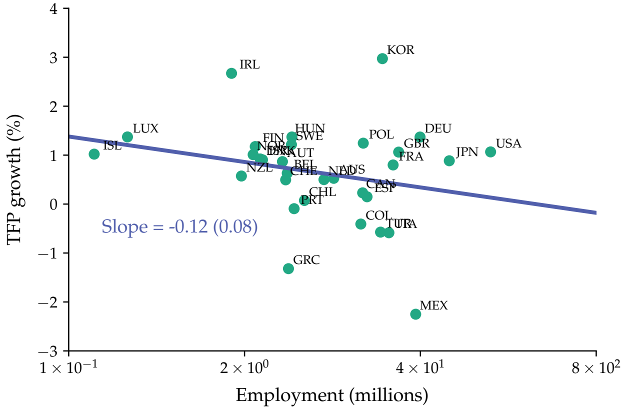
Figure: U.S. Patents and Employment in the Country of Origin in 2019



More people → more researchers → more patents

1. Bigger countries innovate more ... but don't grow faster

Figure: TFP Growth and Employment in OECD Countries, 1980-2019



More people → more researchers → more patents ↛ more growth

A three part case for global growth spillovers ($0 < \omega < 1$)

1. Rich countries grow at similar rates despite innovation differences
2. Country level differences persist, but growth differences do not
3.

2. Country differences persist in levels, but not growth

- We regress country TFP levels and growth on country and year FE:

$$y_{it} = \delta_i + \gamma_t + \epsilon_{it}$$

- We test: $H_0 : \delta_i \neq 0$ for each i

2. Country differences persist in levels, but not growth

Table: Tests of Country Differences in TFP Levels and Growth Rates

	(1)	(2)	(3)
Dependent Variable: Log Level of TFP			
Average p-value on Country FE	0.179	0.180	0.118
Percent of Countries with p-value < 0.05	54.9%	52.8%	69.7%
Dependent Variable: Growth Rate of TFP			
Average p-value on Country FE	0.773	0.475	0.514
Percent of Countries with p-value < 0.05	2.0%	9.0%	7.9%
Year FE	✓	✓	✓
Without Penn World Table Data Flag Countries		✓	✓
No Variety Adjustment			✓
Observations	3978	3471	3471
Countries	102	89	89

A three part case for global growth spillovers $(0 < \omega < 1)$

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- Motivated by the equation of motion for technology, we run the following regression for a panel of countries:

$$\ln(TFP)_{it} = (1-\omega)\ln(TFP)_{i,t-1} + \omega\ln(TFP)^{OECD}_{t-1} + \delta_i + \epsilon_{it}$$

- Estimates consistent with $\omega \approx 0.07$ - modest international spillovers

A three part case for global growth spillovers ($0 < \omega < 1$)

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Literature on globally-interconnected growth

- Technology flows across countries (patents, equipment, hybrid seeds)
  - Eaton and Kortum (1999 IER, 2001 EER), Gollin et al. (2021 JPE)
- Growth differences are transitory
  - Klenow and Rodriguez-Clare (2005), Pritchett and Summers (2014)
- Countries can converge toward, but not surpass, frontier
  - Parente and Prescott (2002, 2005)
- Global growth models:
  - Grossman & Helpman (1991), Acemoglu (2008), Akcigit, Ates, & Impulitti (2018), Buera & Oberfield (2020 ECMA) Cai, Li, & Santacreu (2022 AEJ-Macro), Hsieh, Klenow, & Nath (2021), Hsieh, Klenow, & Shimizu (2022)

Outline

Empirical Strategy

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  - We must account for the responses of **both** temperature and GDP to the temperature shock to make projections
  - Effect of the shocks may depend on **average country temperature**
- Our Approach: State-dependent Local Projections (Jorda, 2005)
  - Estimate longer-horizon impulse responses

Data

- Global Meteorological Forcing Temperature dataset
  - Global grid at 0.25° by 0.25° resolution
  - Population-weighted to the country level
- World Development Indicators for GDP Per Capita

Constructing Temperature Shocks

- Estimating a temperature shock $\boldsymbol{\tau_{it}}$:

$$T_{it} = \sum_{j=1}^{p} \left(\gamma_j T_{i,t-j} + \theta_j T_{i,t-j} \cdot \overline{T_i} \right) + \mu_i + \mu_t + \boldsymbol{\tau_{it}} \qquad (1)$$

  - Shock is the residual of an autoregressive model of temperature T.
  - Lag coefficients vary by country mean temperature, $\overline{T_i}$.
  - μ_i is country fixed effects.
  - μ_t is year fixed effects (included in some specifications).
  - $\boldsymbol{\tau_{it}}$ is the estimated temperature shock.

Impulse Response Estimation

- Temperature response local projections:

$$T_{i,t+h} = \alpha_0^h \boldsymbol{\tau_{it}} + \alpha_1^h \boldsymbol{\tau_{it}} \cdot \overline{T_i} + X_{it} + \zeta_{it}, \qquad h = 1, ..., H.$$

$$\text{where } \; X_{it} = \{ T_{i,t-j}, \;\; T_{i,t-j} \cdot \overline{T_i} \; \}_{j=1}^{p}, \;\; \mu_i, \; \mu_t.$$

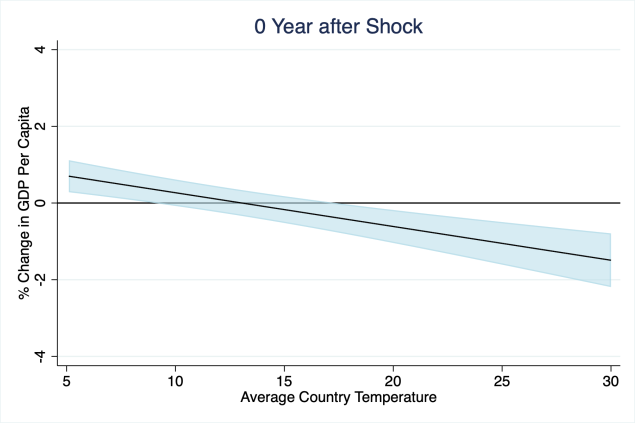
- GDP response local projections:

$$y_{i,t+h} - y_{i,t-1} = \beta_0^h \boldsymbol{\tau_{it}} + \beta_1^h \boldsymbol{\tau_{it}} \cdot \overline{T_i} + Z_{it} + \epsilon_{it}, \qquad h = 0, ..., H.$$

$$\text{where } \; Z_{it} = \{ T_{i,t-j}, \;\; T_{i,t-j} \cdot \overline{T_i}, \;\; \Delta y_{i,t-j} \; \}_{j=1}^{p}, \;\; \mu_i, \; \mu_t.$$

Effect of a Temperature Shock on GDP

Figure: Impact of a 1°C Temperature Shock on GDP
By Long-Run Average Temperature



▸ US TFP Control Instead of Year FE

Effects on GDP Persist After Initial Shock

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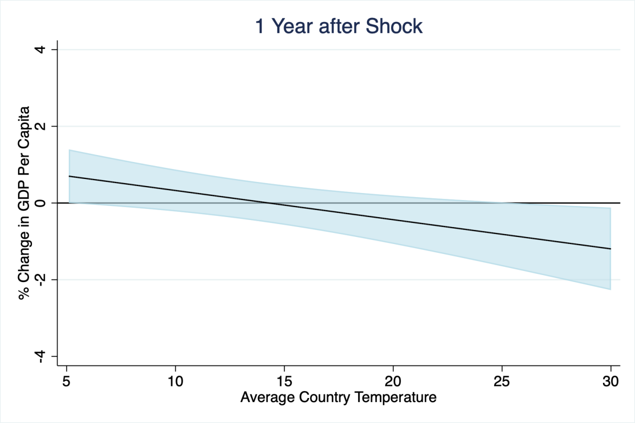

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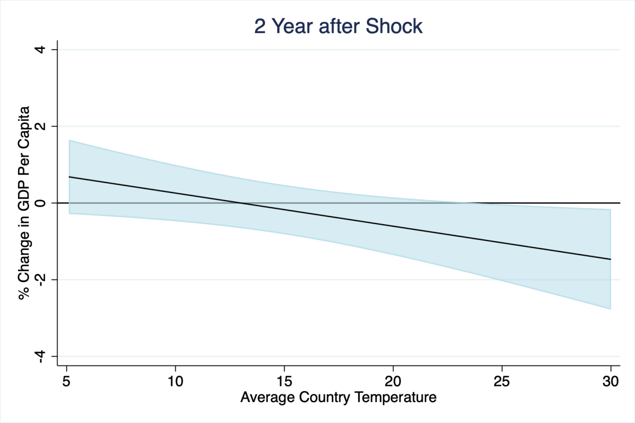

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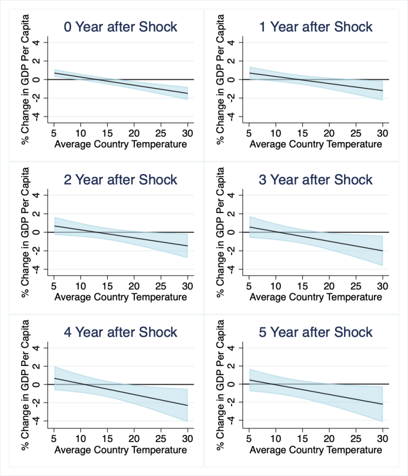

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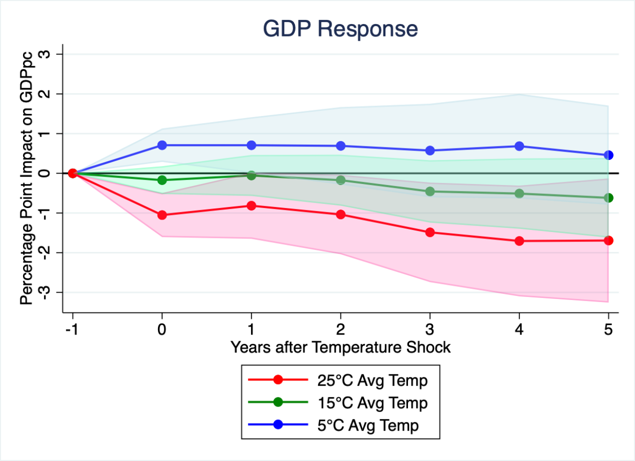

Temperature Response is also Persistent

Figure: Persistence of Temperature Response to a 1°C Shock In Hot Countries

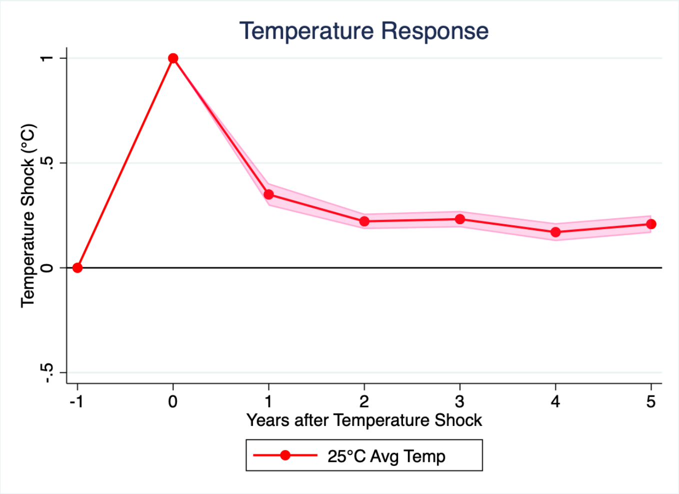

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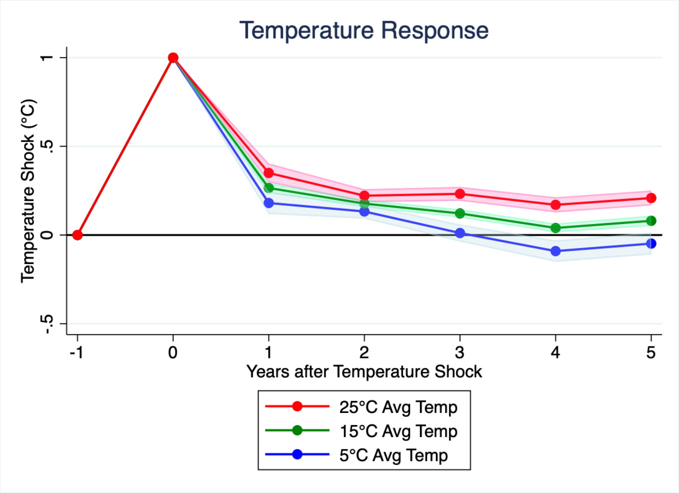
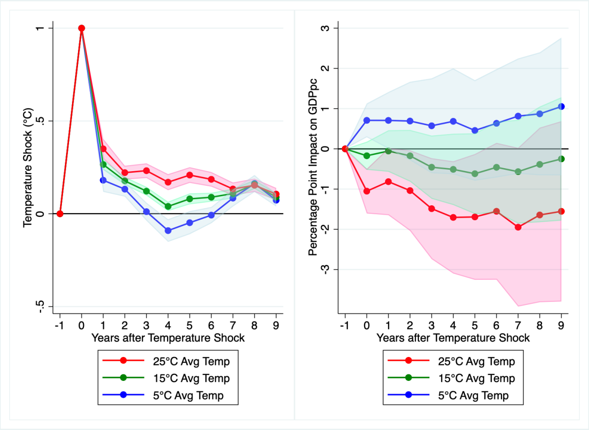
Figure: Persistence of Temperature Response to a 1°C Shock By Long-Run Average Temperature



Both Temperature and GDP Effects of a Shock Persist

Figure: Persistent Effects of a 1°C Temperature Shock
By Long-Run Average Temperature



▸ US TFP Control Instead of Year FE

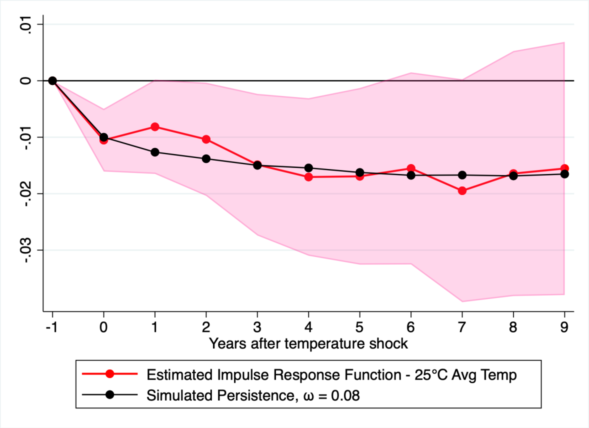
Using Empirical IRFs to Back Out ω

- We construct a simulation of a temperature shock with persistence to compare to the empirical IRF
- Magnitude of 1°C shock to μ_{it} calibrated to match year 0 effect
- Calibrate path of temperature following the shock to match empirical temperature IRF
  - Search for ω that minimizes sum of squared errors between model and empirical IRF

Comparing Empirical and Model IRFs

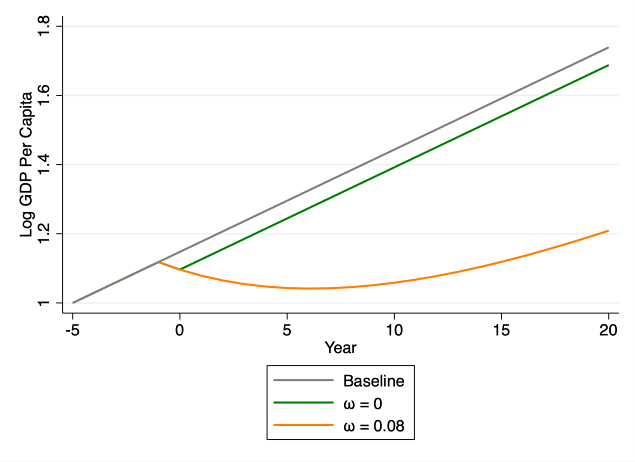
Figure: Simulated and Empirical Effects of Identical *Persistent* Temperature Shock in Year 0

$\omega = 0.08$



Implications of $\omega = 0.08$

Figure: Simulated Effects of Permanent Temperature Shock Starting in Year 0

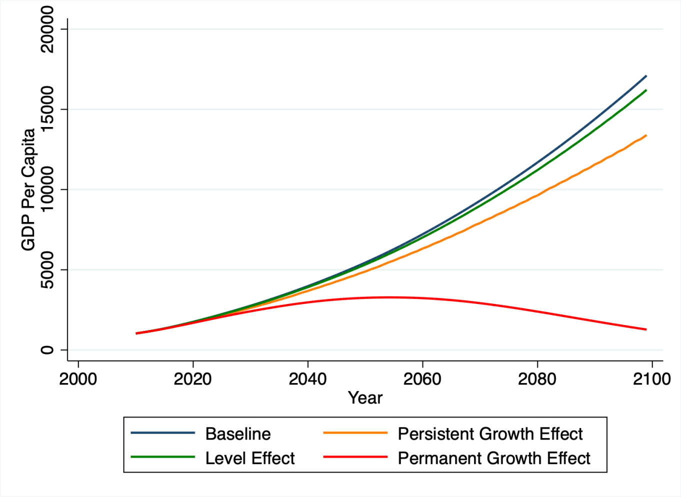


Outline

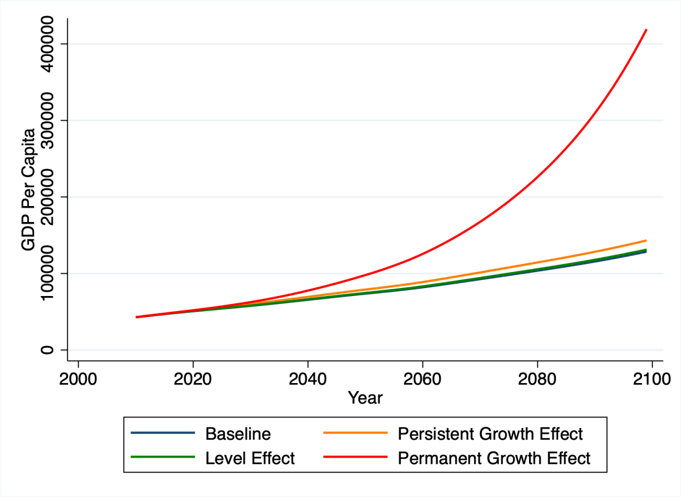
Projection Approach

- Use 10 year *cumulative response ratio* (GDP effect / temperature effect) to project long-run impact of temperature change
- Cumulative response ratio varies by initial temperature
- Temperature projections come from BHM (2015 Nature)
    - Average over many climate models in "baseline" emissions scenario
    - ΔT varies by country, slightly under 4°C for the world

Projection Results: India

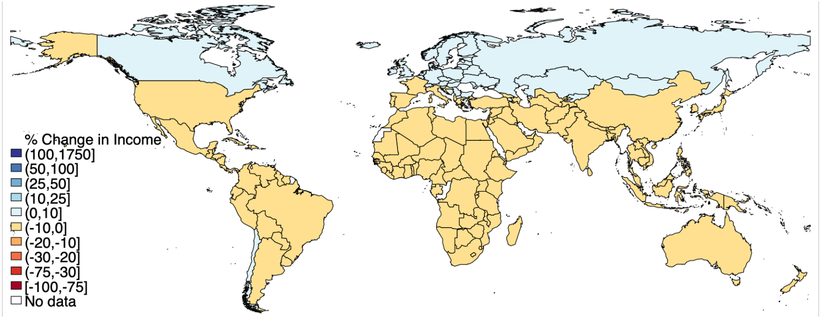


Projection Results: Sweden



Climate Change Projections - Permanent Level Effects

Figure: Impact of Climate Change on Annual Income in 2099



Source: Example Using Our Estimated Contemporaneous Effects Only

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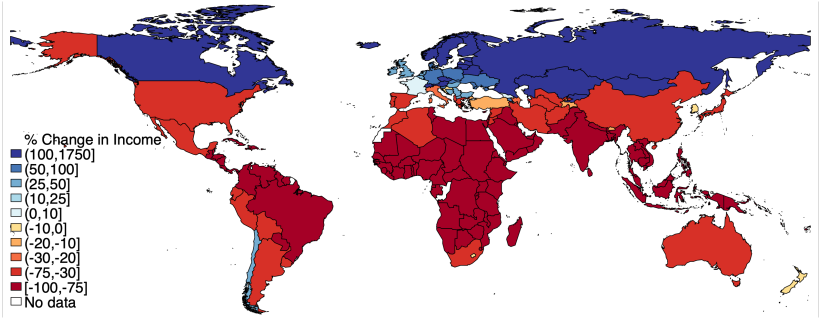

Source: Burke, Hsiang, & Miguel (2015)

Climate Change Projections - Our Estimates

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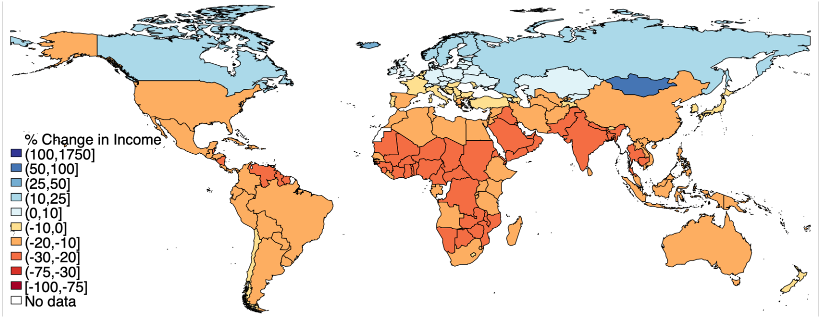


Source: Our estimates using accumulated level effect from 10 lags

Projection Summary

Table: Projected Effects of Unabated Global Warming on 2099 Income
Year Fixed Effect Specification

Region	Persistent Growth Effects	Level Effects	Permanent Growth Effects
Global GDP	-11.5	-2.2	-26.6
Global Population Average	-16.4	-3.6	-58.7
Sub-Saharan Africa	-20.6	-4.8	-86.1
Middle East & North Africa	-20.1	-4.3	-82.5
Asia	-18.0	-4.0	-73.3
South & Central America	-16.1	-3.3	-74.6
North America	-9.6	-1.4	-20.0
Europe	0.6	0.4	96.6

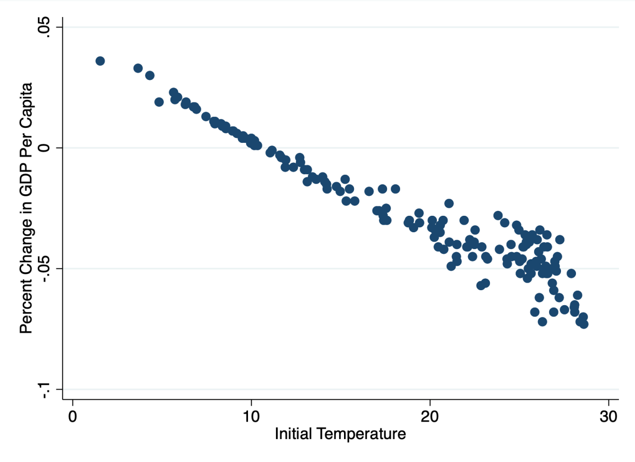
Projection Summary

Table: Projected Effects of Unabated Global Warming on 2099 Income
US TFP Control Specification

Region	Persistent Growth Effects	Level Effects	Permanent Growth Effects
Global GDP	-6.8	-1.9	-26.6
Global Population Average	-10.0	-3.1	-58.7
Sub-Saharan Africa	-13.0	-4.2	-86.1
Middle East & North Africa	-12.1	-3.7	-82.5
Asia	-11.0	-3.4	-73.3
South & Central America	-9.5	-2.8	-74.6
North America	-4.8	-1.2	-20.0
Europe	0.2	0.4	96.6

Projections by Initial Temperature

Figure: Impact of Climate Change on Annual Income in 2099
Level Effect



Source: Example Using Our Estimated Contemporaneous Effects Only

Projections by Initial Temperature

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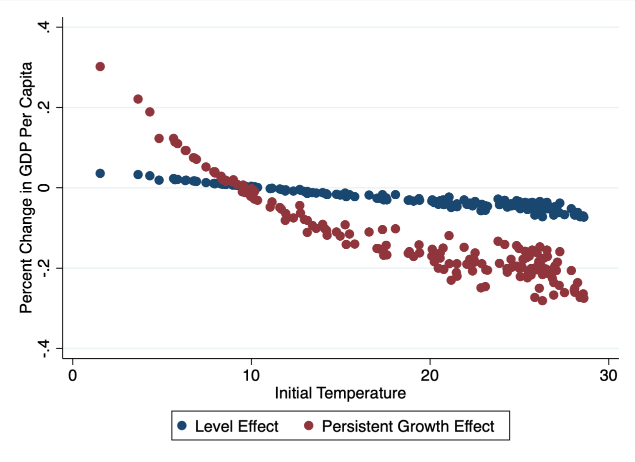

Source: Our Estimates

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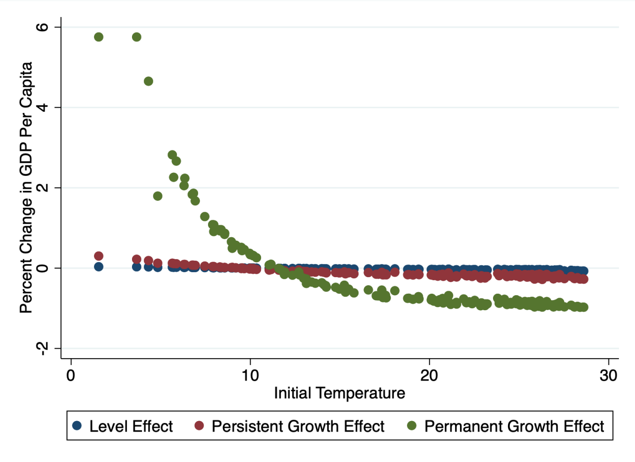


Source: Our Estimates, Burke-Hsiang-Miguel (2015)

Conclusion

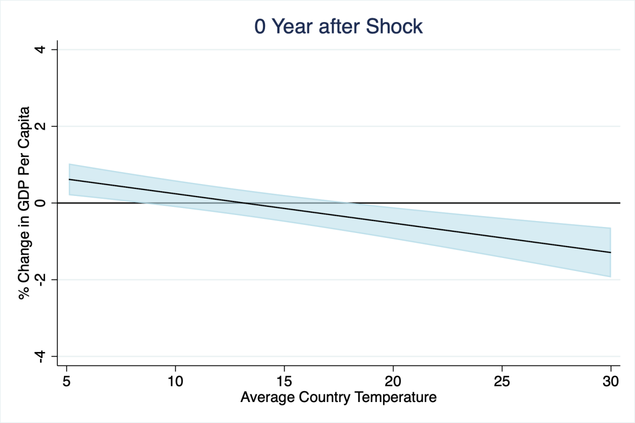
- Model & evidence suggest growth is tied together across countries
  - Temperature unlikely to have permanent country growth effects
  - Trending temperatures can still have global growth effects
- Dynamic estimates show persistent effects of temperature on GDP
  - Moderate persistence of temperature itself
- Projections suggest warming reduces global income 6-12% by 2100
  - $\sim$ 3-5x larger than permanent level effects
  - $\sim$ 3-4x smaller than permanent growth effects
    - Country-specific effects differ even more dramatically

Appendix

EXTRA SLIDES

Effect of a Temperature Shock on GDP

Figure: Impact of a 1°C Temperature Shock on GDP
By Long-Run Average Temperature - US TFP Control Instead of Year FE



Controls for contemporaneous US TFP instead of year FE ▸ Back

Both Temperature and GDP Effects of a Shock Persist

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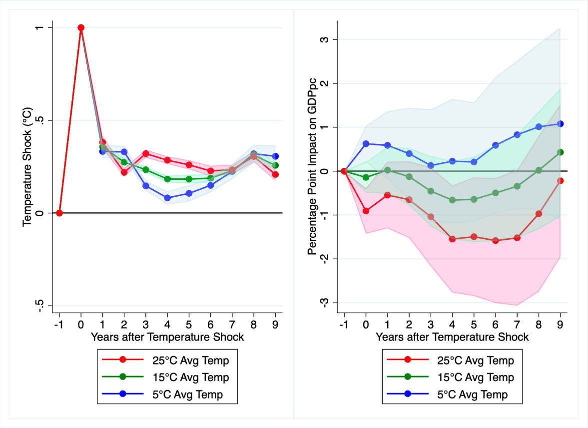
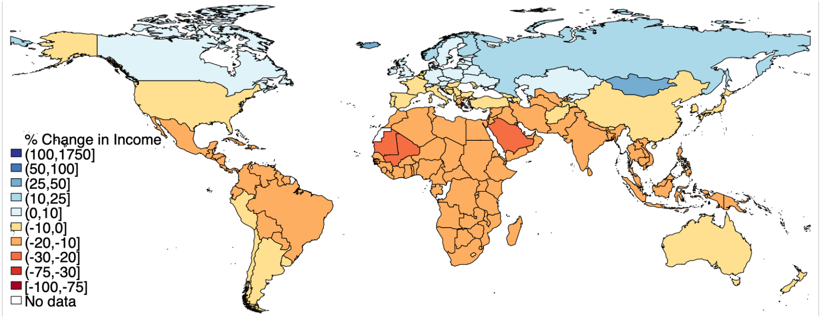
By Long-Run Average Temperature



Controls for contemporaneous US TFP instead of year FE ▸ Back

Climate Change Impact Comparison

Figure: Difference in 2099 Climate Change KNR Estimates vs. Temporary Level Effects



Source: Our dynamic estimates minus pure level effects only

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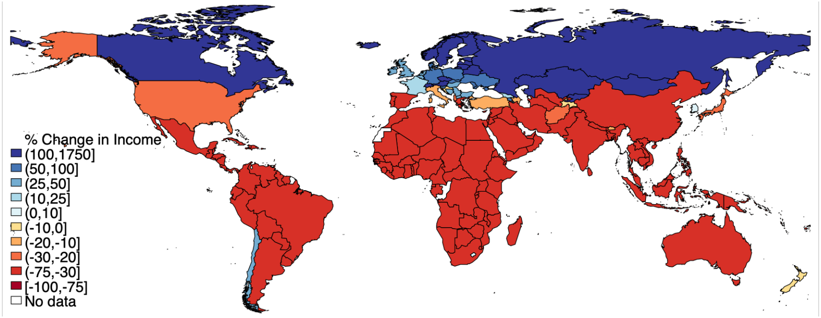
Climate Change Impact Comparison

Figure: Difference in 2099 Climate Change Permanent Growth Effects vs. KNR Estimates



Source: Burke-Hsiang-Miguel (2015) estimates minus our estimates

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