Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis

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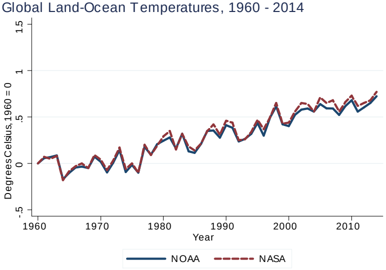
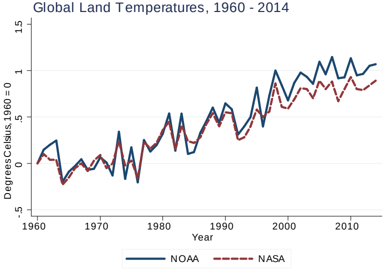
Motivation

- Global temperatures have increased significantly in the past half of a century and extreme weather events, such as heat waves, droughts and floods, as well as natural disasters are becoming more frequent and severe.

- Climate change is not only affecting low-income and developing countries, but also advanced economies—in September 2017 while Los Angeles experienced the largest fire in its history, Hurricanes Harvey and Irma caused major destruction in Texas and Florida, respectively.





Contribution

- We argue that climate change can have *long-term* macroeconomic consequences by suppressing labour productivity, slowing investment and damaging human health; something that is usually overlooked in the literature owing to the *short-term* focus of existing studies.

- We develop a theoretical growth model that links the deviations of climate variables from their historical norms to labour productivity and, hence, **long-term** economic growth.

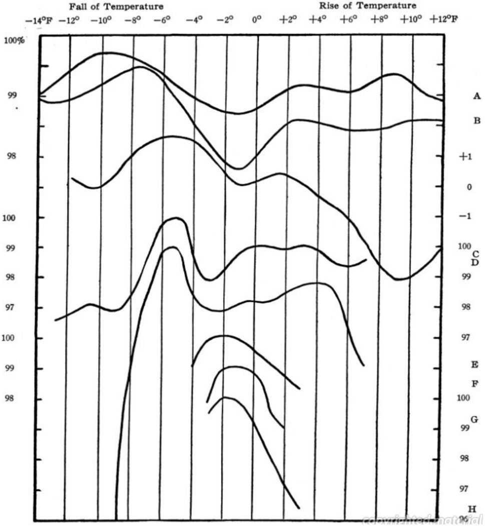
- We put the model to empirical test using a novel econometric strategy; that differentiates between short-term and long-run effects; accounts for bi-directional feedbacks between economic growth and climate change; and deals with temperature being trended.

- We investigate the **long-term** macroeconomic effects of climate change in a panel of 174 countries over 1960–2014 as well as a panel of 48 U.S. states over 1963–2016; i.e., studying both **cross-country** and **within-country** effects.

Literature

- The **climate-economy relationship** has been discussed for many centuries and goes back to at least Ibn Khaldun's 14th Century *Muqaddimah*, in which he attributed **poverty** to the **climate**.
- In fact Montesquieu came to the same conclusion in the *Spirit of Laws* (1750):
  - "There are countries where the excess of heat enervates the body, and renders men so slothful and dispirited that nothing but the fear of chastisement can oblige them to perform any laborious duty..."
- A few centuries later Huntington's (1915) *Civilization and Climate* aims to quantify the effects of climate on economic activity.

Human Activity and Changes of Mean Temperature from Day to Day

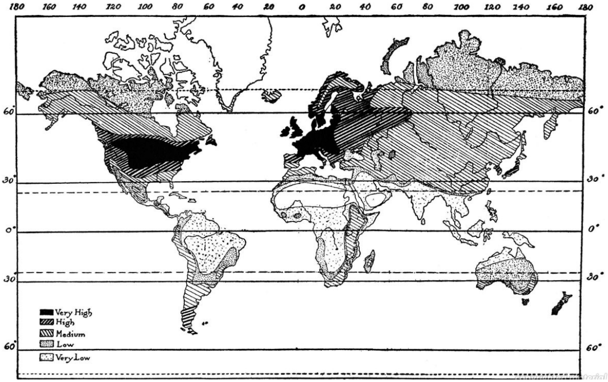


Notes: A. 300 Men in Two Connecticut Factories, 1910-13. B. 256 Girls in Two Connecticut Factories, 1911-13. C. 460 Students in Mathematics and English at West Point and Annapolis, 1909-1913. D. 760 Cigar-makers at Tampa, Fla., in Winter (October-March), 1912 and 1913. Factory A. E. 400 Cigar-makers at Tampa in Winter, 1913. Factory B. F. 400 Cigar-makers at Tampa in Summer (April-September), 1913. Factory B. G. 380 Cigar-makers at Tampa in Summer, 1912. Factory A. H. 380 Cigar-makers at Tampa in Summer, 1913. Factory A.

Literature

- Economists used to (and some still do) ask the question: Can **climate and/or the weather** explain why some countries are poor and others rich?

The Distribution of Human Energy on the Basis of Climate



Literature

- The question that more and more economists are now attempting to answer is: do **weather events and climate change** have consequences for **economic growth**?
- Investigating whether climate change has **long-term** (permanent) or **short-term** (temporary) growth effects is essential for designing mitigation and/or adaptation policies and supporting institutions.
- For example, the macro-climate estimates are a key input in calculating the social cost of carbon.

Literature

- The literature which attempts to quantify the effects of climate change on economic performance (agricultural production, labour productivity, commodity prices, health, conflict, and economic growth) is very young and mainly concerned with **short-run** growth effects—Stern (2007), IPCC (2013), Hsiang (2016) and the recent surveys by Tol (2009) and Dell et al. (2014).

- Moreover, there are a number of grounds on which the econometric evidence of the effects of weather/climate on growth may be questioned.

- Firstly, the literature relies primarily on a **cross-sectional approach** (see, for instance, Sachs and Warner 1997, Gallup et al. 1999, Nordhaus 2006, and Dell et al. 2009), and as such does not take into account the time dimension of the data (i.e., assumes that the observed relationship across countries holds over time as well) and is also subject to the endogeneity problem.

Literature

- Secondly, even the more recent studies in the literature that rely on panel data models and the fixed effects (FE) estimator implicitly **rule out any reverse causality from economic growth to rising average temperatures**; see, for instance, Burke et al. (2015), Dell et al. (2012, 2014), and Hsiang (2016).

- In fact, recent studies on climate science have provided strong evidence that the main cause of contemporary global warming is the greenhouse gases (GHG) released to the atmosphere by human activities (see, for instance, Mitchell et al. 2001 and Brown et al. 2016).

- In which case, when estimating the effect of climate variables on economic growth, temperature may not be considered as strictly exogenous, but merely weakly exogenous to economic growth; in other words economic growth in the past might have feedback effects on temperature in the future.

- In such cases it is well known that the standard FE estimator suffers from small-T bias, and that inference based on it will be invalid. Therefore, one should also be cautious when interpreting the results from these studies using the standard FE estimator.

Literature

- Thirdly, econometric specifications are often in terms of real GDP growth rates and the level of temperature, $\mathcal{T}_{it}$, and in some cases also $\mathcal{T}_{it}^2$; see, for instance, Dell et al. (2012) and Burke et al. (2015).

- But in cases where $\mathcal{T}_{it}$ is trended, which is the situation in almost all countries in the world (as I will show), inclusion of $\mathcal{T}_{it}$ in the regression will induce a quadratic trend in equilibrium log per capita output (or equivalently a linear trend in per capita output growth) which is not desirable and can bias the estimates of the growth-climate change equation.

- Finally, another major drawback of this literature is that the econometric specifications of the climate change–growth relation are generally not derived from or based on a theoretical growth model. Either an *ad hoc* approach is used, where output growth is regressed on a number of arbitrarily–chosen variables, or a theoretical model is developed but not put to a rigorous empirical test.

A Cross-Country Stochastic Solow-Swan Growth Model with Climate Effects

- Theoretical models of growth generally focus on technological progress and human resources as the main drivers of economic growth, and ignore the possible effects of climate on the growth process.

- For instance, Merton (1975), Brock and Mirman (1972), Donaldson and Mehra (1983), Marimon (1989), and Binder and Pesaran (1999), have developed stochastic growth models for single economies.

- We follow this literature and consider the growth process across N countries connected through sharing a common pool of technology and being subject to different weather conditions.

A Cross-Country Stochastic Solow-Swan Growth Model with Climate Effects

- We suppose that productivity is affected by a common technological factor, $\theta_t > 0$, and country-specific climate variables which we take to be the average country temperature, $\mathcal{T}_{it}$, and precipitation, $\mathcal{P}_{it}$. Specifically,

$$\Lambda_{it} = A_i \theta_t^{\lambda_i} \exp\left[-\gamma_i^{+\prime}\left(\mathcal{C}_{it} - \mathcal{C}_{i,t-1}^*\right)^+ - \gamma_i^{-\prime}\left(\mathcal{C}_{it} - \mathcal{C}_{i,t-1}^*\right)^-\right], \tag{1}$$

  where $A_i > 0$, $\lambda_i > 0$, $\mathcal{C}_{it} = (\mathcal{T}_{it}, \mathcal{P}_{it})'$, $\gamma_i^+ = (\gamma_{i\mathcal{T}}^+, \gamma_{i\mathcal{P}}^+)'$, $\gamma_i^- = (\gamma_{i\mathcal{T}}^-, \gamma_{i\mathcal{P}}^-)'$, and $\mathcal{C}_{i,t-1}^* = \left(\mathcal{T}_{i,t-1}^*, \mathcal{P}_{i,t-1}^*\right)'$ is historical climate norms.

- We assume that as long as $\mathcal{T}_{it}$ and $\mathcal{P}_{it}$ remain close to their respective historical norms (regarded as technologically neutral) then the climate variables are not expected to have any effects on labour productivity.

- However, in cases where the climate variables deviate from the historical norms the effects on labour productivity could be positive or negative, depending on the region under consideration.

A Cross-Country Stochastic Solow-Swan Growth Model with Climate Effects

- For example, in a historically cold region a rise in temperature above historical norm might have a positive effect, whilst for a dry region a fall in precipitation below historical norms is likely to have adverse effects on productivity.

- Recent research demonstrates that different regions of the U.S. have acclimated themselves to their own temperature niche. Heutel et al. (2016) document that extreme heat in hotter places in the U.S. causes fewer deaths than extreme heat where such heat is a large deviation from the historical average.

- Note that with the deviations of the climate variables from their historical norms separated into positive and negative deviations allows us to take into account the potential asymmetric effects of climate change on economic growth.

Data

- To test the relationship between economic growth and climate change, we need to obtain annual data on real GDP, temperature and precipitation.
- We construct the population-weighted climate data for each country and year between 1900 and 2014 using the terrestrial air temperature and precipitation data from Matsuura and Willmott (2015), which contains 0.5 degree gridded monthly time series of temperature and precipitation, and the gridded population of the world data from CIESIN (2016), for which we use the population density in 2010.
- We obtain the real GDP per capita data between 1960 and 2014 from the World Bank *World Development Indicators* database.
- Combining the GDP and the climate data we end up with an unbalanced panel, which is very rich both in terms of the time dimension (T), containing data on at most $T = 55$ years with average $T \approx 39$, and in terms of the cross-sectional dimension (N), containing 174 countries.

Evidence of Climate Change

- We first examine whether the global temperature has been increasing over the last half of a century (1960-2014).

- Allowing for the significant heterogeneity that exists between countries when it comes to changes in temperature across time, we estimate the following model using the mean-group (MG) estimator of Pesaran and Smith (1995):

$$\mathcal{T}_{it} = a_{\mathcal{T}i} + b_{\mathcal{T}i}t + v_{\mathcal{T},it}. \tag{2}$$

- The results suggest that the global land temperature has on average risen by 0.0181 degrees Celsius (°C) per year over the sample period.
  - *Goddard Institute for Space Studies* (GISS) at National Aeronautics and Space Administration (NASA): global land temperature has risen by 0.89°C (0.0165°C per year).
  - *National Centers for Environmental Information* (NCEI) at National Oceanic and Atmospheric Administration (NOAA): global land-surface air temperature has risen by 1.07 °C (0.0198 °C per year).

Evidence of Climate Change

Table 1: Mean Group Estimates from Regression of Temperature on a Constant and a Trend, 1960–2014

		Details on $\widehat{b}_{\mathcal{T}i}$:		
		Number of Countries	174	(100.0%)
Constant ($\widehat{a}_{\mathcal{T}}$)	17.8384***	of which positive	169	(97.1%)
	(0.6730)	of which negative	5	(2.9%)
Trend $\left(\widehat{b}_{\mathcal{T}}\right)$	0.0181***	Mean	0.0181	
	(0.0007)	Standard Deviation	0.0086	
		Minimum	-0.0044	(Samoa)
		10th Percentile	0.0069	
		1st Quartile	0.0124	
		Median	0.0181	
Number of Countries (N)	174	3rd Quartile	0.0240	
Number of Years (T)	55	90th Percentile	0.0285	
Number of Observations ($N \times T$)	7,300	Maximum	0.0390	(Afghanistan)

- This is an important result because it provides evidence that $\mathcal{T}_{it}$ is trended. As the econometric specification in the literature is generally in terms of real GDP growth rates and the level of temperature, $\mathcal{T}_{it}$, and in some cases also $\mathcal{T}_{it}^2$; see, for instance, Dell et al. (2012) and Burke et al. (2015).

- But in cases where $\mathcal{T}_{it}$ is trended, which is the situation in almost countries in the world (based on either the 1900–2014 or the 1960–2014 sample), inclusion of $\mathcal{T}_{it}$ in the regression will induce a quadratic trend in equilibrium log per capita output (or equivalently a linear trend in per capita output growth) which is not desirable and can bias the estimates of the growth-climate change equation.

The Long-Run Effects of Climate Change

- To examine the long-run effects of climate change on output growth, we estimate the following panel ARDL model:

$$\Delta y_{it} = \mu_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \boldsymbol{\beta}_\ell' \mathbf{x}_{i,t-\ell} + \varepsilon_{it}, \tag{3}$$

where y_{it} is the log of real GDP of country i in year t, $\mathbf{x}_{it} = [\Delta \left(\mathcal{T}_{it} - \mathcal{T}^*_{i,t-1}\right)^+,$ $\Delta \left(\mathcal{T}_{it} - \mathcal{T}^*_{i,t-1}\right)^-$, $\Delta \left(\mathcal{P}_{it} - \mathcal{P}^*_{i,t-1}\right)^+$, $\Delta \left(\mathcal{P}_{it} - \mathcal{P}^*_{i,t-1}\right)]'$, $\mathcal{T}_{it}$ and $\mathcal{P}_{it}$ are temperature and precipitation of country i respectively, and $\mathcal{T}^*_{i,t-1}$ and $\mathcal{P}^*_{i,t-1}$ are the historical norms of the temperature and precipitation of country i.

- The long-run effects, θ , are calculated from the estimates of the short-run coefficients in equation (3): $\boldsymbol{\theta} = \phi^{-1} \sum_{\ell=0}^{p} \boldsymbol{\beta}_\ell$, where $\phi = 1 - \sum_{\ell=1}^{p} \varphi_\ell$.

- For the historical norms, we consider the moving averages of temperature and precipitation of country i in the past $\overline{T}$ years: $\mathcal{T}^*_{i,t-1} = \overline{T}^{-1} \sum_{l=1}^{\overline{T}} \mathcal{T}_{i,t-l}$ and $\mathcal{P}^*_{i,t-1} = \overline{T}^{-1} \sum_{l=1}^{\overline{T}} \mathcal{P}_{i,t-l}$, with $\overline{T}$ being a large enough number such that the variations of the historical norm in each year is small.

The Long-Run Effects of Climate Change

- Most of the climate-macroeconomy literature provides evidence for the (**short-run**) negative effects of climate change, such as higher temperature, but **only for poor countries**; see, for instance, Sachs and Warner (1997), Jones and Olken (2010), and Dell et al. (2012).

- There are intuitive reasons and anecdotal evidence that **adaptation has been taking place**, especially in advanced economies. For instance, Singapore has attempted to insulate its economy from the heat by extensively engaging in economic activity where air conditioning can help offset the heat to some extent.

- Given the large heterogeneity across the 174 countries in our sample, a follow-up question is whether any potential **long-run negative effects can only be contributed to the poor countries in our sample**?

The Long-Run Effects of Climate Change

- To this end we augment (3) by including an interactive term, $\mathbf{x}_{i,t-\ell} \times \mathbb{I}\,(\text{country } i \text{ is poor})$ to capture any possible differential effects of temperature increases above the norm for the rich and poor countries:

$$\Delta y_{it} = \mu_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \boldsymbol{\beta}_\ell' \mathbf{x}_{i,t-\ell} + \sum_{\ell=0}^{p} \boldsymbol{\zeta}_\ell' \mathbf{x}_{i,t-\ell} \times \mathbb{I}\,(\text{country } i \text{ is poor}) + \varepsilon_{it}, \tag{4}$$

  where, as in Burke et al. (2015) we define country i as poor (rich) if the country's purchasing-power-parity-adjusted GDP per capita was below (above) the global median in 1980.

- Moreover, as there seems to be some evidence that **temperature increases might affect hotter countries more than colder ones**, we also investigate whether there are any differences across hot and cold countries.

Table 2: Long-Run Effects of Climate Change on per Capita Real GDP Growth, 1960–2014 (Historical Norms as the Moving Averages of Past 30 Years)

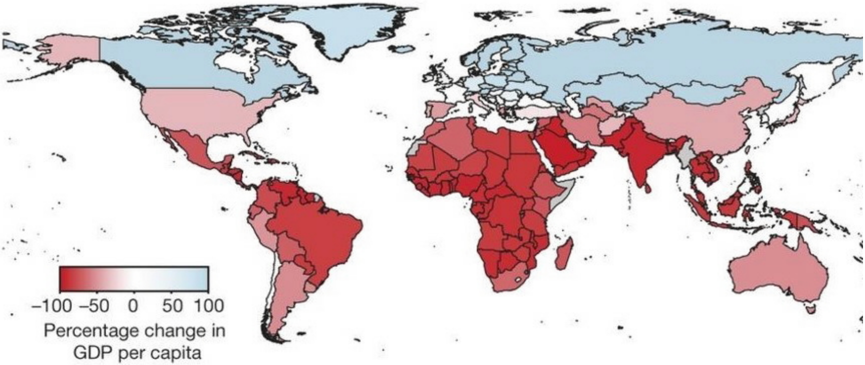
	Specification 1		Specification 2		Specification 3		Specification 4	
	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^*_{i,t-1}\right)^+}$	-0.0376***	-0.0577***	-0.0378***	-0.0586***	-0.0352**	-0.0545**	-0.0476***	-0.0692***
	(0.0126)	(0.0188)	(0.0126)	(0.0187)	(0.0149)	(0.0245)	(0.0127)	(0.0188)
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^*_{i,t-1}\right)^-}$	-0.0451**	-0.0505**	-0.0459**	-0.0520**	-0.0432*	-0.0480*	-0.0576**	-0.0677***
	(0.0223)	(0.0245)	(0.0223)	(0.0245)	(0.0231)	(0.0286)	(0.0236)	(0.0252)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^*_{i,t-1}\right)^+}$	0.0067	0.0079	-	-	-	-	-	-
	(0.0313)	(0.0359)						
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^*_{i,t-1}\right)^-}$	-0.0085	-0.0207	-	-	-	-	-	-
	(0.0372)	(0.0426)						
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^*_{i,t-1}\right)^+\times\mathbb{I}(\text{country } i \text{ is poor})}$	-	-	-	-	-0.0107	-0.0150	-	-
					(0.0251)	(0.0382)		
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^*_{i,t-1}\right)^-\times\mathbb{I}(\text{country } i \text{ is poor})}$	-	-	-	-	-0.0083	-0.0051	-	-
					(0.0546)	(0.0616)		
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^*_{i,t-1}\right)^+\times\mathbb{I}(\text{country } i \text{ is hot})}$	-	-	-	-	-	-	0.0317	0.0354
							(0.0270)	(0.0434)
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^*_{i,t-1}\right)^+\times\mathbb{I}(\text{country } i \text{ is hot})}$	-	-	-	-	-	-	0.0339	0.0540
							(0.0489)	(0.0620)
$\widehat{\phi}$	-0.6706***	-0.6026***	-0.6714***	-0.6038***	-0.6605***	-0.5946***	-0.6717***	-0.6043***
	(0.0489)	(0.0449)	(0.0489)	(0.0449)	(0.0501)	(0.0470)	(0.0490)	(0.0448)
No of Countries (N)	174	174	174	174	165	165	174	174
$\max T$	50	50	50	50	50	50	50	50
avg$T$	38.59	38.36	38.59	38.36	38.98	38.76	38.59	38.36
$\min T$	2	2	2	2	8	8	2	2
No of Observations ($N \times T$)	6714	6674	6714	6674	6431	6396	6714	6674

Table 3: Long-Run Effects of Climate Change on per Capita Real GDP Growth, 1960–2014 (Using Absolute Value of Deviations of Climate Variables from their Historical Norm)

	Specification 1			Specification 2			Specification 3			Specification 4		
Historical Norm:	20 Years	30 Years	40 Years	20 Years	30 Years	40 Years	20 Years	30 Years	40 Years	20 Years	30 Years	40 Years
$\widehat{\theta}_{\Delta\left\|\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right\|}$	-0.0498***	-0.0539***	-0.0479***	-0.0504***	-0.0543***	-0.0486***	-0.0521**	-0.0539**	-0.0475**	-0.0582***	-0.0664***	-0.0610***
	(0.0191)	(0.0183)	(0.0176)	(0.0191)	(0.0183)	(0.0176)	(0.0248)	(0.0237)	(0.0228)	(0.0190)	(0.0185)	(0.0183)
$\widehat{\theta}_{\Delta\left\|\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right\|}$	-0.0119	-0.0085	-0.0197	-	-	-	-	-	-	-	-	-
	(0.0319)	(0.0340)	(0.0346)									
$\widehat{\theta}_{\Delta\left\|\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right\|\times\mathbb{I}(\text{ } i \text{ is poor})}$	-	-	-	-	-	-	-0.0059	-0.0089	-0.0115	-	-	-
							(0.0402)	(0.0378)	(0.0364)			
$\widehat{\theta}_{\Delta\left\|\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right\|\times\mathbb{I}(\text{ } i \text{ is hot})}$	-	-	-	-	-	-	-	-	-	0.0226	0.0363	0.0370
										(0.0442)	(0.0423)	(0.0401)
$\widehat{\phi}$	-0.6038***	-0.6037***	-0.6033***	-0.6042***	-0.6042***	-0.6040***	-0.5959***	-0.5962***	-0.5959***	-0.6047***	-0.6045***	-0.6040***
	(0.0448)	(0.0449)	(0.0449)	(0.0449)	(0.0449)	(0.0449)	(0.0469)	(0.0469)	(0.0469)	(0.0448)	(0.0448)	(0.0448)
N	174	174	174	174	174	174	165	165	165	174	174	174
$\max T$	50	50	50	50	50	50	50	50	50	50	50	50
avg$T$	38.36	38.36	38.36	38.36	38.36	38.36	38.76	38.76	38.76	38.36	38.36	38.36
$\min T$	2	2	2	2	2	2	8	8	8	2	2	2
$N \times T$	6674	6674	6674	6674	6674	6674	6396	6396	6396	6674	6674	6674

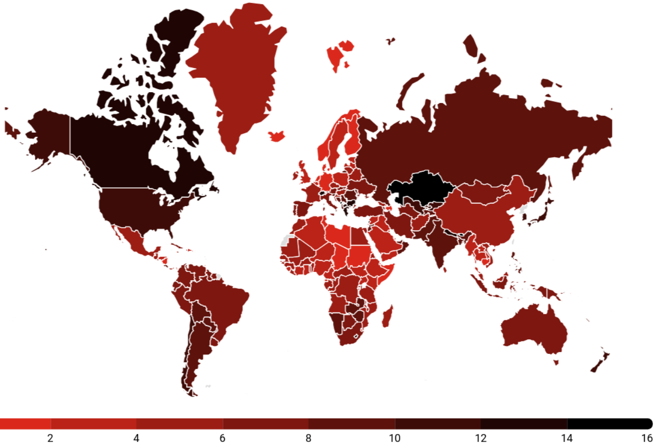
The Long-Run Effects of Climate Change

- These effects are significantly larger than those generally discussed in policy circles, particularly because most existing studies show that climate change has short-term growth effects (and permanent *level* effects) rather than **long-term growth effects** (and an ever-increasing level impact).
- To put our results into perspective, the conclusions one might obtain from existing climate change–macroeconomy literature are the following:
  - when a poor (hot) country is 1°C warmer than usual, its output growth falls by 1–2 percentage points in the short- to medium-term;
  - when a rich (temperate) country is 1°C warmer than usual, there is little impact on its economic activity; and
  - the GDP effect of increases in average temperatures (with or without adaptation and/or mitigation policies) is relatively small—a few percent decline in the level of GDP over the next century.



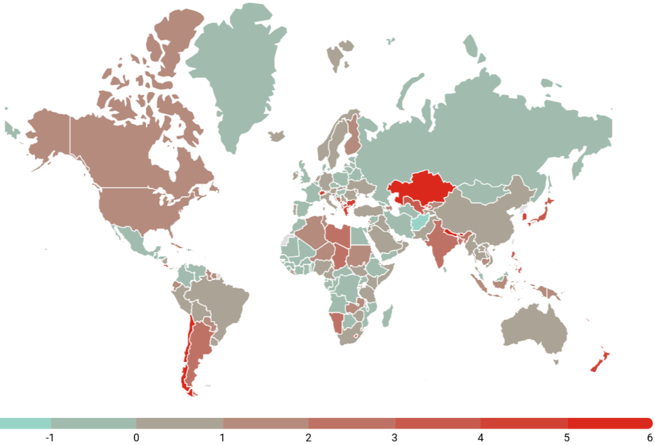
Source: Figure 4(a) in Burke et al. (2015). Global Non-Linear Effect of Temperature on Economic Production. *Nature* 527, 235–239.

Figure 6: Percent Loss in GDP per capita by 2100 in the Absence of Climate Change Policies (RCP 8.5 Scenario)



Notes: The heat map shows $\Delta_{ih}(d_i)$, see equation (31), in year 2100 with $m = 30$, based on the RCP 8.5 scenario.

Figure 7: Percent Loss in GDP per capita by 2100 Abiding by the Paris Agreement (RCP 2.6 Scenario)



Notes: The heat map shows $\Delta_{ih}(d_i)$, see equation (31), in year 2100 with $m = 30$, based on the RCP 2.6 scenario.

Table 7: Percent Loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 Scenarios

	Year 2030 ($h = 16$)			Year 2050 ($h = 36$)			Year 2100 ($h = 86$)		
$m =$	20	30	40	20	30	40	20	30	40
World									
RCP 2.6	-0.01	-0.01	-0.02	0.06	0.11	0.16	0.58	1.07	1.57
RCP 8.5	0.40	0.80	1.25	1.39	2.51	3.67	4.44	7.22	9.96
China									
RCP 2.6	-0.22	-0.45	-0.71	-0.38	-0.80	-1.31	0.24	0.45	0.67
RCP 8.5	0.31	0.58	0.87	0.90	1.62	2.30	2.67	4.35	5.93
European Union									
RCP 2.6	-0.04	-0.08	-0.13	-0.06	-0.13	-0.22	0.05	0.09	0.13
RCP 8.5	0.24	0.50	0.80	0.79	1.53	2.35	2.67	4.66	6.69
India									
RCP 2.6	0.12	0.26	0.42	0.41	0.81	1.27	1.44	2.57	3.69
RCP 8.5	0.60	1.16	1.78	2.13	3.62	5.08	6.37	9.90	13.39
Russia									
RCP 2.6	-0.07	-0.14	-0.23	-0.16	-0.34	-0.56	-0.33	-0.71	-1.19
RCP 8.5	0.51	1.03	1.63	1.62	3.08	4.61	5.28	8.93	12.46
United States									
RCP 2.6	0.10	0.20	0.33	0.29	0.60	0.96	0.98	1.88	2.84
RCP 8.5	0.60	1.20	1.86	2.13	3.77	5.39	6.66	10.52	14.32

Notes: We consider persistent increases in temperatures based on the RCP 2.6 and RCP 8.5 scenarios. Numbers are PPP GDP weighted averages of $\Delta_{ih}(d_i)$, see equation (31), with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 20$, 30, and 40.

Table 7: Percent Loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 Scenarios (continued)

	Year 2030 $(h = 16)$			Year 2050 $(h = 36)$			Year 2100 $(h = 86)$		
$m =$	20	30	40	20	30	40	20	30	40
Rich Countries									
RCP 2.6	0.02	0.05	0.09	0.12	0.23	0.37	0.58	1.09	1.62
RCP 8.5	0.42	0.84	1.33	1.46	2.67	3.93	4.74	7.76	10.75
Poor Countries									
RCP 2.6	-0.08	-0.16	-0.25	-0.08	-0.18	-0.32	0.55	0.99	1.43
RCP 8.5	0.37	0.72	1.09	1.24	2.18	3.11	3.78	6.05	8.25
Hot Countries									
RCP 2.6	0.00	0.00	0.01	0.08	0.15	0.23	0.62	1.11	1.60
RCP 8.5	0.39	0.76	1.17	1.35	2.37	3.39	4.17	6.65	9.10
Cold Countries									
RCP 2.6	-0.01	-0.02	-0.03	0.05	0.09	0.14	0.56	1.05	1.57
RCP 8.5	0.41	0.81	1.28	1.40	2.56	3.76	4.53	7.40	10.24

Notes: We consider persistent increases in temperatures based on the RCP 2.6 and RCP 8.5 scenarios. Numbers are PPP GDP weighted averages of $\Delta_{ih}(d_i)$, see equation (31), with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 20$, 30, and 40.

Table 8: Percent Loss in GDP per capita by 2030, 2050, and 2100 under the RCP 8.5 Scenario: the Role of Climate Variability

	Year 2030 ($h = 16$)	Year 2050 ($h = 36$)	Year 2100 ($h = 86$)
World	2.02	5.18	13.11
China	0.78	1.99	5.02
European Union	1.45	3.71	9.37
India	2.62	6.70	16.92
Russia	2.00	5.13	12.94
United States	2.66	6.81	17.19
Rich Countries	2.24	5.74	14.51
Poor Countries	1.52	3.92	9.91
Hot Countries	1.76	4.54	11.52
Cold Countries	2.10	5.39	13.62

Notes: We consider persistent increases in temperatures based on the RCP 8.5 scenario but set $\sigma^1_{\mathcal{T}i} = \frac{\mu^1_{\mathcal{T}i,j}}{\mu^0_{\mathcal{T}i}} \sigma^0_{\mathcal{T}i}$ in equation (31). Numbers are PPP GDP weighted averages of $\Delta_{ih}(d_i)$, with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 30$.

A Within-Country Study: United States

- To provide **further evidence for the consequences of climate change for advanced economies and the role of adaptation at the macro level**, we examine the validity of our results for the case of U.S.—an advanced country with a high level of economic development and some resilience-building activities against climate change across states and various sector.

- It is typically expected that advanced economies suffer less from climate change:
  - have more economic activity taking place indoors where, for instance, air conditioners can be installed,
  - should see better diffusion of adaptive technology,
  - could restructure with more ease due to more flexible labour forces and physical capital, and
  - are more able to afford to divert investment from productive to adaptive technologies.

- However, the fact that we found a long-run negative relationship between economic growth and climate change at the cross-country level regardless of whether a country is "rich" or "poor" (hot or cold), seems to indicate that dampening effects of adaptation has at best been limited.

A Within-Country Study: United States

- The **geographic heterogeneity** of the U.S. enables us to compare whether economic activity in the "hot" or "dry" states responds to a temperature increase in the same way as economic activity does in "cold" or "wet" states.
- Focusing on different sectors/industries also helps shed light on the **channels** through which climate change affects the United States economy.
- Considering the **richness of U.S. data**, we can examine the long-run impact of climate change on labour productivity and employment growth directly.

U.S. Climate and Economic Activity Data

- We obtain and construct data on economic activity at the state level from the Bureau of Economic Analysis (BEA): real Gross State Product (GSP) data is available from 1977 and nominal GSP data is available from 1963.

- BEA also provides output by sector at the state level from 1963, however there was a change in industrial classifications in 1997: over the period 1963 and 1997 the Standard Industrial Classification (SIC) is used (consists of ten division), while from 1997 onwards the North American Industry Classification System (NAICS) gradually replaces the SIC (branching the ten divisions into fifteen sectors). Matching the two we construct real output series by sector and state for the period 1963 to 2016.

- We collect state-level area-weighted climate data from the NOAA's National Centres for Environmental Information (NCEI). The NCEI reports monthly average temperature and precipitation for each state from aggregates of temperature readings across weather stations, adjusting for the distribution of stations and terrain.

- Finally, we obtain U.S. employment data from the Bureau of Labor Statistics.

Table 9: Long-Run Effects of Climate Change on the Growth Rate of Major Economic Indicators for the United States, 1963–2016

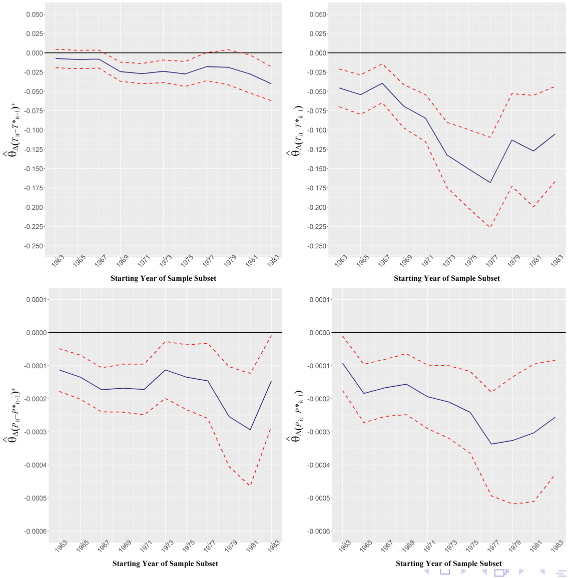
Historical Norm:	20 Year MA		30 Year MA		40 Year MA	
	Real GSP	Real GSP per Capita	Real GSP	Real GSP per Capita	Real GSP	Real GSP per Capita
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right)^{+}}$	-0.0245***	-0.0143**	-0.0152**	-0.0073	-0.0074	-0.0014
	(0.0081)	(0.0064)	(0.0077)	(0.0061)	(0.0073)	(0.0058)
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right)^{-}}$	-0.0672***	-0.0444***	-0.0697***	-0.0454***	-0.0485***	-0.0275**
	(0.0162)	(0.0124)	(0.0166)	(0.0124)	(0.0169)	(0.0127)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right)^{+}}$	-0.0001***	-0.0001***	-0.0001***	-0.0001***	-0.0001***	-0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right)^{-}}$	-0.0001**	-0.0001	-0.0001***	-0.0001**	-0.0002***	-0.0001**
	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0001)	(0.0000)
$\widehat{\phi}$	-0.7263***	-0.8896***	-0.7210***	-0.8875***	-0.7109***	-0.8734***
	(0.0491)	(0.0530)	(0.0494)	(0.0532)	(0.0495)	(0.0533)
No. of states (N)	48	48	48	48	48	48
T	48	48	48	48	48	48
$N \times T$	2304	2304	2304	2304	2304	2304

Table 10: Long-Run Effects of Climate Change on the Growth Rate of Major Economic Indicators for the United States, 1976–2016

Historical Norm:	**20 Year MA**				**30 Year MA**				**40 Year MA**			
	Real GSP	Real GSP per Capita	Real GSP per Employed	Employment	Real GSP	Real GSP per Capita	Real GSP per Employed	Employment	Real GSP	Real GSP per Capita	Real GSP per Employed	Employment
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right)^{+}}$	-0.0391***	-0.0279***	-0.0188***	-0.0136**	-0.0379***	-0.0273***	-0.0190***	-0.0135**	-0.0371***	-0.0271***	-0.0188***	-0.0125**
	(0.0108)	(0.0084)	(0.0067)	(0.0065)	(0.0107)	(0.0083)	(0.0067)	(0.0062)	(0.0105)	(0.0082)	(0.0065)	(0.0062)
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right)^{-}}$	-0.1554***	-0.1199***	-0.0604***	-0.0723***	-0.1951***	-0.1505***	-0.0779***	-0.0954***	-0.2089***	-0.1616***	-0.0847***	-0.1027***
	(0.0315)	(0.0233)	(0.0166)	(0.0183)	(0.0358)	(0.0259)	(0.0191)	(0.0205)	(0.0388)	(0.0283)	(0.0207)	(0.0221)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right)^{+}}$	-0.0001*	-0.0001*	-0.0000	-0.0000	-0.0002**	-0.0001***	-0.0000	-0.0001**	-0.0001**	-0.0001**	-0.0000	-0.0001**
	(0.0001)	(0.0001)	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right)^{-}}$	-0.0003***	-0.0002***	-0.0001	-0.0002***	-0.0003***	-0.0002***	-0.0001	-0.0003***	-0.0004***	-0.0003***	-0.0001	-0.0003***
	(0.0001)	(0.0001)	(0.0000)	(0.0001)	(0.0001)	(0.0001)	(0.0000)	(0.0001)	(0.0001)	(0.0001)	(0.0000)	(0.0001)
$\widehat{\phi}$	-0.5092***	-0.6327***	-0.7219***	-0.4371***	-0.5016***	-0.6301***	-0.7035***	-0.4382***	-0.4975***	-0.6215***	-0.6942***	-0.4290***
	(0.0503)	(0.0529)	(0.0756)	(0.0445)	(0.0504)	(0.0530)	(0.0756)	(0.0444)	(0.0502)	(0.0530)	(0.0749)	(0.0445)
No. of states (N)	48	48	48	48	48	48	48	48	48	48	48	48
T	36	36	36	36	36	36	36	36	36	36	36	36
$N \times T$	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728

Long-Run Effects of Climate Change on Growth in the U.S.

- If the U.S. economy was adapting should we not expect the negative effects of deviations from their historical norms to be shrinking over time?



Long-Run Effects of Climate Change on Growth in the U.S.

- Do these results cast doubt on adaptation in the United States over the last five decades?

- First, adaptation **within industries** does not necessarily affect output in the aggregate economy.

- Second, depending on whether adaptation outpaces **intensification of climate change**, we may or may not expect to observe significant relationships between climate change and economic growth.

- Third, if firms underestimate the likelihood or severity of future weather events, then they may not adapt sufficiently to maintain productivity as the climate changes. In a survey of private sector organizations across multiple industries within OECD countries, Agrawala et al. (2011) find that while **firms are generally aware of climate change risks, few take further steps to assess and manage those risks**.

- Fourth, since adaptation can be costly, some firms may undergo **partial or no adaptation**, meaning their productivity is shielded from climate change only to some extent. This is in line with the results of Deryugina and Hsiang (2014), who argue that adaptation has been limited in the US.

Evidence from U.S. Sector Level Data

- Overall the evidence seems to suggest that (at least for now) **adaptation has had limited effects** in dampening the negative effects of climate change in the United States.

- Given that adaptation is relatively easier and more effective to implement in some industries compared to others, **we exploit these inter-industrial differences** so as to shed more light on the matter of adaptation to climate change in the U.S. economy.

- Instead of Gross State Product, we make use of data on output for ten individual sectors at the state level.

Table 11: Long-Run Effects of Climate Change on the Output Growth of Various Sectors in the United States, 1963–2016

	Agriculture Forestry Fisheries	Mining	Construction	Manufacturing	Transport Communication Public Utilities	Wholesale Trade	Retail Trade	Finance Insurance Real Estate	Services	Government
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right)^{+}}$	-0.0323*	-0.0030	-0.0587***	-0.0666***	-0.0261**	-0.0628***	-0.0531***	0.0730***	-0.0336***	0.0182*
	(0.0178)	(0.0400)	(0.0204)	(0.0163)	(0.0112)	(0.0209)	(0.0126)	(0.0161)	(0.0110)	(0.0107)
$\widehat{\theta}_{\Delta\left(\mathcal{T}_{it}-\mathcal{T}^{*}_{i,t-1}\right)^{-}}$	-0.0184	-0.1887***	-0.1777***	-0.1136***	-0.0633***	-0.2365***	-0.1674***	0.0050	-0.1201***	-0.0446**
	(0.0315)	(0.0728)	(0.0400)	(0.0270)	(0.0175)	(0.0389)	(0.0237)	(0.0309)	(0.0252)	(0.0199)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right)^{+}}$	-0.0003***	-0.0006***	-0.0002**	-0.0002***	0.0001**	-0.0001	-0.0001	-0.0000	-0.0001*	0.0000
	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
$\widehat{\theta}_{\Delta\left(\mathcal{P}_{it}-\mathcal{P}^{*}_{i,t-1}\right)^{-}}$	-0.0005***	-0.0003	-0.0002	-0.0003***	-0.0001	-0.0003**	-0.0002***	0.0000	-0.0001*	0.0000
	(0.0001)	(0.0003)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
$\widehat{\phi}$	-1.8892***	-0.8133***	-0.6412***	-0.9599***	-0.8536***	-0.4830***	-0.5787***	-0.5944***	-0.4135***	-0.3902***
	(0.0843)	(0.0459)	(0.0331)	(0.0726)	(0.0581)	(0.0394)	(0.0312)	(0.0546)	(0.0414)	(0.0458)
No. of states (N)	48	47	48	48	48	48	48	48	48	48
T	48	48	48	48	48	48	48	48	48	48
$N \times T$	2304	2256	2304	2304	2304	2304	2304	2304	2304	2304

Evidence from U.S. Sector Level Data

- As expected, there is notable heterogeneity in the effects of climate change experienced by different industries, even though for the most part every sector is negatively affected by climate change in some way.

- While certain sectors in the U.S. economy might have adapted to higher temperatures, economic activity in the U.S. overall and at the sectoral level continues to be sensitive to deviations of temperature and precipitation from their historical norms.

- The evidence from both the cross-country analysis and the U.S. within-country study seems to suggest that while adaptation might have reduced the negative effects in certain sectors it has not completely offset the negative effects of climate change at the macro level. In line with Behrer and Park (2017), who note that even the hottest and most well adapted regions in the United States suffer negative production impacts from hotter temperatures.

Concluding Remarks

- We showed that climate change has a **long-term negative impact on economic growth**. If temperature deviates from its historical norm by 0.01 °C annually, economic growth will be permanently lower by 0.06 percentage points per year.
- Our counterfactual analysis suggests that without adaptation and mitigation, the loss in real GDP per capita is large (varying significantly across countries).
- We also provided evidence for the **substantial costs of climate change for the United States** and across all economic performance measures as well as across various economic sectors.
- Acknowledging past adaptation efforts, the evidence from our cross-country and within-country analyses suggests **limited success in reducing the negative economic effects of climate change in various sectors and at the macro level across countries**.
- Our findings call for a more forceful policy response to the threat of climate change.