# How Much Will Global Warming Cool Global Growth?

Ishan Nath | Valerie Ramey | Pete Klenow

SF Federal Reserve | Hoover Institution & NBER | Stanford & NBER

November 9-10, 2023

Yale Climate, Environment, and Economic Growth Conference

# Motivation: Wide Divergence in Climate-GDP Projections

# Motivation: Wide Divergence in Climate-GDP Projections

- Prevailing literature: modest impacts
  - Barrage and Nordhaus (2023): 1.6% of global GDP from 3°C warming by 2100
  - IPCC (2014): 0.2 to 2% from 2°C of warming

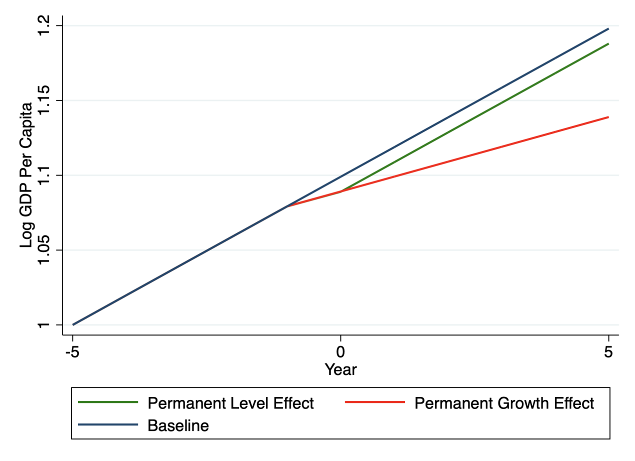
# Motivation: Wide Divergence in Climate-GDP Projections

- Prevailing literature: modest impacts
  - Barrage and Nordhaus (2023): 1.6% of global GDP from 3°C warming by 2100
  - 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: Why impact estimates diverge

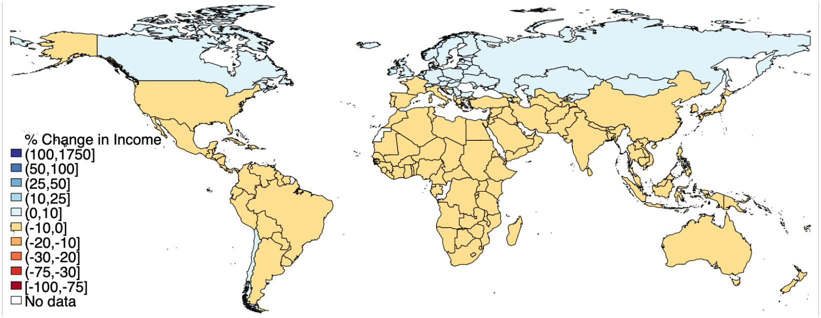
Does a permanent ↑ in temperature affect long-run growth or levels?

Figure: Effects of Permanent Temperature Change in Year 0



# Climate change impacts: permanent level effects

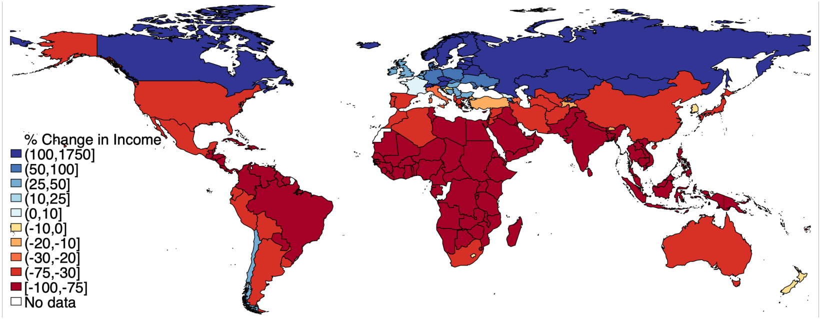
Figure: Percent Change in Annual Income in 2099




Source: Example Using Permanent Level Effect Estimates

# Climate change impacts: permanent growth effects

Figure: Percent Change in Annual Income in 2099



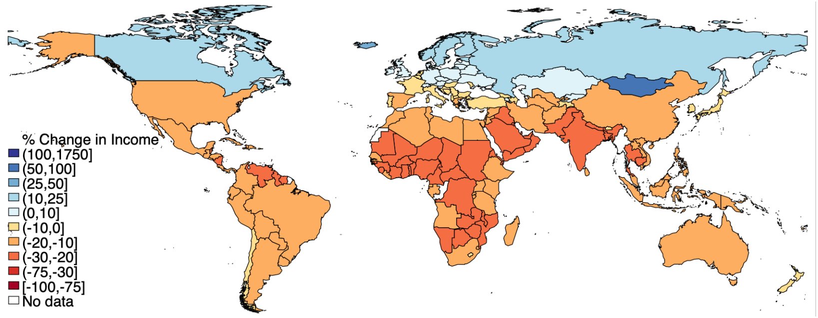

Source: Burke, Hsiang, & Miguel (2015)

# 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

1. Introduction
2. Are Country Growth Rates Connected?
3. Empirical Estimates
4. Projections

# A Stylized Model of Global Growth

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

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

# A Stylized Model of Global Growth

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

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

- $\mu_i$ of frontier countries drives global technological progress:

$$Q^*_{t+1} \propto \mu^*_t \cdot Q^*_t.$$

# A Stylized Model of Global Growth

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

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

- $\mu_i$ of frontier countries drives global technological progress:

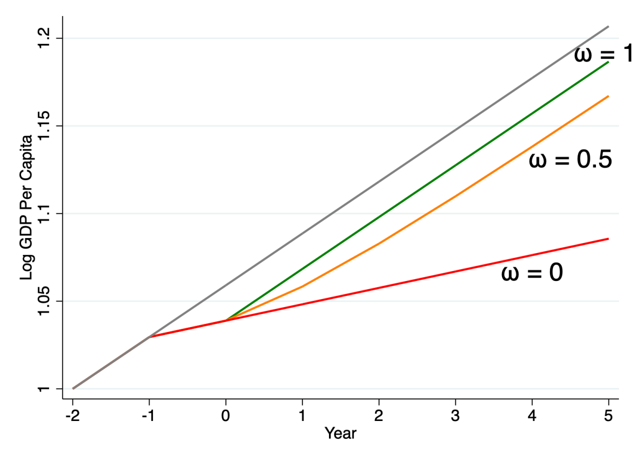
$$Q^*_{t+1} \propto \mu^*_t \cdot Q^*_t.$$

- 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 - Permanent Shock to $\mu_i$

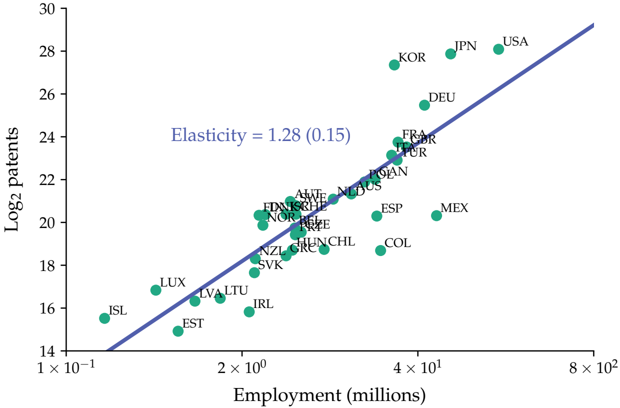
Figure: Effects of Permanent Temperature Shock Starting in Year 0



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

# 1. Bigger countries innovate more ...

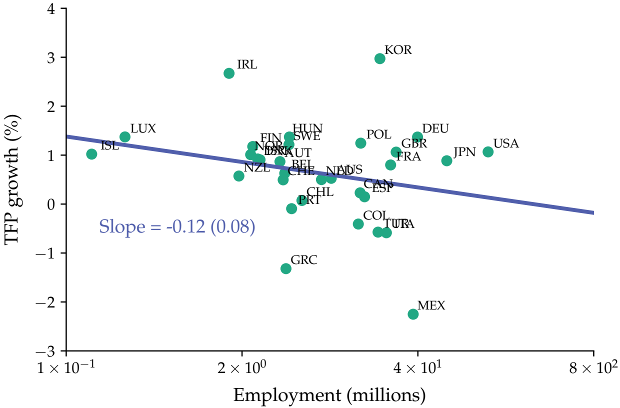
Figure: U.S. Patents and Employment in the Country of Origin in 2019




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 $\rightarrow$ more researchers $\rightarrow$ more patents $\not\rightarrow$ more growth

# 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

- 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 $i$

- For TFP levels, we reject equality for 50 - 70% of countries.

# 2. Country differences persist in levels, but not growth

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

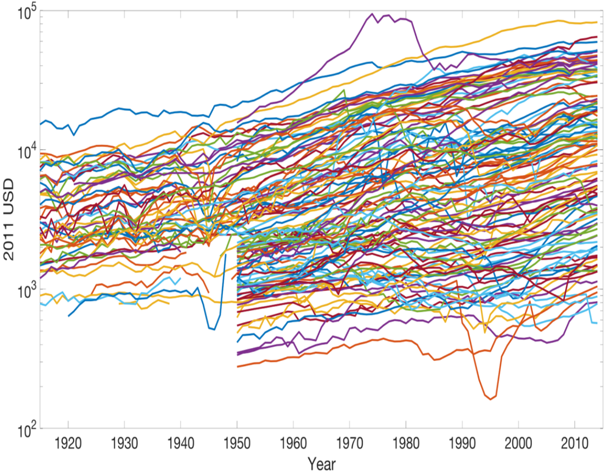
$$y_{it} = \delta_i + \gamma_t + \epsilon_{it}$$

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

- For TFP levels, we reject equality for 50 - 70% of countries.

- For TFP growth rates, we reject equality for only 2 - 9% of countries

# Log GDP per capita, 1915-2014, 112 countries




Sources: Penn World Tables; Müller, Stock, and Watson, (2022)

# 3. Frontier country technology predicts global growth

- Estimate model-implied equation of motion for technology:

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

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

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

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

# 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

1. Introduction
2. Are Country Growth Rates Connected?
3. Empirical Estimates
4. Projections

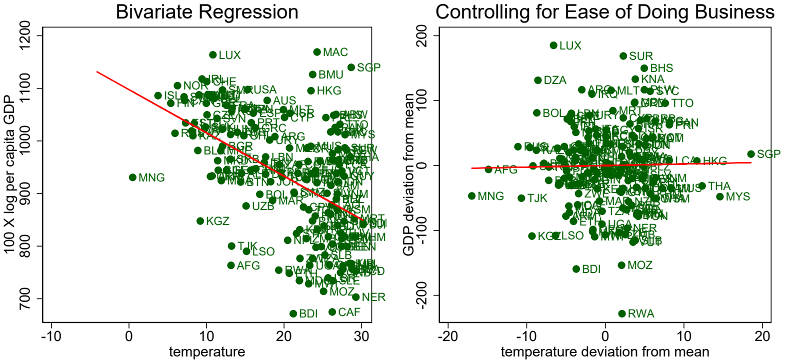
# How to Estimate the Effects of Temperature on GDP

- Cross-country regressions.
  - Advantage: Captures long-run effects, adaptation.
  - Disadvantage: historical influences of temperature on institutions

# How to Estimate the Effects of Temperature on GDP

- Cross-country regressions.
  - Advantage: Captures long-run effects, adaptation.
  - Disadvantage: historical influences of temperature on institutions
- Time-series regressions
  - Advantage: Directly measures correlation between temperature and GDP over time
  - Disadvantage: other trends in GDP, most temperature variation is temporary

# Cross-Country Regression GDP on Temperature for 2015




| Variable | Bivariate regression | Controlling for Business Ease |
|---|---|---|
| Temperature | -8.22 (1.07) | 0.24 (0.97) |
| Business ease | | 7.65 (0.57) |
| $R^2$ | 0.26 | 0.67 |

# Our Empirical Strategy: Use Panel Data Variation

# Our Empirical Strategy: Use Panel Data Variation

- Key Challenges:

# Our Empirical Strategy: Use Panel Data Variation

- Key Challenges:
  - Temperature is autocorrelated, so we must use **temperature shocks** to estimate dynamic causal effects

# Our Empirical Strategy: Use Panel Data Variation

- Key Challenges:
  - Temperature is autocorrelated, so we must use **temperature shocks** to estimate dynamic causal effects
  - Temperature shocks contain **transitory and permanent components**

# Our Empirical Strategy: Use Panel Data Variation

- Key Challenges:
  - Temperature is autocorrelated, so we must use **temperature shocks** to estimate dynamic causal effects
  - Temperature shocks contain **transitory and permanent components**
  - We must account for the responses of **both** temperature and GDP to the temperature shock to make projections

# Our Empirical Strategy: Use Panel Data Variation

- Key Challenges:
  - Temperature is autocorrelated, so we must use **temperature shocks** to estimate dynamic causal effects
  - Temperature shocks contain **transitory and permanent components**
  - 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 Empirical Strategy: Use Panel Data Variation

- Key Challenges:
  - Temperature is autocorrelated, so we must use **temperature shocks** to estimate dynamic causal effects
  - Temperature shocks contain **transitory and permanent components**
  - 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 $0.25^\circ$ by $0.25^\circ$ 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, $\overline{T_i}$.
  - $\mu_i$ is country fixed effects.
  - $\mu_t$ is year fixed effects (included in some specifications).
  - $\boldsymbol{\tau_{it}}$ is the estimated temperature shock.

# Impulse Response Estimation

- Temperature response local projections:

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

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

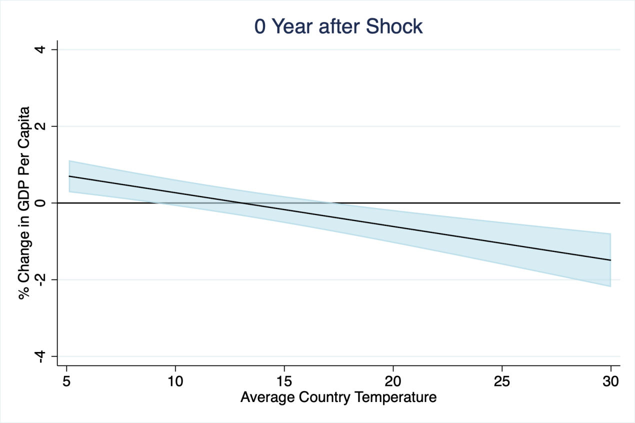
- GDP response local projections:

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

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

# Effect of a Temperature Shock on GDP

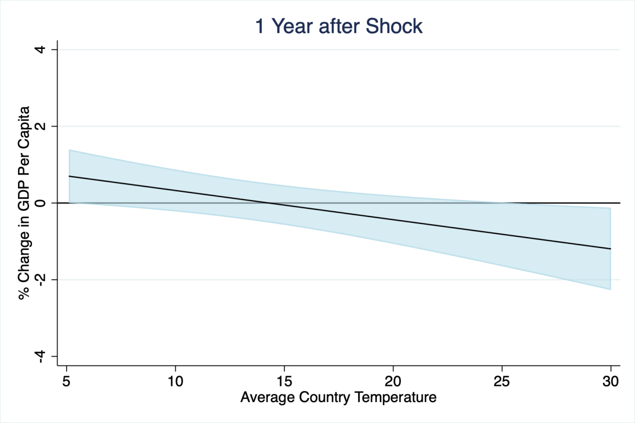
Figure: Impact of a 1°C Temperature Shock on GDP
By Long-Run Average Temperature




▸ US TFP Control Instead of Year FE

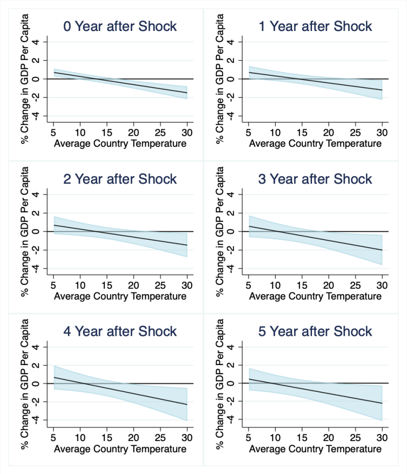
# Effects on GDP Persist After Initial Shock

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



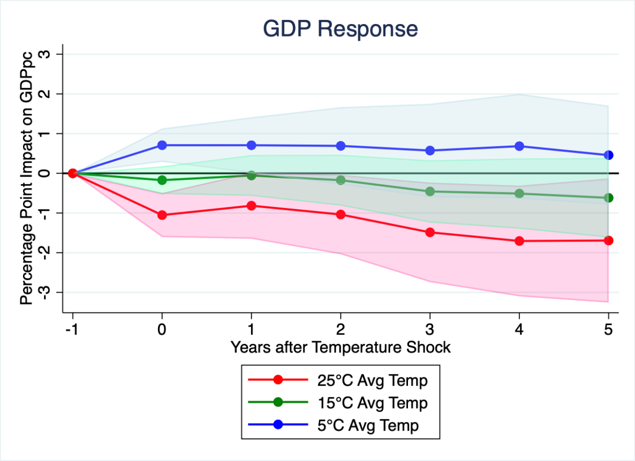
# Effects on GDP Persist After Initial Shock

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



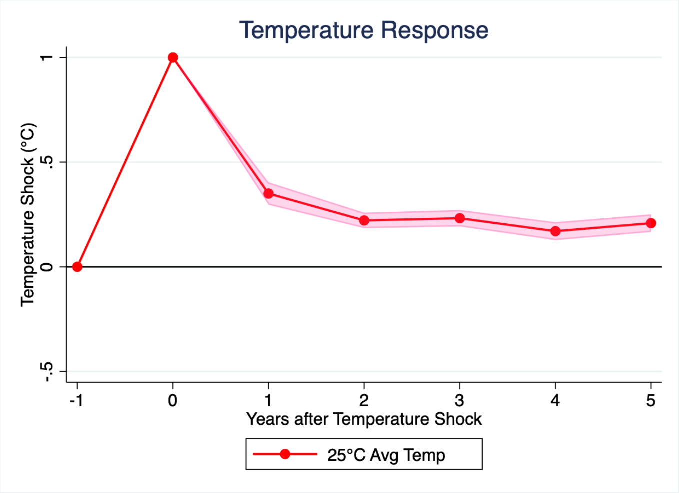
# Effects on GDP Persist After Initial Shock

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



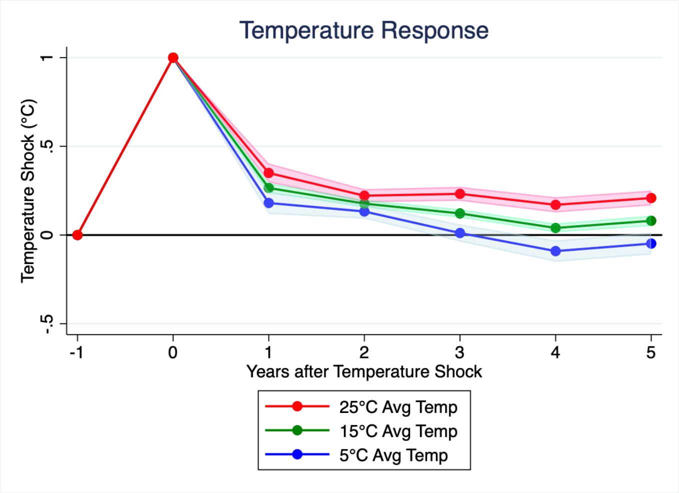
# Temperature Response is also Persistent

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



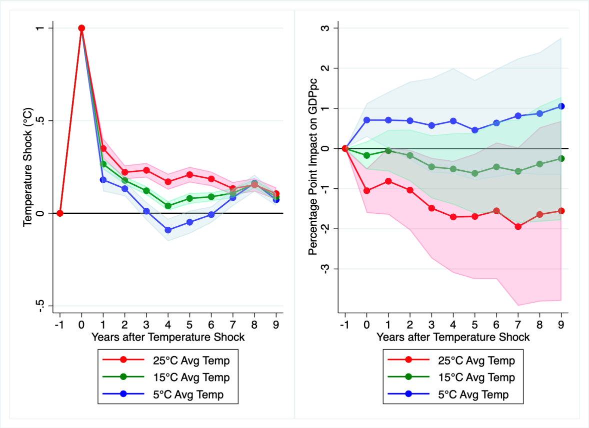
# Temperature Response is also Persistent

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



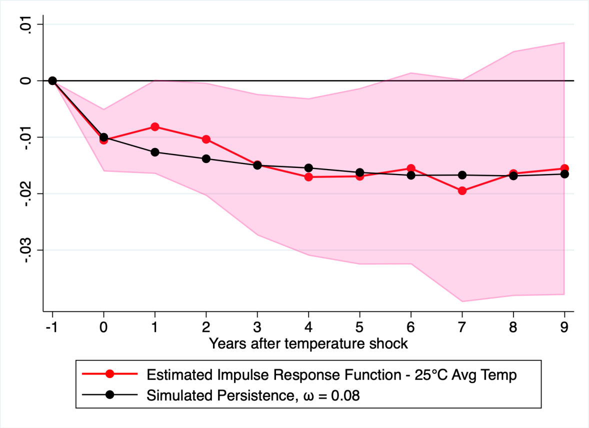

▸ US TFP Control Instead of Year FE

# Using Empirical IRFs to Back Out $\omega$

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

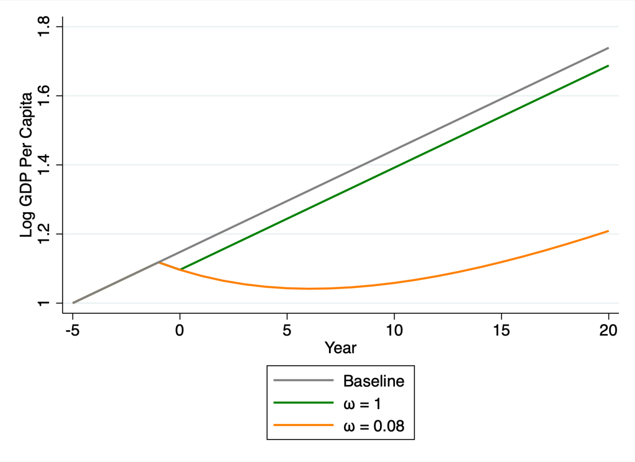
# Comparing Empirical and Model IRFs

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

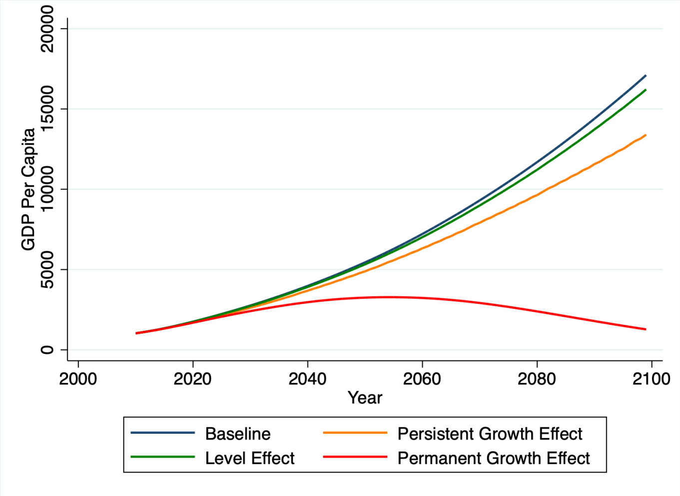


# Outline

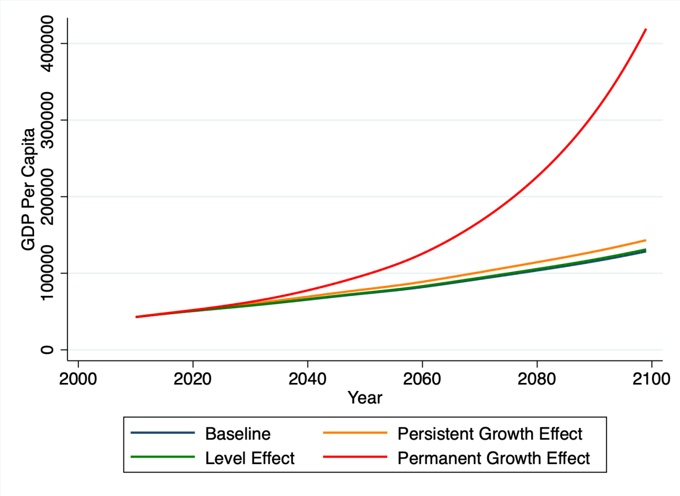
# Projection Approach

- 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
    - $\Delta T$ varies by country, slightly under 4°C for the world

# Projection Results: India

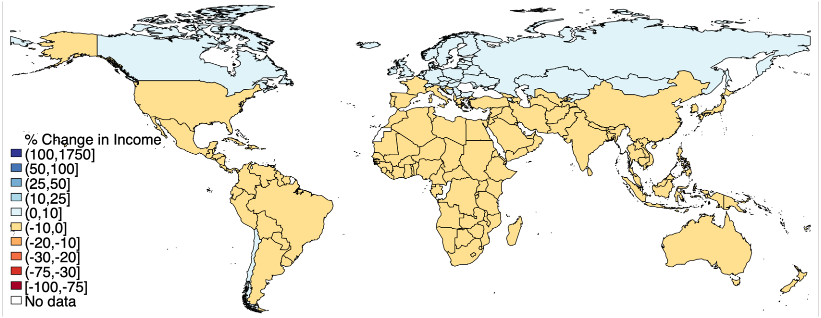


# Projection Results: Sweden



# Climate Change Projections - Permanent Level Effects

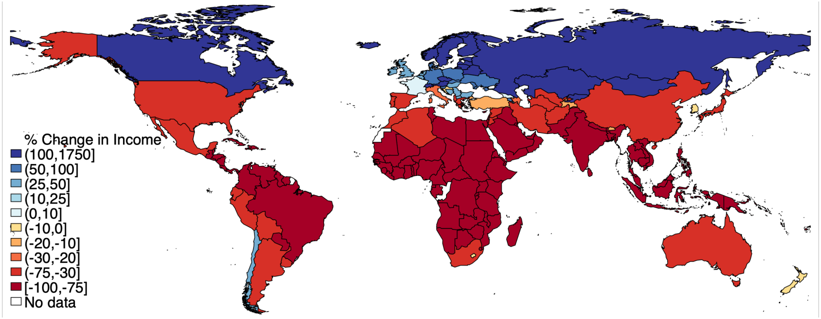
Figure: Impact of Climate Change on Annual Income in 2099




Source: Example Using Our Estimated Contemporaneous Effects Only

# Climate Change Projections - Permanent Growth Effects

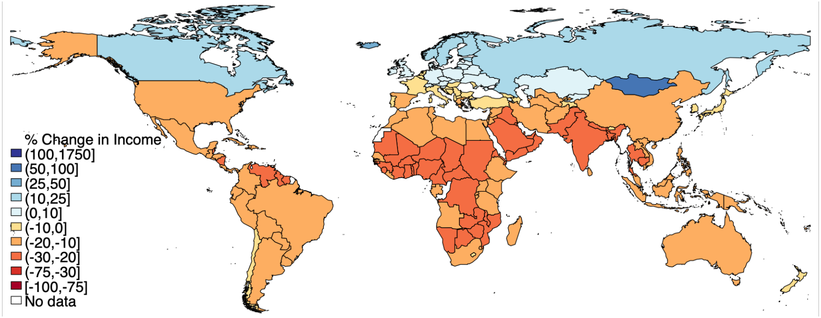
Figure: Impact of Climate Change on Annual Income in 2099




Source: Burke, Hsiang, & Miguel (2015)

# Climate Change Projections - Our Estimates

Figure: Impact of Climate Change on Annual Income in 2099




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 |

# Conclusion

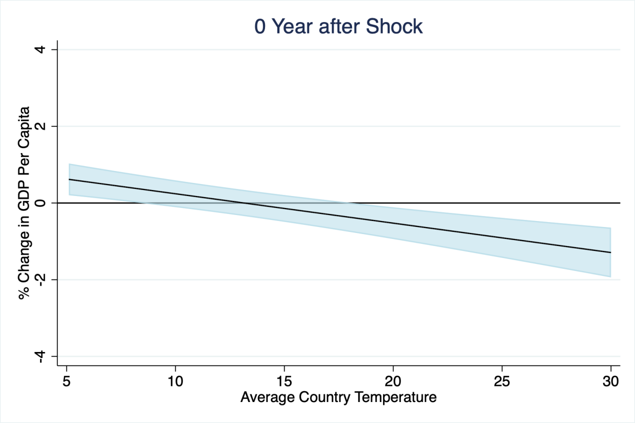
- Model & evidence suggest growth is tied together across countries
  - Temperature unlikely to have permanent country growth effects
  - Trending temperatures can still have global growth effects
- Dynamic estimates show persistent effects of temperature on GDP
  - Moderate persistence of temperature 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

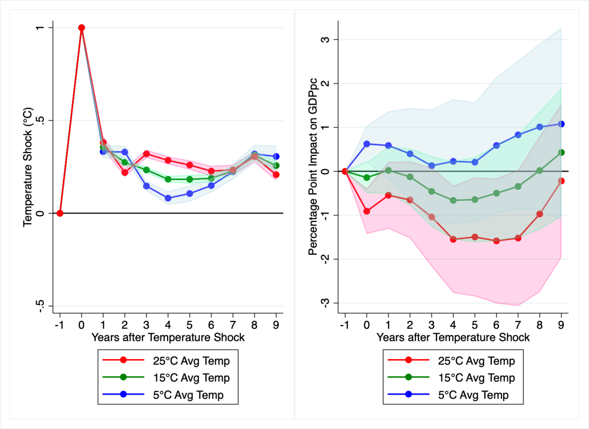
Figure: Impact of a 1°C Temperature Shock on GDP
By Long-Run Average Temperature - US TFP Control Instead of Year FE




Controls for contemporaneous US TFP instead of year FE ▸ Back

# Both Temperature and GDP Effects of a Shock Persist

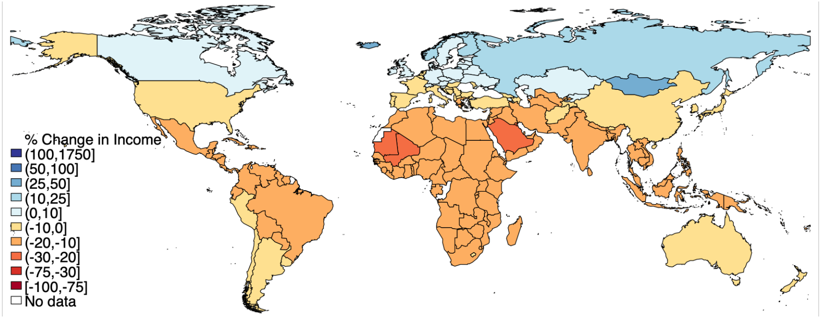
Figure: Persistent Effects of a 1°C Temperature Shock
By Long-Run Average Temperature




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

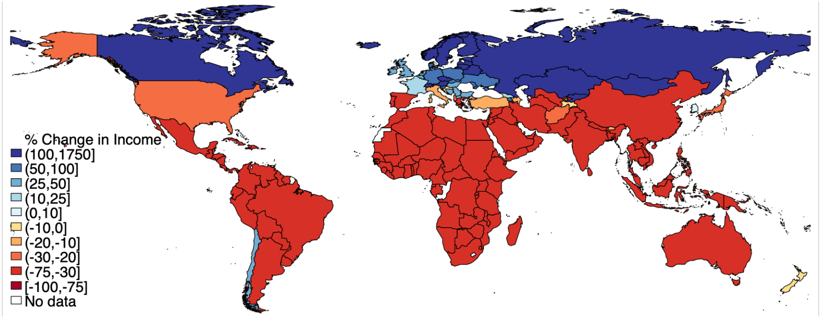



Source: Our dynamic estimates minus pure level effects only

Back

# 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

Back