GDP and Temperature: Evidence on Cross-Country Response Heterogeneity

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Climate Change Economics

1. GHGs (mostly CO_2) stay in atmosphere, cause global warming.
2. Related literatures
   - Integrated Assessment Models (IAMS): Stochastic or deterministic growth models with a climate module. Production $\rightarrow CO_2 \rightarrow$ economic losses. Compute social cost of carbon (SCC), informs policy makers.
   - Empirical Damage Assessment: Estimate economic effect of climate change using historical, observational data. Informs IAM damage function specification. This paper is in this camp.

Our Paper Revisits the Evidence

1. We comment, reassess an empirical literature running panel regressions of country GDP per capita growth on country temperature with country and time fixed effects.
   Depending on the study, conclusion is either
   - Higher temperature lowers income (or growth) of all countries
   - Higher temperature lowers income (or growth) only for poor countries. Effect on rich countries is negative but insignificant.

Two Points of Departure

1. Panel regression imposes extensive homogeneity restrictions across countries. Heterogeneity of response is suppressed or severely limited. We want to investigate heterogeneity of response.
2. Implied data manipulations of time fixed effects obscure the direct effects of temperature on growth.

Our Main Findings

- The rich are damaged. Negative growth responses for six of the G-7 countries (exception is Canada).
- Some poor have benefitted. Positive responses for four of the nine poorest countries.
- Controlling for latitude, the growth impulse responses are decreasing in average real GDP per capita and in long-term growth.
- Temperature affects growth as well as levels.
- Temperature induced losses in year 2100 of real GDP per capita for the United States (-1.9 percent), and potentially large gains for China (+9.6 percent). Seems small, but magnitudes are in line with other studies. Problem with observational data?

Data

1. Real GDP per capita from the World Bank's, *World Development Indicators*. Valued in constant 2010 USD with maximal span 1960-2017.
2. Temperature are population-weighted by year and country. Source: *Terrestrial Precipitation: 1900-2017 Gridded Monthly Time Series (V 5.01)* Matsuura2018, monthly dataset estimated from weather station records and interpolated to a 0.5-degree by 0.5-degree latitude/longitude grid, overlay with population data in 2000 from the *Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11*

Temperature Data

- Country temperature T_{it} trends up and is noisy. Quadratically detrend. Call the detrended τ_{it}.
- Decompose τ_{it} into global (common) τ_t and idiosyncratic τ_{it}^o components.

$$\tau_t = \frac{1}{N} \sum_{j=1}^{N} \tau_{jt}$$

and τ_{it}^o is residual from regressing τ_{it} on τ_t.

Data

Figure: Cross-Sectional Average of Population-Weighted Country Annual Temperature

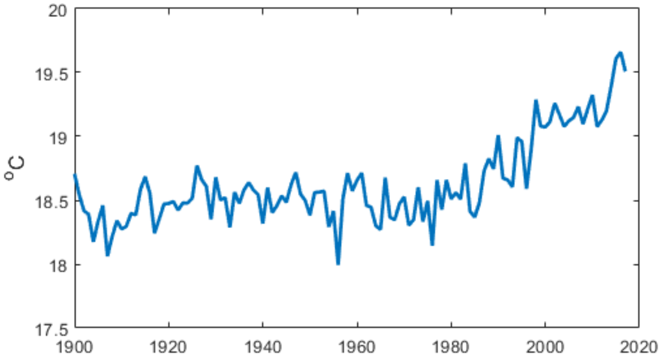
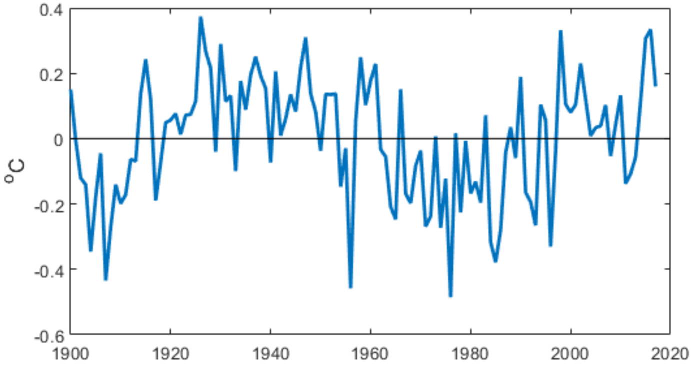


Figure: (Detrended) Global Temperature



Two Issues of Panel Regression with Time FE

$$\Delta y_{j,t} = \theta_t + \beta T_{j,t} + \epsilon_{j,t}. \tag{1}$$

$$\frac{1}{N}\sum_{j=1}^{N}\Delta y_{j,t} = \theta_t + \beta\frac{1}{N}\sum_{j=1}^{N} T_{j,t} + \frac{1}{N}\sum_{j=1}^{N}\epsilon_{j,t}. \tag{2}$$

Subtracting equation (2) from equation (1) elimates the time-fixed effect giving,

$$\Delta y_{j,t} - \frac{1}{N}\sum_{j=1}^{N}\Delta y_{j,t} = \beta\left(T_{j,t} - \frac{1}{N}\sum_{j=1}^{N} T_{j,t}\right) + \left(\epsilon_{j,t} - \frac{1}{N}\sum_{j=1}^{N}\epsilon_{j,t}\right). \tag{3}$$

1. The variables are deviations from cross-sectional averages.
2. Are the homogeneity restrictions justified?

Test the Homogeneity Restrictions

- Regress growth on two lags and temperature.

$$100\Delta y_{jt} = \beta_j \tau_{jt}^f + x_{jt}' \gamma_j + \epsilon_{jt}$$

- Sort countries by $\hat{\beta}_j$. Divide into groups of positive and negative. Run constrained system (with j fixed effects) for each group

$$100\Delta y_{jt} = \beta_p \tau_{jt}^f + x_{jt}' \gamma_j + \epsilon_{jt}$$

$$100\Delta y_{jt} = \beta_n \tau_{jt}^f + x_{jt}' \gamma_j + \epsilon_{jt}$$

- Test $\beta_p = \beta_n$

$y_{j,t}$ is log real GDP per capita, $\tau_{j,t}^f \in \{\tau_{j,t}, \tau_t, \tau_{j,t}^o\}$ is temperature measure being considered. $x_{j,t}' \gamma_j = \sum_{k=1}^2 \delta_{j,k} \Delta y_{j,t-k} + c_j$ are controls

Rejection of Homogeneity Restrictions

Table: Tests of Extensive Homogeneity Restrictions

	β_p	t-ratio	β_n	t-ratio	$\beta_p = \beta_n$	p-val
A. All Countries						
Country	1.273	6.110	-1.273	-7.218	87.003	0
Global	2.735	5.496	-2.861	-6.065	66.611	0
Idiosyncratic	1.201	5.548	-1.453	-7.350	81.959	0
B. Poor Countries						
Country	1.807	5.052	-1.542	-5.303	52.790	0
Global	2.923	4.527	-2.854	-3.661	32.566	0
Idiosyncratic	1.589	4.130	-1.793	-5.602	45.662	0

Notes: The slope is β_p in the positive beta group and is β_n in the negative beta group. A Wald test of the hypothesis $\beta_p = \beta_n$ is χ_1^2 under the null. Country temperature is $\tau_{j,t}$, global temperature is τ_t, and idiosyncratic temperature is $\tau_{j,t}^o$. Poor countries are those whose average real GDP per capita over the sample is below the median.

Local Projections

Horizons $h = \{0, ..., 7\}$ for country $j = \{1, ..., 162\}$,

$$100 \left(y_{j,t+h} - y_{j,t-1} \right) = \beta_{j,h} \tau^{f}_{j,t} + x'_{j,t} \gamma_{j,h} + \epsilon_{j,t+h}, \tag{4}$$

$\beta_{j,h}$: percent impulse response in real GDP per capita from $t-1$ to $t+h$ due to a $1^{o}C$ shock in temperature at t.

Pseudo Panels of Similarly Sized Beta Groups

Increase significance with little point estimate distortion

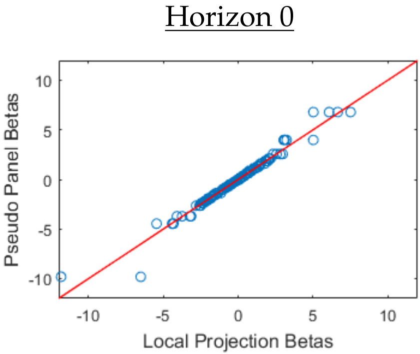
1. For horizon h, sort countries by local-projection betas. Form groups of four countries.
2. For each group, estimate constrained beta specification,

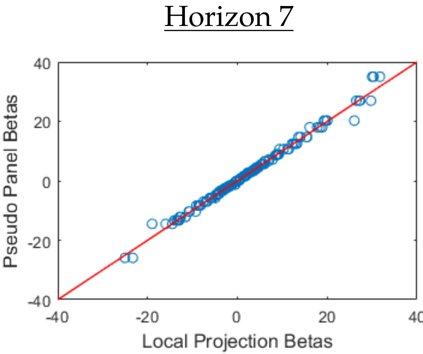
$$100 \left(y_{j,t+h} - y_{j,t-1} \right) = \beta_h \tau^f_{j,t} + x'_{j,t} \gamma_{j,h} + \epsilon_{j,t+h}, \quad (5)$$

   Only local-projection beta is constrained.
3. Group membership can vary by h.
4. Estimate each pseudo-panel by GMM with country j regressors as instruments for that equation.

Point Estimate Distortion

Figure: Country Temperature Pseudo-Panel Local-Projection Betas and Local-Projection Betas

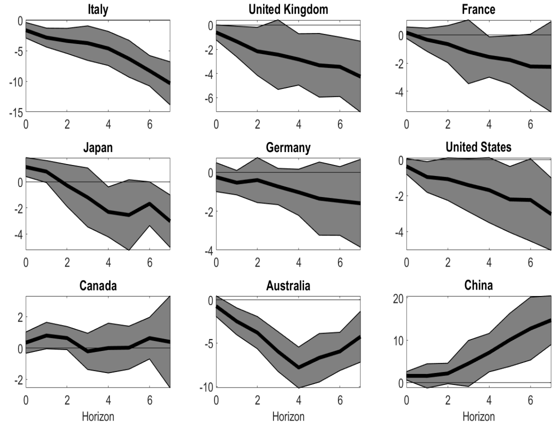




Notes: 45^o line in red. Local-projection betas are estimates from equation (4) and pseudo-panel local-projection betas are estimates from equation (5) for $h = 0$ and $h = 7$. For Horizon 7, two outliers not shown and are the Solomon Islands (49,35) and Equatorial Guinea (-84,-26).

Damages to the Rich

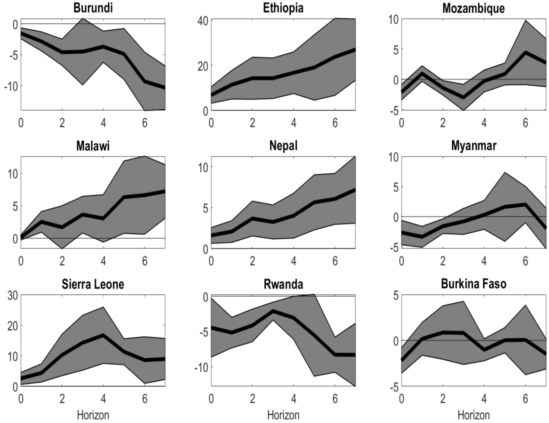
Figure: Impulse Responses to Country Temp: Selected Rich Countries



Notes: Shaded areas are plus and minus 1.96 standard error bands.

Benefits to Some Poor

Figure: Impulse Responses to Country Temp: Nine Poorest Countries



Notes: Shaded areas are plus and minus 1.96 standard error bands.

Figure: Horizon 0 Map: Impulse Responses to Country Temperature Shocks

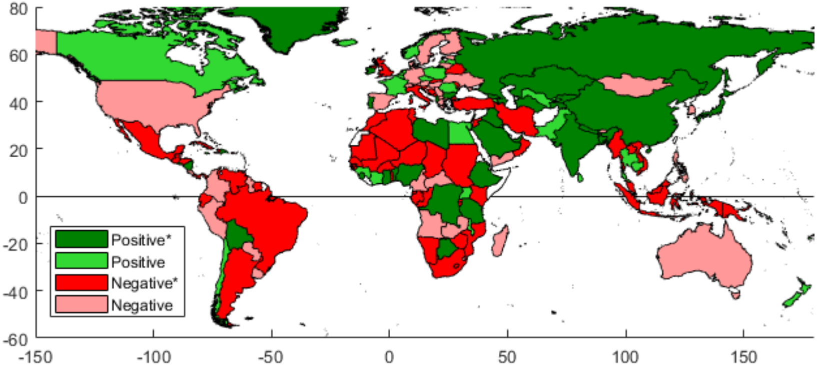
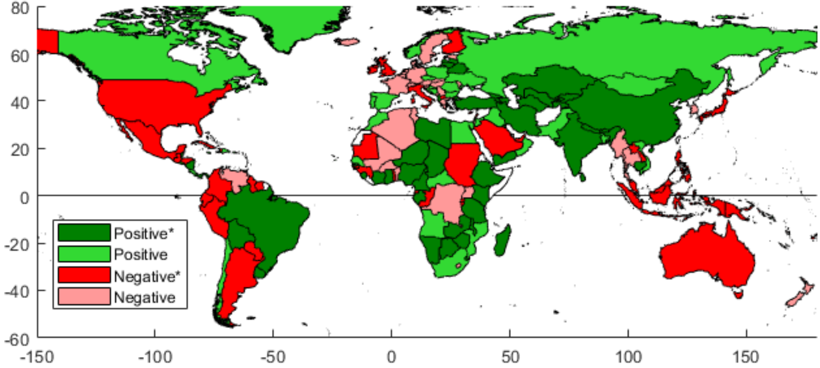
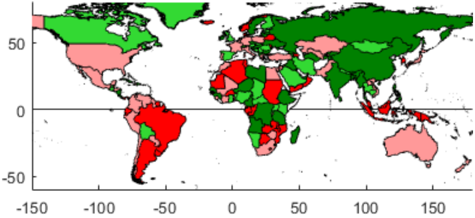


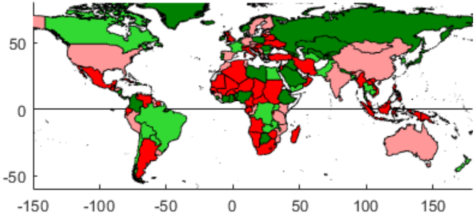
Figure: Horizon 7 Map: Impulse Responses to Country Temperature Shocks



Horizon 0: Global and Idiosyncratic Temp shocks

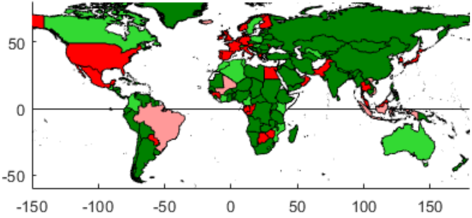


Global

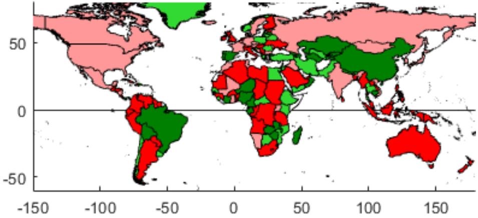


Idio

Horizon 7: Global and Idiosyncratic Temp shocks

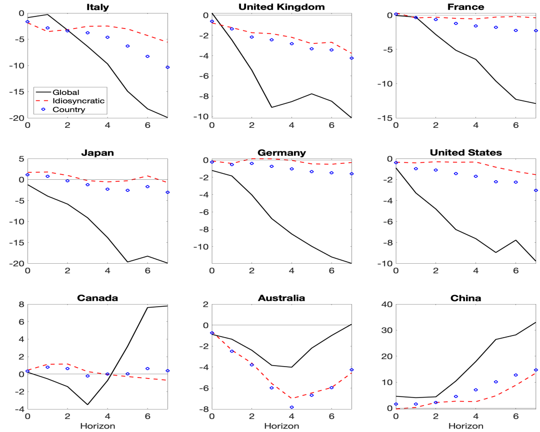


Global

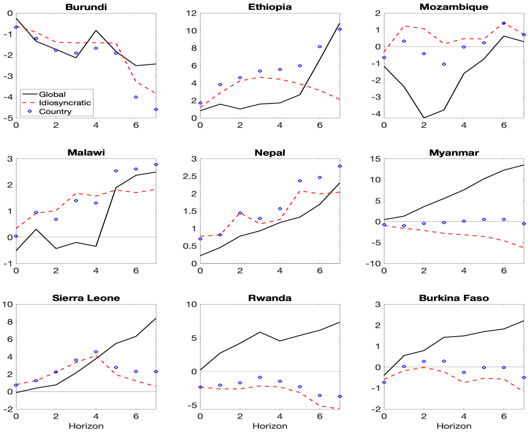


Idio

Rich: Impulse Response Shock Comparison

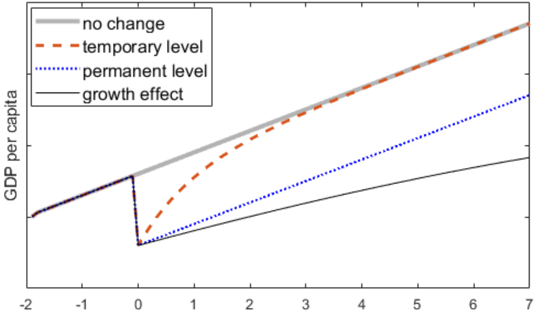


Poor: Impulse Response Shock Comparison



Level versus Growth Effects

Figure: Stylized Negative Responses to Temperature Shock at Time 0



Level versus Growth Effects

- Note: $\beta_7 - \beta_0 = \Delta y_{t+7} + \cdots + \Delta y_{t+1}$. Negative growth effect if conditional on negative point estimate $\hat{\beta}_7 < 0$, we reject

$$\beta_7 - \beta_0 = 0|_{\hat{\beta}_7 < 0}$$

- Negative level effect
  A: set of countries such that β_0 is significantly negative.
  B: set of countries such that $\beta_7 < \beta_0$ and significant
  C: set for which $\beta_7 > 0$ and significant
  Set of countries that experience only a negative level effect is

$$A - \{[A \cap B] \cup [A \cap C]\}.$$

Table: Level and Growth Effects from Country Temperature Shock

Negative Level	Algeria	Bahamas, The	Belarus	Bosnia and Herzegovina
	Brazil	Burkina Faso	Cabo Verde	Chad
	Gabon	Iran, Islamic Rep.	Jordan	Kenya
	Lesotho	Mali	Moldova	Montenegro
	Morocco	Mozambique	Myanmar	Namibia
	Niger	Oman	Panama	Senegal
	Slovak Republic	Slovenia	South Africa	Tunisia
	Turkey	Vanuatu	Venezuela, RB	Vietnam
	West Bank and Gaza	Zimbabwe		
Negative Growth	Argentina	Belgium	Burundi	Colombia
	Comoros	Congo, Rep.	Cuba	Cyprus
	Ecuador	Equatorial Guinea	Fiji	Finland
	Guatemala	Guinea	Guinea-Bissau	Guyana
	Haiti	Honduras	Iceland	Indonesia
	Ireland	Italy	Japan	Lao PDR
	Lebanon	Luxembourg	Malaysia	Mauritania
	Mexico	Netherlands	North Macedonia	Papua New Guinea
	Paraguay	Philippines	Rwanda	Saudi Arabia
	Sudan	Suriname	Thailand	Trinidad and Tobago
	United Arab Emirates	United States		

Table: Level and Growth Effects from Country Temperature Shock

Positive Level	Bangladesh	Benin	Bulgaria	Dominican Republic
	Greenland	Iraq	Ireland	Japan
	Lebanon	Portugal	Saudi Arabia	St. Vincent and the Grenadines
	United Arab Emirates			
Positive Growth	Albania	Armenia	Azerbaijan	Belarus
	Belize	Bhutan	Bolivia	Botswana
	Brazil	Brunei Darussalam	Cabo Verde	Cambodia
	Cameroon	Chad	China	Cote d'Ivoire
	Croatia	Eswatini	Ethiopia	Gabon
	Gambia, The	Georgia	Ghana	Iran, Islamic Rep.
	Jordan	Kazakhstan	Kenya	Kuwait
	Kyrgyz Republic	Latvia	Libya	Lithuania
	Madagascar	Namibia	Nicaragua	Niger
	Nigeria	Panama	Russian Federation	Samoa
	Sierra Leone	Solomon Islands	Sri Lanka	Tajikistan
	Tanzania	Turkey	Turkmenistan	Uruguay
	Uzbekistan	Yemen, Rep.	Zambia	Zimbabwe

Table: Level and Growth Effects from Global Shocks

A. Global Temperature Shocks				
Negative Level	Algeria	Argentina	Azerbaijan	Belarus
	Brazil	Burkina Faso	Ecuador	Iceland
	Indonesia	Lebanon	Lesotho	Malawi
	Mauritania	Mozambique	Panama	Papua New Guinea
	Sudan	Suriname	Tunisia	Uruguay
	Yemen, Rep.	Zambia		
Negative Growth	Austria	Bahamas, The	Belgium	Belize
	Botswana	Burundi	Congo, Rep.	Cyprus
	Denmark	Egypt, Arab Rep.	Equatorial Guinea	Finland
	France	Gabon	Gambia, The	Germany
	Greece	Guinea-Bissau	Ireland	Italy
	Iraq	Japan	Korea, Rep.	Luxembourg
	Malaysia	Mexico	Moldova	Norway
	Oman	Pakistan	Paraguay	Portugal
	Puerto Rico	Spain	St. Vincent and the Grenadines	Thailand
	United Kingdom	West Bank and Gaza	Zimbabwe	

Table: Level and Growth Effects from Global Shocks

A. Global Temperature Shocks				
Positive Level	Cameroon	Cyprus	Eswatini	Fiji
	Guinea	Hungary	Ireland	Jamaica
	Slovenia	Sweden	Ukraine	United Arab Emirates
Positive Growth	Albania	Angola	Argentina	Armenia
	Azerbaijan	Bangladesh	Belarus	Benin
	Bhutan	Bolivia	Bosnia and Herzegovina	Brunei Darussalam
	Bulgaria	Burkina Faso	Cabo Verde	Cambodia
	Central African Republic	Chad	Chile	China
	Comoros	Congo, Dem. Rep.	Costa Rica	Croatia
	Cuba	Czech Republic	Dominican Republic	Ecuador
	El Salvador	Estonia	Ethiopia	Georgia
	Ghana	Greenland	Guyana	Honduras
	India	Iran, Islamic Rep.	Peru	Jordan
	Rwanda	Saudi Arabia	Kyrgyz Republic	Lao PDR
	Latvia	Libya	Sri Lanka	Madagascar
	Suriname	Switzerland	Mongolia	Togo
	Myanmar	Namibia	Nepal	New Zealand
	Nicaragua	Niger	Nigeria	North Macedonia
	Panama	Papua New Guinea	Peru	Philippines
	Poland	Romania	Russian Federation	Rwanda
	Samoa	Saudi Arabia	Senegal	Serbia
	Sierra Leone	Slovak Republic	Solomon Islands	South Africa
	Sri Lanka	Sudan	Suriname	Tajikistan
	Tanzania	Trinidad and Tobago	Tunisia	Turkey
	Turkmenistan	Uganda	Ukraine	Uruguay
	Vanuatu	Venezuela, RB	Yemen, Rep.	Zambia

Table: Level and Growth Effects from Idiosyncratic Shocks

B. Idiosyncratic Temperature Shocks				
Negative Level	Bahamas, The	Belarus	Bhutan	Bosnia and Herzegovina
	Cabo Verde	Cameroon	Central African Republic	Croatia
	Gabon	Iran, Islamic Rep.	Jordan	Lithuania
	Madagascar	Mali	Mexico	Namibia
	Niger	Oman	Senegal	Solomon Islands
	Turkey	Vietnam	Zimbabwe	
Negative Growth	Algeria	Angola	Argentina	Australia
	Benin	Brunei Darussalam	Burkina Faso	Burundi
	Chad	Colombia	Comoros	Congo, Dem. Rep.
	Congo, Rep.	Cuba	Cyprus	Ecuador
	Equatorial Guinea	Fiji	Finland	Guatemala
	Guinea-Bissau	Guyana	Haiti	Honduras
	Indonesia	Ireland	Italy	Lao PDR
	Lebanon	Libya	Luxembourg	Malaysia
	Mauritania	Myanmar	Netherlands	North Macedonia
	Papua New Guinea	Paraguay		

Table: Level and Growth Effects from Idiosyncratic Shocks

B. Idiosyncratic Temperature Shocks				
Positive Level	Botswana	Colombia	Greenland	Iceland
	Iraq	Ireland	Israel	Nicaragua
	Norway	Poland	Romania	Russian Federation
	Samoa	Saudi Arabia	Sierra Leone	St. Vincent and the Grenadines
	Uzbekistan			
Positive Growth	Albania	Armenia	Azerbaijan	Bahamas, The
	Belize	Bolivia	Brazil	Cabo Verde
	Cambodia	Cameroon	China	Cote d'Ivoire
	Dominican Republic	Eswatini	Ethiopia	Gabon
	Georgia	Iran, Islamic Rep.	Jamaica	Kazakhstan
	Kuwait	Kyrgyz Republic	Malawi	Niger
	Oman	Panama	Portugal	Puerto Rico
	Solomon Islands	Spain	Tajikistan	Turkmenistan
	West Bank and Gaza	Yemen, Rep.	Zambia	Zimbabwe

What Explains Response Heterogeneity?

Does country geography, economic structure, level of growth, and development explain how weather impacts growth?

- Absolute value of latitude.
- Log average real GDP per capita
- Long term growth
- GDP share of agriculture: High labor and crop exposure
- GDP share of manufacturing: Labor productivity exposure
- GDP share of industry:
- If X_j is vector of country $j's$ characteristics, then

$$\hat{\beta}_{j,h} = X_j'\gamma + u_h, \quad (6)$$

Table: Correlations of Explanatory Variables

	GDPPC	Growth	Agriculture	Industy	Manufacturing
Latitude	0.516	0.106	-0.509	-0.052	0.138
GDPPC		-0.001	-0.609	0.143	0.055
Growth			-0.120	0.104	0.282
Agriculture				-0.406	-0.257
Industy					0.296

Notes: GDPPC is the logarithm of average real GDP per capita, Growth is measured from beginning to end of the available sample, and Agriculture, Industry, and Manufacturing are logarithms of the average sectoral shares of GDP.

Table: Horizon 7: Cross-Section

Nobs	R^2	Latitude	GDPPC	Growth	Agriculture	Industry	Manufacturing
				Country			
162	0.009	0.068					
		(1.196)					
162	0.083	**0.215**	**-3.040**				
		(3.139)	**(-3.593)**				
162	0.135	**0.222**	**-2.776**	**-3.882**			
		(3.331)	**(-3.349)**	**(-3.062)**			
162	0.148	**0.213**	-0.520	**-4.147**	3.134		
		(3.195)	(-0.316)	**(-3.259)**	(1.588)		
161	0.156	**0.260**	**-3.308**	**-3.788**		4.342*	
		(4.001)	**(-3.885)**	**(-3.112)**		(1.676)*	
158	0.141	**0.233**	**-2.734**	**-3.566**			-0.541
		(3.608)	**(-3.384)**	**(-2.804)**			(-0.269)
158	0.169	**0.255**	-1.205	**-3.899**	2.897	5.154*	-1.946
		(3.847)	(-0.752)	**(-3.068)**	(1.511)	(1.825)*	(-0.920)
				Global			
162	0.010	0.217					
		(1.294)					
162	0.090	**0.665**	**-9.282**				
		(3.310)	**(-3.737)**				
162	0.208	**0.698**	**-8.105**	**-17.343**			
		(3.714)	**(-3.469)**	**(-4.854)**			
162	0.209	**0.693**	-6.826	**-17.494**	1.776		
		(3.661)	(-1.462)	**(-4.840)**	(0.317)		
161	0.324	**0.895**	**-12.759**	**-19.826**		**36.880**	
		(4.992)	**(-5.422)**	**(-5.892)**		**(5.149)**	
158	0.214	**0.689**	**-8.009**	**-17.418**			-3.864
		(3.611)	**(-3.351)**	**(-4.631)**			(-0.649)
158	0.352	**0.937**	**-9.113**	**-18.578**	5.089	**43.689**	**-14.833**
		(5.180)	**(-2.083)**	**(-5.354)**	(0.972)	**(5.666)**	**(-2.569)**

Table: Horizon 7: Idiosyncratic

Nobs	R^2	Latitude	GDPPC	Growth	Agriculture	Industry	Manufacturing
162	0.025	**0.127**					
		(2.038)					
162	0.052	**0.225**	**-2.026**				
		(2.921)	**(-2.124)**				
162	0.060	**0.228**	**-1.909**	-1.719			
		(2.966)	**(-1.994)**	(-1.174)			
162	0.080	**0.216**	1.063	-2.068	4.127*		
		(2.816)	(0.561)	(-1.411)	(1.814)*		
161	0.071	**0.242**	-1.809*	-1.225		-0.642	
		(3.211)	(-1.832)*	(-0.868)		(-0.214)	
158	0.071	**0.243**	**-1.926**	-1.425			0.739
		(3.271)	**(-2.070)**	(-0.973)			(0.319)
158	0.085	**0.228**	0.527	-1.691	3.266	-0.838	0.787
		(2.959)	(0.283)	(-1.144)	(1.466)	(-0.255)	(0.320)

Counterfactual Analysis

- What? Estimate temperature induced economic damages.
- How? Combine future temperature scenarios with our historical estimates of the effect of temperature shocks on real GDP per capita growth to perform counterfactual analysis from 2017 to 2100, and to construct empirical damage functions.
- Caution. Historical relationships, may break down.
  - Nonlinear new relationship at high and unexperienced temperatures, environmental tipping points, shifting population, or from adaption to higher temperatures by economic agents.

Future Temperature Scenarios

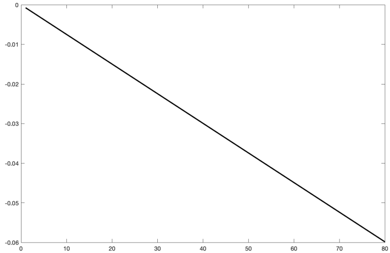
- Climate scientists build and run General Circulation Models to generate future temperature scenarios.
- Models are complex.
    - Radiative forcing (earth's net energy capture)
    - Climate sensitivity ($CO_2 \rightarrow$ temperature)
    - Effectiveness of carbon sinks (ocean surface, deep ocean)
    - Permafrost melt releases methane
    - Future land use, cement production
    - Adaptation, migration
    - Water vapor.

Naive USA Loss from Warming

- $\hat{\beta}_8 = -8.38 \rightarrow -1.197\%$ annual growth for 1^{o}C warming.
- Let temperature in 2100 increase $5^o C$ linearly, deterministically ($0.0625^o C$ per year).

$$y_t = -(0.0625)(0.0197)t$$

$y_{2100} - y_{2020} = -0.0599$ or about 6%.



Implied Loss from Estimates

- Treat projected country temperature changes as shocks. There will be more positives than negatives. Feed into estimated equations.
- Exploit all 8 horizon estimates for a joint prediction.

$$y_t - y_{t-2} = \Delta\tau_{t-2}\beta_2, y_{t-1} - y_{t-2} = \Delta\tau_{t-2}\beta_1 \rightarrow$$

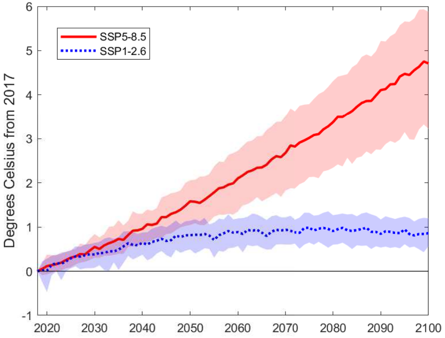
$$y_t - y_{t-1} = \Delta\tau_{t-2}(\beta_2 - \beta_1)$$

$$y_t - y_{t-3} = \Delta\tau_{t-3}\beta_3, y_{t-1} - y_{t-3} = \Delta\tau_{t-3}\beta_2\beta_2 \rightarrow$$

$$y_t - y_{t-1} = \Delta\tau_{t-3}(\beta_3 - \beta_2)$$

Etc. Take the average over the 8 horizons to get estimate annual growth loss.

Figure: SSP1-2.6 and SSP5-8.5 Future Temperature Scenarios



Notes: The shaded areas are the middle 80 percent of model projections for each climate scenario.

Figure: Percent Change in Real GDP Per Capita Between 2017 and 2100: SSP5-8.5 Scenario Relative to No Temperature Change Scenario

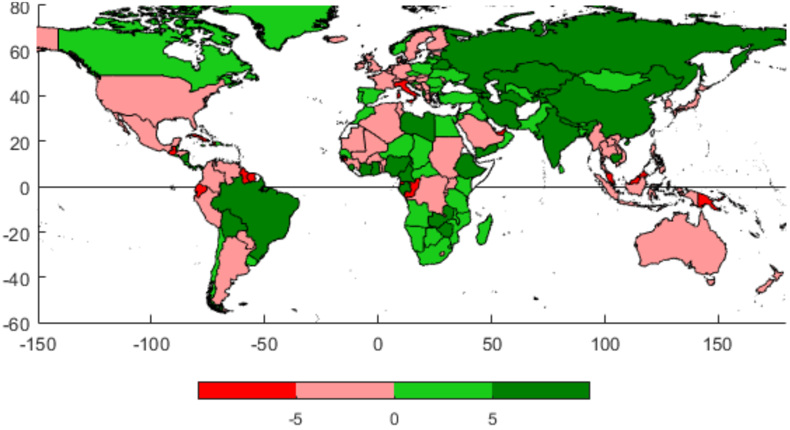
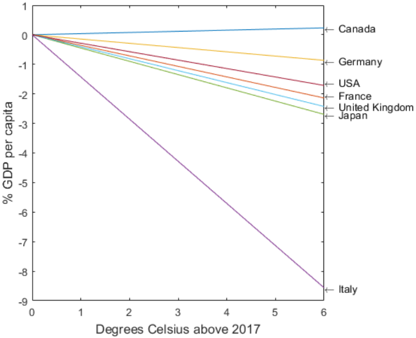


Figure: G-7 Estimated Damage Functions



Concluding Remarks

- Country response varies.
- Damages accrue to most rich countries.
- Benefits (historically) conveyed to many poor countries.
- Should incentivize rich countries to invest in mitigation, not just adaptation