Virtual Seminar on Climate Economics

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How Much Will Global Warming Cool Global Growth?

Ishan Nath — SF Federal Reserve
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Pete Klenow — Stanford & NBER

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Federal Reserve Bank of San Francisco

Motivation: Wide Divergence in Climate-GDP Projections

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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

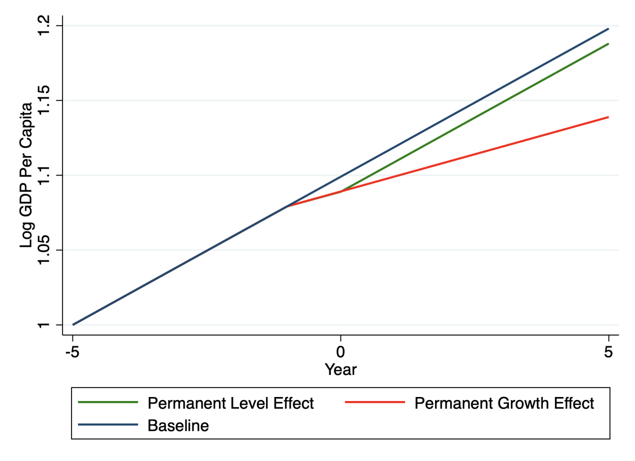
Motivation: Damage estimates are highly influential

- 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

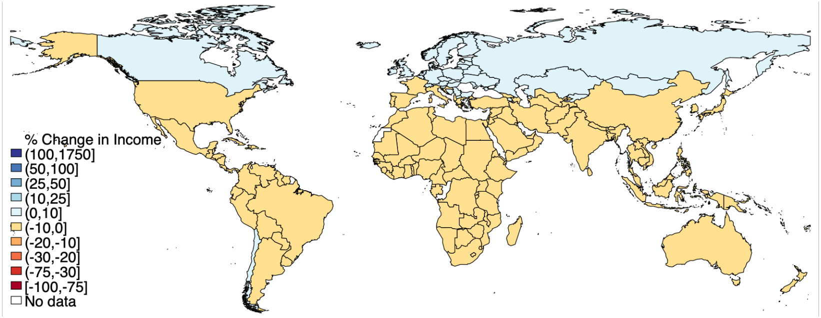
Does a permanent ↑ in temperature affect long-run growth or levels?

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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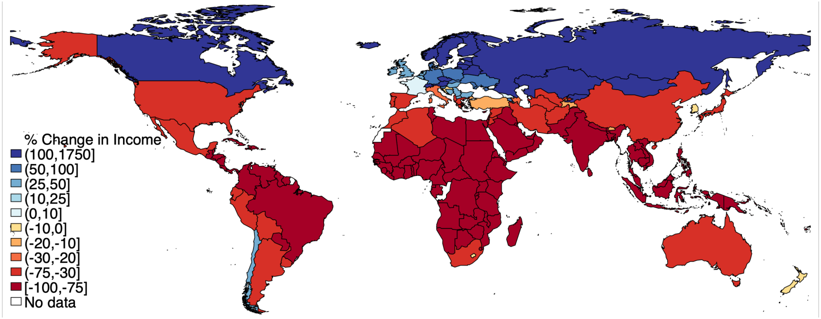

Source: Burke, Hsiang, & Miguel (2015)

Key Challenge - Interpreting a Temperature IRF

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

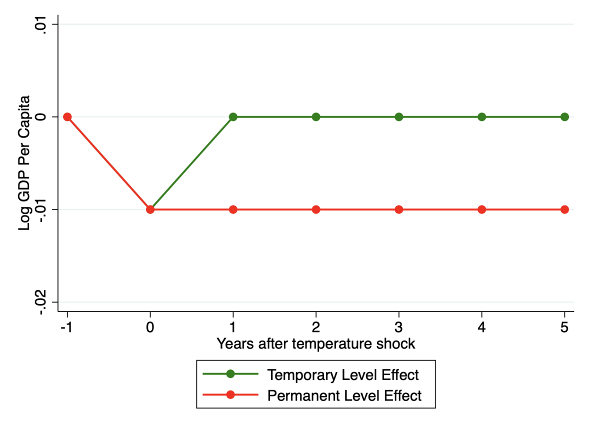

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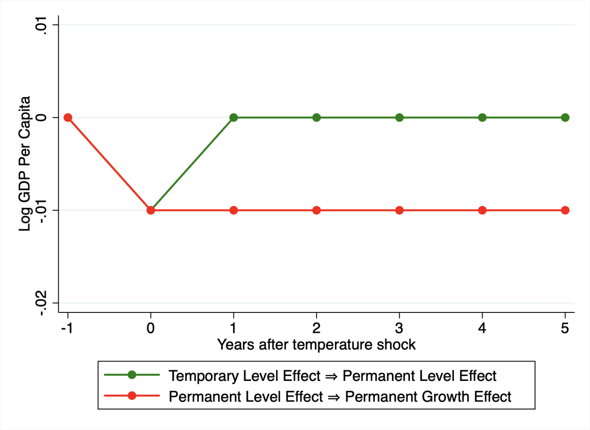
Figure: Implications of *Temporary* Shock for Projecting *Permanent* Shock



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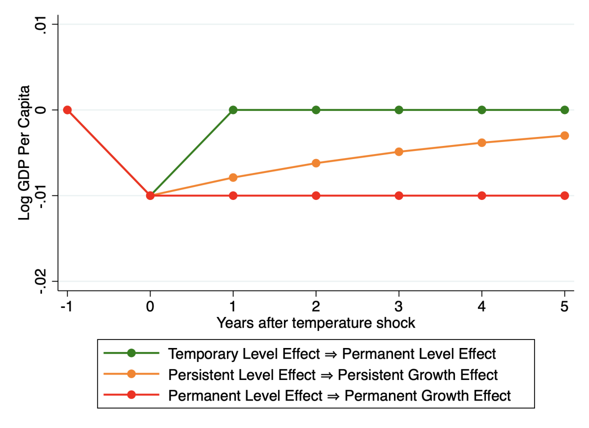

This Paper

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

Results Preview

- Model estimates suggest growth is linked across countries
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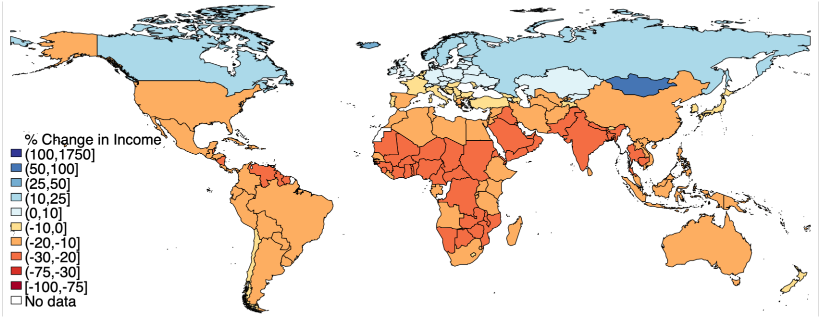
- Projections $\implies$ warming reduces global GDP 6-12% by 2100

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); Bilal and Kaenzig (2024)

- 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. Panel Estimates
4. Projections

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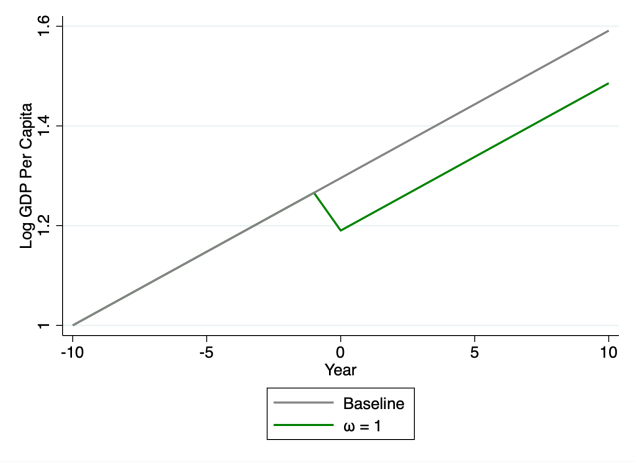
- Each country's per capita income is proportional to its productivity:

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

Comparative Statics - Permanent Shock to μ_i

Figure: Effects of Permanent Temperature Shock Starting in Year 0



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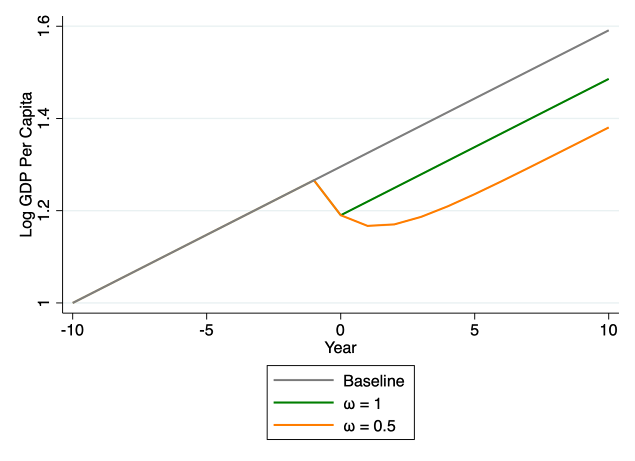

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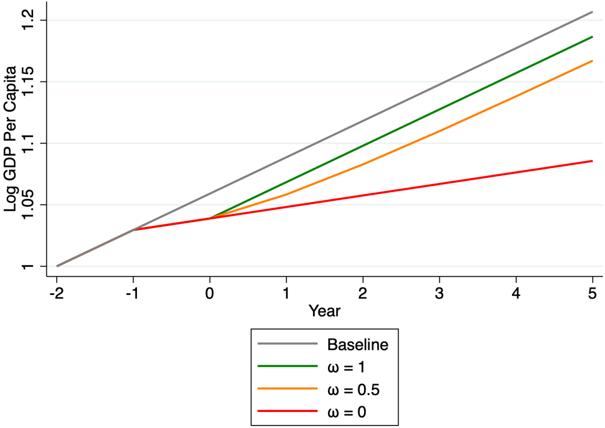

A three part case for global growth spillovers ($0 < \omega < 1$)

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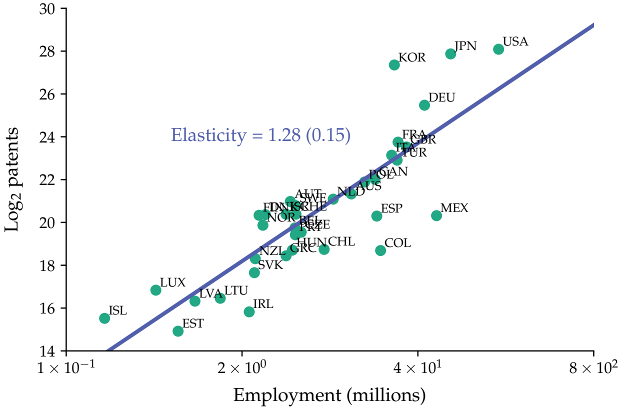
1. Rich countries grow at similar rates despite innovation differences
2.
3.

1. Bigger countries innovate more ...

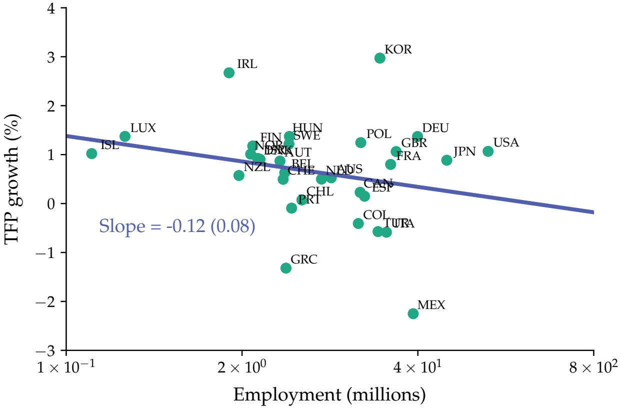
Figure: U.S. Patents and Employment in the Country of Origin in 2019



More people → more researchers → more patents

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

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



More people → more researchers → more patents $\not\to$ more growth

▸ Growth vs. Other Variables

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

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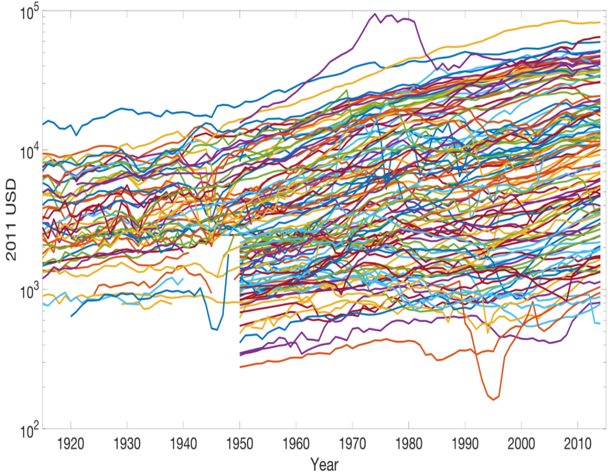

Log GDP per capita, 1915-2014, 112 countries
Sources: Penn World Tables; Müller, Stock, and Watson, (2022)

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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

Table: Regressions of Q_{it} on Q_{it-1} and Q^*_{it-1}

	Unconstrained		Constrained		Bias-Corrected ω
	Coeff. on $\ln Q_{it-1}$	Coeff. on $\ln Q^*_{it-1}$	Coeff. on $\ln Q_{it-1}$	Coeff. on $\ln Q^*_{it-1}$	Consistent with the constraint
Baseline	0.931 (0.006)	0.100 (0.012)	0.925 (0.005)	0.075 (0.005)	0.071
OECD Q*	0.935 (0.007)	0.133 (0.022)	0.928 (0.006)	0.072 (0.006)	0.063
No Employment Weighting	0.923 (0.006)	0.047 (0.018)	0.926 (0.005)	0.074 (0.005)	0.061
No Variety Adjustment	0.926 (0.006)	0.081 (0.009)	0.924 (0.006)	0.076 (0.006)	0.069
With Outlier Countries	0.890 (0.007)	0.103 (0.021)	0.890 (0.007)	0.110 (0.007)	0.073

Notes: The underlying data is from Penn World Table version 10.0. The baseline row uses U.S. TFP net of a variety adjustment as a proxy for Q*, weights countries by their employment, and excludes PWT outlier countries from the sample. The regression specification allows for μ_{it} to follow an AR(1) process with country-specific intercept, serial correlation, and innovation variance. The bias-corrected ω is the one that generates the constrained empirical OLS $\widehat{\omega}$ when OLS estimation is carried out on simulated data.

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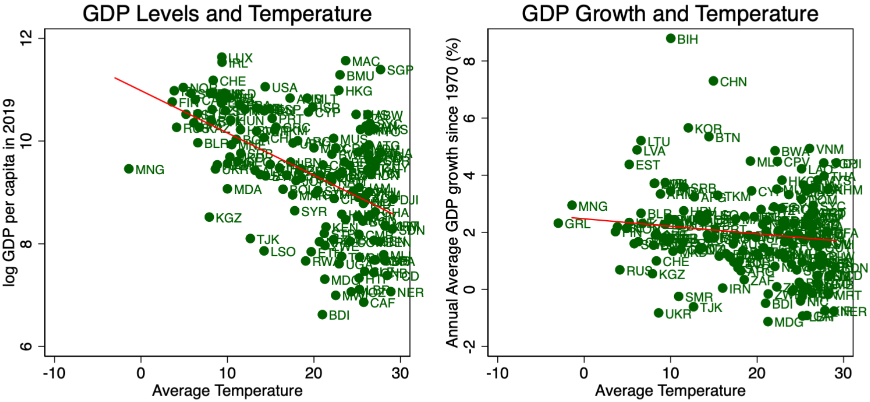
Applying our Model to Temperature Effects

- If temperature affects technology adoption efficiency (μ_{it}) and if $\omega > 0$:
  - Temperature can affect the log level of GDP
  - Temperature can't affect the long-run growth rate of GDP
- What is the relationship between GDP levels and growth rates and temperature across countries?
  - Cross-country correlations of temperature and average GDP growth incorporate convergence and adaptation.
  - The correlations shown on the next slide are robust to arguably exogenous controls such as legal origin.

Cross-Country Regressions of GDP on Temperature



- Levels: 1 °C increase associated with -8.2% lower GDP per capita
  - s.e. = 1.1, R^2 = 0.28, N = 156
- Growth rates: 1 °C increase associated with -0.027% lower avg. annual growth
  - s.e. = 0.018, R^2 = 0.015, N = 134

Summary

- Our theory model presents a mechanism for interconnected-global growth.
- Three types of general evidence support the notion that country growth rates don't diverge.
- Correlations of GDP levels and growth rates and temperature are consistent with our theory.
- However, cross-country regreesions have weaknesses, so we turn to panel evidence.
- Remember two key estimates for later reference: ω=0.07 and 1 °C is associated with 8.2% real GDP per capita.

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    - Disadvantage: Omitted variable bias, including bad controls, no medium-run effects
  - Time-series regressions
    - Advantage: Directly measures effects of temperature shocks over time
    - Disadvantage: other trends in GDP, most temperature variation is temporary and small

Estimating the Effects of Temperature from Panel Data

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- Burke, Hsiang, and Miguel (BHM) version

$$\Delta y_{it} = \beta_1 T_{it} + \beta_2 T_{it}^2 + \text{fixed effects} + \text{controls} + \eta_{it},$$

  - Regress GDP *growth* Δy on temperature *level* T
  - Include nonlinear effects of temperature
  - Controls are precipitation and country-specific quadratic trends

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1. Levels vs. growth effects
2. Modeling nonlinear temperature effects
3. Estimating dynamic causal effects of temperature on GDP
    - Need to identify shocks
    - Shocks with temporary vs. permanent effects
    - Proper scaling of estimates to make projections

1. Levels vs. Growth Effects

- Consider a simple time series model of temperature and growth:

$$\Delta y_t = \lambda + \rho \Delta y_{t-1} + \beta T_t + \theta_1 T_{t-1} + \theta_2 T_{t-2} + \eta_t, \qquad \eta_t \sim \mathcal{N}(0, \sigma_\eta^2)$$

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- Transitory effect of T on growth $\Rightarrow$ $\theta_1 = -\beta(1+\rho)$ and $\theta_2 = \beta\rho$
  - **Sign reversal**: coefficients on lagged temperature reverse the previous GDP effect
  - BHM model excludes lags $\rightarrow$ **constrains** the model to have growth effects

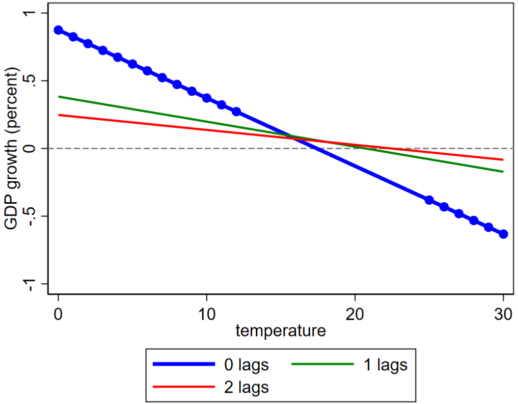
1. Levels vs. Growth Effects (continued)

- Our Monte Carlo demonstrates that **omitting lags biases the estimates** in favor of growth effects

- Demonstration in actual data
  - Use Burke, Hsiang, and Miguel (BHM) model in which growth depends on a quadratic in temperature
  - Estimate on our new panel data
  - Compare cumulative impact with/without lags of temperature included

Common Literature Specification with and without Lags

Figure: Estimated Cumulative Marginal Effects in BHM Model: Effects of Adding Lags of Temperature



Solid dots indicate that estimate is statistically different from zero at the 90% level.

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- **Problems** with this functional form
  - Source of identification is not strictly "within group"
  - Implicitly introduces multiple nonlinear terms in the temperature shock
- Our nonlinear alternative: **state-dependent model**
  - The effect of temperature shock depends on country's average temperature
  - Fits the data better and avoids quadratic model problems

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    $\rightarrow$ use cumulative response ratio (like a cumulative multiplier)
- Our Strategy: **State-dependent Local Projections Model**

Data

- Global Meteorological Forcing Temperature dataset
  - Global grid at 0.25° by 0.25° resolution
  - Population-weighted to the country level
  - Annual, 1950-2015
- World Development Indicators for constant LCU GDP Per Capita
  - Annual, 1960-2019
- TFP (in PPP terms) from Penn World Tables

Identifying Causal Effects of Temperature

- Identify the temperature shock as the innovation from an AR(p) model of temperature where the parameters depend on country mean temperature.
- Assume that a country's GDP does not directly affect its temperature.
- Control for either year fixed effects or frontier TFP and global GDP in our GDP equations.
- Estimated shock contains both weather and climate shocks, idiosyncratic country and global temperature shocks.
  - Estimates must be scaled to account for the fact that shock also has persistent effects on temperature.
  - We focus on IRFs from longer horizons to isolate the medium and long-run effects.

Econometric Model: Estimation of Temperature Shock

- Estimate a temperature shock $\boldsymbol{\tau_{it}}$ as the innovation to temperature, allowing differences by country temperature:

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

  - T_{it} is temperature in country i in year t
  - $\overline{T_i}$ is country mean (or initial) temperature
  - μ_i is country fixed effects
  - μ_t is year fixed effects or global TFP and GDP controls
  - p is the number of lags included.

Econometric Model: Estimation of IRFs

- State-dependent local projections:

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

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

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

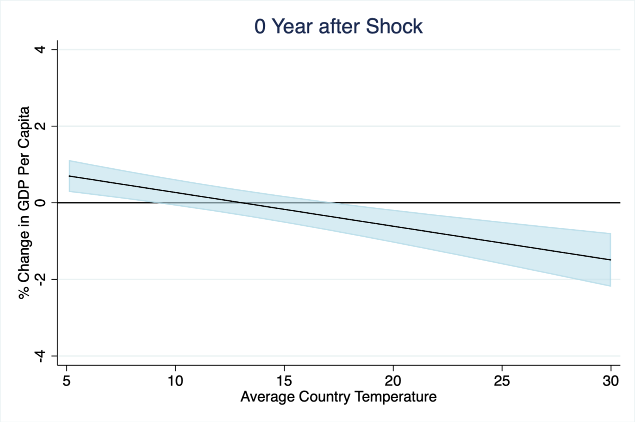
$$\text{where } Z_{it} = \{ T_{i,t-j}, \;\; T_{i,t-j} \cdot \overline{T_i}, \;\; \Delta y_{i,t-j} \}_{j=1}^{p}, \;\; \mu_i, \; \mu_t.$$

Alternative Model for Robustness Checks

- Inspired by Berg, Curtis, and Mark's (2021, 2023) study of heterogeneity of country responses to temperature
- Estimate the time series model country-by-country
  - Allows country-specific coefficients on temperature, global controls, and lag coefficients
- Create cross-country dataset of the estimated IRFs
- Regress estimated IRFs on country characteristics, such as average temperature.

Effect of a Temperature Shock on GDP: Panel with Year Fixed Effects

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
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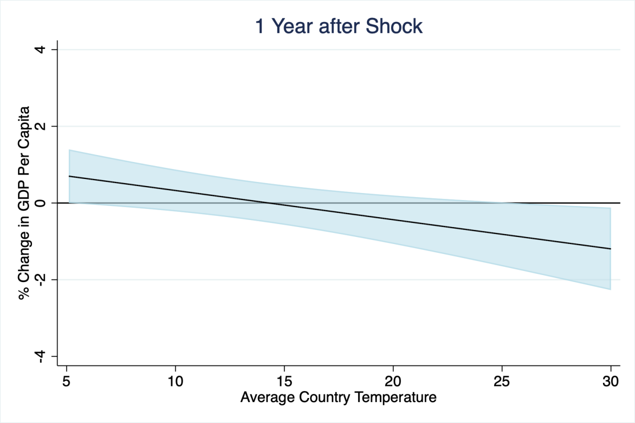

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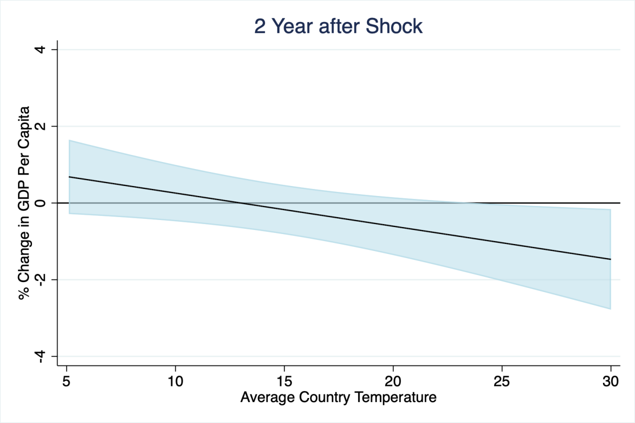

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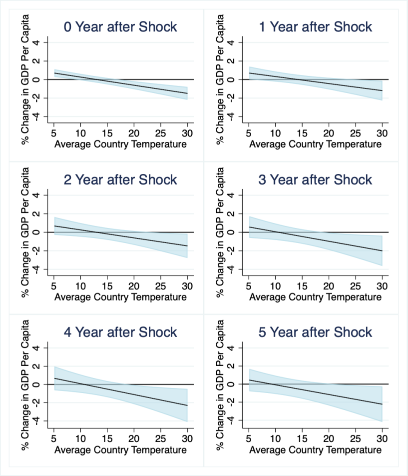

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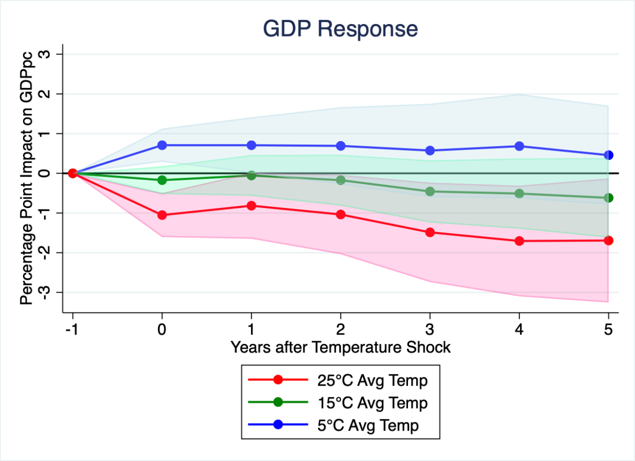
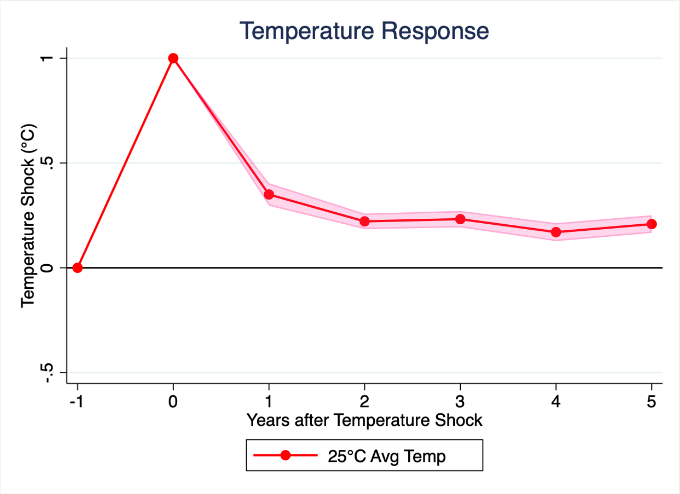


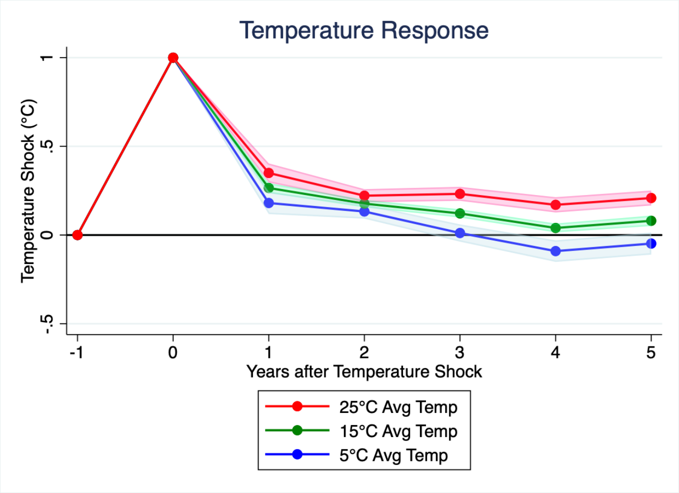
Effects on Temperature Persist Too

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



Effects on Temperature Persist Too

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



Both Temperature and GDP Effects of a Shock Persist

Figure: Persistent Effects of a 1°C Temperature Shock
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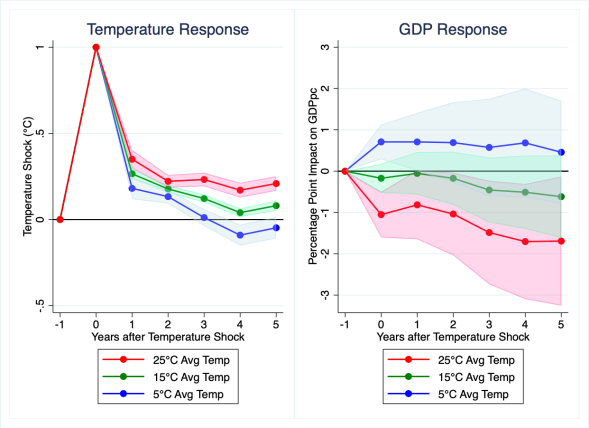

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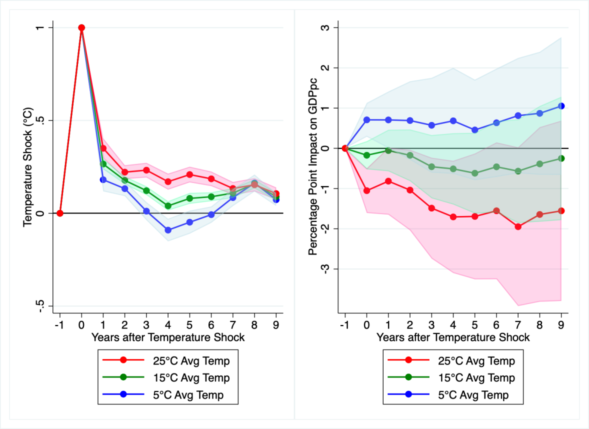

Specification includes control Year FE

Both Temperature and GDP Effects of a Shock Persist

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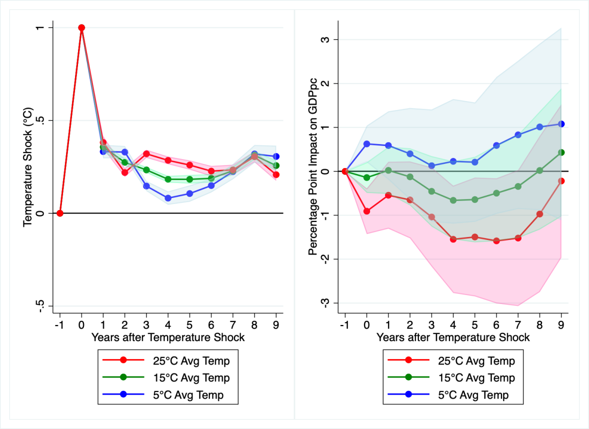
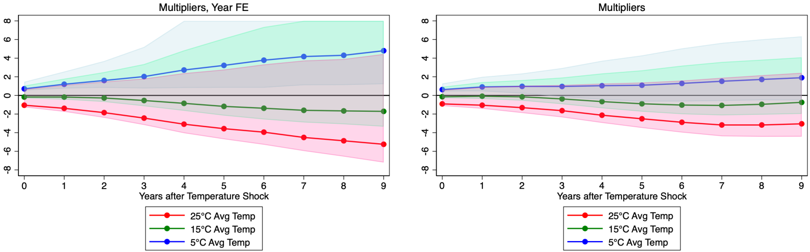


Specification includes control for US TFP, global GDP instead of Year FE

Medium-Run GDP Effect from a Pulse of Temperature

Figure: Cumulative Response Ratio from a 1°C Temperature Shock By Long-Run Average Temperature



Panel specification

Medium-Run GDP Effect from a Pulse of Temperature

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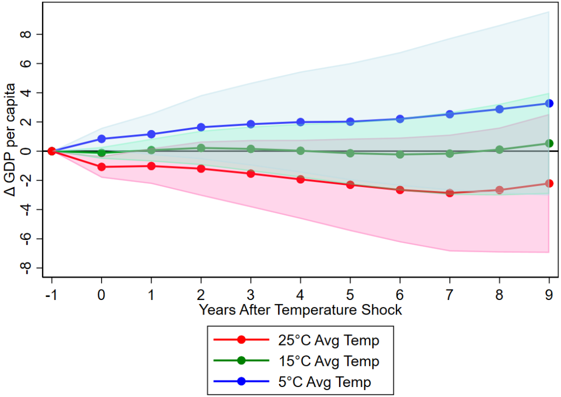


Country-by-country specification, U.S. TFP and global GDP controls

Panel vs. Cross-Sectional Regression

- Recall that simple cross-country estimates $\rightarrow$ 1 °C $\uparrow$ in temperature lowers GDP per capita by 8.2%.

Panel vs. Cross-Sectional Regression

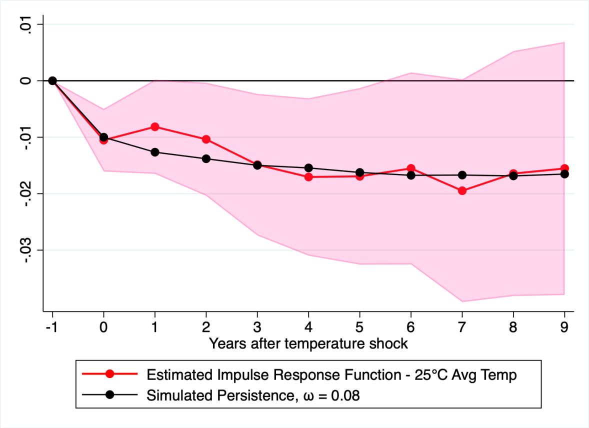
- Recall that simple cross-country estimates $\rightarrow$ 1 °C $\uparrow$ in temperature lowers GDP per capita by 8.2%.
- Estimates for 25°country, avg. response at horizons 6-9 years:
  - With year fixed effects
    - 1 °C $\rightarrow$ in temperature lowers GDP per capita by 12.3%
  - Without year fixed effects
    - 1 °C $\rightarrow$ in temperature lowers GDP per capita by 6.5%

Using Empirical IRFs to Back Out ω

- Recall that ω indexed the degree of global spillovers and persistence of growth effects
- 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

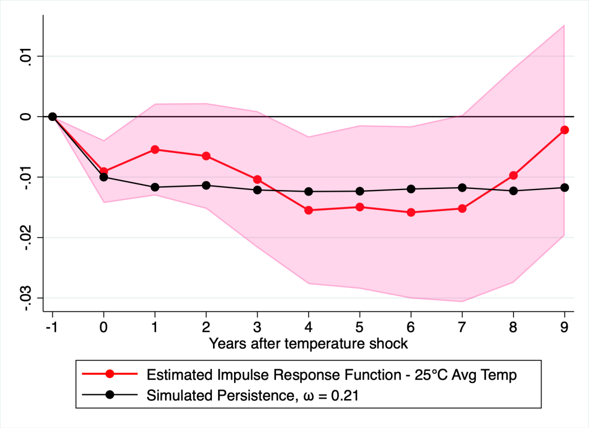
Comparing Empirical and Model IRFs

Figure: Simulated and Empirical Effects of Identical *Persistent* Temperature Shock in Year 0
$\omega = 0.08$



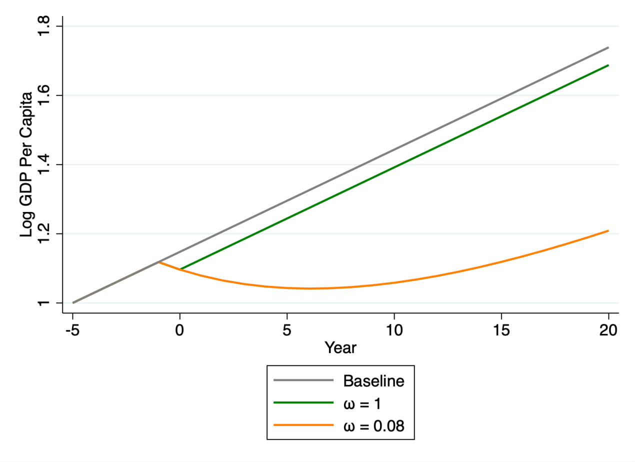
Comparing Empirical and Model IRFs

Figure: Simulated and Empirical Effects of Identical *Persistent* Temperature Shock in Year 0
$\omega = 0.21$



Implications of $\omega = 0.08$

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



Outline

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

Projection Approach

- Use the 10 year *cumulative response ratio* (GDP effect / temperature effect) to project long-run impact of temperature change
- CRR varies by initial temperature
  - Integrate across temperatures for each increment of warming
- 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

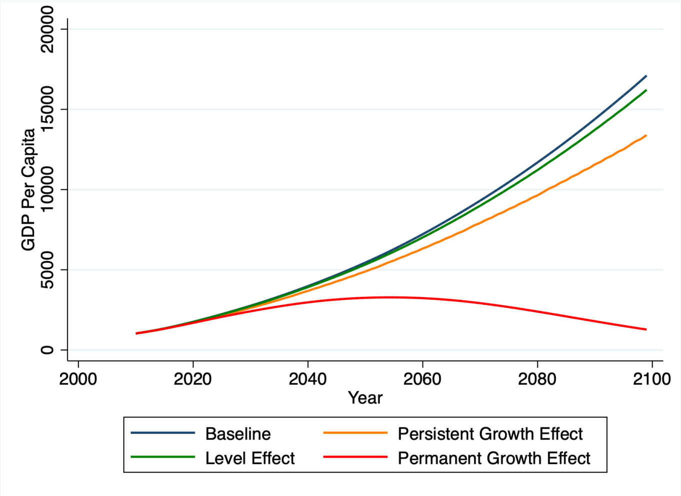
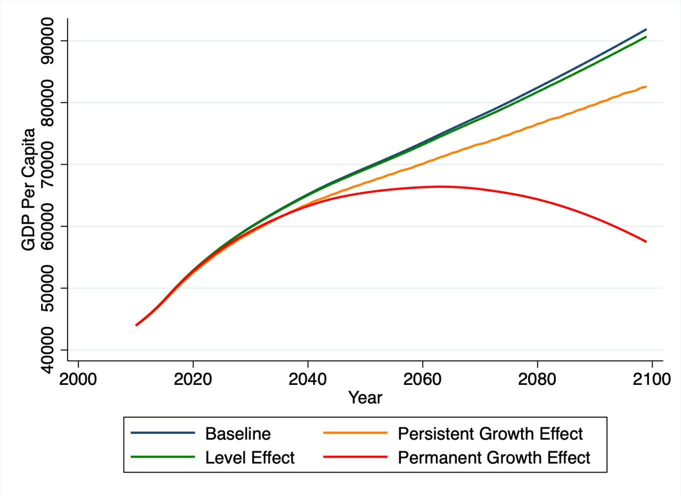


Figure: Impact of Climate Change on Annual Income in India in 2099

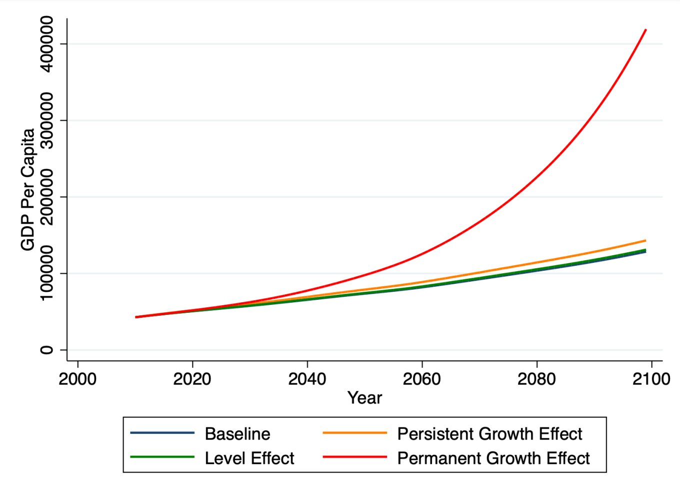
Projection Results: United States

Figure: Impact of Climate Change on Annual Income in the USA in 2099



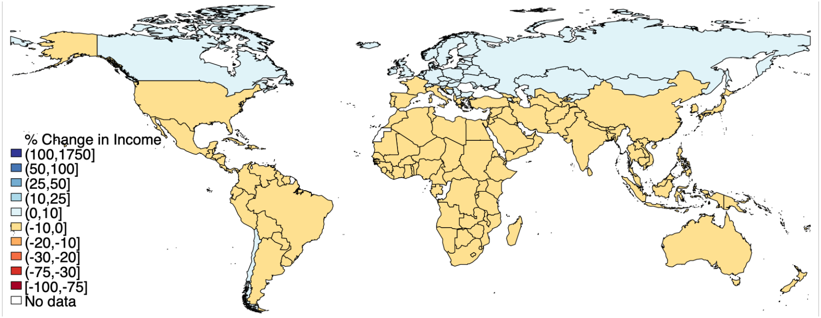
Projection Results: Sweden

Figure: Impact of Climate Change on Annual Income in Sweden in 2099



Climate Change Projections - Permanent Level Effects

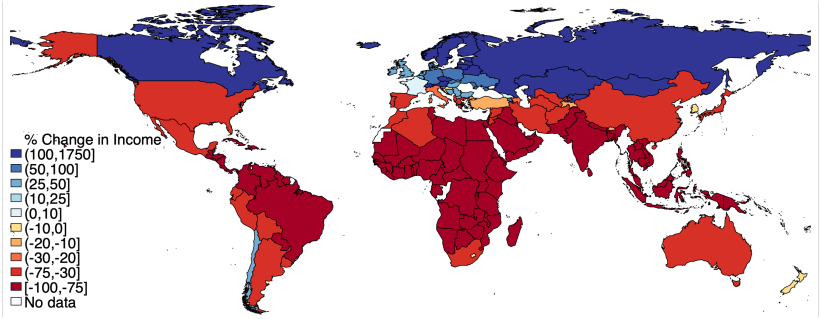
Figure: Impact of Climate Change on Annual Income in 2099



Source: Example Using Our Estimated Contemporaneous Effects Only

Climate Change Projections - Permanent Growth Effects

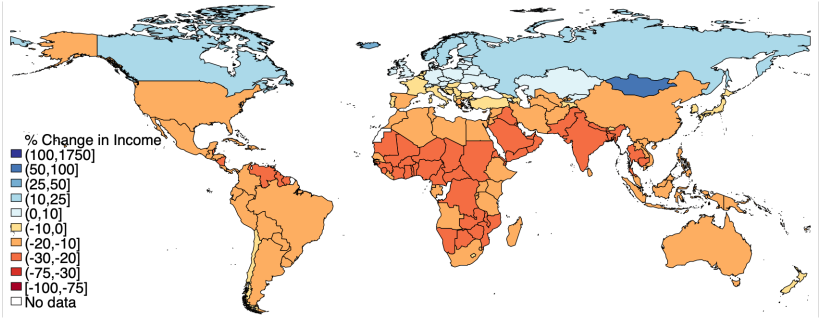
Figure: Impact of Climate Change on Annual Income in 2099



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

Comparison to Temporary Level Effect Comparison to Permanent Growth Effect

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

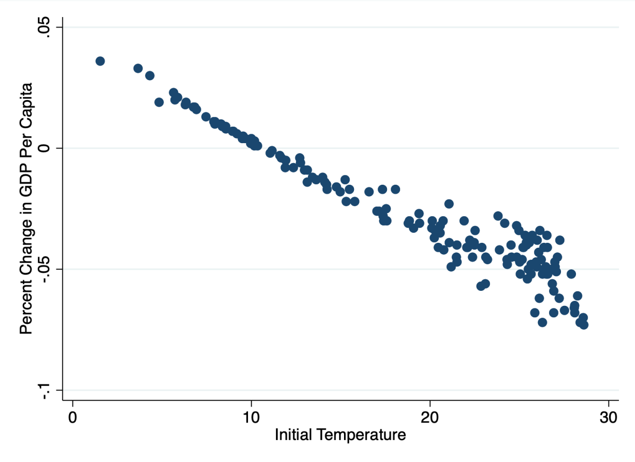
Region	Persistent Growth Effects	Level Effects	Permanent Growth Effects
Global GDP	-6.8	-1.9	-26.6
Global Population Average	-10.0	-3.1	-58.7
Sub-Saharan Africa	-13.0	-4.2	-86.1
Middle East & North Africa	-12.1	-3.7	-82.5
Asia	-11.0	-3.4	-73.3
South & Central America	-9.5	-2.8	-74.6
North America	-4.8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

Additional Projection Caveats

- Effects on Q^*
  - Projections could be missing a common global growth effect
  - However, $\approx$0 effects on frontier countries, depending on included countries and weights
- Effects beyond the 10-year horizon
  - Potential underestimate, but ω estimates with year FE suggest $\approx$80% of effects are realized within first decade
  - Negligible effects past first decade for ω implied by US TFP control
- Additional adaptation, technological progress, state-dependence with growth, tipping points ...

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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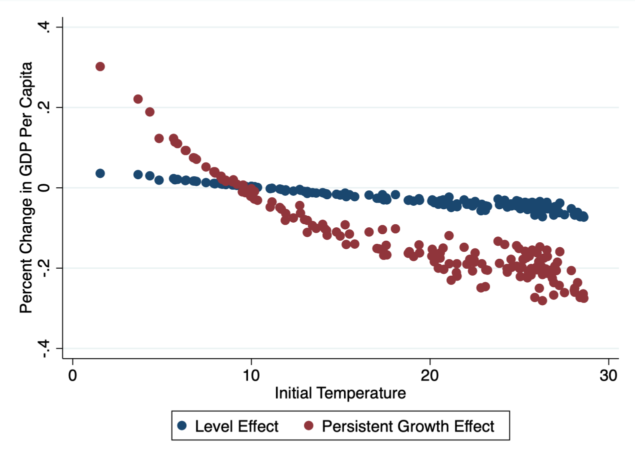

Source: Our Estimates

Projections by Initial Temperature

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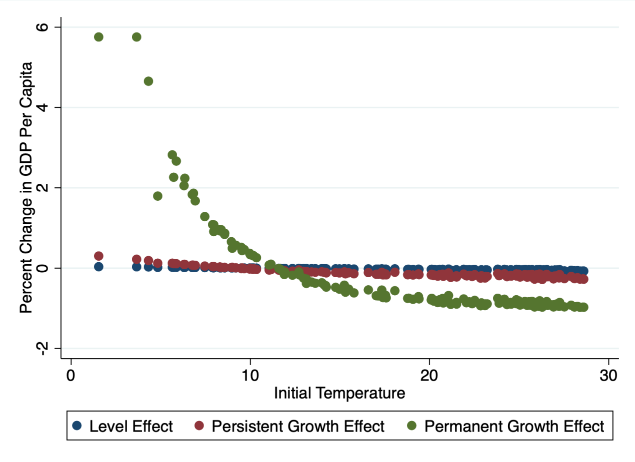


Source: Our Estimates, Burke-Hsiang-Miguel (2015)

Conclusion

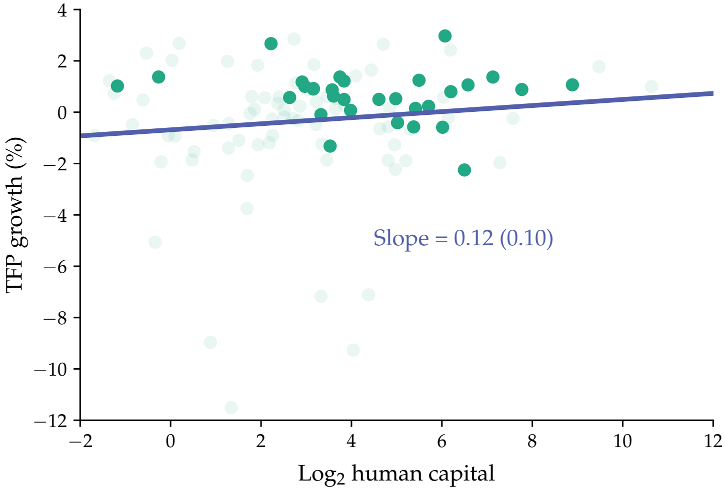
- Model & evidence suggest growth is tied together across countries
  - Temperature unlikely to have permanent country growth effects
  - Trending temperatures can still have global growth effects
- Dynamic estimates show persistent effects of temperature on GDP
  - Moderate persistence of temperature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

Other Domestic Factors Also Don't Correlate With Growth

Figure: TFP Growth vs. Human Capital, 1980-2019



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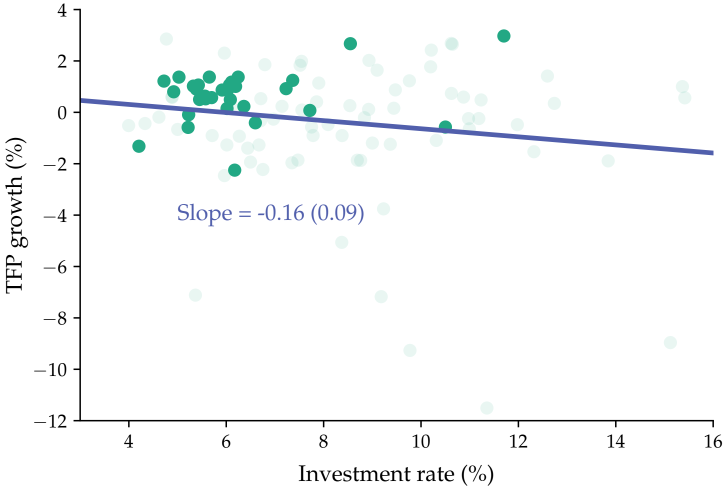
Other Domestic Factors Also Don't Correlate With Growth

Figure: TFP Growth vs. Investment Rate, 1980-2019



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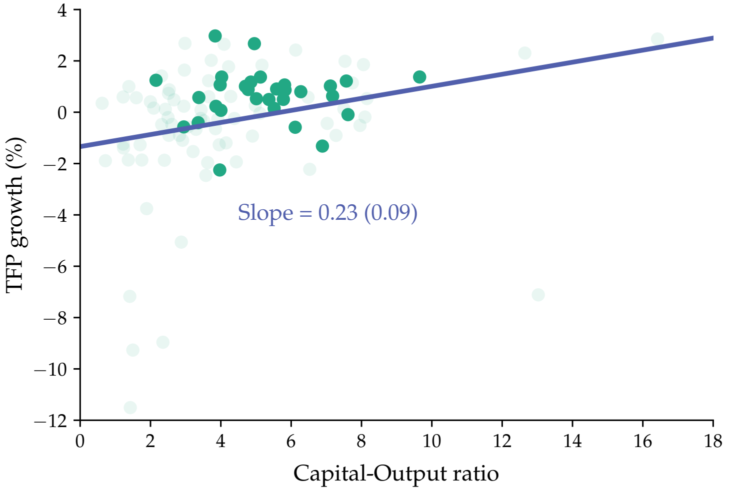
Other Domestic Factors Also Don't Correlate With Growth

Figure: TFP Growth vs. Capital-Output Ratio, 1980-2019



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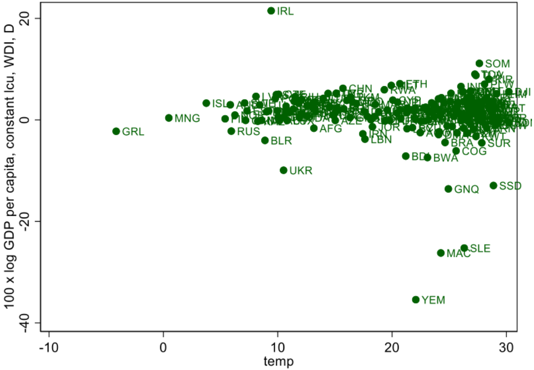
Temperature Does Not Correlate With Growth

Figure: Average GDP Per Capita Growth vs. Temperature in Our Sample



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Both Temperature and GDP Effects of a Shock Persist

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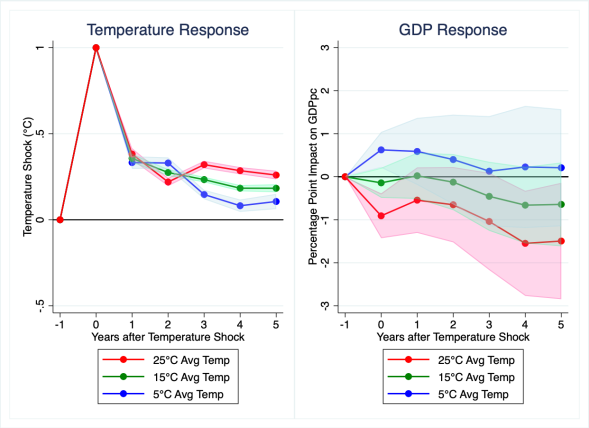

Controls for contemporaneous US TFP instead of year FE ▸ Back

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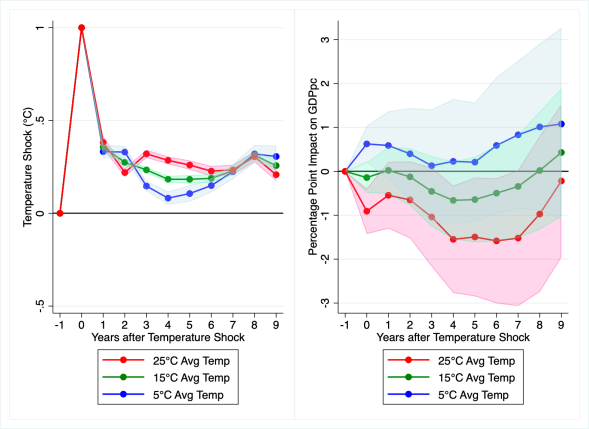

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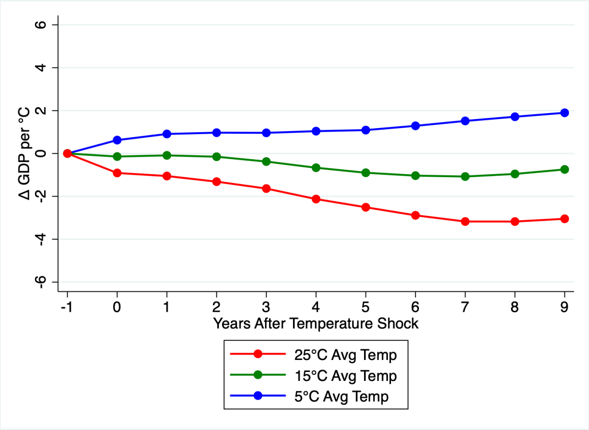
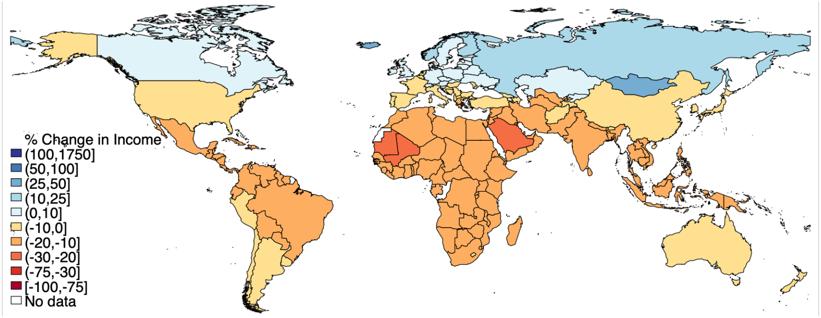


▸ US TFP Controls Instead of Year FE

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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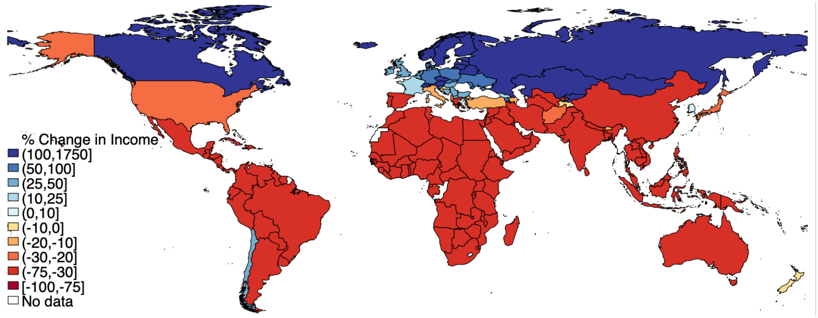
Climate Change Impact Comparison

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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